Potential on- and off- site environmental impacts of large agricultural investments versus small-scale farming in Kenya and Mozambique

by

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DECLARATION

I hereby certify that this dissertation which I hereby submit for the degree MSc (Agric) Agronomy at the University of Pretoria, Department of Plant and Soil Sciences, is my own work and has not previously been submitted by me for a degree at another university or institution of higher education. I also certify that no plagiarism was committed in writing this dissertation.

Signed ____________________

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Abbreviations

AP	Acidification Potential
APSIM	Agricultural Production System sIMulator
CA	Conservation Agriculture
CDE	Centre for Development and Environment
CETRAD	Centre for Training and Integrated Research on ASAL Development Codes
CO_2-e	Carbon Dioxide Equivalent
EI	Environmental Impacts
EP	Eutrophication Potential
ET	Evapotranspiration
FAO	Food and Agriculture Organization
GLVF	Gurue Large-scale Virtual Farm
GSVF	Gurue Small-scale Virtual Farm
GWP	Global Warming Potential
IPCC	Intergovernmental Panel for Climate Change
LAI	Large-scale Agricultural Investment
LCA	Life Cycle Assessment
NAE	Agronomic Nitrogen-use Efficiency
NLVF	Nanyuki Large-scale Virtual Farm

NRE	Non-renewable Energy
NSVF	Nanyuki Small-investment Virtual Farm
OC	Organic Carbon
SSF	Small-Scale Farmer
WF	Water Footprint

Abstract

Over the last decade, Africa has been targeted by large-scale agricultural investments (LAIs) in the global rush for agricultural land and resources. This potential land use change has generated multifaceted and controversial political, environmental, economic, legal, and ethical issues. Despite this, in the case of Mozambique and Kenya, land use in the region remains dominated by small-scale farmers (SSFs) who are competing with LAIs for limited natural resources. In this study, the agronomic potential and environmental impacts of LAIs versus SSFs for two case studies in Kenya and Mozambique were investigated. The aim was to highlight major yield-limiting factors and environmental threats to better inform resource management and the sustainable integration of LAIs into the local landscape. Using data collected from interviews with LAIs and SSFs, a characterization of representative management practices and cropping systems was constructed. These “virtual farms” were analysed using a Life Cycle Assessment (LCA) approach to quantify potential off-site environmental impact indicators, namely: Eutrophication Potential (EP), Acidification Potential (AP), Global Warming Potential (GWP), the Water Footprint (WF), and Non-Renewable Energy (NRE) consumption. Furthermore, the APSIM model calibrated with local soil and weather data was used to quantify on-site soil degradation in the form of soil organic carbon (C) and total soil nitrogen (N) depletion and investigate yield gaps for each system.

Water scarcity was identified as the main limiting factor for SSF production in the Kenyan study region. The relatively high WF of LAIs and the collective WF of SSF irrigation pose a serious threat to already scarce blue water resources. A high demand for land was observed in the Mozambican study region. LAIs are contributing to land issues indirectly by displacing SSFs, thereby expanding cropland into areas previously under natural vegetation, and more directly through soil degradation.

The LAIs’ strategy of input intensification resulted in relatively high potential off-site impacts in both regions. In Kenya, this was offset by high yields, while in Mozambique the LAI yield gap remained high indicating low resource-use efficiency. Yield gaps for SSFs were high in both regions due to negligible input use in Mozambique and low resource-use efficiency in Kenya. Even though LAI systems are more productive than SSF systems, their intensification strategies have been shown to be unsustainable if management practices are not improved. On the other hand, the low yields observed in SSF systems are agronomically unproductive and also environmentally unsustainable.

While acknowledging that there are a myriad of factors contributing to the adoption of sustainable crop production practices, management strategies should be revised if both systems are to co-exist sustainably for decades to come. It is recommended that policies should be implemented to capture the positive spill-over effects from the introduction and re-introduction of LAIs to the region, specifically by promoting sustainable technology and information transfers, credit and short-term loans, and by improving the supply chains of important agrochemicals.

Keywords: land grabbing, life cycle assessments, APSIM modelling, water footprint, virtual farm

Introduction

Over the last decade, there has been a major increase in the number of foreign large-scale agricultural investments (LAIs) as part of the global rush for agricultural land and resources (Nolte *et al.,* 2016). These transnational land deals have been described by various authors as a response to a combination of factors, most significantly, global economic and food security crises, the adoption of new bioenergy policies, and the new investment opportunities in land resources (Arezki *et al.,* 2015; Dell'Angelo *et al.,* 2017; Nolte *et al.,* 2016). Econometric results by Arezki *et al.,* (2015) describe agro-suitability as a key determinant in the choice of the investment location. Additionally, countries where land sector governance and tenure security are weak have attracted the most investment (Arezki *et al.,* 2015). Consequently, Africa is the most targeted continent, with 422 concluded deals by 2016 equivalent to a total area of almost 10 million hectares (Nolte *et al.,* 2016). This represents 46.8% of all the globally acquired land area (Nolte *et al.,* 2016). This dissertation examines LAIs at a case-study level, focusing on study regions in Kenya and Mozambique where this extensive land use has generated multifaceted and controversial political, environmental, and economic issues (Joala *et al.,* 2016; Lanari *et al.,* 2016). Despite this, land use in these regions remains dominated by small-scale farmers (SSFs) who are competing with LAIs for limited shared resources (Hanlon & Smart, 2013; Njeru & Gitonga, 2004).

Supporters of these developments argue that LAIs are a necessary driver for agricultural growth and have the potential to alleviate poverty by increasing the agricultural productivity of underutilized land and stimulating rural economies (Dell'Angelo *et al.,* 2017). This is due to the belief that LAIs hold the economic and political power to capture economies of scale in input procurement, production, processing, storage, and marketing, (AGRA, 2013; Joala *et al.,* 2016). Combined with their ability to raise large amounts of capital, it is argued that LAIs can take advantage of innovations in breeding, mechanization, and information technology to maximize agronomic efficiency, allowing for higher yields and profits to be realized (Deininger *et al.*, 2010).

Whether these LAIs can hold up to these declarations is under debate, with global concern over their sustainability (Dell'Angelo *et al.,* 2017). Among socio-economic concerns, are doubts over their ability to increase productivity and warnings of their contribution to potential environmental degradation (Dell'Angelo *et al.*, 2017). There is particular concern that popular LAI management practices, such as monoculture, irrigation and agrochemical-use intensification, may result in higher yields but as a consequence also accelerate environmental degradation (Dell'Angelo *et al.,* 2017; Nolte *et al.*, 2016). However, these impacts should be viewed in context of the development goals of each host country and the agronomic efficiency and environmental impacts of alternative agronomic systems, which in this study is considered as pre-existing SSF production. Both Gurúè and Nanyuki, the two chosen study regions, have received international attention with a focus on the impact of LAIs (Di Matteo & Schoneveld, 2016; Joala *et al.,* 2016; Lanari *et al.,* 2016; Mekonnen *et al*., 2012; Muriithi & Yu, 2015; Smart & Hanlon, 2014). However, there have been no studies to date which contrast LAI production systems against the dominant SSF production system in terms of agronomic efficiency and potential environmental impacts using the same methodology.

In light of the dichotomous perceptions on LAIs versus SSFs as an argument of yield generation versus environmental degradation, this work aims to quantify the production potentials and on- and off-site environmental impacts of LAIs in comparison to the already present land users (SSFs). The specific objectives are:

- To collect qualitative and quantitative data on management practices of representative scenarios of LAI and SSF production systems in each study region.
- To quantify the potential and actual yields of LAI and SSF production systems and investigate the major limitations to production in each region as indicators of agronomic efficiency.
- To assess the Eutrophication, Acidification, and Global Warming Potential, Non-Renewable Energy consumption, and Water Footprint of the representative production systems per unit area and per unit yield as indicators of off-site environmental impact.
- To assess soil degradation potential as represented by the modelling of soil organic carbon (SOC) and total soil nitrogen (N) loss per unit area for LAI and SSF scenarios as an indicator of on-site environmental impact.

Chapter I: Literature Review

Large-scale agricultural investments (LAIs) were defined by Osabuohien (2014) as the 'possession of and/or controlling a scale of land for commercial/industrial agriculture production that is disproportionate in size in comparison to the average land holding in a region'. In recent years there has been growing concern over the fact that the number of LAIs worldwide has increased to unprecedented levels (Anseeuw *et al.*, 2012; Dell'Angelo *et al.*, 2017; Messerli *et al.*, 2013). Since small-scale farmers manage the majority of land worldwide this shift in systems of production could dramatically reshape the world's agrarian landscape which will have environmental implications (Dell'Angelo *et al.,* 2017).

This phenomenon has attracted not only the attention of international development organizations, United Nations (UN) agencies, and civil society, but also triggered research activities which have produced a growing body of literature analysing LAIs and their impacts and driving forces (Messerli *et al.,* 2013). LAIs have become a multi-disciplinary topic, according to Messerli *et al*., (2013), the main perspectives so far have been approached through the framework of political economy, political ecology, and agrarian change.

Studies show that the current land investments primarily target developing countries in Africa, specifically those that are among the poorest, are poorly integrated into the world economy, have a high incidence of hunger, and/or weak land governance (Anseeuw *et al.,* 2012; Bracco, 2015). In this context, there are two primary opposing perspectives on the subject: while studies have shown major threats to the rights and livelihoods of the rural poor with the colloquial terms 'land grabbing' and 'water grabbing' being used, others have portrayed the new investments as a much needed development opportunities for long-neglected sectors (Anseeuw *et al.,* 2012). Regardless of these political perspectives, the extensive and/or intensive land use change from predominantly smallholder agricultural production to LAI will have, in addition to socio-economic influences, agronomic, hydrological, and environmental implications (Dell'Angelo *et al.,* 2017).

1. The Gurúè case-study

Large agribusinesses are not a novel concept in the Gurúè region as sugar, sisal, and tea were produced on large plantations during the colonial era for export (Amanor, 2016). The history of Mozambique in the last century can be divided into:

a) The Portuguese colonial period (1498-1975)
b) Independence (1975)
c) Civil war (1977-1992)
d) Democratic era (1994-)

After independence colonial companies were nationalized into state farms (Clover & Eriksen, 2009). Agrarian policies favoured large-investment mechanized farms, but these farms would also buy produce from SSFs for processing and provide employment (Clover & Eriksen, 2009). During this time sale of produce was reliable and prices set, but they were often low and payments were late (Smart & Hanlon, 2014). From 1977 to 1992, civil war took place which led to the collapse of the agricultural sector, destruction of infrastructure, and a large build-up of foreign debt (Amanor, 2016). During the war it is estimated that four million people were displaced within the country (FAO, 2011). Gurúè district was also heavily affected by the war, with many communities fleeing from their villages (Smart & Hanlon, 2014). After civil war, Mozambique abandoned "socialism" and opened itself to liberal market reform (Amanor, 2016). State investment into agriculture became minimal, with only 4% of the annual budget during 2000 to 2008 allocated to agriculture, while international aid and the number of NGOs increased drastically (Amanor, 2016). As a result, Mozambique became heavily dependent upon food aid, which accounted for 86% of food consumption in the early 2000s compared to 9% in 1975 (Amanor, 2016).

Since independence, much of the debate and conflict around Mozambican agriculture revolves around land. Specifically, who can farm it more intensively to produce higher yields (Smart & Hanlon, 2014). The Mozambican government has endorsed a dual strategy whereby policies support both small-scale subsistence farmers and large-scale investment. Smart & Hanlon (2014) construes that:

"Underlying the dual strategy is the belief that if peasants could survive on their 1 ha, then there would be millions of hectares of farmland available to foreign and domestic investors who would create modern plantations and end rural poverty."

Large-scale agricultural investments were alleged to be key drivers of agricultural development for Mozambique by the neo-liberal government (Joala *et al.,* 2016). There was a belief that extensive production would allow for farmers to achieve economies of scale and maximize profits, which would generate trickle-down benefits (Di Matteo & Schoneveld, 2016). This approach contributed to the promotion and facilitation of capital-intensive large-scale commercial agriculture by the Mozambican government (Joala *et al.,* 2016). However, in recent years there has been a change in the discourse around agricultural policy as commercial agricultural investments have failed to encourage smallholder development and produce broad-based economic growth (Di Matteo & Schoneveld, 2016). Although there is a growing body of research into the impacts of the growing LAI sector in Mozambique, there still lacks a unified vision from the Mozambican government on how to best capitalize on and mitigate the risks of these investments (Di Matteo & Schoneveld, 2016; Smart & Hanlon, 2014).

In the global context, Mozambique is seen as a country with a large population of smallholders (3.2 million) with low productivity and although it is a net-importer of staple foods, it classifies 63.5% of its total land as arable, (Beekman *et al.,* 2014; Smart & Hanlon, 2014). Through this lens, the appeal of the large-scale agricultural production model is apparent. Economically, LAIs have access to cheaper credit, more negotiating powers with the government and the International Monetary Fund (IMF), and are able to ensure markets by more easily matching supply and demand (Smart & Hanlon, 2014). Moreover, LAIs have the potential of improving rural livelihood by introducing sanitation programmes, schools, clinics, providing employment, and constructing roads and communal buildings through Corporate Social Responsibility (CSR) (Fisseha, 2011). However, these advantages have not been sufficient to eventuate the successful, and profitable establishment of these new LAIs in rural Mozambique as of yet (Smart & Hanlon, 2014).

With the exception of sugar (*Saccharum officinarum*) and tobacco (*Nicotiana tobacum*) companies, which work through contract farming, the majority of LAIs in Mozambique have failed to become economically profitable or uplift rural communities (Smart & Hanlon, 2014). A thorough review of the different types of LAIs and motives for their failure and success was analysed and reviewed by Di Matteo & Schoneveld (2016) and Smart & Hanlon (2014). Along with on-farm management challenges, failure of LAIs are often due to changes in global economics with fluctuating oil prices and problems with financial aid during times of economic crisis (Anseeuw *et al.,* 2012). Failures have been observed particularly with investors that demand quick profits, rapid expansion, and high initial productivity (Smart & Hanlon, 2014). Bankruptcy of LAIs is especially devastating when it occurs after communities have been relocated and they have become reliant on the commercial farms for income (Schut & Florin, 2014).

Despite claims by the government that Mozambique had huge tracts of available land, it is challenging to assemble large areas of uninhabited, fertile land (Smart & Hanlon, 2014). Consequently, most of the land leased to investors was former state farms and colonial plantations that had been "abandoned" since the civil war (Di Matteo & Schoneveld, 2016; Smart & Hanlon, 2014). In many of these cases smallholders had returned to those lands for cultivation activities and access to resources, such as river and timber and non-timber forest products, after the civil war (Di Matteo & Schoneveld, 2016). Therefore, in reality, the acquired land was not "available", but rather occupied by smallholders that established farmlands interspersed between forests and shrubland (Di Matteo & Schoneveld, 2016). As a consequence, Di Matteo & Schoneveld (2016) reported that in Mozambique, out of the 69 LAIs investigated, 51.8% conceded that smallholder farmland and/or settlements were directly displaced. However, they caution that some LAIs may not be willing to disclose displacement information or take direct responsibility for those encroachments since land occupants are protects by the Land Law of 1997 (Van den Brink, 2008), which recognizes the land rights of communities and individuals acquired by customary or long-term occupation (Joala *et al.,* 2016). It is therefore highly probable that more LAIs were involved in displacement than the data suggests (Di Matteo & Schoneveld, 2016). This in turn has resulted in community conflicts as investors were met with strong resistance from farmers and civil rights organizations (Hanlon & Smart, 2013).

Over the last decade, Gurúè district has attracted different types of agro-investors, which Joala *et al.* (2016) categorized into three groups. The first group is made up of agribusinesses like Hoyo-Hoyo, AgroMoz and Murrimo Macadamia which are characterized by large-investment land acquisitions. The second group includes agri-dealers managing operations such as contract farming, grain trade sourcing and input provisions, such as Cargill and Phoenix Seeds. The third group comprises of international non-governmental organizations (NGOs) invested in agriculture, such as TechnoServe, the World Food Programme, and the National Cooperative League of the United States of America (NCLUSA). In this study focus is only placed on the first group, the LAIs which are compared to SSFs. However, we acknowledge that NGOs and agri-dealers have their own history and influence in the region which has potential impacts on the establishment and production practices of LAIs. A map containing the location and delineation areas occupied by major agro-businesses was created by Dr. Aurélien Reys from the AFGROLAND research project (Figure 1; Appendix A).

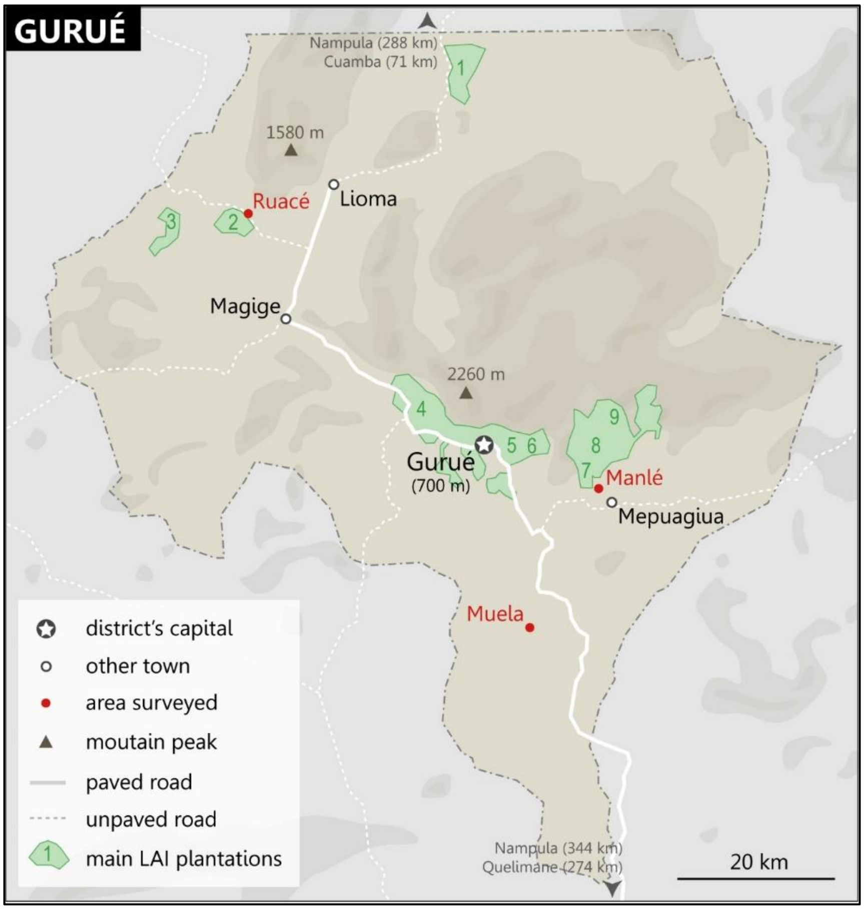

Fig. 1: Study area showing location of major agro-companies across the Gurúè district 1. AgroMoz (soybean), 2. Hoyo-Hoyo (soybean), 3. Rei do Agro (soybean), 4. Murrimo

Macadamia (macadamia nuts), 5. Chazeira de Mocambique (tea), 6. SDZ (tea), 7. ATFC (eucalyptus), 8. Cha Magoma (tea), 9. GF Macadamia (macadamia nuts). realized by Dr. Aurélien Reys for the AFGROLAND research project (personal communication; Appendix A)

1.1. Location and description of Mozambican study region

The district of Gurúè (city of Gurúè at 15.4715° S, 36.9810° E), in the north of the province of Zambézia is a highland area featuring a temperate climate with higher rainfall and lower evapotranspiration (ET) than other parts of the province (Joala *et al*., 2016). Administration of the district is divided between two posts in Lioma and Mepuagiua that have jurisdiction over a total of approximately 250 000 inhabitants (Aalerud, 2010).

Using Lioma's weather station (15.1765° S, 36.8062° E) as a representation of the study region's climactic characteristics as it was the station closest to the LAIs. Potential ET is 1300 mm per annum, mean rainfall is 1000 mm per annum, and mean annual temperature is 22.7^{o}C (MAE, 2005). The warmest month is October reaching a mean maximum temperature of 32.5^{o}C and the coldest month is July with the lowest average temperature at 13.6^{o}C (MAE, 2005). There is only one rainy season in the summer, which starts in November and ends in April of the next year (MAE, 2005). In winter there is a water deficit with the lowest monthly precipitation at an average of 10 mm in August (MAE, 2005). This limits recommendations for dryland production to one growing season per year during the summer (MAE, 2005).

There are two principal soil types found in the region. The first soil type is characterized by medium-textured red soil, it is well-drained with a low natural fertility and moderate erosion risk (MAE, 2005; Souirji, 1997). The second soil type is characterized as a medium-textured brown soil, it is a medium-depth, well-drained soil with low fertility, and highly prone to erosion (MAE, 2005; Souirji, 1997). According to the Soil Atlas of Africa found in Jones *et al.,* (2013), Northern Mozambique is dominated by lightly leached, clay-rich Luvisols, interspersed with Ferralsols and Leptosols.

The landscape of the district covers areas of mountainous zones separated by rugged peneplain areas, resulting in few occurrences of vast planal areas (MAE, 2005). This irregular topography coupled with high rainfall has allowed for numerous waterways to form throughout the region (MAE, 2005). Data on abstraction rates from the rivers and streams by different land users is lacking, but it is recognized as an important resource for drinking, cooking, and cleaning (MAE, 2005). Wedged between the mountain slopes and the natural waterways, even in dense forests and swampy areas, villages are scattered across the district (Joala *et al.*, 2016).

1.2. Gurúè small-scale farmers

Despite an influx of LAIs, Gurúè's economy is primarily dependent on agriculture which is still dominated by smallholder production (Aalerud, 2010; Joala *et al.*, 2016). The majority of land is characterized by a mosaic of smallholder croplands interspersed by forests and shrublands (Di Matteo & Schoneveld, 2016). Smallholders predominantly practice subsistence farming with a small percentage cultivating cash crops (Aalerud, 2010). These communities are therefore reliant on their plot of land for their livelihood and food security (Heltberg & Tarp, 2002).

1.2.1. Agronomic practices

Cropping systems typically involve rotations of mixed cropping of subsistence crops, namely maize (*Zea mays*), cassava (*Manihot esculenta*), beans (*Phaseolus vulgaris*), ground nuts (*Arachis hypogaea*), pigeon pea (*Cajanus cajan*), and cash crops such as soybeans (*Glycine max*), sunflowers (*Helianthus annuus*), tobacco (*Nicotiana tabacum*), and sesame (*Sesamum indicum*) (MAE, 2005; Joala *et al.*, 2016). From these commonly produced crops, three main crops were investigated: maize, soybean, and pigeon pea. Out of these three crops, maize is considered as the most important crop in the region, contributing to food security and income stabilization (Cunguara & Garrett, 2011). In the Zambezia Province, more than 80% of households produce maize, out of which 45% cultivated maize as a cash crop (Cunguara & Garrett, 2011). Soybean production has been a relatively recent "success story" in the Gurúè district (Hanlon & Smart, 2013). According to Hanlon & Smart (2013), the Gurúè district alone contains one-fifth of the Mozambican soybean producers. Soybean was first introduced in the 1980s to the Lioma State Farm by a team of Brazilians and has since been backed by NGOs such as NCLUSA, TechnoServe, International Institute of Tropical Agriculture (IITA) and others. These organizations provided technological support through improved seeds, inoculants, equipment, and extension services turning soybean into a profitable crop in the region (Hanlon & Smart, 2013). In 2014, Mozambique was the fifth largest producer of pigeon pea globally, and the third leading exporter of the crop (Walker *et al.* 2015). Pigeon pea was introduced as an ideal 'peasant' crop: it is nitrogen-fixing so it improves soil fertility, it is not a good crop for large farms due to difficulties with mechanization, and there is an assured market for export to India to make dhal (Walker *et al.* 2015). The most attractive quality for smallholders is that, other than reduced weeding, it requires negligible inputs, making it one of the most stable-yielding crops in the smallholder sector of Mozambique (Walker *et al.* 2015).

1.2.2. Production challenges

Crop yields in the study region have been reported as unproductively low (Aalerud, 2010). Research conducted by the National Cooperative Business Association under the Cooperative League of America (NCBACLUSA, 2016) reported average yields of 1.77 tonnes ha^{-1} for maize in Lioma. Hanlon & Smart (2013) reported average yields of 1.09 tonnes ha^{-1} for soybean in the Gurúè district. Walker *et al.* (2015) reported yields of 0.49 tonnes ha^{-1} for pigeon pea for Mozambique in 2012 based on the National Agricultural Survey in Mozambique (TIA).

The low crop yields of these three crops have been attributed to numerous factors. Firstly, the majority of SSFs do not have access to improved seed and are therefore reliant on traditional, less productive cultivars (FAO, 2011). Post-harvest losses are also markedly high due to high humidity, attack by pests, and theft during the storage stage (FAO, 2011). This is especially problematic as research done by FAO (2011) indicates that farmers rely on seed saved from the previous season for subsequent cultivation and consumption. In addition, crop yield produced during the rainy season supports a household for only eight months of the year, resulting in four months of food shortages (Cunguara & Garrett, 2011). December and January, the first months of cultivation, are therefore the most critical months for food security and considered as the "lean months" (Cunguara & Garrett, 2011).

To date, labour on smallholder farms is done by the farming household and day labourers using rudimentary tools such traditional hoes (*enchada*) and axes (*machade*) (Aalerud, 2010). Keeping livestock is not common in the Zambézia Province, consequently only 1.5% of SSFs were reportedly using animal traction (Cunguara & Garrett, 2011). There are good areas for pastures, but keeping livestock is not a traditional practice in the region (MAE, 2005). Tick-borne diseases, lack of funds, and poor extension services are some of the obstacles preventing SSFs from adopting livestock practices (MAE, 2005). As a result, the most affordable and least labour-intensive method of land preparation is through field burning (Di Matteo & Schoneveld, 2016). Planting, weeding, harvesting, and threshing is then all mostly done by hand (Hanlon & Smart, 2013).

Smallholder farmers are cultivating an average of 1 ha of land (Aalerud, 2010; Silici *et al*. 2015). This is partly because that is all that a family can till with hoes in a year (Smart & Hanlon, 2014). Smart & Hanlon (2014) explain that food shortages, especially during the lean months, means that insufficient calories are consumed to work an entire day, so even 1 ha can be difficult. As a consequence of these labor limitations it is also common for smallholders in Southern Africa to space crops at a low plant density of 1.5-3 plants per m^2 (Whitbread *et al.* 2010). These limitations are a major threat to food security, Smart & Hanlon (2014) warns that under these conditions no smallholder in Mozambique can feed itself and earn a bit of cash from 1 ha alone.

The cropping year for SSFs is mainly dependant on rainfall as irrigation is not common in the region (Silici *et a*l., 2015). A baseline survey by Cunguara & Garrett (2011) found that only 12% of households irrigated their crops in the Zambézia Province. Although SSFs produce year-round crops, like cassava, their main harvest will come from what they cultivate during the rainy season in summer (MAE, 2005). The growing season begins with planting at the onset of the rainy season, varying from November to December, and then ends with the last month of the dry season in September the following year (MAE, 2005). More than other crops, soybean is particularly photo-period critical (Hanlon & Smart, 2013). Planting must be done in December, and harvesting must occur after the seeds dry but before the seed pods crack open (Hanlon & Smart, 2013). Planting a month late, for example, can reduce production by 40% (Hanlon & Smart, 2013).

The smallholder system in Mozambique and the Gurúè district is characterized as a low-input-low-output system (FAO, 2011). There is an extremely low to non-existent use of agricultural inputs such as improved seeds, fertilizers and pesticides. Access to inputs is limited, most SSFs purchase or obtain inputs through tobacco companies and/or NGOs (Aalerud, 2010). A survey conducted by Cunguara & Garrett (2011) reported that seeds and labour were the most important inputs in Zambézia Province according to SSFs. About a third of the households interviewed reported pursuing improved seeds and only a tenth of households hired outside persons to help with labour activities. The demand for fertilizers and pesticides was observed as low, it was speculated that this might be due to the unavailability of these inputs or because they are too expensive (Cunguara & Garrett, 2011).

Smart & Hanlon (2014) explain that risk is a major limitation to SSFs investing in inputs. The threat of crop failure after the family has purchased inputs keeps SSFs conservative. They know that if they continue traditional practices they will produce something at the end of the season (Smart & Hanlon, 2014). A cost analysis by Hanlon & Smart (2013) reported that buying improved seed and two 50 kg bags of fertilizer would cost a typical smallholder family the majority of their annual income. SSFs know that fertilizers are useful, for example, tobacco farmers have reported using some of the fertilizer supplied to them by tobacco companies for their other crops (Hanlon & Smart, 2013). However, very few can afford to buy two bags of fertilizer a year and those who do purchase inputs have limited access to extension services (FAO, 2011; Hanlon & Smart, 2013). In a survey by Cunguara & Garrett (2011), only about 15% of rural households had contact with an extension agent in the Zambézia Province. FAO (2011) further reports that agricultural research and extension services are of low quality and have limited coverage.

Access to credit that can empower SSFs to purchase inputs is limited in the rural landscape. A lack of rural finance services is prevalent throughout Mozambique and the government's attempts to provide subsidized rates over the last two decades have been unsuccessful (FAO, 2011). Most government and donor programmes have involved the least expensive aid strategies such as advice, market information, and free or subsidised seed (Hanlon & Smart, 2013). Hanlon & Smart (2013) argue that organizations should be providing capital to allow for SSF production practices to change so that yields can consistently increase. Currently, most rural districts have no formal banking facilities and they rely on input credit and short-term loans from agribusiness companies and traders (FAO, 2011). Furthermore, SSFs suffer from weak market integration due to complex and burdensome systems of approval, licences, and levies that impede market entry and further raise the costs of doing business (FAO, 2011). If there is to be significant smallholder agricultural market expansion in Mozambique, improvements are required in risk management strategies, access to markets, and credit (Heltberg & Tarp, 2002).

1.2.3 Potential environmental impacts

Soil degradation through SSF farming practices has been identified as a major threat towards environmental sustainability (Silici *et al.*, 2015). SSFs' negligible use of agro-inputs, coupled with slash-and-burn to clear fields, and a limited fallow period may lead to rapid land degradation (Silici *et al.*, 2015). This vicious cycle of over-exploitation of land and the resultant process of nutrient mining and erosion could render soils in the Gurúè region unproductive (Headey & Jayne, 2014). Land degradation along with pests, diseases, and extreme weather conditions further exacerbate SSFs low agricultural productivity. Therefore, it is clear from existing literature that SSFs need to adopt more intensive cropping systems with improved farming techniques, but that this change should be done "sustainably" (Silici *et al.*, 2015). There is, however, a lack of quantitative data on the environmental impacts of SSFs in the Gurúè region to support this claim.

1.3. Gurúè large-scale agricultural investments

Since the pilot project, ProSavana, there has been an increase in Brazilian investors and technical cooperation in the Nacala Corridor. This has been an attempt at re-creating the agricultural revolution of the Brazilian *cerrado* in northern Mozambique's Nacala Corridor (German *et al.*, 2013). This involves echoing the large-investment mechanized soy-farming model prevalent in Brazil (Di Matteo & Schoneveld, 2016). Studies have shown that at least two companies, Hoyo-Hoyo and AgroMoz, are emulating this input intensive soybean cultivation model in the Gurúè region (Hanlon & Smart, 2013; Joala *et al.*, 2016). Joala *et al.* (2016) has identified LAIs producing soybean, macadamia, tea, and horticultural products in the Gurúè region. However, due to the prevalence and potentially high environmental impacts associated with the input intensification and mechanization of the Brazilian model, this study only focuses on LAI soybean cropping systems (Di Matteo & Schoneveld, 2016).

1.3.1 Agronomic practices

In these LAI annual cropping systems, soybean has been cultivated in rotation with maize to generate short-term cash flows as well as to practice crop rotation to maintain soil quality and avoid pest and disease buildup (Di Matteo & Schoneveld, 2016). However, the goal is to cease maize cultivation activities once soybean is established and starts to generate consistent revenues (Di Matteo & Schoneveld, 2016). This would result in continuous monoculture which could minimize costs and streamline management, but also potentially increase susceptibility to pests and soil degradation (Bonini *et al.*, 2018).

The biggest driver of soybeans production in Mozambique is currently soy-cake demand by the poultry industry (Joala *et al.*, 2016). Nationally, Hoyo-Hoyo and AgroMoz are targeting the feed end-market by supplying three big poultry companies, based in Nampula and Manica Provinces, with soybean and maize for stock feed (Joala *et al.*, 2016).

In terms of input intensification, Di Matteo & Schoneveld (2016) report that 83.1% of LAIs in Mozambique (n=69) involve some mechanization of production processes and 18.8% (n=69) used herbicides, insecticides, and fertilizers. Soybean investments across the country were found to have fully mechanized cultivation activities and to make full use of agro-chemicals. This supports the description of soybean cultivation in Mozambique as an input intensive system. In the Gurúè region, these soybean-producing LAIs procure seeds, fertilizer, and machinery mainly from Brazil and South Africa. While the major supplier of chemicals is Agri-Focus, a Mozambican company based in Maputo. At the time of the interviews conducted by Joala *et al.*, (2016), AgroMoz was finalizing plans for the construction of a dam that would capture the flood waters of natural streams for irrigation, while Hoyo-Hoyo had no plan or intention to invest in irrigation, due to the high costs involved in such an investment (Joala *et al.*, 2016). These studies show that although input intensification is the agronomic strategy of the majority of LAIs, access to inputs and infrastructure is a major challenge towards achieving it.

1.3.2 Production challenges

Other challenges reported by Joala *et al.* (2016) include the low level of education and skills of workers. This was the case with AgroMoz which utilizes modern tractors with sophisticated technology that they claim cannot be operated by workers from the neighboring villages (Joala *et al*., 2016). This highlights the discrepancy between the technological advances LAIs hope to make and the realistic adoption possible in the current socio-economic environment. According to Joala *et al*., (2016), Hoyo-Hoyo's biggest challenge, according to the farm manager, was the displacement of SSFs required to acquire 2 000 ha for production so as to achieve economies of scale. A 2012 Global Positioning System (GPS) survey by Environmental Justice Atlas (2014) indicated that 836 farmers with 1 945 ha were displaced and that Hoyo-Hoyo had the potential to impact up to 15 000 people in the neighboring Lioma and Ruace villages (Joala *et al.,* 2016).

This loss of land has inevitable negative spill over effects upon the community, the productivity potentials of SSFs, and the environment. Although it is not in the capacity of this study to thoroughly investigate community impacts, such as the loss of common pool resources, it should be understood that these factors contribute to the production capacity of a SSF. For example, the loss of access to medicinal plants, timber and non-timber forest products, and perennial water described by displaced SSFs in Joala *et al*., (2016), will have indirect impacts on the ability of SSFs to cultivate their land. More directly, the study by Joala *et al*., (2016) shows that displacement by Hoyo-Hoyo resulted in reduced SSF agricultural productivity due to issues such as the loss of land ownership, poor quality soils of the replacement land, and the inability of SSFs to coordinate activities and share resources. This in turn has resulted in frequent social unrest and conflicts between the LAI and neighbouring communities (Hanlon & Smart, 2013).

Despite these challenges, the comparatively high level of input use and mechanization by most investments, especially when compared to typical Mozambican production systems, has enabled LAIs to realize yields considerably higher than national averages (Di Matteo & Schoneveld, 2016). AgroMoz began soybean cultivation in 2013 with 370 ha and achieved a low yield of 1.89 tonnes ha^{-1} (Joala *et al.*, 2016). In 2014 they increased their planting area to 1 300 ha and managed to improve yields slightly up to 2 tonnes ha^{-1} (Joala *et al.,* 2016). When Hoyo-Hoyo initially began cultivation in 2012 they planted 1 000 ha of soybean but only achieved a yield of 1.5 tonnes ha^{-1} (Hanlon & Smart, 2013). Yields have not improved much since, with soybean yield of 2 tonnes ha^{-1} and maize yield of 4 tonnes ha^{-1} in 2015 (Joala *et al.,* 2016). Considering that these yields are comparatively higher than those achieved by SSFs, Di Matteo & Schoneveld (2016) argues that the adoption of intensive production practices does translate into enhanced agricultural productivity in Mozambique. Nevertheless, these yields are economically unprofitable and indicative of potentially low resource-use efficiency. This raises the question as to why, from an agronomic perspective, LAIs have not been able to reach yield potentials? It has been shown that economic and social limitations do pose challenges, however, the area has been described as a high potential agro-ecological zone. This question has remained unanswered due to the lack of published agronomic studies on realistic yield potentials or assessments on yield gaps for the Gurúè region.

1.3.3 Potential environmental impacts

In terms of environmental impacts, a significant potential impact is the conversion of land-extensive smallholder-forest-shrubland to plantation monoculture. Di Matteo & Schoneveld (2016) reported that 75.1% of investments in Mozambique involved a declared conversion of natural habitat. While acknowledging that SSFs were already potentially degrading the habitat, the conversion to LAI land-use often involves deforestation, pollution, biodiversity loss, soil erosion, and nutrient mining. A “leakage effect” is also expected in cases where investors have displaced SSFs from their land. This tends to result in SSFs seeking out new lands, thus exacerbating the rate of conversion of natural habitats to agricultural production while also advancing local land scarcity (Di Matteo & Schoneveld, 2016).

Di Matteo & Schoneveld (2016) reported that 75.6% of investors were implementing at least one or more conservation measures. The typical conservation measures adopted by LAIs were the preservation of environmentally significant tree species, the creation of riparian buffer zones, the preservation of high conservation value areas, the avoidance of cultivation on steep terrain and/or fragile soils, and the adoption of environmental monitoring systems. These environmental monitoring systems are particularly useful in a high-input system, like those used by LAIs, as they monitor agro-chemical use and pollution, application of soil erosion prevention techniques, recycling of wastes, adoption of integrated pest management systems and the implementation of mechanisms to control pollution.

Although increased investment in agriculture is critical to realizing long-term global and national food, energy, and water security targets, numerous critics have expressed concerns that the benefits of LAIs do not outweigh the costs (Dell'Angelo *et al.,* 2017). These impacts are especially severe in countries like Mozambique where weak governance structures lack the ability and political will to capture the positive spill-overs of LAIs while still enforcing existing social and environmental protections (Di Matteo & Schoneveld, 2016)

2. The Nanyuki case-study

The history of land ownership over the last century in the study area and Kenya in general can be divided into three significant periods:

(1) The pre-colonial period when the Masai community had communal ownership over land which they used for pastoralism,
(2) The British colonial period (1895-1963) where land ownership was divided into two land categories: the 'white highlands' and the 'native reserves', and
(3) The post-colonial period which brought new land laws and reforms.

The post-colonial government acquired formerly white-owned lands and subdivided it into 1.5 to 5 ha parcels to distribute ownership to thousands of African SSFs (Lanari, 2014). This resulted in the rapid immigration of SSFs, especially from areas with high population pressures, onto these newly available lands, including the Laikipia County. Njeru & Gitonga (2004) reported that the population in the Laikipia County increased from an estimated 30 000 in 1964 to 450 000 in 2002.

Land use systems have transformed drastically in recent years towards agricultural intensification. This has brought focus to the dilemma of how to sustain profitable production while still conserving the fragile environment and managing upstream–

downstream water conflicts (Ngigi *et al.,* 2008). Current land use practices were identified and categorized into five main land use practices by Muriithi & Yu (2015):

(1) Irrigation-dependant, all-season, large-investment intensive horticulture,
(2) All-season, contract-based, small-scale intensive horticulture,
(3) Subsistence and cash crop mixed-farming,
(4) Urban uses which include residential settlement and small industry, and
(5) Forest.

This mix of land users each poses their own environmental impacts that require different management strategies. This study focuses on the production practices of Groups 1 and 3, categorized as LAIs and SSFs, respectively.

2.1. Location and description of the Kenyan study region

The Kenyan case study area is situated around the town of Nanyuki (1 947m, 0.0074^0 N, 37.0722^0 E) on the western slopes of Mount Kenya. It is part of the Rift Valley and Central Provinces and falls under the administration of the Laikipia, Meru, and Nyeri counties (Zaehringer *et al.* 2018). The topography of the region traverses seven ecological zones: from the humid to semi-humid upper mountain slopes where mean annual rainfall can reach 1000-1500 mm, to the arid lowlands where rainfall can be as low as 350 mm (Lanari, 2014). Vegetation patterns are substantially variable across the region depending on the degree of effective precipitation, soil type and anthropogenic modifications (Taiti, 1992). A total of 12 categories of natural, semi-natural, and anthropogenic vegetation types have been identified, ranging from agricultural and urban vegetation to natural and plantation forests, grassland, bushland, and marshy wetlands (Taiti, 1992).

The study area receives an average rainfall of 700 mm yr^{-1} with a bimodal rainfall pattern (Njeru & Gitonga, 2004). It is characterized by long rains from mid-March to mid-June and short rains from October to December (Njeru & Gitonga, 2004; Lanari, 2014). The relatively low amount of rainfall is attributed to the location of the study area on the leeward side of Mount Kenya (Mutiga *et al.* 2010). Annual potential evapotranspiration

(PET) rates range from 2000-2500 mm yr^{-1}, which compared to annual rainfall attests to a large water deficit making the area semi-arid. Nonetheless, crop growth and, consequently, socio-economic development is predominantly dictated and limited by rainfall distribution which is variable between years and throughout the year rather than total quantity (Ngigi et al., 2008; Njeru & Gitonga, 2004). An abundance of water resulting in flood flows occurs during the long rains while severe water scarcity is experienced during the dry season (Njeru & Gitonga, 2004). This means that rainfall is usually not consistent enough to meet crop water demand without some periods of water stress. Consequently, there has been an over-abstraction from river sources for crop irrigation during the periods (Njeru & Gitonga, 2004). Abstraction was found to increase from 20% of the total average abstraction during the rainy season to over 70% during the dry season, and as a result, river flows have progressively decreased to about 30% of 1960 levels (Ngigi *et al.* 2008). This combination of highly variable rainfall and high PET is aggravated by high competition for water during the dry periods and has created an extremely risky environment for crop production (Njeru & Gitonga, 2004).

Several different soil types have been identified along the topographical gradient and details of their specific characteristics are discussed in Njeru & Gitonga (2004) and Muriithi & Yu (2015). Briefly, soils in the district have formed as a result of volcanic activity along the Rift Valley (Muriithi & Yu, 2015). The mountainous soils are mainly deep Andosols, Acrisols, and Alisols with a loam to clay texture, high organic matter content, are prone to acidity and erosion, and exhibiting highwater storage capacity (Njeru & Gitonga, 2004). Plateau soils are mostly deep Luvisols, Phaeozems, and Vertisols with a sandy clay to clay texture, moderate organic matter content, high fertility and high-water storage capacity (Njeru & Gitonga, 2004). According to Njeru & Gitonga (2004), due to the continuous production by small-scale farmers, soil degradation in the form of declining soil organic matter and fertility is expected in the region.

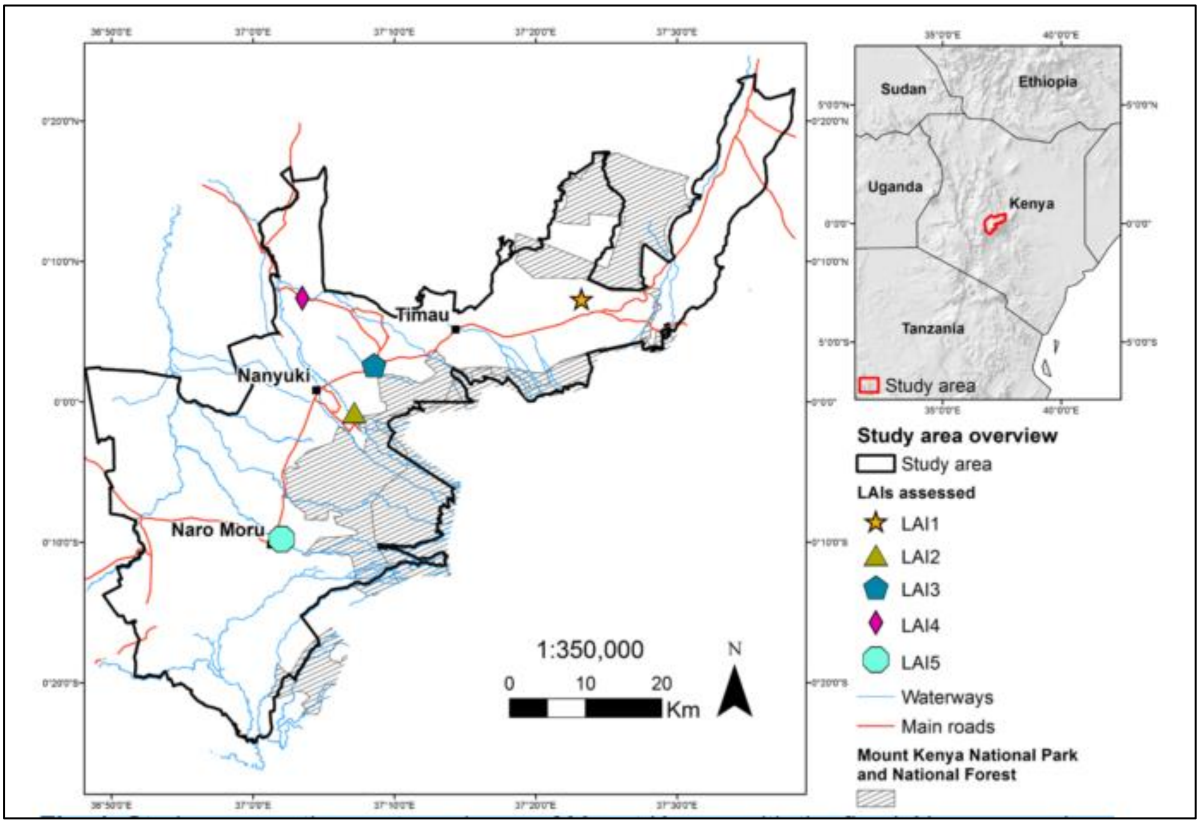

Fig. 2: Study area on the slopes of Mount Kenya, including the five large-scale agricultural investments (LAIs) assessed, as well as major towns, roads, waterways and the Mount Kenya National Park and National Forest (Eckert *et al.*, 2017).

2.2. Nanyuki small-scale farmers

The livelihood strategies and production systems of SSFs in the Nanyuki region have been thoroughly studied for more than 20 years (Ulrich *et al.,* 2012; Zaehringer *et al.,* 2018; Kiteme *et al.,* 2008; Ogalleh *et al.,* 2012; Wiesmann, 1992). Since the agro-ecological conditions in the study region are so extremely diverse, a very wide variety of 'reactive' crop management practices are represented (Sheahan *et al.,* 2013). Through reviewing previous studies common agricultural practices, challenges to crop production, and potential environmental impacts were identified, while acknowledging that massive generalizations are being made.

2.2.1. Agronomic practices

The most common SSF production system includes intercropping and livestock keeping on an average plot size of approximately 1-3 ha, mostly for subsistence and occasionally for the market (Ulrich, 2014; Zaehringer *et al.,* 2018). Intercropping and crop diversification is not only a traditional practice in the region, SSFs have also expressed its ecological benefits for pest management, soil quality improvement and efficient crop spacing (McCord *et al.,* 2015).

When it comes to crop selection, there is a multitude of factors that influence the cultivation of specific crops. These include, the ability to cope with adverse weather and market events, food security, maintenance of traditional practices, and productivity potential (Gichuki & Kihara, 2000). Due to the culmination of these factors, the staple crops grown in the region are maize, beans, potatoes (*Solanum tuberosum*), wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*) (Gichuki & Kihara; Ulrich *et al.,* 2012). In a survey by Ulrich *et al.* (2012) in 2010, crop choice resulted from the desire of SSFs to achieve food security and maintain a traditional diet. Few SSFs will also grow higher value horticultural products such as kale (*Brassica oleracea var. sabellica*), spinach (*Spinacia oleracea*), cabbage (*Brassica oleracea var. capitat*a), and garden peas (*Pisum sativum*) (Ulrich *et al.,* 2012). Subsistence crops such as maize and beans are mainly intercropped, while cash crops like potatoes and wheat are often grown in pure stands (Njeru & Gitonga, 2004). In this study maize, beans, and wheat were chosen for detailed investigation. Potatoes were excluded from the research because there was not enough data from the surveys to do any significant analyses.

Estimating average crop production yields is notoriously challenging due to the variable and erratic rainfall patterns in the region and farmers say that "it is impossible to refer to a normal year of production" (McCord *et al.,* 2015). Potential yields in the study region have been investigated through long-term field trials and crop modelling by Njeru & Gitonga (2004). It was estimated that, based on Kalalu weather station data, if no water conservation measures are taken the maize grain yields range from nil to 8.7 tonnes ha^{-1}, with the 21% chance of crop failure (<0.4 tonnes ha^{-1}). The average grain yield for beans under these rainfed conditions did not exceed 0.4 tonnes ha^{-1}. Estimated water use remained below model-estimated crop water demand in many of the seasons, ranging from seasons where the crop water requirement could not be fully met, to seasons where complete crop failure would occur (Njeru & Gitonga, 2004). Various studies have shown that the high variability in crop water supply makes crop production in the study area highly risky (McCord *et al.,* 2015; Njeru & Gitonga, 2004; Ulrich *et al*., 2012). Finding studies capturing the average actual yields of SSFs in the region was challenging, this then poses difficulties in analysing general yield gaps.

In terms of input use, after market liberalization in the mid-1980s the private sector participation in marketing systems expanded and in many parts of Kenya this resulted in easier accessibility to agricultural inputs (Mathenge *et al*., 2014). Swanckaert (2012) reported 11 maize seed companies selling a variety of improved maize cultivars with 164 varieties released from 1964 up until 2009 in Kenya. Consequently, the numbers of improved maize varieties and hybrids grown on smallholder farms have also increased tremendously (Sheahan *et al*., 2013).

In 2010 the average distance to the nearest fertilizer dealer was estimated at 3.5 km from the SSF's home and commercial fertilizers were deemed affordable across a large portion of Kenya's maize producing areas (Sheahan *et al*., 2013). Although Njeru & Gitonga (2004) states that soil fertility does not greatly limit crop growth and production in the study region, Sheahan *et al*. (2013) found that most households in the Rift Valley Province are using fertilizer at high application rates and that some households may even benefit from a reduction in the amount of N they apply.

A study by Nyakundi *et al.* (2017) found that pesticides are readily available and widely used by SSFs in the Rift Valley and Central Provinces of Kenya. The main herbicides used were identified as Linurex 50 wp and Diurex 80 wp while insecticides included Diazol 60EC and Methomex 90S, fungicides included Folicur EW and Dithane M45 (Nyakundi *et al.,* 2017). Unfortunately, pesticide misuse is common in Kenya due to factors such as high illiteracy levels, inaccessibility to reliable protective clothing, availability of unregistered products, the sale of expired products, and cases of decanting and reweighing (Nyakundi *et al.,* 2017).

Small-scale farming systems include both rainfed and irrigated production, with irrigation farming covering an estimated 14.9 km^2 of the Ewaso N'giro Basin (Gichuki & Kihara, 2000). Most irrigators use flood and sprinkler irrigation methods which can be inefficient irrigation methods that result in unproductive losses through runoff, deep drainage, and evaporation (Gichuki & Kihara, 2000). Ngigi *et al*. (2008) observed that SSFs irrigation efficiency in Kenya was low at 25–40% and coupled with inadequate flood irrigation methods, water use efficiency is consequently very low. This is particularly problematic in the context of Nanyuki as a water scarce region where water is the major limiting factor for crop production (Njeru & Gitonga, 2004). Various authors argue that smallholder farmers who are practicing rainfed agriculture lack the appropriate knowledge and techniques of water conservation and this, in turn, results in low crop productivity and frequent crop failures (Gichuki & Kihara, 2000; Njeru & Gitonga, 2004; Ulrich *et al.,* 2012)

2.2.2. Production challenges

As noted above, the Nanyuki region poses a multitude of agro-ecological challenges, most notably the rainfall season variability, deteriorating levels of soil organic matter (SOM), and high potential evapotranspiration (PET) rates (McCord *et al*., 2015). According to Ulrich *et al*., (2012), the average plot size has been similar since 1997, and Kohler (1987) argues that these plots are not large enough to secure subsistence under the present agro-ecological conditions, limiting the potential for sustainable smallholder agriculture. This is reflected in surveys by Ulrich *et al*., (2012) which assessed the ability of households to live off their own production. Results showed that during the "bad years" of low productivity, most households could not live off their own production for more than three months. These surveys also highlighted that several farmers indicated that the last "good year" of production was as far back as 1998. These studies reflect that only a low level of subsistence is possible with the current land size under the given environmental conditions.

Due to the influx of LAIs in the region, there has been an increasing pressure on already limited natural resources (Ulrich *et al.,* 2012). As discussed for the Mozambican case study, the loss of natural resources has potential impacts on the production possibilities of SSFs. Along with constraints such as price fluctuations, lack of market, political instability, post-harvest losses and poor health, the main limiting factor to improving their production potential has, repeatedly, been attributed to water scarcity. Kohler (1987) estimated that maize is only free of water stress for 25% of the season, and beans and potatoes for 45% of the season. Mekonnen & Hoekstra (2014a) explain that the temporal and spatial variability of rainfall combined with the high crop water requirements typical in the semi-arid conditions prevents the region from being suitable for rainfed crop production. However, since the available surface and sub-surface water is limited, irrigated crop production is regarded as an unrealistic way of addressing production issues in the region and there is a growing emphasis on increasing water-use efficiency (Mekonnen & Hoekstra, 2014a; Njeru & Gitonga, 2004; Flury, 1987)

2.2.3 Potential environmental impacts

The majority of SSFs in the region consider keeping livestock as an important component of their agricultural practices that they use to generate cash income and as a buffer during food deficit periods (Ulrich *et al.,* 2012). However, the removal of crop residue from the field is done so to use as fodder for livestock. This removal exposes the soil to high evaporation losses, increases runoff, and potentially lowers the fertility of the soil (Gichuki & Kihara, 2000).

The resultant high population growth after migration led to an expansion of agricultural production into marginal areas, previously used for grazing, and to fragile mountain slope ecosystems prone to erosion (Njeru & Gitonga, 2004). Erosion then contributes to increased sediment loading in rivers, dams, and lakes, further deteriorating scarce water resources and reducing reservoir capacity (Muriithi & Yu, 2015). Not only does high population growth force farmers to cultivate suboptimal agricultural land, but it also drives SSFs to use the same plots of land season after season with no fallow period to replenish the soils (Sheahan, 2011). This can result in soil fertility depletion if nutrients are not returned to the soil, which can result in decreased agricultural productivity and erosion (Sheahan, 2011). However, the high fertilizer use in the province could counteract this degradation. Available data on actual or potential soil fertility degradation by SSFs in Nanyuki is lacking and, therefore, a better understanding of this phenomenon is needed.

Moreover, the Eutrophication Potential (EP) of SSF system is amplified due to the use of dry livestock manure and sludge, which is associated with high nitrate concentrations ending up in surface water (Muriithi & Yu, 2015). Muriithi & Yu (2015) warns that the pollution of current water resources coupled with the evident increase in water abstraction will lead to the potential aridification of the region.

2.3. Nanyuki large-scale agricultural investments

In the last few decades, the Nanyuki region has become one of the prime areas for flower and vegetable production in the world and an attractive area for large-scale agricultural investment (Lanari, 2014). The region exhibits relatively good agro-ecological conditions, which paired with its ideal location near the equator allows for year-round, relatively efficient, and profitable horticultural production (Lanari, 2014). After independence, international investments in the Kenyan horticulture sector grew rapidly (Lanari, 2014). This boom in investments consisted of export-orientated, highly-mechanized, input-intensive, greenhouse horticulture and floriculture that has since continued to grow (Zaehringer *et al, 2*018). By the end of the 1980s, Kenya was the leading supplier of fresh vegetables to 12 European countries (Lanari, 2014). Between independence in 1963 and 1991, horticultural exports increased around 12fold in terms of volume and fortyfold in terms of value (Lanari, 2014). From 2003 to 2013 the number of recorded LAIs increased from 24 to 35 transforming commercial, intensive agriculture into the norm (Lanari, 2014). Moreover, there has been a major shift from vegetable crop production to floriculture, with roses as the dominant crop (Lanari, 2014). In 2013, roses were planted on 328 ha out of the total 421 ha under floriculture and produced approximately 294 million stems that year (Lanari, 2014). Therefore, this study focuses on LAI rose cultivation for further investigation into its agricultural practices and consequent environmental impacts, including its contribution to the use of scarce water resources.

Commercial horticulture in Nanyuki and its various impacts and development has been studied intensively from a variety of perspectives. Scholars have mainly analysed the influence of LAIs on livelihood strategies (Kiteme *et al.,* 2008, Ulrich *et al.,* 2012), economic impacts (Chandra, 2006), and environmental impacts, particularly with a focus on how to manage scarce water resources (Hoekstra *et al.,* 2015; Mekonnen & Hoekstra, 2014a; Tipis & Mpusia, 2006). Lanari (2014) comprehensively captured the development of the horticultural sector in Nanyuki, particularly relating to its impacts on river water resources. However, an inventory on the agricultural practices of LAIs in the rose sector of the Nanyuki region is lacking.

2.3.1. Agronomic practices

The region-specific LAI research done by Lanari (2014) for LAIs in the Nanyuki region was lacking specific details relating to production practices of LAIs however insufficient to fully understand the LAIs. Therefore we examined the results from Sahle & Potting, (2013) in Ethiopia, and Mekonnen *et al.,* (2012) and Tipis & Mpusia, (2006) in the nearby region of Lake Naivasha for a review on representative LAI rose cultivation practices.

According to Lanari (2014), roses are predominantly cultivated in tunnels in the Nanyuki region. These are mostly modern climate-controlled systems that allow for better crop-water use, while also protecting the high-value crops from damage by heavy rains (Tipis & Mpusia, 2006). Furthermore, farm managers in the Nanyuki region claim that rainwater harvesting off the greenhouse rooves has the potential to collect 50-55% of the irrigation water requirements (Lanari, 2014). This results in higher quality crops grown on less land, using less water, and therefore with an improved water use efficiency and productivity.

Sahle & Potting (2013) explained that rose plants are produced from seedlings grafted to soil-borne disease-resistant rootstocks that are productive for 5-10 years, depending on cultivar selection. Lanari (2014) identified three main rose varieties grow in Kenya: (a) ‘Hybrid Teas’, (b) ‘Sweethearts’, and (c) ‘Sprays’. Cultivar selection is variable as it is mostly dependant on consumer preference, market needs and the availability of disease- and pest-free parent material (Lanari, 2014). However, ‘Hybrid Teas’ were identified as the most dominant cultivars in the Nanyuki region (Lanari, 2014). These cultivars produces high-quality, large flower heads with long stems, which are only obtainable due to the such as those in the Nanyuki region (Lanari, 2014).

To produce high-quality roses fertigation is constantly applied, year-round, to meet nutrient and water requirements of the rose plant (Sahle & Potting, 2013). Mekonnen *et al.,* (2012) estimated the fertilizer application for roses based on generalized FAO fertilizer use statistics to be 325 kg N ha^{-1}, 63 kg P_2O_5-P ha^{-1}, and 252 kg K_2O-K ha^{-1} in the Lake Naivasha region. Pesticides are also required to combat pathogens and insect pests through direct application to the plant or through the irrigation system, to ensure the roses produced are of a high quality (Lanari, 2014). In Ethiopia, the average rose yields are 200-350 stems m^{-2} yr^{-1} and are dependent on cultivar variety, management practices, growing area, and weather conditions (Sahle & Potting, 2013).

The main advantage of the Nanyuki area for rose cultivation is the climate, which is linked to the altitude and latitude of the region. Lanari (2014) explains that year-round production is possible due to the study site's location on the equator providing the ideal 12-hour daylight. The high altitude of the study site and its location in the rain shadow of Mount Kenya results in a cool and dry climate (Njeru & Gitonga, 2004). The comparably colder climate with constant cooler night temperatures results in slower growth resulting in lower yields (Lanari, 2014). Consequently, the slower growth also allows for leaves to assimilate more sunlight and grow longer stems and larger heads desired by many customers (Lanari, 2014). Another benefit of the cold and dry environment is the low pest pressure, which means lower pesticide use. Therefore, although rose cultivation in Nanyuki produces lower yields compared to the Lake Naivasha region and the global averages, the higher quality provides the LAIs with an economic competitive edge (Lanari, 2014).

2.3.2. Production challenges

A significant challenge to rose production in the Nanyuki region is its relations with the European market, which are inconsistent and unpredictable (Lanari, 2014). The stringent requirement from the European Union (EU) regarding the maximum chemical residue levels, labour welfare and price pressures often result in product rejection (Lanari, 2014). This is particularly problematic as profit margins are increasingly shrinking and as competition with exports from Ethiopia and Tanzania increases (Lanari, 2014). The year-round nature of rose cultivation means that full-time labourers are required. However, in Nanyuki the availability and quality of labour, from general workers to reliable management, is lacking. This has resulted in high competition between LAIs to employ labourers and so employee poaching is common (Lanari, 2014). LAIs are also required to build roads, establish access to electricity, and ensure water supply by building water storage systems to support their own production, as infrastructure is lacking in the region. The distance from Nairobi has also been identified as a challenge for LAI management as many farm inputs and technical backups are only available in the capital (Lanari, 2014). From an environmental perspective, LAIs have identified rainfall unpredictability as a major challenge and the most constraining factor as water availability (Lanari, 2014; Ulrich, 2014).

2.3.3. Environmental impacts

A study conducted by Ulrich *et al.* (2012) found that the majority of SSFs identified over-abstraction of river water and declining water quality as the two critical environmental impacts of LAIs. In a study by Zaehringer *et al.* (2018), water conflicts were present around most LAIs in the Nanyuki study area. The main source of conflict between SSFs and LAIs was the use of river water for irrigation (Kiteme *et al.,* 2002). Conflicts were so severe that smallholder land users had decided to abandon or reduce irrigation farming (Zaehringer *et al.,* 2018). Kiteme *et al.,* (2002) reported that conflicts related to scarcity have even resulted in fatal physical conflicts among upstream and downstream users. The perception by the community of a decreasing availability of river water was confirmed through river flow studies by Liniger *et al.* (2005). By monitoring the river flow of three selected sub-catchments in the slopes of Mount Kenya from 1960 to 2004, it was revealed that the extremely low flow of rivers was reduced to 10%, 23%, and 71% of the average flow, while the rainfall regime did not show significant change (Liniger *et al.,* 2005; Ulrich, 2014). It was further revealed that over 10 years between 1995 and 2004 the number of abstraction points had more than doubled, and there was a two- to eight-fold increase in the amount of river water abstracted (Liniger *et al.,* 2005).

Nonetheless, LAIs are not necessarily solely responsible for the decreasing river flow. Evidence shows that the horticulture farms have reduced their dependence on extracting water directly from rivers for irrigation in the last decade (Lanari *et al.,* 2016). In 2003, 41-62% of irrigation water came from river sources, in 2013 it decreased to 10-31% with the rest being sourced from groundwater, rainwater, and floodwater harvested during the rainy season and stored in dams (Lanari, 2014). Lanari (2014) explained that the impact that commercial horticulture has had on local river water abstraction varies widely depending on the presence of water storage facilities and groundwater availability. Although LAIs are major water users in the study region, studies have attributed the decline partly to the increasing population, growing irrigated agricultural production, and environmental factors, such as changing rainfall, glacial melting, and groundwater discharge (Lanari *et al.,* 2016).

In terms of water quality, the claims of increased water pollution by the community were partly confirmed by Muriithi & Yu (2015). This study measured water quality in selected rivers in Laikipia and Meru Districts and found that concentrations of dissolved solids, electrical conductivity (EC), and salinity spiked at locations with intensive small-scale and large-investment horticulture. The prevalence of heavy metal traces (cadmium, phosphate, and zinc) was also linked to intensive LAI farming, including rose production falls (Muriithi & Yu, 2015). The traces of phosphates, specifically, were explained by the soluble liquid fertilizers applied by LAIs. Phosphorus promotes bud formation and flowering, it is also used extensively by LAIs to promote crop development and increase yield (Muriithi & Yu, 2015). These fertilizers also contained N and, according to Erickson *et al.* (2001), more than 30% of N applied to ornamental plants leaches out of the soil. Sahle & Potting (2013) estimated that rose cultivation practices leads to a leaching of 3 g of nitrate per bunch of roses. Leaching and runoff of P and N are common in horticulture, especially during excessive rainfall or over-irrigation (Muriithi & Yu, 2015). The traces of cadmium and copper can be traced to the concentrated use of copper-based herbicides and fungicides commonplace in intensive horticulture (Muriithi & Yu, 2015). Muriithi & Yu, (2015) further reasoned that horticultural effluents are concerning and necessitates the introduction of standards of compliance to regulate the greenhouse horticulture industry.

Along with water issues, there are other resultant impacts to input-intensive production. Plant growth management was found by Sahle & Potting (2013) to dominate all environmental impact categories in their Life Cycle Assessment (LCA). The study found that the use of calcium nitrate dominated ozone depletion-, acidification-, and freshwater aquatic ecotoxicity-potential. The emissions from fertilizer use resulted in high acidification and eutrophication potential, while pesticide-related emissions dominated terrestrial ecotoxicity, freshwater aquatic ecotoxicity, and photochemical oxidation potential. Results from the study clearly indicated that, in the rose cultivation sector, nutrient and pesticide use are practices that require serious environmental optimization to reduce impact (Sahle & Potting, 2013).

Chapter II: Methodology

3. Research design

The AFGROLAND project is compiled of a team of multi-disciplinary researchers investigating the African food, agriculture, land, and natural resource dynamics, in the context of global agro-food-energy system change. The project was financed jointly by France, South Africa and Switzerland through the Belmont Forum and the Joint Programming Initiative on Agriculture, Food Security and Climate Change (FACCE-JPI). Additional information on partnerships is available on the AFGROLAND website and in Appendix A (http://www.afgroland.net/Pages/About-us.aspx).

The project consists of five work packages (WP):

1) WP1 focuses on the drivers of change and governance on global and national levels,
2) WP2 focuses specifically on agricultural production and investment models being developed and their evolutionary dynamics within a broader context of local food systems,
3) WP3 focuses on land use, natural resources and soil related ecosystem services,
4) WP4 focuses on food security,
5) WP5 focuses on synthesis, recommendations, and dissemination.

This dissertation falls under the WP3 framework and goals. This means that the methodology of this dissertation was created with the framework and goals of WP3 in mind. The aim of WP3 was to produce quantitative assessments of land use and its impact on natural resources at a local level that could be used as a "footprint" to compare across various investment schemes. There were many limitations to what could be done in this study due to the collaborative nature of the research project and remote location of the case studies. Therefore, the aim was simply to create a baseline assessment of the environmental impacts and productivity of SSFs and LAIs at a case study level, against which future monitoring and evaluation can be compared.

Field work consisted of a week-long workshop in Kenya in February 2016 were all five WPs congregated facilitated by the local partners, CETRAD. For two months from

September to October 2016 I was based in Mozambique doing intensive field work that included a mulit-stakeholder workshop in Nampula and data collection in Monapo, Mecuburi and Gurúè. I accompanied teams from WP3 and WP4 in collaboration with our local partners, Helvetas and the Catholic University of Mozambique (UCM campus). More time was required in Mozambique than in Kenya as partnerships with the local networks and LAIs in the region were poorly established in the Gurúè study region. Whereas in the Nanyuki study region there was an established local support system (CETRAD) that had ongoing communication with the LAIs. There were also a number of completed and ongoing research projects in the Nanyuki region.

This study was organized into three successive stages; (i) the initial explorative stage (data acquisition), (ii) the descriptive stage (virtual farm synthesis), and (iii) the analytical stage (Life Cycle Assessment (LCA) and APSIM crop modelling):

i) When theoretical knowledge was not sufficient to allow for necessary analysis, an explorative methodology was applied (Lanari, 2014). Accordingly, explorative principles were adapted to overcome the limited understanding of large-scale agricultural investments (LAIs) and small-scale farmers (SSFs) production systems in the context of the chosen study areas. In this first stage, semi-structured interviews and household surveys with SSFs, LAIs, and key stakeholders were held to identify principal actors, their agricultural practices, and critical limitations to production.

ii) The descriptive stage consolidated the results from the explorative stage with existing studies to create production systems called "virtual farms" (VF). These VFs represent SSFs and LAIs in each country by serving as an inventory of the 'average' agricultural practices of each production system. In this study there were four VFs and they were defined in terms of farm design, soil management practices, and input consumption within defined agro-ecological conditions.

iii) The inputs consolidated in the descriptive stage were then analysed to quantify the outputs of each these four VFs using specific indicators relating to agronomic efficiency and environmental impacts. Based on the prioritization of specific issues and available data, indicators were chosen and then quantified using the relevant methods. The LCA methodology, which includes water footprint analysis, along with APSIM crop modelling, were chosen to generate these indicators.

4. Data Acquisition

Data collection took place in multiple overlapping steps:

i) Locating and identifying LAIs and SSFs in each study region,
ii) Conducting interviews with LAI representatives,
iii) Conducting semi-structured interviews with SSFs, and
iv) Conducting household surveys with SSFs.

Although methodological development began in Kenya and was recreated in Mozambique, the lack of data and local support in Mozambique meant that additional data collection steps were required. These included discussions with stakeholders at the AFGROLAND kick-off meeting and the collection of soil samples in the Gurúè study region from SSF plots. In both study regions, when primary data collected during field work was not sufficient, secondary data from literature was utilized.

4.1. Study site selection

Due to the connection of this study to the broader AFRGOLAND goals, this work had multiple spatial levels. The first spatial separation was on a country case level, this included Mozambique and Kenya. The second level was the study region, which refers to a well-defined area with specific case studies. In Kenya it was the Nanyuki study region, and in Mozambique it was the Gurúè study region. Case studies were the most specific level and referred to one land investment or smallholder. A group of case studies from the same business type (SSF or LAI) was then referred to as a case study group.

The criteria for the country and study region selection was chosen by the AFGROLAND project and included:

i) Presence of different investment models,
ii) Large size of investments in terms of land (>200 ha) or large capital invested,
iii) Agricultural production-based land investments,

iv) Timeframe of investment or re-investment since 2000,
v) Availability of local research team or secondary data, and
vi) Access to LAIs and relevant SSFs.

These conditions resulted in the selection of Nanyuki as the study region for Kenya and the Nacala Corridor as the study region for Mozambique. However, due to the large area of the Nacala Corridor, the AFGROLAND project selected two study regions within the corridor for further analysis. Namely, the Gurúè district in the interior of the corridor, and Monapo district, which is located closer to the coast. Considering the differences in agro-ecological conditions, SSF management practices, and LAI systems between these two regions, my study focused only on the Gurúè study region as representative of the Nacala Corridor.

The criteria for LAI case study selection was initially chosen by AFGRROLAND Work Package 3 (WP3) and then refined for this study's needs. In the Nanyuki study region, to assess the impact of LAIs on SSFs' land use, WP3 selected five of the total 35 LAIs in the study area. Out of these five LAIs, this study selected two LAIs for closer investigation, as they related specifically to rose cultivation, but still fell within the chosen LAIs from WP3. In the Gurúè study region, WP3 identified 12 active companies with investments in agriculture and selected three for analysis. This study selected two of these three LAIs, which remain anonymous, as they both had the same maize-soybean production system.

The SSF case study groups were primarily chosen based on their proximity to the LAIs. The selection of SSF case studies for the semi-structured interviews were facilitated by AFGROLAND's local partner the Centre for Training and Integrated Research in ASAL Development (CETRAD) in Nanyuki and by extension officers from the District Level Services for Agricultural and Economic Activities (SDAE) in Gurúè. Criteria for selection included SSFs located proximally upstream and downstream from LAIs, and the willingness of the respondents to participate in discussions. Consequently, this initial round of interviews was not wholly randomized as case studies were chosen due to their connection with local partners. However, randomization was not required as the semi-structured interviews were simply meant to provide context for the region, and the results were not used for statistical analysis.

Case study groups for the household surveys were randomly selected from the vicinity around each of the LAIs under investigation. ArcGIS was used by Dr. Sandra Eckertt a researcher from WP3 to generate coordinates for households within a 2 km buffer around the delineation of each LAI (Eckert *et al.*, 2017). Enumerators chosen by WP3 members then selected households closest to each of these random coordinates to interview. If the participants did not agree to the interview, they moved to the next available household. This method was used in both Nanyuki and Gurúè.

4.2. Interviews with representatives of large-scale agricultural investments

During the first field mission to Kenya in March 2016, Dr. Julie Zaehringer, Dr. Sandra Eckertt, Prof. Michael van der Laan, researchers of the WP3 team and myself visited four LAIs; Chestnut Farms, Turi Farms. Bloomingdale, and Kariiki Farm. A single semi-structured interview guide (Appendix B) created by me, with the direction of Prof. Michael van der Laan, guided all the interviews with the LAI managers or owners about their agricultural practices and the major challenges facing the sector.

Lanari (2014) warned that access to commercial horticulturalists in the study region is a major challenge to field work as LAIs have a reputation of being private and reluctant to share information. Fortunately, due to the working relationships established by CETRAD, obtaining access to the field and to relevant data was easier than expected. Still, challenges arose during the subsequent data collection. Due to the competitive nature and bad press related to the influx of LAIs in the region, our interview questions were not always answered thoroughly. Respondents were particularly hesitant to answer questions regarding the quantities of agro-chemicals they applied. Once the field mission concluded, supplementary follow-up questions with LAI representatives were conducted by CETRAD members, although, once again, the answers to the interview questions were often incomplete.

Access to LAIs was especially challenging when field work was done in the Gurúè region during the field mission from September-October of 2016. During my field work in the North of Mozambique I was joined by Dr. Aurélien Reys, Koen Dekeyser, and Dr. Jose Adalima from the AFGROLAND research project who would accompany me during LAI interviews. Logistically, the LAIs are far from Gurúè City and each other, finding transport to get to the LAIs requires good local connections, and the commute can take up to two hours on local motorbike taxis due to the poor quality of the dirt roads. Convincing LAI representatives to allow us an interview was laborious and often required multiple attempts, with different representatives. Considering that these LAIs have experienced negative portrayals in the press, condemning them for exploiting workers, polluting, and displacing SSFs, many of the LAI representatives did not trust us. When we were permitted interviews, we were often received with defensive responses which negatively impacted our access to information. Furthermore, visits to production fields were not permitted by any of the LAIs in the Gurúè region. Granted, the LAIs had not begun sowing at the time of interview, so they did not consider these visits to be beneficial.

4.3. Semi-structured interviews with small-scale farmers

The purpose of the semi-structured interviews was as a type of scoping study to build an understanding of SSF practices and the challenges thereof. Accordingly, a preliminary guide (Appendix C) was constructed by me with the direction of Prof. Michael van der Laan and used to gauge the concerns and practices of SSFs in the context of their agro-ecological conditions, but still allowed for respondents to interject and change the direction of the interview. Answers from the SSFs were written down in the allotted spaces in the survey form and the answers informed the construction of the household survey.

During the Kenyan field mission, the WP3 team interviewed 10 smallholder farmers to obtain this preliminary information (Photo 1 & 2). The entire process, from transport to the selection of SSFs was facilitated by CETRAD, allowing for a stress-free interview process. These interviews were conducted over two days during the same period as the LAI interviews, in March 2016. Interviews were often conducted at the respondent's fields, so preliminary inspections on crop quality, pest infestation, disease occurrence, and soil quality could also be assessed by WP3 members, including myself. By the end of the interviews, a report was compiled highlighting major challenges along with crucial information that provided context for the subsequent surveys.

Photo 1 & 2: Semi-structured interviews with small-scale farmers in Nanyuki held in the respondents' fields

In the Mozambican case, connections established during the kick-off meeting in September 2016 with extension officers at SDAE were utilized to introduce the team to SSFs in neighbouring villages (Photo 3 & 4). Access to the field was extremely challenging and required travelling on dirt roads, often for more than 100 km, on the back of motorbike taxis. Meetings with local leaders were also required to ask for permission to interview community members. Initiating these factors meant that visits to the field were limited. Two trips were organized to Ruace Village neighbouring the Hoyo-Hoyo Plantation and one trip to Nintulu Village neighbouring the AgroMoz plantation. Support was limited in the region and therefore the interviews were conducted by me accompanied by members of the AFGRLOAND project, or a SDAE official when possible. These included interviews at the participants homestead as well as visits to their farms, which were often located a few kilometres outside of the village. In total there were 10 semi-structured interviews conducted by me in the Gurúè district.

Photo 3 & 4: Semi-structured interviews with small-scale farmers in Gurúè district at the respondents' fields

4.4. Household surveys

As part of AFGROLAND's WP3 goals, WP3 team members collected necessary primary data for analysis through household surveys. Due to the collaborative nature of the AFGROLAND project, the survey included questions for all the studies under WP3 (Appendix D). Dr. Julie Zaehringer and Dr. Sandra Eckertt constructed Parts 1-3 of the household survey while I constructed Part 4 with the guidance of Prof. Michael van der Laan. Part 1 of the household survey was used for context of who the farmers were and where they were operating but only the results of Part 4 of the survey were analysed in this study.

In Nanyuki, the surveys were carried out between January and February of 2017 by three teams of Kenyan enumerators coordinated by CETRAD and WP3 members (Drs. Julie Zaehringer and Sandra Eckertt, University of Bern). In Mozambique, the surveys were carried out between January and March of 2018 by enumerators from the University of Cuamba coordinated by WP3 members (Drs. Julie Zaehringer and Sandra Eckertt, University of Bern). The survey lasted between 45 minutes and two hours and were conducted by the enumerators in the preferred local language. Enumerators then translated the results to English and digitally captured the data. Although I contributed questions to the household surveys, I did not take part in the interview process of the survey in Kenya or Mozambique.

Due to the different goals within WP3, the data collection methodology was different for the Gurúè study. Unlike this study, the aim of other members of WP3 was to cover both Monapo and Gurúè as representative of the Nacala Corridor. This resulted in 50 household surveys in Gurúè and 50 household surveys in Monapo. Consequently, this study has an uneven dataset with 100 interview results for Kenya and only 50 for Mozambique. Otherwise, the data collection methodology was conducted in the same manner in Kenya as in Mozambique to allow for the comparison of attributes between the country case studies.

4.5. Kick-off meeting with key stakeholders in Mozambique

Coordination with stakeholders was critical in the Mozambican case to link the project to key local data and help collect information on LAIs and SSFs. Stakeholders included the SDAE, LAI representatives, non-governmental organizations (NGO), and the National Union of Peasant Workers (UNAC) representatives. The main purpose of the kick-off meeting was to introduce stakeholders to the AFGROLAND project while facilitating the sharing of information. Accordingly, the meeting began with a presentation from each WP including myself as representative of WP3. As the speaker for WP3 I explained our relevant goals, this included our hopes to gain access to local weather and soil data recorded by the stakeholders, the identification of agricultural production limitations, and the average yields for the region. The central idea communicated was that we wanted to identify the environmental impacts and agronomic efficiency of LAIs and SSFs, and that the results thereof would be shared with stakeholders once completed.

The presentation was then followed by in-depth discussion tables (Photo 5 & 6), during which stakeholders were randomly grouped and rotated between WP tables as in the “Word café” method. At the WP3 table, the discussion was divided into four components: land use change, production challenges of SSFs, management of natural resources, and ecosystem services. In this setting, extension officers from SDAE were of importance as they are the focus point of information flow from rural areas to the district agricultural offices and back. Therefore, they are able to identify agricultural practices and limitations of SSF production. While LAI representatives provided the contacts of key managers able to answer our questions on management practices. Significant findings were written down and displayed on a pin board so that, as groups would rotate, new participants could add on to previous comments and support or counter the written statements.

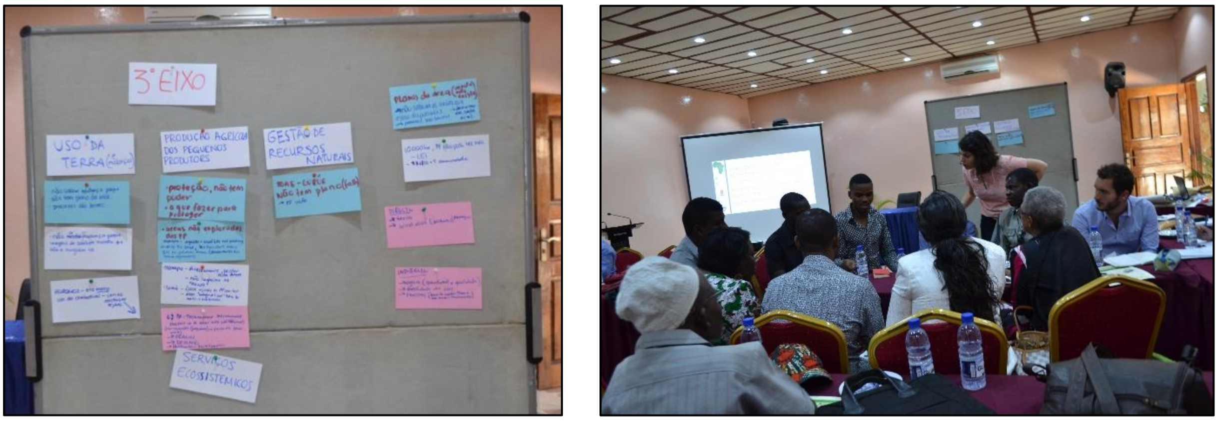

Photo 5 & 6: Pin-board of collective ideas with stakeholders and group discussion at WP3 table.

4.6. Soil sample collection

The aim of soil sampling was to determine representative characteristics in the Gurúè study region to calibrate the APSIM model. The nearest soil laboratory was at the Agricultural Institute of Agriculture in Mozambique (IIAM) institute in Nampula, approximately 300 km away from the case studies. Soil samples were collected from a SSF smallholding chosen to represent the Gurúè study region. Due to the high cost of analysis, accessibility to the field, and limited budget only one location was used.

In terms of equipment, the goal was to borrow a soil auger from the IIAM institute in Nampula. However, we were cautioned that at that time of the year, the soil was too hard to sample with a soil corer. Therefore, they did not permit me to use of the laboratories' auger. Instead, they advised that a hoe and shovel be used to take soil samples which was temporarily borrowed from Helvettas, AFGROLAND's local partner in Nampula. Hoes belonging to the SSF were also utilized by the SSFs to assist in taking soil samples. During the field visit, GPS coordinates were taken delineating the farm, along with sampling details and observations such as the types of crops cultivated on the land, inputs used, and visual soil surface conditions, such as signs of erosion.

The number of samples taken at the site was based on accuracy and confidence levels described in Dalgliesh & Foale (2009). Assuming that the study sites had one single soil type, five sets of soil samples were taken at each field to achieve an 80% confidence value. An 80% confidence signifies that out of the five sets of samples, one of the samples would probably fall outside of the desired accuracy limits. This allowed for a medium level of accuracy where the true nitrate (NO_3^-) value is ± 20% of mean and water value is ± 2% of the mean. More samples are needed to assess NO_3^- concentration than for gravimetric water because N is more variable throughout the soil (Dalgliesh & Foale, 2009).

A random sampling pattern was used along the full-length of the field to adequately cover variability across the field, with GPS points taken at each spot. None of the fields received N fertilizer applications, so the N levels were not attributed to residual fertilizer application. However, the levels of N were still expected to be spatially and temporally dynamic and vary between rows and inter-rows (Dalgliesh & Foale, 2009). To address this, samples were taken at different widths within and between the rows.

According to Dalgliesh & Foale (2009), when simulating crops in order to relate supplies of water and N to potential yield, sampling should extend to the full potential depth of roots. This would allow for a fuller account of all the critical resources that are potentially available to the crop (Dalgliesh & Foale, 2009). Even though water and N in the deeper layers of the profiles may not be used every year, these resources are potentially available at some stage (Dalgliesh & Foale, 2009). A sampling to the full depth of rooting would allow for the assessment of N bulges, salinity conditions, pH and other important soil variables affecting yield. But due to the hardness of the soil and the high cost of analysing additional sub-samples, sampling the whole potential rooting depth was not possible. Instead, only a surface sample was taken at three layers: 0-0.10 m, 0.1-0.2 m, and 0.2-0.3 m.

The set of soil sub-samples were then bulked according to their depth in the soil layer. Once separated into soil layer position, the samples were thoroughly mixed. Considering that the samples needed to travel from sites in the Gurúè district to Nampula City, they were air-dried, carefully stored in sealable, plastic bags to avoid contamination by other samples and the environment and carefully labelled. Speedy transport from the field to the soil laboratory in Nampula was not possible due to various limitations of group field work in rural conditions. Once they were taken, the trip was long and hot. It is acknowledged that these conditions could have allowed for chemical changes to occur such as denitrification and mineralisation. However, as the samples were air-dried before transport the chances for chemical changes were probably minimized.

Once the samples arrived at IIAM's soil laboratory in Nampula, they were weighed and measured out into sub-samples and dried at 105^{o}C for two days. After drying, samples were weighed again to calculate gravimetric water content. Soil texture is defined as the proportion of sand, silt, and clay in the soil. Soil texture was analysed using two methods, namely, separation by sieving, and separation by sedimentation based on Stoke's Law. Soil pH was measured using a calibrated pH meter and electroconductivity (EC) was measured using a calibrated EC meter. The probes were rinsed with deionized water between each sample test to prevent contamination. Exchangeable acidity, or the amount of hydrogen (H^+) and aluminium (Al^{3+}) ions released from the soil when an unbuffered potassium chloride (KCl) solution was added to it, was measured by titration with sodium hydroxide (NaOH) (Van Reeuwijk, 2002). Phosphorus concentration in the soil was tested using the Mehlich III procedure described in Mehlich (1984). While potassium and N were measured using specialized in-field pocket meters by LAQUAtwin (from Spectrum technologies) (Photo 7 & 8).

Photo 7 & 8: Nitrate LAQUAtwin meter, and Potassium LAQUAtwin meter

Macronutrient (calcium (Ca), magnesium (Mg), and sodium (Na)) and micronutrient (Iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn)) concentrations were estimated using the Agilent 4200 MP-AES technology (from Agilent Technologies, United States) (Photo 9) based on the methodology described by Vummiti (2015). Soil organic matter (SOM) was measured by applying the potassium permanganate ($KMnO_4$) method from Weil *et al.,* (2003) to estimate the concentration of active carbon in the soil. Soil bulk density was quantified using the Nimbus Analytical balance from Adam Equipment (South Africa). It is acknowledged that due to the disturbance of the soil from its natural volume, the results may not be an accurate representation of the actual bulk density, but the tests were done as they were part of the laboratory's protocol.

Photo 9 & 10: 4200 MP-AES system by Agilent Technologies, Nimbus balance by Adam Equipment

4.7. Data accuracy

4.7.1. Direct crop measurements

The most robust method of data collection for crop model parametrization is via direct crop measurements in the field. This allows for more accurate predictions to be made on how the crop will realistically respond to changes in environmental conditions and management practices. However, there were limitations to extracting primary data in-field. Firstly, the costs associated with data collection in these remote locations was prohibitively high and transporting equipment to rural areas was challenging. Secondly, the field visits to Mozambique were done during the dry season when SSFs were preparing for the next cropping season, and therefore most fields were bare, sparsely cultivated, or at the end of harvesting from the previous season. In the case of the Kenyan study site, field visits were done over three days, which was not sufficient to organize for crop measurements in SSF fields. In the case of LAIs, we were not permitted to visit the production fields in Mozambique, and in Kenya we were not at the site for sufficient time to plan for measurements. Thirdly, relationships were not sufficiently developed in any of these cases so that direct crop measurements could be taken, this is particularly the case with the LAIs who were apprehensive about sharing information in general. Therefore, the next best option was to rely on interview data, which has its own limitations but allows for assessments to be made and speculations made.

4.7.2. SSF household survey data

In this study, the selection process for interviewees was not orientated based on SSF typology such as market orientation, socio-economic status, or farm system design. Rather, interviewees were randomly selected based on if they belong to a farming household within the study site. This lack of targeted selection is problematic as heterogeneity was recognized within the study sites as SSFs used diverse farming strategies according to a variety of factors. Franke *et al*. (2014) explains that the diversity in farming systems "determine[s] the opportunities for uptake of different technology". To expand on this concept, each farm typology has a different ability to manage technologies which then results in varying degrees of environmental impacts and a variety of yield potentials. Ideally, this study would generate a wider range of in-depth interviews to identify more farm typologies for SSFs in the study area based on factors that lead to statistically significant differences in environmental impacts and yield potentials.

As mentioned previously, however, the household surveys were not solely constructed for this study, diminishing the possibility of tailoring the surveys exclusively to this study's requirements. Technical and financial factors similarly hindered the appropriate classification of the SSFs' farming systems. But, it is recognized that transparency is imperative when describing the virtual farm. Therefore, each case study includes an account of the source of each value for a thorough understanding of what type of SSF system the virtual farm is representing. Even though the virtual farms characterized in this study are a generalization of farming practices for each study area, it has allowed for the creation of a base on which to explore the impacts of production scenarios of both LAI and SSF farming systems.

4.7.3. Semi-structured interviews data

The largest hindrance to accurate data collection from LAI representatives was the question of trust between interviewer and interviewee. This was similarly experienced by Joala *et al.,* (2016) in Gurúè and Lanari (2014) in Nanyuki. It is acknowledged that the representatives' knowledge was not without bias, especially when talking about sensitive topical issues such as land use change and potentially polluting emissions. However, as Lanari (2014) explains "there is no way to verify the truthfulness of the statements given by methodological interventions", especially in this study, as direct measurements could not be taken to validate the data provided by the LAI representatives.

It is noted that the construction of interviews is a science of its own and that having two different interview guidelines for SSFs and LAIs may have created bias. This was due to the different time allotted to each group. There were more SSFs to interview and therefore less time to spend with each SSF compared with an LAI representative. This meant that we were able to ask more in-depth questions to LAI representatives than to the SSFs. Although this allowed for additional context to be provided for the LAIs the type of quantitative data extracted from the interviews was the same for LAIs and SSFs.

5. Data compilation

5.1. Virtual farm synthesis

Throughout Africa there is a wide diversity of farming systems (Franke et al., 2014). In the chosen study areas heterogeneity is similarly observed even at the SSF and LAI level, influenced by a myriad of biophysical, socio-economic, and political factors and resulting in a varying degree of agronomic efficiencies and environmental impacts. Since it is impossible to analyse all the individual farms within each production system, typologies must be defined to allocate farming systems into groups (Franke et al., 2014). This was the basis of the virtual farm concept: a generalized representation of a typical production system for the study area under investigation.

Criteria for defining virtual farm typology differ depending on the study's goal and on the method of analysis. For example, Franke *et al.*, (2014) had five different farm typologies for SSFs in Malawi based on combinations of their wealth class, main source of income, and production orientation to better understand their uptake of new technologies.

Although it is acknowledged that these factors would affect the management strategies and related agronomic efficiencies and environmental impacts, the farm typology applied in this system is much more generalized. Typology is divided into SSF and LAI, and then differentiated as part of the Kenyan or Mozambican study region. In this study the virtual farm typologies are therefore the Gurúè SSFs (GSVF), Nanyuki SSFs (NSVF), Gurúè LAIs (GLVF), and Nanyuki LAIs (NLVF).

These VFs therefore represent SSFs and LAIs for each region by serving as an inventory of the 'average' agricultural practices of a typical production system. This collection of average practices not only allows for comparison using APSIM and life cycle assessment (LCA), but also enhances the knowledge base of common LAI and SSF production practices in the region and allows for further analysis by various agronomic, economic, and environmental assessment tools.

Defining a VF was centred around management practices, particularly those required as inputs to run the APSIM model and complete the LCA analysis. Management practices were defined as agronomic practices (crop selection, cropping system (monocrop versus intercrop), planting dates, and planting densities), soil management practices (tillage, leaving crop residues on the soil surface, and burning), and input utilisation (agrochemicals, water consumption and energy utilisation) within defined agro-ecological conditions.

For the construction of both SSF VFs, data were primarily used from the household surveys. Simple econometric statistics (mode, mean, and significant difference) were applied to the survey results to obtain the representative values. Using Sheahan *et al.,* (2013) as a template:

"Extreme values were dropped from the dataset prior to estimation in order to limit the leverage of potentially erroneous observation. These ranges were determined based on an understanding of reasonable values in the study site's context and literature."

When data were lacking or unsuitable, results from the semi-structured interviews or previous studies were applied. The source of each data value was recorded and displayed in the VF results section. For the construction of the LAI virtual farms, the values obtained during the semi-structured interviews with farm managers were utilized and then complimented with the data from previous studies to fill incomplete data sets. Similarly, as in the SSF scenario, information on the source of each value was included in the results section of the VF.

6. Data analysis

6.1. The APSIM crop model

The Agricultural Production Systems sIMulator (APSIM) is a process-based crop simulation model that is ordered around a central engine which allows for communication between different modules (Keating *et al.,* 2003). According to Keating *et al.* (2003) this framework is made up of:

a) a set of biophysical modules that simulate biological and physical processes within farming systems,

b) a set of management modules that allow the user to specify the intended management rules that characterise the scenario being simulated,

c) various modules to facilitate data input and output to and from the simulation,

d) a simulation engine that drives the simulation process and controls all messages passing between the independent modules.

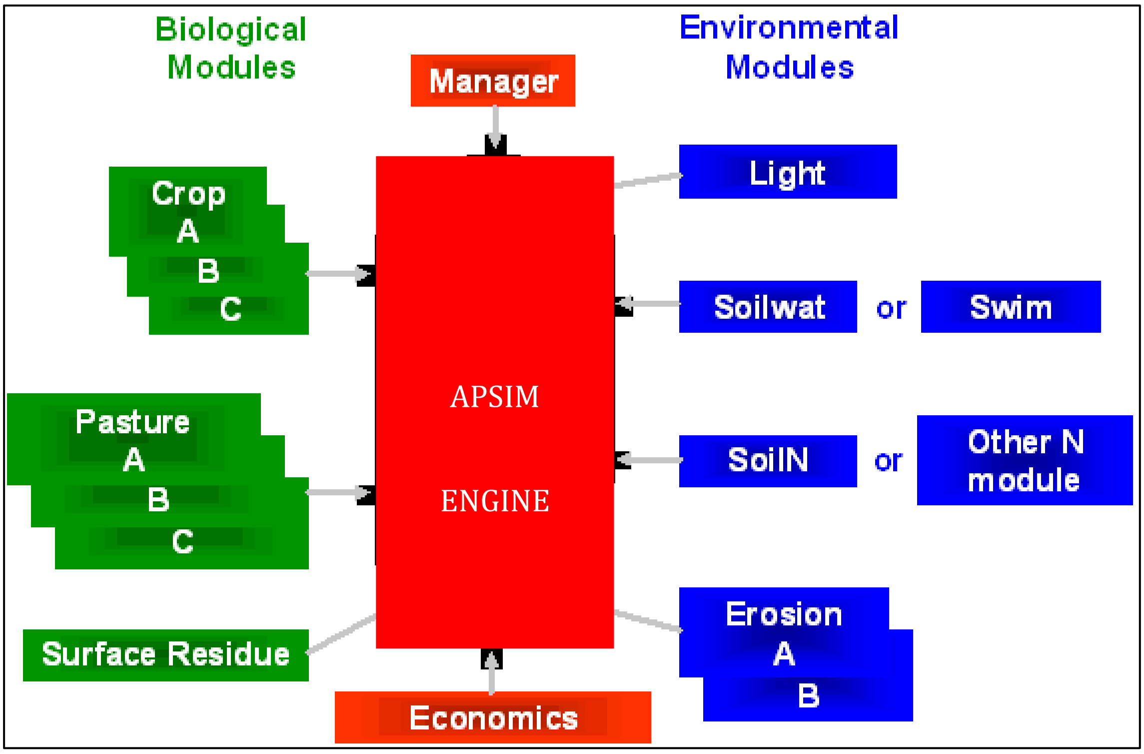

Fig. 3: Diagrammatic representation of the APSIM simulation framework with individual crop and soil modules, module interfaces and the simulation engine (Keating *et al.,* 2003)

In this study, APSIM (version 7.7) was calibrated using weather and soil parameters that represent the Gurúè and Nanyuki study regions. The model was then used to simulate cropping system performance and soil C and N dynamics from 1980 to 2030 (50 years) under representative management practices described for each virtual farm. This was done in accordance with the following objectives:

(I) To utilize APSIM to evaluate the yield performance of SSF systems in contrast with LAI systems in the Gurúè and Nanyuki study sites,

(II) To examine and forecast simulated soil C and N dynamics to explore sustainability implications of SSF systems compared with LAI systems,

(III) To determine whether SSF and LAI systems can maintain soil fertility and crop yields over the long-term.

This study does not aim to validate APSIM's ability to model these cropping scenarios, but rather initialises the model to explore key system impacts and opportunities, with special emphasis on comparing SSF with LAI systems. Validation of the APSIM model under cropping scenarios similar to those studied here has been successfully executed and the impacts on soil dynamics have been adequately simulated in previous studies (Holzworth *et al.*, 2014; Keating *et al.,* 2003; Ollenburger, 2012; Smith *et al.,* 2016; Whitbread *et al.,* 2010). If parameterized correctly with meteorological and soil data, APSIM is able to simulate long-term yield estimates in response to management practices while accounting for the consequence of these practices on soil resource and N dynamics. Reviews by Keating *et al.* (2003) and Holzworth *et al.* (2014), in particular, contain extensive citation lists for APSIM model testing along with application studies such as support of on-farm decision making and risk assessment. In addition, Whitbread *et al.,* (2010) defined parameter modifications to account for certain modelling constraints expected from southern African SSF systems, which were then applied to the GSVF and NSVF modelling scenarios.

6.1.1. Model Parameterization

6.1.1.1. The Gurúè region

The soil profile was parameterized using results from the soil sample analyses in conjunction with field trials by Tsujimoto *et al.* (2015). The critical data from the soil samples applied to the parametrization of the soil characteristics were soil pH, EC, texture, SOM, and micro- and macronutrient levels. The missing parameters required for the description of the soil profile included soil organic carbon (SOC), carbon nitrogen ratio (C: N), BD, saturation (SAT), drained upper limit (DUL), 15-bar lower limit (LL) and soil water at air dry (AD). Total SOC was determined as a function of organic matter (OM) using the conversion factor of 1.724 (Swanepoel et al. 2016). The C:N ratio was estimated using results from field trials conducted by Tsujimoto *et al.* (2015) in Gurúè (Latitude: 15°19′S, Longitude: 36°42′E) in the growing season of 2012-2013. Texture data was used in the Soil-Plant-Air-Water (SPAW) model to estimate BD, SAT, DUL and LL (Saxton & Willey, 2006). The AD was calculated as half of LL. The final values used to calibrate the model are displayed in Tables 1.

Due to a lack of locally available measured weather data, data including daily rainfall, minimum and maximum air temperatures, and solar radiation was obtained for the period of 1979 to 2014 from the Global Weather Data for SWAT database (http://globalweather.tamu.edu/) for the Gurúè region (quadrant defined as south latitude: -15.6336, west longitude: 36.8056, north latitude: -15.3133, east longitude: 37.1709). Weather data was also extrapolated for the years 2015-2030 by replicating the weather data from 1999-2014 to model different scenarios over a 50-year period. The goal of the extrapolation was simply to estimate the potential impact of management practices on soil degradation. This study does not attempt to make any predictions on how the soil would degrade under climate change and acknowledges that the results are limited to these weather conditions.

Table 1: Soil physical and chemical properties for the Gurúè region

Variable	unit	Layer 1	Layer 2	Layer 3
Depth	**m**	0-0.1	0.1-0.2	0.2-0.3
Air dry water	**$mm\ mm^{-1}$**	0.1	0.1	0.1
Drained upper limit	**$mm\ mm^{-1}$**	0.3	0.3	0.2
Lower limit	**$mm\ mm^{-1}$**	0.2	0.1	0.1
Saturation	**$mm\ mm^{-1}$**	0.5	0.4	0.4
Bulk density	**$g\ cm^{-3}$**	1.5	1.4	1.5
Organic carbon	**%**	1.6	1.2	1.5
pH (KCl)	**-**	5.5	5.5	5.3
Ammonium ($NH4^+$)	**$mg\ kg^{-1}$**	0.6	0.6	0.6
Nitrate (NO_3^-)	**$mg\ kg^{-1}$**	3.8	3.8	3.8
Clay	**%**	31	17	18
Silt	**%**	19	10	12
Sand	**%**	50	73	70
Cation exchange capacity	**$cmol\ kg^{-1}$**	4.2	4.2	4.2

6.1.1.2. The Nanyuki region

A representative Kalalu soil was parametrized by Njeru & Gitonga (2004) using a combination of documented physical and chemical characteristics described by the Natural Resource Monitoring, Modelling and Management (NRM3) project and the Laikipia Research Programme (LRP) (Njeru & Gitonga, 2004). Air dry soil water content, LL, DUL, plant available water content (PAW), soil water saturation point, soil bulk density, SOC, soil pH, and NH_4^+ and NO_3^- concentrations were obtained from Njeru & Gitonga (2004) to parametrize the soil conditions (Table 2).

Weather data was sourced from the SWAT database for Kalalu, the closest station to the study site, situated 12 km North-East of Nanyuki (0.0156 ^{0} N, 37.1875^0 E). Data included rainfall, maximum and minimum temperature, and solar radiation on a daily time-step from 1980 to 2014. Similar to the Gurúè case study, weather data was then extrapolated for the years 2015-2050 by repeating the 15 years of weather data from 1999 to 2014. The aim of this investigation was to estimate the potential impact of management practices on soil degradation and yield gaps over the longer term. For this purpose, projected weather data that considers climate change were not used as it would introduce confounding factors that would influence the results, for which there are relatively high levels of uncertainty. Therefore, this study does not attempt to make any predictions on how the soil would degrade or crop yields change under climate change.

Table 2: Soil physical and chemical properties of the Nanyuki region (Njeru & Gitonga, 2004)

Variable	unit	Layer 1	Layer 2	Layer 3	Layer 4
Depth	**cm**	0-20	20-45	45-75	75-100
Air dry water	**%**	5.0	5.0	7.5	10.0
Drained upper limit	**mm mm^{-1}**	0.31	0.29	0.21	0.21
Lower limit	**mm mm^{-1}**	0.20	0.12	0.13	0.13
Saturation	**%**	59.3	59.3	52.1	52.1
Bulk density	**g cm^{-3}**	1.0	1.0	1.2	1.2
Organic carbon	**%**	2.4	1.0	0.7	0.4
pH		6.4	6.4	5.4	5.4
Ammonium ($NH4^+$)	**mg kg^{-1}**	1	2	1	1
Nitrate (NO_3^-)	**mg kg^{-1}**	8	8	8	8
Clay	**%**	57	67	73	71
Silt	**%**	21	15	11	11
Sand	**%**	22	18	16	18
CEC	**cmol kg^{-1}**	28.2	22.6	13.2	10.5

6.1.2. Scenario setup

APSIM was only used to model the GSVF, GLVF, and NSVF production systems. The NLVF could not be modelled using APSIM as roses are not included as a crop module in the

APSIM programme and there was no data to calibrate the model to the precise climate conditions in the tunnels used for the production of roses.

6.1.2.1 Gurúè small-scale virtual farm (GSVF)

The cropping system is based on a two-year cycle of a maize and pigeon pea intercrop rotated with soybean as explained in the GSVF agronomic practices section. The APSIM model setup was based on an existing maize-legume-weed simulation which was adapted for the GSVF. Specifically, the scenario run was set up as follows:

i) The existing peanut module was removed from the simulation and replaced with the soybean and pigeon pea modules. The rotational system was achieved by applying the manager module “rotation with intercrop” where the winter fallow (WF) period ends by the 01-October and the rotation sequence set to “pigeon pea; WF; soybean; WF; maize; nil”. Intercropping was achieved by linking the maize and pigeon pea modules with the canopy module to simulate intercropping competition. This resulted in an intercrop of maize and pigeon pea in one growing season (year one) followed by a rotation with a soybean monocrop in the following growing season (year two).

ii) The cultivars chosen in the GSVF are not included in APSIM, therefore existing cultivars were adjusted to simulate them: “mwi_local” is a Malawian maize cultivar that was used to represent the traditional Mozambican local cultivar. The “mwi_local” represents local Malawian varieties by having a lower harvest index (influenced by the parameter “grain no. max”) and slower response to available resources (grain growth rate) compared to hybrid varieties. Further downwards adjustments to the crop leaf area index (from the range 0.1-4 to the range 0.1-2.) and transpiration efficiency coefficient (from 0.009 to 0.006) were made to better represent the lower yield potential of the Mozambican cultivar. The soybean cultivar “MG_5” was used to represent yields obtained by Gurúè SSFs, it is a generic soybean cultivar with a relatively intermediate growth duration (Robertson & Carberry, 1998). The APSIM “Medium-duration” pigeon pea cultivar was used as it adequately modelled Gurúè SSFs’ pigeon pea yields and time to maturation.

iii) The sowing conditions were set using "Sow using a variable rule with intercrop" for all crops. The sowing window was set to "Must sow" from the 1st November to 30th January with sowing occurring when 20 mm of rainfall was accumulated within a three-day period or when soil water reached 20 mm soil depth or more, while if neither of these conditions were met then sowing proceeded on the last day of the sowing window period (Smith *et al.,* 2016). The sowing density was set to 2,5 maize plants m^{-2}, 2 pigeon pea plants m^{-2}, and 6,5 soybean plants m^{-2} as described for the GSVF. Crops were sown at a 50 mm depth with 900 mm row spacing to simulate sparse growing conditions (Whitbread *et al,.* 2013).

iv) Fertilizer applications were set to zero for all crops and the volume of crop residues incorporated during tillage was set to 50%.

v) The seedbed preparation tillage type was set to "90% burn removing 50% of weeds 30 days before planting" to simulate the SSFs burning their fields before planting.

vi) The harvesting criteria for the fraction of stover to remove was set to zero to simulate the SSFs retaining crop residues on the surface after harvest.

vii) The soil simulation was initiated with low N concentrations to represent the lack of fertilization, NO_3 was set to 3,8 ppm and NH_4 to 0,6 ppm in 1986 (Whitbread *et al.* 2013). Initial soil water content was unknown and therefore set to "50% full, filled from the top".

6.1.2.2. Gurúè large-scale virtual farm (GLVF)

According to the GLVF, the cropping system is based around a cycle of two years of maize rotated with two years of soybean separated by a winter fallow. The scenario setup was based on an existing maize-legume-weed simulation which was adapted for the GLVF's management practices. The scenario run was set up as follows:

i) The existing peanut module was removed from the simulation and replaced with the soybean module. The rotational system was achieved by setting the winter fallow (WF) period to end by the 1 October and the rotation sequence set to "soybean; WF; soybean; WF; maize; WF; maize; WF; nil". This resulted in a rotation of two growing seasons of maize followed by two growing seasons of soybean.

ii) The medium-late maturing maize cultivar "sc623" from Zimbabwe was used to simulate the medium-maturing PAN 53 and PAN 12 from South Africa used by the GLVF (PANNAR, 2013). However, yield was slightly higher than that the GLVF average and therefore the grain growth rate was changed from 8 mg grain per day to 7 mg grain per day. The long-duration "MG_4" soybean cultivar was used to represent yields obtained by the LAIs 143-day cultivar.

iii) The sowing conditions were set using "Sow using a variable rule with intercrop" for all crops. The sowing window was set to "must sow" between the 1st of November and the 30th of January with sowing occurring when 20 mm of cumulative rainfall was attained by the end of three days or if the amount of soil water reaches 20 mm, if neither of these conditions are met the crop is sown on the last day of the sowing window (Smith et al., 2016). The sowing density was set to 5.5 maize plants m^{-2} and 5 soybean plants m^{-2} according to the GLVF. Crops were sown at 50 mm depth with 750 mm row spacing.

iv) Maize fertilization was set to 18 kg "NH_4_N" during planting (150 kg MAP ha^{-1}) followed by then 190 kg N ha^{-1} as urea as a top-dress 6 weeks after planting (before tasselling). Soybean fertilization was set to 18 kg "NH_4_N" at planting (150 kg MAP ha^{-1}).

v) The zero-tillage practiced by the GLVF was simulated by setting "must till" to "no".

vi) The harvesting criteria for the fraction of stover to remove was set to zero to simulate the crop residues being left on the soil surface of the field.

vii) Land use before LAI production was SSF production, therefore the soil simulation was initiated after the same values as the GSVF with NO_3 set to 3.8 mg kg^{-1} and NH_4 to 0.6 mg kg^{-1} in 1986 (Whitbread *et al.* 2013). Initial soil water content was unknown and therefore set to "50% full, filled from the top".

6.1.2.3. Nanyuki small-scale virtual farm (NSVF)

Following the NSVF management practices, the cropping system was based around a cycle of two growing seasons in one year where an intercrop of maize and legume was planted during the long rains (Mar-Aug/Sep) and wheat was planted during the short rains (Nov-Jun/Jul). The SSF scenario setup was based on an existing maize-legume-weed simulation which was adapted for the NSVF's management practices. The scenario run was set up as follows:

i) The existing peanut module was removed from the simulation and replaced with the soybean and cowpea modules. The rotational system of two continuous cropping seasons in one year with no fallow period was achieved by applying the manager module "Rotation with intercrop" with the rotation sequence set to "wheat; maize; cowpea; nil". Intercropping was set by parameterizing the CANOPY module to "maize; cowpea". This resulted in an intercrop of maize and cowpea in the first growing season and wheat in the second growing season within the same year.

ii) The cultivars chosen for the NSVF were based on their time to maturity to allow for the simulation of two growing seasons within one year. The maize cultivar chosen was the early-maturing Zimbabwean hybrid 'sc401' and the cowpea cultivar 'banjo'. According to APSIM's program files, both varieties are early maturing cultivars. While the "axe" wheat cultivar simulated was a very early maturing variety suited to drought-stressed locations and planted in shorter growing seasons or for late sowing according to APSIM's software programme files.

iii) The sowing conditions were set using "Sow using a variable rule with intercrop" rule. For the long rains the sowing window was set to "Must sow" between the 20th March and the 2nd April with sowing occurring when 10 mm of cumulative rainfall was attained by the end of three days. For the short rains the sowing window was set to “Must sow” between the 30th September and the 15th October. If these conditions were not met, the crop would be sown on the last day of the sowing window. The sowing density was set to 4.4 maize plants m^{-2}, 4 pigeon pea plants m^{-2}, and 7 wheat plants m^{-2} according to the NSVF. Crops were sown at 50 mm depth with 900 mm row spacing (Whitbread *et al.* 2010).

iv) For all crops, fertilizer applications were set to 22 kg N ha^{-1} as “NH4_N” at planting and 22 kg “NH4_N” 42 days after planting to simulate application by the NSVF.

v) Initial surface residues at planting in 1986 was set to 500 kg ha^{-1} according to Njeru & Gitonga (2004). Crop residues were removed from the soil surface by setting “Enter fraction of stover to remove” to 95%.

vi) Seedbed preparation tillage type was set to “Disc” 21 days before the sowing window removing 50% of weeds from the field.

vii) The soil simulation for N and soil water for Nanyuki was initiated according to calibration values from Njeru & Gitonga (2004) (Table 2).

6.1.3. Simulation analysis

Once model parameterization was complete, scenarios were run to estimate agronomic efficiency, resource-use efficiency and to estimate the potential soil degradation of each VF system in terms of soil C and N loss.

6.1.3.1. Potential yield analysis

The agronomic efficiency of each VF was estimated by comparing the average actual and simulated potential maize yields. Maize was chosen in particular as it was the only crop that was used in all three VF systems analyzed using APSIM. As a rule, the simulated average maize yield under all scenarios was calculated over a 50-year period, excluding crop failures. Due to the low observed mean yields obtained for maize across the three VFs, crop failures were considered as 10% of the mean actual maize yield assumed in the VF results. The potential yields under varying conditions were estimated by simulating different scenarios, specifically:

I) Agro-ecological yield was estimated as the mean maize yield over the 50-year simulation when the early maturing cultivar "sc_501" was cultivated as a monocrop, at planting density of 5 plants m^{-2}, under rainfed conditions with zero N fertilization.

II) The N-limited yield was estimated as the average maize yield over the 50-year simulation when the early maturing cultivar "sc_501" was cultivated as a monocrop, at planting density of 5 plants m^{-2}, under optimal irrigation scheduling for the region and zero N fertilization.

III) The water-limited yield was estimated as the average maize yield over the 50-year simulation when the early maturing cultivar "sc_501" was cultivated as a monocrop, at planting density of 5 plants m^{-2}, under rainfed conditions and 100 kg NH_4-N fertilizer. Fertilization was split into 20 kg NH_4-N at sowing and 80 kg NH_4-N 30 days after planting.

IV) The potential maize yield was estimated as the average maize yield over the 50-year simulation when the early maturing cultivar "sc_501" was cultivated as a monocrop, at planting density of 5 plants m^{-2}, under optimal irrigation scheduling and 100 kg NH_4-N fertilizer. Fertilization was split into 20 kg NH_4-N at sowing and 80 kg NH_4-N 30 days after planting

Analyzing these potential yields allowed for an understanding of the limitations of N and water stress to maize yield. However, to fully understand the determinants of agricultural productivity in each VF systems additional factors were more thoroughly investigated. Nape (2011) explains that rainfall is the single most important agro-climactic variable determining the productivity and variability of the overall agricultural productivity in rainfed areas under semi-arid conditions in southern Africa. Accordingly, the addition of irrigation to the simulated system was used to estimate the contribution of water stress to maize productivity. According to Subedi & Ma (2009) the most important management factors influencing maize yields was the selection of suitable cultivars, adequate fertilization rates, optimizing plant population density, appropriate planting dates, and timely weeding. In terms of cultivar choice, the yields of the cultivar used in the VF scenario were compared to the yields that could be obtained if a high-yielding maize cultivar was used, in these simulations the high-yielding maize hybrid was Pioneer 3237. Cultivars of different maturity classes were also investigated in each simulation for a better understanding of the growing period in the region. The APSIM cultivars used in these cases were the early maturing "sc401", early-medium "sc501", medium-late "sc601", and the late maturing "sc709". Different levels of these management practices were investigated to estimate their contribution to yield and to determine the ideal management scenario. These management practices were simulated individually and in combination to investigate ideal management practices and to comment on the management choices of the production systems. Nitrogen stress and water stress during critical times under these varying management techniques was also investigated for a better understanding of the simulation. This was achieved by using the output variables relating to "N_stress" and "water_stress" within the crop modules.

The statistical program, IBM SPSS, was then used to determine if there was significant difference between means of yields from alternative management practices by applying the paired *t*-test. The Wilcoxon signed ranks test was also applied using the IBM SPSS software when necessary to assess the number of positive and negative ranks of each management practice. However, weeds and consequently weeding were not included in the simulations as their impacts were not adequately modelled.

6.1.3.2. Resource-use efficiency analysis

Resource use-efficiency was also investigated by calculating the potential Agronomic Nitrogen-Use Efficiency (NAE) using the methodology described in Whitbread *et al.,* (2013) when applicable. In this methodology, NAE (kg grain kg^{-1} N) was defined as "the increase in maize grain yield per unit of N fertilizer applied over the control yield without N fertilizer application" using the following equation:

$$\text{NAE} = \frac{Yf - Yc}{F}$$

In the equation, Yf was defined as the maize yield per hectare when F amount of N fertilizer was applied and Yc was the maize yield per hectare in the control simulation without N fertilization (Whitbread *et al.,* 2013). The F variable was defined as the amount of fertilizer added per hectare (Whitbread *et al.,* 2013). According to Whitbread *et al.* (2013), an NAE of equal or more than 25 kg grain per kg N applied was considered a high N response, 15-25 kg grain per kg N applied was an intermediate response, and below 15 kg grain per kg N applied was considered as a low response.

6.1.3.3. Soil degradation analysis

According to a review on soil degradation by Biancalani *et al.,* (2012), soil degradation has been assessed by providing a qualitative evaluation to chosen physical and chemical degradation processes separately. In this study, we focused on chemical degradation, with a specific focus on nutrient mining, as this was where the primary data was the strongest. Nutrient mining occurs due to poor management practices that do not replenish the nutrients taken out of the soil during cultivation (Biancalani *et al.,* 2012). The nutrient mining potential of each VF system was examined by monitoring SOC and total soil N in each soil layer over a 50-year period. SOC is often used as an indicator of soil 'health' as it is a fundamental determinant of fertility, contributing to the biological, chemical and physical aspects of the soils which are key to sustaining plant growth (Biancalani *et al.,* 2012). Furthermore, soil is the main pool of OC on Earth, holding around 1 500 Gt of OC, a quantity greater than the combined atmospheric and vegetation pools (Lal, 2004). Monitoring soil N was critical as it is the most required plant nutrient and would therefore determine the ability of the crop to produce high yields (Cardoso *et al.,* 2013).

The N state of the soil was analyzed by monitoring N mineralization (dlt_n_min) and total N (nit_tot) in the soil after each cropping year, over 50 years. The SOILN module in APSIM allowed for simulation of the flow of C and N in the SOM pool (Figure 4) (Njeru & Gitonga, 2004). In APSIM, there are three SOM pools i.e. fresh organic matter (FOM), microbial biomass and microbial products (BIOM), and humus (HUM) (Njeru & Gitonga, 2004). The model further assumes that the SOM pools (BIOM and HUM) have set C:N ratios that ensure that there is a constant immobilization demand (Keating *et al.,* 2003). Consequently, if there is an inadequate supply of mineral N from the decomposition (mineralization) of crop residues and roots (i.e. from FOM) and/or from drawing on the mineral N in the soil layer to meet immobilization demands it would lead to decelerated mineralization (decomposition) rates (Keating *et al.,* 2003). Therefore, by analyzing the rates of N mineralization it was assessed whether there was an inadequate supply of mineral N to support OM demands and if the VF system is therefore mining soil N. The soil module for each scenario was parametrized in the APsoil model for APSIM with an initial total N. To further understand the relationship of each VF's management practices on available N and assess the potential status of soil N after 50 years of production, the Total N (nit_tot) was monitored annually from its initial measured N status. Additionally, SOILN allows for a comprehensive analysis of the C balance. In APSIM, C is added to the SOM system via crop residues and/or roots (with a set C:N ratio) and organic amendments (animal manures), the carbon that is decomposed is then either emitted as CO_2 or synthesized into the BIOM and HUM pools (Keating *et al.,* 2003). Besides microbial decomposition enhanced by soil disturbances such as tillage, C losses are also associated with erosion, fire, harvest, and leaching (Lorenz & Lal, 2016). By monitoring the SOC levels ("OC%") in each soil layer over a 50-year period we examined the impacts of different management strategies utilized by the VFs on the rate of SOC decline.

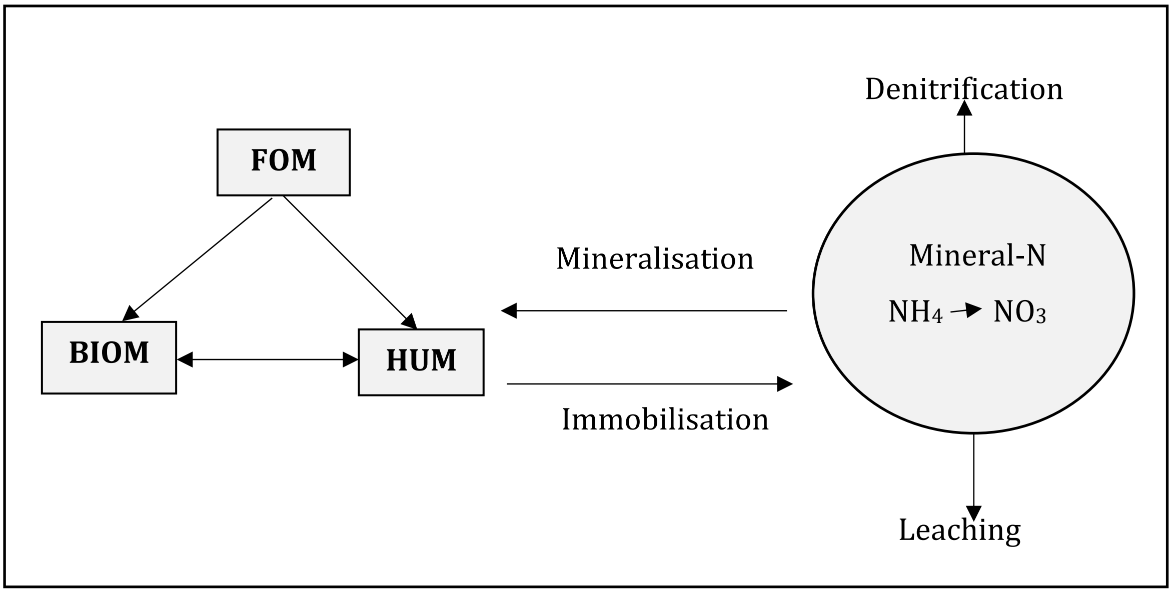

Fig. 4: Diagram of transformations occurring in each soil layer in the APSIM model (BIOM: microbial biomass and microbial products, FOM: fresh organic matter, HUM: humus, N: Nitrogen, NH_4: Ammonium, NO_3: Nitrate) (Delve & Probert, 2004)

6.2. Life Cycle Assessment (LCA) methodology

The standards for LCA methodology were set by the International Organization for Standardization (ISO) and were defined in ISO 14040 (ISO, 2006). This methodology was applied in this study to assess a range of Environmental Impacts (EIs) connected with a year of production for each virtual farm system. According to ISO (2006), the LCA is divided into four interconnected steps (Figure 5):

1) Goal and scope definition
2) Life cycle inventory
3) Life cycle impact assessment
4) Interpretation

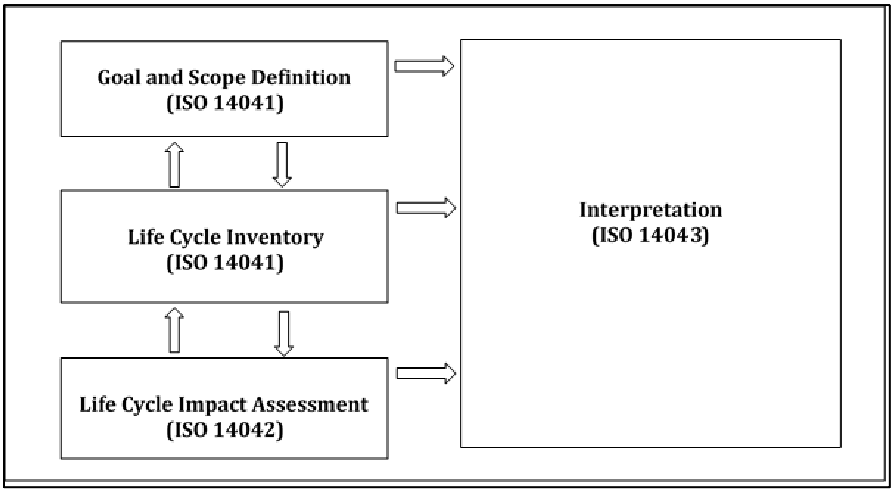

Fig. 5: Life cycle assessment framework (ISO, 2006)

Goal and Scope definition:

The goal of this LCA is to develop a suitable assessment to quantify, evaluate, and compare the environmental burden of SSF and LAI systems based on selected impact category indicators. The outcomes of this study are aimed at future LCA practitioners, policy advisors, and any organizations working with these two types of systems, including the farmers themselves. The four systems under investigation are the "virtual farms" which represent the conventional management practices of SSFs and LAIs in the Gurúè and Nanyuki study regions. Details are further described in the virtual farm synthesis in the results section of this study.

The scope of this study included the production-related activities on the farmer's field. Specifically, mechanized operations, fertilizer and pesticide application, leaving crop residues on the soil surface, burning crop residues, and irrigation. Also included were the emissions related to the manufacturing of agro-inputs, particularly fertilizers and pesticides. The system boundary covers the span of one year and begins at the input production phase and ends with the final raw product, consequently it was out of scope to include transportation beyond the farm boundary, and any processing or packaging of the product. Considering that each virtual farm produces different crops, the functional unit (FU) selected is **one hectare of cultivated land**, instead of the conventional one metric tonne dry weight. Although, when applicable, for comparison, this FU can be converted to metric tonne dry weight according to yield (tonne ha^{-1}).

1) Life cycle inventory analysis

The second step is the Life Cycle Inventory (LCI), which is a compilation of all the resources used and all the emission released into the environment during the cultivation of one hectare, over one growing season, as defined by ISO 14041 (Brentrup *et al.,* 2001). Essentially, it is an inventory of input/output data associated with the system under investigation (ISO, 1998).

The data collected to construct each virtual farm (VF) was used to assemble the inputs, which in this study were selected based on their environmental relevance. They were categorized as fertilizer, pesticide, fuel, crop residue, and water consumption. The goal was to identify the significant inputs associated with site-specific environmental issues, however, each input is not environmentally relevant across all VFs (ISO, 1998). Nevertheless, all inputs were included in the analysis of each VF to allow for comparisons to be drawn. Inputs were then divided into their component processes to quantify their outputs (Table 3). Quantifying the output categories described in Table 4 through direct measurements is notoriously challenging, so estimating the potential emissions by relating them to input use is employed instead. By applying estimations and measurement from previous studies, given in Table 3, we were able to estimate the potential outputs emitted from the consumption of each input.

Table 3: Life Cycle Inventory component breakdown

Input	Component Processes	Output	Unit	Reference
Fertilizer				
	Nitrification & denitrification	N_2O direct emissions	**kg**	FAO (2014); IPCC (2006)
	Volatilization & leaching	N_20 indirect emissions	**kg**	FAO (2014); IPCC (2006)
	Volatilization	NH_3 emissions	**kg**	Sahle & Potting (2013); Skowronska & Filipek (2014)
	Nitrification & denitrification	NO_x emissions	**kg**	Sahle & Potting (2013); Skowronska & Filipek (2014)
	Leaching	NO_3^--N	**kg**	FAO (2014); IPCC (2006)
	Leaching	P	**g**	Own estimation
	Manufacturing	Non-renewable energy consumption	**MJ**	Brentrup & Pallière (2008)
Pesticides				
	Emissions into air	Active ingredient (AI)	**kg AI**	Sahle & Potting (2013)
	Leaching	Active ingredient	**kg AI**	Margni *et al.* (2002)
	Manufacturing	CO_2	**kg**	Lal (2004)
	Manufacturing	Non-renewable energy consumption	**MJ**	Mashoko *et al.* (2010); Van der Laan *et al.* (2015)
Fuel (Diesel)	Combustion	Direct non-renewable energy consumption	**MJ**	IPCC (2006)
	Combustion	CO_2	**kg**	IPP (2006); Lal (2004)
	Combustion	CH_4	**kg**	IPCC (2006)
	Combustion	N_2O	**kg**	IPCC (2006)
	Combustion	NO_x	**kg**	IPCC (2006); Sahle & Potting (2013)
Crop residues	Nitrification & denitrification	N_2O direct emissions	**kg**	FAO (2014); IPCC (2006)
	Crop residue burning	N_2O direct emissions	**kg**	FAO (2014); IPCC (2006)
	Volatilization & leaching	N_20 indirect emissions	**kg**	FAO (2014); IPCC (2006)
	Crop residue burning	CH_4	**kg**	FAO (2014); IPCC (2006)
	Crop residue burning	NO_x	**kg**	Pouliot *et al.* (2012)
	Crop residue burning	SO_2	**kg**	Pouliot et al. (2012)
	Crop residue burning	NH_3	**kg**	Pouliot et al. (2012)
Water consumption	Evapotranspiration	Blue water	**m³**	Hoekstra *et al.* (2011)
	Evapotranspiration	Green water	**m³**	Hoekstra *et al.* (2011)

2) Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) phase described in ISO 14042 is divided into mandatory and optional steps (ISO, 2000). The mandatory steps aim at converting the inventory data into effective EI categories using equivalence factors (Brentrup *et al.,* 2004). These equivalence factors represent the potential of a single emission or resource consumption to contribute to its respective EI category (Brentrup *et al.,* 2004). This typically allows for an improved understanding of the data for reporting purposes, by relating them to EIs that are 'user-friendly' to decision-makers (ISO, 1998). The optional steps are the weighting and the normalization phases which result in values that are, subjectively, globally-comparative. However, it was beyond the scope of this study to include the optional steps.

This study translated outputs estimated in the LCI into EI categories, namely: Non-Renewable Energy consumption (NRE), Global Warming Potential (GWP), Eutrophication Potential (EP), Acidification Potential (AP) And Water Footprint (WF). NRE was a main concern as it quantifies the potential decrease in the availability of influential abiotic resources for future generations and therefore indicates the sustainability of the system under investigation (Brentrup et al., 2004). Global warming results from the emissions of gases with specific radiative characteristics which leads to an unnatural warming of the Earth's surface, in turn causing global and regional climatic changes (Brentrup *et al.,* 2004). The main greenhouse gas (GHG) contributors are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Felix & Gheewala, 2012). Each GHG has a different, quantitative effectiveness in trapping heat, this potential is referred to as the gas's GWP and is measured in CO_2 equivalents (CO_2-eq) (Felix & Gheewala, 2012). Eutrophication is the undesired increase in biomass production in water and a shift in species composition caused by nutrient enrichment (Brentrup *et al.,* 2004). It can be caused by the transportation of inorganic fertilizers into waterways by waste water discharge, and air pollutants (Felix & Gheewala, 2012). This is particularly damaging in surface water systems because it can result in algal blooms and subsequent oxygen-consuming degradation processes which can result in the death of the total aquatic biocoenosis (cyanobacteria and blue-green algae), and the degradation of water quality (Brentrup et al., 2004). Eutrophication can be divided into aquatic and terrestrial eutrophication, but in this study, we focus simply on EP which encompasses both. Acidification refers to the addition of acids which have negative effects on terrestrial and aquatic ecosystems and are mainly caused by gaseous emissions of sulphur dioxide (SO_2) nitrogen oxides (NO_x) and ammonia (NH_3) (Brentrup *et al.,* 2004). These acidifying pollutants react with water vapour in the atmosphere resulting in acid rain, which can damage soils, plants, animals, building material, and result in fish mortality (Felix & Gheewala, 2012). AP is measured in units of sulphur dioxide equivalent (SO_2-eq).

Due to the lack of primary data relevant to the systems under investigation, eco-toxicity, land use change, and the formation of photo-oxidants were excluded from this analysis. Sahle & Potting (2013) explain that there are several methodologies that characterize EIs, but that they largely overlap with most notable differences traced back to country or continent parametrizations. Therefore, there are no decisive objective grounds that place one approach above another (Sahle & Potting, 2013). In this study the chosen EIs were calculated using the following methodologies:

- *Non-renewable energy consumption (NRE)* measured the total fossil fuel consumption required to power on-farm activities and during the manufacturing of fertilizers and pesticides (Brentrup *et al.,* 2004; Van der Laan *et al.,* 2015)
- *Global warming potential (GWP)* was expressed in CO_2 equivalents and calculated based on the Intergovernmental Panel on Climate Change (IPCC) (2007). GWP was estimated over a 100-yr time horizon using 298 for N_2O and 25 for CH_4.
- *Eutrophication potential (EP) and the acidification potential (AP)* were estimated according to the Eco-indicator 95 approach using the equivalence factors displayed in Figure 6 (Brentrup *et al.,* 2001).
- *Water consumption* was based on the Water Footprint (WF) approach described in Hoekstra *et al.* (2011). Due to the extensive nature of the WF, a sub-section was dedicated to the thorough description of the methodological steps involved in the assessment.

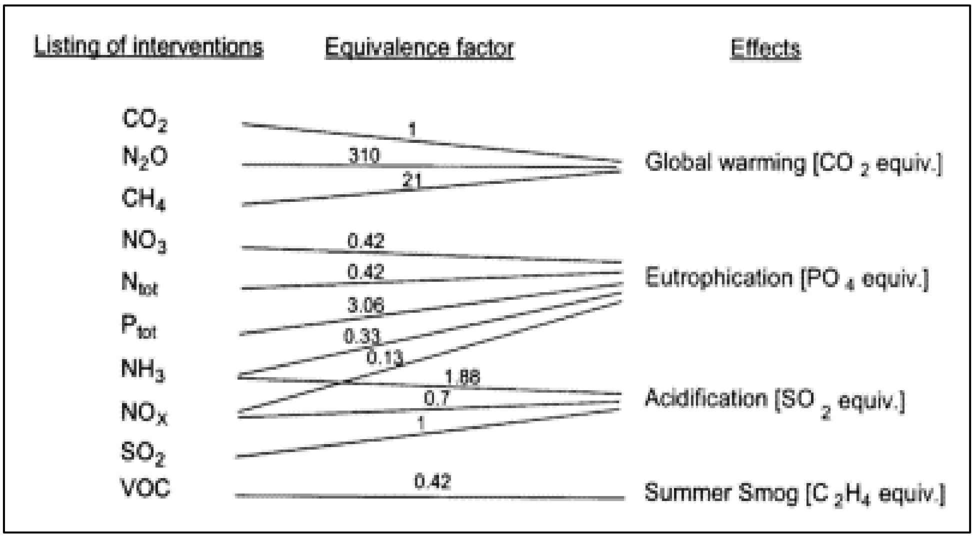

Fig. 6: Classification of equivalence factors based on Eco-indicator 95 method (Brentrup *et al.,* 2001)

3) Life Cycle Interpretation

The life cycle interpretation phase was based on the methodology described in ISO 14043 (ISO, 1999). It describes the final phase of the LCA in which the results from the LCIA are systematically summarized and discussed in accordance with the goal and scope definitions (ISO, 2000). This phase also allowed for the explanation of certain limitations, created links between other methodologies, and provided recommendations based on the reported results (ISO, 2000).

It was the goal of this study to calculate the EI of each VF system in an average year of production. To convert the EIs associated with each crop to EIs for an average year of production, the contribution of each crop to an average year of production was considered. The contribution of each crop was assessed according to the number of growing seasons within a year and the type of cropping system. If the crop had one growing season then the EIs associated with one growing season was considered as 100%, therefore if the crop was intercropped then only 50% of its EI would contribute the EI of an average year of production. If the cropping system consisted of a rotation between two crops every two years, then each crop would contribute 50% of its EIs to the average EI. If there were two growing seasons within a year, the crop cultivated in the first growing season would contribute 50% and the crop cultivated in the second growing season would contribute 50%. Combinations of these conditions were also considered so that a crop that was intercropped followed by a rotation with a sole crop would only contribute 25% during an average year of production.

6.3. Water footprint methodology

The water footprint component of the LCA was based on the methodology described in Hoekstra *et al.* (2011). Water footprint assessments allow for the estimation of the volume of water consumed and impact on water quality during the process of growing crops (Hoekstra *et al*., 2011). The total water footprint is expressed as the amount of water consumed (m^3 ha^{-1}) to corresponding crop yield (tonnes ha^{-1}) (Mekonnen *et al.*, 2012). Water consumption is divided into green, blue, and grey water. These three components make up the water footprint:

$$WF_{tot} = WF_{green} + WF_{blue} + WF_{grey} \quad \text{[volume/mass]} \qquad (1)$$

Distinguishing between the blue and green water footprint is necessary as their hydrological, environmental, economic, and social impacts are explicitly different (Hoekstra *et al*., 2011). Blue water is the amount of available surface or sub-surface water during a given period. Hoekstra *et al.* (2011) defines the blue water footprint as the consumption of available surface water or groundwater during the production process. Where crop evapotranspiration (*ET*) is attributed to the application of irrigation water it is considered as blue water use.

Green water refers to the precipitation fraction that is stored in the soil and available for vegetation growth only. The green water footprint is defined in Hoekstra *et al.* (2011) as the quantity of rainwater consumed during the production process divided by yield.

The grey water footprint is defined by Hoekstra *et al.* (2011) as the volume of freshwater required to assimilate the load of emitted pollutants based on natural background concentrations and existing ambient water quality standards. In this study, a grey water footprint was not considered in this assessment, as well-developed LCA methodology was used to quantify potential impacts on water quality, such as the eutrophication and ecotoxicity impact categories.

The water footprint of green and blue water was calculated according to Hoekstra *et al.* (2011) as consumptive water use (CWU) divided by the crop yield (Y - tonnes ha^{-1} yr^{-1}):

$$WF_{green} = CWU_{green}.Y^{-1} \quad \text{[volume/mass]} \quad (2)$$

$$WF_{blue} = CWU_{blue}.Y^{-1} \quad \text{[volume/mass]} \quad (3)$$

Hoekstra *et al.* (2011) refers to "consumptive water use" as one of the following four cases:

1. Water that is evapotranspired;
2. Water incorporated into the harvested product;
3. Water that does not return to the same catchment area, for example, it is returned to another catchment area or the sea;
4. Water the does not return in the same period, for example, it is withdrawn in a scarce period and returned in a wet period.

ET is the most significant source of water consumption and is often equated to the total consumptive water use (*CWU*) (Hoekstra *et al*., 2011). The amount of water incorporated into the harvested product is not typically accounted for in the water footprint as its quantity is usually in the order of 0.1-1.0% of evapotranspired water (Hoekstra *et al*., 2011). ET for each case study was therefore equated to *CWU* in this study. ET calculations were approached using two methodologies depending on the data that was available.

When the APSIM model could be directly applied to simulate the cropping system, it was appropriated for deriving ET in mm. For each day, the model takes the minimum value between the atmospheric demand and the soil water that is available for uptake and defines it as crop water uptake. Crop water uptake is annotated as "EP" in ASPIM and calculated in the crop module. *EP* in each case study scenario was calculated on a daily time step and the average cumulative *EP* for each crop was used for the water footprint calculations. Evaporation from the soil surface was modelled in APSIM's soil module using the variable "*ES*". APSIM calculates soil evaporation (*ES*) using the approach of Campbell (1985) assuming isothermal vapor transport (Huth *et al*. 2012). Average ES over 50 years was linked to a specific crop or crops (inter-cropping) and added to EP to obtain an ET value used in the WF calculations. Transpiration from weeds was not considered, although it was acknowledged that this could have a substantial contribution to soil water losses, especially for weed-abundant systems like the SSF systems.

In cases where APSIM could not be employed, the crop coefficient-reference *ET* (K_cET_o) procedure (Equation 4), was used to estimate actual crop evapotranspiration (ET_c) (Tipis & Mpusia, 2006).

$$ET_{crop}=(ET_o)\ x\ Kc^{-1}\ \text{[volume/time]} \qquad (4)$$

Using this methodology, ET_o was multiplied by an empirical crop coefficient (K_c) to produce an estimate of ET_c (Tipis & Mpusia, 2006). ET_o represents the evaporative demand of the atmosphere on a standardized vegetative surface. The only factors affecting it are weather variables, so it can be calculated from weather data alone (Allen *et al*., 1998). Computation of ET_o was done using weather data from CLIMWAT (FAO 1992) applied to the FAO designed CROPWAT model which estimates ET_o on a monthly time-step using the Penman-Monteith equation described in Allen *et al.* (1998). K_c is the ratio of ET_c to the reference ET_o and was used to represent the effects of major crop characteristics such as crop canopy cover that distinguishes ETc from reference ET_o.

For the production of roses specifically, ET_o was calculated on a monthly time-step by applying the Nanyuki weather variables from CLIMWAT to the CROPWAT model. K_c was derived from a study conducted by Singh *et al.* (2016) where ET_c values were determined daily from drum lysimeters kept inside and outside of greenhouses. This was done for Dutch roses for three years of full crop cycles and then averaged monthly. The rose plant is perennial and so it has more than one harvest cycle which consequently affects the K_c value. During periods of full canopy cover the K_c needs to be increased and as pruning and harvesting is done the K_c decreases accordingly. It was found that under greenhouse conditions the K_c during the initial stage is 0.48 to 0.6, 0.6 to 0.86 during the development stage, 0.87 to 0.96 during the middle stage, and 0.96 to 0.76 during the late season. Data on LAI dynamics of roses under the NLVF practices were unavailable. So the utilization of K_c values for each development stage was not possible, and instead the values recommended by Singh *et al.* (2016) were averaged to 0.81 and applied for the whole year.

The ET_c value was then further adapted to accommodate the modified conditions in a greenhouse when necessary. Due to factors such as decreased solar radiation by an average 20%, nearly zero wind speeds, and increases in relative humidity, authors have observed decreased evaporative demand inside greenhouses compared to outdoors (Tipis & Mpusia, 2006; Singh *et al*. 2016). For roses, a study was conducted by Tipis & Mpusia (2006) which proposed that ET_c for roses in a greenhouse in Kenya was 65% of outdoor ET_c at an LAI of 0.85.

Beyond the WF calculations for each virtual farms' cropping system, this study also considered the potential impact of irrigation, water storage, and rainwater harvesting on the WF. When sufficient data on irrigation practices, such as scheduling methods and source of irrigation water was not available, CROPWAT was used to estimate crop water use. This allowed us to circumvent these limitations and still offer a perspective on the potential blue water demand. This "potential blue water demand" is defined as the amount of water that would need to be supplied by irrigation to prevent crop water stress and maximize crop production if effective rainfall is utilized fully (Chiarelli *et al*., 2016). CROPWAT is a computer program developed by the Land and Water Development Division of the FAO (FAO, 1992). It allows for the calculation of ETc, ETo, effective rainfall, and irrigation requirements using crop and soil data from the FAO and weather data from the CLIMWAT model (FAO, 1992). For our purposes, the CLIMWAT weather station data for Nanyuki (Nanyuki weather station) and Gurúè (Gurúè weather station) were utilized which include monthly rainfall, and temperature, relative humidity, wind speed and solar radiation. Crop data from the FAO was generic and considers Kc values, phenological stages in days, rooting depth, yield response, and crop height. The *Kc* values used for modelling in CROPWAT were generic values based on FAO crop parameters. If more specific Kc values were applied in CROPWAT, the reality may be that the total water footprint and irrigation requirements could be less than predicted. Results from the model were then used to calculate a potential WF and discuss the production systems' irrigation requirements.

When applicable, the WF of water storage (WF_{storage}) was accounted for and considered as blue water consumption (WF_{blue}). The calculation of WF_{storage} equates it to the evaporation from the dam surface (Equation 5) (FAO, 2015). Where E_v was the dam evaporation in volume and A was the reservoir surface area in m^2.

$$E_v = ET_o \, x \, A \text{ [volume/area]} \qquad (5)$$

This calculation was adapted by FAO (2015) from Equation 56 of Allen *et al.* (1998) by exchanging K_c with the open water coefficient (K_w). K_w was assumed by FAO (2015) to equal to one for simplicity. This value was a rough estimation that could introduce errors of up to -35% and +25% in the deeper portion of the dam and -5% error in the shallower portion depending on the season (FAO, 2015). Nevertheless, FAO (2015) still considered these errors acceptable due to the rough nature of the analysis. This equation was then further adapted to the water footprint methodology by considering crop yield:

$$WF_{storage} = (ET_o . A) \, x \, Y^{-1} \text{ [volume/mass]} \qquad (6)$$

To calculate the amount of rainwater harvested ($R_{harvested}$) that was available for irrigation the following simple equation was used where R is rainfall (mm), SA was the size of the rainwater collection area (m^2), and E_{roof} was the K_w factor which allows for the consideration of rain water lost to evaporation and interception.

$$R_{harvested} = R \, x \, SA \, x \, E_{roof} \text{ [volume/time]} \qquad (7)$$

SA includes the area of the greenhouse roof used for collecting rainwater as well as the dam surface area but does not include the area of catchment surrounding the dam. This was due to the lack of data on the total area of the catchment surface, slope length and degree, and material which would influence the amount of rainwater that would runoff into the dam. It is understood that a portion of rainfall would be intercepted via leaks in the roof and evaporation, this factor was accounted for by multiplying the volume of rain harvested by 0.9 to account for an estimated 10% loss. The main purpose of calculating $R_{harvested}$ was to evaluate if it is possible to harvest enough water during the rainy season to support crop growth during the dry season, considering losses from E_v. The results of this comparison between $R_{harvested}$ and CWU therefore considers and addresses the limitations discussed here.

Chapter III: Results

7. Management practices

7.1. Small-scale farmer household survey

An overall summary of data compiled from the household surveys with Gurúè and Nanyuki SSFs is displayed in Table 4.

Table 4: Results from the SSF household surveys in Gurúè and Nanyuki organized by WP3 of the AFGROLAND project

Management practices	Units	GSVF (n=50)	NSVF (n=100)
Average total area	**ha**	2,5	0,98
Fertilizer use	**% yes**	0	52
Fertilizer type	**% use**	-	DAP (32)
	% use	-	CAN (13)
	% use	-	17:17 (12)
	% use	-	23:23 (6)
	% use	-	20:20 (5)
	% use	-	Urea (1)
	% use	-	Foliar feed (4)
Fertilizer quantity	**kg ha^{-1}**	0	250
Pesticide use	**% use**	12	90
Pesticide type	**% use**	-	Dimethoate (4)
	% use	-	Bulldock (3)
	% use	-	Karate (3)
	% use	-	Bestox (3)
	% use	-	Gramoxone (1)
	% use	-	Roundup (1)

Irrigation	**% yes**	0	37
	% use	-	Sprinkler (15)
	% use	-	Hose pipe (4)
	% use	-	Unspecified (18)
Crop rotation	**% yes**	19	75
Fallow	**% yes**	7	46
Mechanization	**% yes**	1	65
Leaving crop residues on soil surface	**%yes**	42	30
Weeding methods	**% use**	Manual (100)	Manual (76)
	% use	-	Chemical (8)
	% use	-	Both (13)

7.1.1. Gurúè small-scale virtual farm (GSVF)

All the households interviewed (n=50) were found to be cultivating crops for both subsistence and the market, except one household that was not cultivating any crops. Out of the households that did farm with crops, the average size of cultivated land was 2.5 ha and the three most commonly produced crops by the SSF respondents were, in order of popularity: maize, soybean, and pigeon pea. The average yields calculated from the estimates provided by the SSFs were 1.2 tonnes ha^{-1} for maize, 1.6 tonnes ha^{-1} for soybean, and 0.76 tonnes ha^{-1} for pigeon pea. However, yields ranged from 0.01-7 tonnes ha^{-1} for maize, from 0.25-4 tonnes ha^{-1} for soybean, and from 0.1-3 tonnes ha^{-1} for pigeon pea.

This high variability in yield can have been attributed to numerous reasons since yields in the area are not easily measured. Among them, lack of cohesive units of measurement; some farmers sold their maize on the cob while others only sold the grain. In the case of soybean, the beans were harvested multiple times for consumption or for the market, so the total amount harvested could have been difficult to estimate. Absence of record-keeping by the majority of SSFs may have also played a role, complicating the observation of trends in average yields. Additionally, SSFs were often unaware of the official size of their land resulting in inexact estimates of cropping area. Intercropping and mixed cropping also posed challenges for calculating the proportion of land allocated to a specific crop. These factors explained some of the challenges to SSFs being able to accurately estimate average yields in a format that was suitable for agronomic assessment.

In terms of soil management, all interviewed households were found to be preparing their soil manually with a hoe, except one who used a tractor to till the soil before planting. The percentage of SSFs who were burning their fields to clear them for planting was not appropriately captured in this survey. Only 19% of respondents reported that they were practicing crop rotation. While 7% allowed for their land to remain fallow for at least a season, the rest were found to be continuously cultivating their land. However, to regain fertility, as many as 42% would leave crop residues on the soil surface.

The SSFs interviewed in the Mozambican study region did not use fertilizer for maize, soybean or pigeon pea cultivation. However, there were several cases where pesticides were applied, with about 12% of SSFs found to be using pesticides. Pesticides were utilized for soybean production, but not for maize or pigeon pea. In terms of irrigation, rainfed agriculture was practiced by all the SSF respondents, as there were zero cases captured where irrigation was utilized. Weeding was done is every case (n=50), but no herbicides were used, all the work was done manually by hand.

7.1.2. Nanyuki small-scale virtual farm (NSVF)

All households (n=100), except one, engaged in crop cultivation. While 22% did so exclusively for subsistence, the rest produced for the market and for subsistence. The respondents that did cultivate crops dedicated an average 0.98 ha to crop production. Results indicated that potatoes (*Solanum tuberosum*), maize (*Zea mays*), and beans (*Phaseolus vulgaris*) were the most commonly cultivated crops, with wheat (*Triticum spelta*) as the fourth most common crop. The average yields were found to be 3.02 tonnes ha^{-1} for maize (range: 0.4-8 tonnes ha^{-1}), 1.21 tonnes ha^{-1} for beans (range: 0.17-7 tonnes ha^{-1}), and 3.65 tones ha^{-1} for wheat (range: 1-8 tonnes ha^{-1}).

To prepare the soil before planting, tractors and ox-drawn ploughs were used by 65% of SSF respondents. About 70% of the interviewed SSFs removed crop residues from the field to use as either fodder for livestock or to make compost to sell. While 75% were found to be practicing crop rotation to ensure soil fertility and/or control pests.

In terms of input use, about 51% of the SSFs interviewed were using fertilizers. Of these respondents the average fertilizer rate was estimated at 250 kg ha^{-1} and the most common fertilizers used were diammonium phosphate (DAP), followed by NPK, and then calcium ammonium nitrate (CAN). Mixing fertilizers was also found to be common, with 45% of the respondent using fertilizers using more than one type of fertilizer. As many as 90% of respondents were applying pesticides to their crops. With the most commonly applied chemical was identified as the insecticide Dimethoate. Additionally, a significant 37% of SSF respondents were found to be irrigating their crops, while the other 62% were practicing rainfed agriculture.

7.2. Virtual farm synthesis

Heterogeneity was recognized within the study sites as each farmer interviewed used diverse farming strategies which resulted in differences in yields and consequently environmental impacts. However, for the purpose of analysis a generalized representative system was compiled that was as close to the majority of practises as possible.

7.2.1. Gurúè small-scale virtual farm (GSVF)

Crops and yield

The type of crops cultivated in the GSVF were chosen based on results from the household survey, they were maize, soybean, and pigeon pea. The household survey indicated that the average yield for these crops were 1.2 tonnes ha^{-1}, 1.6 tonnes ha^{-1}, and 0.7 tonnes ha^{-1}, respectively. However, the variability in yield estimates were high. Therefore, efforts were made to identify systematic bias in the data to determine yield estimates nearer to a realistically representative average yield for the GSVF inventory.

Walker *et al.* (2015) explains that small plots of less than 0.05 ha are often incorrectly associated with very high productivity as it is more challenging for the SSF to estimate their exact yields. It was hypothesized that production orientation may also play a role in the estimated yield variability, with speculation that market-orientated farmers would have higher yields than subsistence farmers. This was not the case based on the data collected from the household survey, as variability in estimated yields was not attributed to size nor production orientation. Owing to lack of systematic bias, the estimation of the average representative yield incorporated all the yields estimated in the household survey, regardless of their farm size or production orientation. This was deemed acceptably representative of the SSF system as the average yield obtained from the household survey results echoed yields found in previous studies (Hanlon & Smart, 2013; Walker et al., 2015).

Unpublished (private) research conducted and obtained by the National Cooperative Business Association under the Cooperative League of America (NCBA CLUSA) estimated average yield of 1.77 tonnes ha^{-1} for maize in the neighbouring village of Lioma. Hanlon & Smart (2013) reported average yields of 1.09 tonnes ha^{-1} for soybean in the Gurúè district. Walker *et al.* (2015) reported yields of 0.49 tonnes ha^{-1} for pigeon pea for Mozambique in 2012 based on the TIA survey (National Agricultural Survey in Mozambique). The minor deviation from the chosen yields is negligible as time and location are considered credible reasons for the level of deviation. Therefore, the average yields from the household survey of 1.2 tonne ha^{-1} maize, 1.6 tonnes ha^{-1} for soybean, and 0.7 tonnes ha^{-1} for pigeon pea were used to represent the GSVF.

Seed sector and cultivar selection

According to Marapusse *et al.* (2014), 91 % of small subsistence farmers are trading and producing local seed varieties obtained through the informal sector, even though policies exclude them from being officially recognized and registered . SSFs explained that the majority of farmers save local seed from the previous season but if finances become available they invest in improved seeds produced by breeders such as the Mozambican Institute of Agricultural Research (IIAM) and Pannar. However, SSFs are reluctant to purchase improved seed for a variety of reasons. During the semi-structured interviews, SSFs' major complaint was that improved seeds were too expensive, and the potential yield improvement of improved seed was not considered worth the extra cost. Additionally, it was also explained that saved seed was kept outside the home in a raised granary (*celeiros)* or indoors on a raised bed to avoid moisture. According to FAO (2011) SSFs can experience more than 30% yield losses in six months of storage. This is mainly due to high humidity, attack by insects/weevils, rodents and large animals and theft during the storage stage (FAO, 2011). Although post-harvest losses are a concern for the region, its quantification was beyond the capacity and focus of this study.

The semi-structured interviews confirmed previous research that local maize seed was predominately of the open-pollinated variety and recycled from previous seasons (Antonio et al., 2016). However, during the semi-structured interviews it was divulged that the improved maize seed available in the region included Pannar's hybrids PAN 53 and 67, as well as medium-maturity hybrids created by IIAM; Matuba, Changalane, Djamba, Hluvukani, Olipa, Molocue and SP-1 among others.

According to semi-structured interviews with SSFs, soybean seed and inoculant was initially obtained from NGOs for free. At the time of interview, the farmers were no longer receiving free inputs and were therefore recycling seed from previous seasons. SSFs complained about the difficulty in obtaining seed as they would have to drive into Gurúè city to purchase seed. IIAM was also developing soybean seed varieties in a project with the NGO IITA (Hanlon & Smart, 2013). TGX-1937-1F is an improved seed soybean cultivar that was recently released in Mozambique and is grown in the Gurúè district among other cultivars. It is an indeterminate cultivar with a relatively long growth duration of 110-120 days to maturity (Tsujimoto et al., 2015).

The semi-structured interviews revealed that the formal seed sector of pigeon pea was poorly developed in the region, this was corroborated by Walker *et al.* (2015), which reported the failure of a pilot scheme for the multiplication and production of pigeon pea in the early 2000s. The venture was unsuccessful, and no new schemes were reported during interviews with SSFs and key stakeholders. SSFs reported that they would use "good seed" from the previous season that was free of pests and moisture. The pigeon pea varieties available in the Gurúè district were not divulged during the household surveys or semi-structured interviews. However, Walker *et al.* (2015) explained that the long duration variety of 240 to 270 days and the medium duration variety with a reported 180 days to maturity were available in Mozambique.

Farm design

The household survey and semi-structured interviews all indicated that the majority of farmers in the Gurúè district were practicing mixed cropping of more than two crops in one field, which varied from broadcasting a variety of seeds to sowing crops on alternating rows. Field visits to the Gurúè district confirmed reports by Silici *et al.* (2015) that maize was most popularly cultivated as a dominant intercrop with pigeon pea, while grain legumes such as soybean and common bean were interspersed between the intercrop within one field. However, it was also common to find soybean cultivated as a monocrop since it was seen as an important cash crop in the region.

Furthermore, it was found that beyond the mixed cropping system, crops were indeed grown in a mosaic-type system of crop-forest/shrubland described by Di Matteo & Schoneveld (2016), where extensive rotational cropping systems were intermixed with forests and or/shrubland. This highly heterogeneous landscape presented a challenge for quantifying the percentage of land allocated to each crop and subsequently the inputs applied to each of them. It was also not possible to analyse this mixed planting scenario using the current APSIM model version. Therefore, to allow for simulation using APSIM, the GSVF farm design was simplified to an intercropping system of maize and pigeon pea, using alternate rows, with a biennial crop rotation of soybean.

Plant densities used were based on intercrop and crop rotation field trials executed in Malawi by Smith *et al.* (2016) and Whitbread *et al*. (2010). The majority of Gurúè SSFs were unable to establish a uniform plant population at the densities described by Smith *et al*. (2016) and were more likely to sow at the lower planting densities described by Whitbread *et al.* (2010) of 1.5–3 plants.m^{-2} for maize. A low-medium planting density between these studies was therefore chosen for the GSVF as 2.5 maize plants m^{-2}, 2 pigeon pea plants m^{-2}, and 6.5 soybean plants m^{-2}. All crops were sown at a 0.05 m depth with

0.9 m row spacing to simulate the sparse growing conditions common in Southern African SSF system (Whitbread *et al.,* 2010)

Planting dates

The planting dates for GSVF was based on results from the semi-structured interviews. The three charted crops fell under two cropping years, with maize and pigeon pea intercropped in year one and then rotated with a soybean monocrop in year two. The Gurúè region had one growing season that began at the onset of the rainy season, varying from November to December, and ended with the last month of the dry season in September the following year. Semi-structured interviews with SSFs highlighted that although light rains occur in October, the SSFs wait for the heavier rain onset in late November/early December to sow. SSFs explained that if the rains were late and they only planted in late December or early January then their crops would have poor yields or experience crop failure.

Using this information, a synopsized timeline of a representative growing year was created for the district and is represented in Table 5. The exact planting dates used in the GSVF was different for each year as it was based on an accumulation of rainfall which was calculated by APSIM for each growing season using daily weather data to similarly mimic how the SSFs choose their planting date. However, a sowing window was set between 15-Novemberr and 30-January.

Table 5: Timeline of planting dates (light grey), harvesting dates (black), and burning dates (horizontal lines) of maize, soybean and pigeon pea in the Gurúè district

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maize	░		■	■	■				▤	▤	░	░
Soybean	░		■	■	■				▤	▤	░	░
Pigeon pea	░					■	■	■	▤	▤	░	░

Soil management practices

Findings in this study confirmed that of Smart and Hanlon (2014) who observed that SSFs were using the land continuously every year. However, we observed a short fallow period in September-October when the fields were burnt to prepare the soil for planting in November. SSFs reported that they needed to continuously produce food for subsistence and because yields were low, they did not have the luxury of allowing their soils to rest for a growing season.

Soil preparation begins after harvest in September and November. It was described during the interviews that after harvest, the SSFs left crop residues on the soil surface and in some cases the residues were also incorporated into the soil with a hoe. When asked why crop residues were left on the soil, the SSFs explained that leaving the residues on the surface was "free fertilizer". However, the benefits of the crop residues are reduced as entire fields are burned to clear them before planting. The percentage of SSFs who were burning their fields to clear them for planting was not appropriately captured in the household survey. It was expected that the respondents would have reported that they had burned their field during the question on soil preparation, however there was miscommunication between the enumerator and the respondents and this was not made clear. It was already known, however, that SSFs were burning their fields to prepare for planting through the semi-structured interviews and field visits. The main reason for this was that it greatly decreased the amount of labour required to clear the fields, especially since all the field work is done manually with the help of a hoe. The SSFs explained in interviews that there was no affordable, alternative way of clearing their fields for planting the next season's crops.

NGOs in the area such as NCLUSA teach conservation agriculture (CA) with the aim of combating soil degradation which is prevalent in the area due to burning, lack of fertilization, and tillage practices (Pittelkow *et al.,* 2015). Their methodology includes demonstration plots where SSFs gather to learn about CA benefits through visual comparisons between traditional agricultural methods and CA. Unfortunately, the adoption rate of CA is poor, even the farmer responsible to the demonstration plots was not converting to CA practices in their personal plots. Based on this data, the GSVF soil management practices include manual tillage using a hoe and leaving crop residues on the soil surface until the end of the dry season in September when they are burned.

Fertilizer use

The household surveys confirmed that the average SSF in the study region did not use fertilizer (manure, organic or synthetic) for maize, soybean or pigeon pea cultivation. The semi-structured interviews did, however, highlight that it was common to find SSFs using fertilizer for selected vegetable crops. For example, SSFs used fertilizer to grow onions because the local population accepted a collective buy-in that onions could only be grown in the region with fertilizer. Additionally, it was found that fertilizers would be used occasionally for cash crops like common bean. It was acknowledged that if a SSF was intercropping with these fertilized crops, the fertilizer applied adjacent to maize, soybean, or pigeon pea may have been available to them. However, to quantify this effect would be out of the scope of this study. Since this study aims at capturing the production practices for the three chosen crops, we assess the production practices for maize, soybean and pigeon pea by a Mozambican SSF that does not include fertilization.

Pesticide use

According to the household survey results, although negligible amounts of fertilizer were used by SSFs in the Gurúè study region, there are significant cases where pesticides are being applied. Results show that pesticides were utilized for soybean production but not for maize or pigeon pea. However, none of the farmers interviewed during the survey were able to estimate the quantity of pesticide they applied to each crop or even per unit area, only that they did apply. However, through semi-structured interviews it was found that many soybean farmers were “copying” tobacco farmers by using Bandit 350 SC (350g/L Imidacloprid active ingredient) for their pest problems. Respondents explained that they dilute 12.5 ml sachet of Bandit 350 SC with 5 L of water and that they use 40 L per hectare in one growing season. It was also explained that they split the application into two sprays of 20 L, one month apart. This means that 8 sachets are used per hectare totalling to 100 ml of Bandit 350 SC which contains 0.035 kg of the active ingredient Imidacloprid. According to the Bandit 350 label, it is a systemic suspension concentrate insecticide for the control of insect as listed on citrus, cotton, potatoes, cucurbits, cruciferae, apples and tobacco as well as for the suppression of thrips on sugarcane. The efficacy of the pesticide on soybean is unknown and application is not recommended by the manufacturer. There is no other available data on how much or how often Mozambican SSFs are spraying pesticides. However, as pesticide application was the only significant input found in the region, the above application quantities were assumed for the GSVF simulation.

Energy use

The household survey reported that SSFs practice dryland agriculture and that the majority of farms were not mechanized, often the two major sources of fuel consumption in the SSF system. However, the semi-structured interviews did expose a few cases where farmers were using a diesel pump to irrigate their soybean crops, but it was not a common practice in the region. This was primarily due to the additional costs of renting the pump and the cost of diesel. There were no cases of irrigated maize and pigeon pea because SSFs viewed these crops as resilient to water stress. A few farmers also had access to tractors for rent, for example the NCBA CLUSA and three contract farming companies provided a few tractors for ploughing (Smart & Hanlon, 2014). Nevertheless, when looking at the number of SSFs with access to mechanization, its rarity is apparent and the majority of SSFs are not using NRE sources for maize, soybean or pigeon pea production in the study area. This is applied in the GSVF simulation.

7.2.2. Gurúè large-scale virtual farm (GLVF)

Crops

According to the LAI farm managers, the LAI harvest in 2016 yielded 3.10 tonnes ha^{-1} of maize and 1.91 tonnes ha^{-1} of soybean. The LAIs in this study cannot be said to be representative of all the LAIs in Northern Mozambique, but it is an example of the yields that are obtained by an LAI in the Gurúè study region. These yields are similar to those recorded by Joala *et al.,* (2016) for LAIs producing these crops in the study region. Therefore, the GLVF was parameterized to produce 3.1 tonnes ha^{-1} for maize and 1.91 tonnes ha^{-1} for soybean.

Seed sector and cultivar selection

Interviews with farm managers indicated that access to cultivars adapted to the climactic conditions of the region was a major limiting factor to high productivity. A manager reported that they were not able to purchase the soybean cultivar they needed in the 2015-2016 season. In addition, the cultivars for maize and soybean they cultivated were not suited to the agro-ecological conditions of the region, although it was explained that the LAI was experimenting with different cultivars. Furthermore, it was reported that the LAIs in the region purchased seeds from South Africa, Zimbabwe, and Brazil through brokers. A manager reported that some of the maize cultivars purchased from South Africa were PAN 53 and PAN 12.

Farm design

The cropping system described by the farm managers included the rotation of maize with soybean every two years. Based on the practices described by LAI farm managers in the Gurúè region, the average planting density in the GLVF simulation was 55,000 plants ha^{-1} for maize and 250,000 plants ha^{-1} for soybean. LAI farm managers explained that soybean cultivars with a longer cycle were planted at lower densities of 230-240,000 plants ha^{-1} while cultivars with shorter cycles were planted at higher densities 300,000 plants ha^{-1} to achieve higher canopy cover over a shorter time. However, in the simulation only one cultivar was selected for each crop and they were planted at densities of 5.5 plants m^{-2} for maize and 25 plants m^{-2} for soybean.

Planting dates

According to interview results with farm managers, there was one growing season per year in the summer. The GLVF rotated soybean with maize every two years to make use of the N fixed by soybean. The planting date for maize and soybean began in November, although it was dependant on the onset of rains and could therefore be pushed to December if the rains were late, resulting in poorer yields according to the farm managers. Depending on planting dates, harvesting was then done in June for maize and between April-May for soybean (Table 6).

Table 6: Timeline of planting dates (black) and harvesting dates (grey) for the Gurúè large-scale virtual farm (GLVF)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maize	■					▒					■	■
Soybean	■			▒	▒						■	■

Soil management practices

It was revealed that those interviewed as representatives of the LAIs were practicing CA as a means of conserving water and minimizing soil degradation. This included practicing zero tillage on the majority of cultivated land. However, where compaction and poor soil conditions were an issue for planting, discing and ripping was done, although this was not a common practice. In terms of soil fertility conservation, crop residues were left on the soil surface as a way of returning nutrients to the soil. Based on this information about common LAI practices, the GLVF soil management practices include zero tillage and leaving crop residues on the soil surface.

Fertilizer use

According to the semi-structured interviews, fertilization application rates for the Mozambican LAI were determined by the farm manager using a combination of soil analyses and fertilizer recommendation guidelines. An interview with the LAI farm manager provided us with the rates applied in 2017. They were 150 kg ha^{-1} of MAP applied to maize during sowing followed by a topdressing of 190 kg ha^{-1} of Urea 46%. While soybean was only fertilized with 90 kg ha^{-1} of MAP at sowing. These application rates were replicated for the parameterization of APSIM for the GLVF.

Pesticide use

Interviews with LAI farm managers disclosed the specific pesticides used by the LAI and that the relevant rates applied were based on the label's dosage instructions. The insecticide Baythroid XL (Pyrethroid) was used against the fall army worm, Amistar fungicide (Azoxystrobin) was applied as a preventative treatment and Nativo fungicide (Tebuconazole-triazole) was applied as a corrective treatment. Therefore, the GLVF applies these aforementioned pesticides at the rates recommended on the label in the simulation.

Energy use

According to interview results, production of maize was completely mechanized including planting, fertilization, pesticide application, and harvesting. While soybean production was based on manual labour as they did not possess the appropriate equipment to move through the soybean fields, except for direct seed planting which was done mechanically. Furthermore, it was explained that the LAIs planned to improve efficiency by increasing mechanization in the future. Using this information, a summarized table on fuel consumption was calculated using the guidelines in DAFF (2016). Under these conditions, maize cultivation consumed 118 L ha^{-1} annually and soybean cultivation consumed an estimated 31 L ha^{-1} in a year of production (Table 7).

Table 7: Diesel consumption for an agronomic season of maize and soybean under Gurúè large-scale virtual farm (GLVF) management practices

Machinery	Unit	Maize	Soybean	Source
Tractor with implement				
Planter	**L ha^{-1}**	31.19	31.19	DAFF (2016)
Spray pesticide	**L ha^{-1}**	41.58	0	DAFF (2016)
Top-dress	**L ha^{-1}**	17.33	0	DAFF (2016)
Trailer (harvest)	**L ha^{-1}**	8.32	0	DAFF (2016)
Combine harvester	**L ha^{-1}**	20	0	Benes *et al.* (2014)
Total	**L ha^{-1}**	118.42	31.19	

7.2.3. Nanyuki small-scale virtual farm (NSVF)

Crops and crop yield

The household survey indicated that maize, beans, and potatoes were the three dominant crops in the study region, with wheat as an emerging crop. Crops were grown in both rainy seasons and there was some differentiation between crops grown in the short and long-rains. According to the semi-structured interviews, SSFs reported that yields were lower during the short rains and most farmers would not produce maize during the short rains due to the high risks of crop failure. Potatoes were excluded from the NSVF as there was limited data from survey results and external sources to allow for it to be analysed using APSIM and LCA methodology.

Although maize was the most widely grown crop, the household survey revealed relatively low average yields of 3.02 tonnes ha^{-1} (Range: 0.4-8 tonnes ha^{-1}). The household survey found that beans were grown mainly for subsistence and had an average yield of 1.21 tonnes ha^{-1} (Range: 0.17-7 tonnes ha^{-1}), while wheat was both a commercial and subsistence crop with an average yield of 3.65 tones ha^{-1} (Range: 1-8 tonnes ha^{-1}). The average yields from the household survey were accepted as an adequate representation for the NSVF.

Seed sector and cultivar selection

Compared to the Gurúè region, the Nanyuki region in Kenya had a more developed input market which included a well-developed seed sector. According to semi-structured interviews, many SSFs were making use of a variety of hybrid seed cultivars for all crops under investigation. In addition, the importance of cultivating improved hybrid seeds to obtain higher yields was acknowledged by the majority of SSFs during the semi-structured interviews. Specifically, for the APSIM simulations the cultivars chosen for the NSVF were based on their time to maturity to allow for the simulation of two growing seasons within one year and for their yield potential. The maize cultivar chosen was the early-maturing Zimbabwean hybrid 'sc401' and the early-maturing cowpea cultivar 'banjo'. The "axe" wheat cultivar was used for the simulation and was a very early maturing variety suited to drought-stressed locations and planted in shorter growing seasons or for late sowing.

Farm system design

The household survey and semi-structured interviews both revealed that SSFs are cultivating multiple crops in the Nanyuki region. The interviews revealed that unlike the Mozambican SSFs who often broadcast seeds and practice mixed cropping, the SSFs in Nanyuki will have a more organized row design with sections dedicated to each crop. Accordingly, the NSVF was based on a maize and bean intercrop during the long rains with a rotation of wheat during the short rains. This was supported by Njeru & Gitonga (2004) which explained that SSFs in Nanyuki often intercrop maize with beans while wheat is commonly grown in a pure stand.

Due to the lack of primary data on planting densities, depths, and distance between rows, the NSVF uses recommendations from the National Agricultural Information Service (NAFIS) of Kenya for the Rift Valley Province. For a maize intercrop NAFIS (2017) recommended a normal planting depth of 0.025-0.05 m and a planting density of 44 000 plants ha^{-1}. Legumes were sown at a density of 40 000 plants ha^{-1} in alternating rows of 0.15 m with maize and sowed at a depth of 0.05 m (NAFIS, 2017). It was recommended that wheat was 'dry planted' two to three weeks before the onset of the short rains, consequently it was planted at a depth of 0.10 m (NAFIS, 2017). Row spacing for wheat was set to 0.75 m in the simulation, as recommended by NAFIS (2017).

Planting dates

Due to the bimodal rainfall distribution experienced in the study region, Njeru & Gitonga (2004) reported that there were two growing seasons in the region each year where farmers generally planted in late March for the long rains and mid-October for the short rains (Table 8). Semi-structured interviews revealed that due to the high variability in rainfall onset, planting for the long rains could be delayed to April, and dry planting for the short rains season could be brought up to September- two to three weeks before the onset of rains. Accordingly, the NSVF cropping year began with an intercrop planting of maize and beans in a sowing window between the 20-March and the 2-April. Maize was then harvested between August and mid-September and beans between June and July. Wheat was planted in the sowing window between the 30-September and the 15-October and then harvested in early-mid March.

Table 8: Timeline of planting dates (black), growing season (light grey), and harvesting dates (horizontal lines) for the Gurúè large-scale virtual farm (GLVF)

	Jan	Feb	Mar		Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maize				■	■	░	░	░	▤	▤			
Bean				■	■	░	▤	▤					
Wheat	░	░	▤							■	■	░	░

Soil management practices

By means of the semi-structured interviews, it was found that the SSFs perception of their soil quality was extremely variable, not only over topographical gradients, but also within the same topographical region. However, the most prevalent soil concern was fertility and the majority of SSFs felt that their soil required fertilizer or manure to produce good yields, even if they perceived their soil to be of a good quality.

Results from the household survey, showed that the majority (75%) of SSFs were practicing crop rotation and 46% left their land fallow for at least a season. However, insights from the semi-structured interviews showed that most SSFs would only leave their soil fallow as a reactionary measure to a previous decrease in yield with the perception that soil fertility had decreased. SSFs who did not leave their land to fallow, did so due to the small size of their land and their need to continuously produce on it to sustain their household.

Crop residues were removed from the fields by 70% of the interviewees to be used as either fodder for livestock or to make compost to sell. While the other 30% who kept crop residues on the soil surface, did so with soil fertility in mind as a CA practice. Not considering crop residue removal, soil conservation seemed to be a well understood concept and was expressed as a priority during the semi-structured interviews. Additionally, in terms of mechanized soil preparation, tractors and ox-drawn ploughs were used by 65% of SSFs to prepare the soil before planting.

Using this collection of information, the NSVF soil management practices were parametrized to include the seasonal rotation of crops, no fallow periods, tillage (discing) before sowing, and the removal of crop residues after harvest.

Fertilizer use

Out of 100 households in the survey, 51% of SSFs applied fertilizers to their fields. The average fertilizer rate was 250 kg ha^{-1} and the most common fertilizers used were DAP (18:20) and NPK (17:17:14). Mixing fertilizers was also found to be common, with 45% of SSFs who fertilize using more than one type of fertilizer. Furthermore, Sheahan *et al.* (2013) explained that some farmers in Kenya apply all their fertilizer at sowing, while some only apply it as top-dress, and others split their application into pre-sowing and top-dress. Using this data, the NSVF simulation applied a 250 kg ha^{-1} mixture of DAP and NPK and that half was applied during sowing and the other half as a top-dress 30 days after sowing (Table 9).

Table 9: Fertilizer quantities used for Nanyuki small-scale virtual farm (NSVF)

Input	**Quantity (kg ha^{-1})**
Nitrogen Phosphorus Potassium (NPK)	125
Diammonium phosphate (DAP)	125
Total Nitrogen	16
Total Phosphorus	15
Total Potassium	15

Pesticide use

Results from the household surveys indicated that 90% of the SSFs interviewed were applying pesticides. This supported the views expressed by SSFs during the semi-structured interviews that "Chemicals are needed to succeed". The most common agro-chemical applied was found to be the pesticide Dimethoate. Varying concentrations were recorded in the survey and interviews as the label instructions were not often considered by SSFs. Consequently, SSFs applied pesticides at rates below and above recommended quantities which could result in built-up resistance, decreased efficacy, and water and soil contamination. Due to the high variation in application methods and the consequent gap in data, the NSVF simulation applied pesticides at the rate recommended on the label for Adama Dimethoate 400 for all crops.

Energy use

A widespread use of ox-drawn ploughs and tractors for soil preparation and occasionally for harvesting was identified during the semi-structured interviews and from the household survey results. However, results on the proportion of SSFs using tractors versus ox-drawn plough was unclear. Furthermore, SSFs were unable to provide data on the quantities of fuel they consumed and literature containing this information was lacking. Therefore, due to the lack of credible estimates, energy use was not included in the NSVF. Taking into account the high availability of animal traction and the prevalent use of manual labour, this value was considered to be negligible anyway.

Irrigation

Results from the household survey showed that 37% of SSFs were using irrigation. Although this was a substantial contribution to water consumption in the area, the lack of data on irrigation scheduling by SSFs motivated the description of the NSVF as a rainfed system. Consequently, this also allowed for a better comparison with the GSVF of Mozambique.

7.2.4. Nanyuki large-scale virtual farm (NLVF)

Crop

According to interview results, rose yields in the study region ranged from 100-130 stems m^{-2} yr^{-1}, of this value an estimated average of 15% of stems were rejected due to pest damage. The NLVF's marketable yield parameter, which excluded rejected stems, was therefore set to 100 stems m^{-2} yr^{-1}. This was a lower yield than that produced in other countries and areas in Kenya, for example the gross production of roses in Ethiopia was as high as 213 stems m^{-2} yr^{-1} and 264 stems m^{-2} yr^{-1} in the Lake Naivasha region (Sahle & Potting, 2013; Mekonnen *et al.,* 2012). However, the longer stems and larger heads obtained by the LAIs in Nanyuki are indicators of high quality, which fetch higher market prices.

Cultivar selection

According the interview results, Roses were produced year-round with seedlings grafted to a hardy soil borne disease-resistant rootstock that is productive for 5-10 years depending on cultivar selection (Sahle & Potting, 2013).

Farm system design

According to interview results, roses were found to be cultivated under one hectare-size polyethylene greenhouses imported from China. The rose bushes were estimated at having a life cycle of 5-10 years, depending on the cultivar grown at the time. In addition, the NLVF simulated the planting density used by the LAIs which were expressed as an average of 8 rose plants m^{-2}.

Soil management practices

Roses were found to be cultivated in an open-system where seedlings were planted on raised beds in greenhouses. This allowed for the fertigation mixture not taken up by the rose plants to leach out of the soil (Sahle & Potting, 2013). Moreover, the LAIs were practicing continuous fertigation, which, along with consequences of practicing monoculture with no crop rotation, could have resulted in soil acidity and the build-up of disease. Consequently, the LAIs projected that they would need to remove the top layer of soil completely after 6-7 years of production. This continuous use of soil was applied to the NLVF case to replicate the intensive soil practices by the LAIs.

Irrigation

Water restrictions were enforced in the study region, with river extractions only permitted during the rainy season. The government and water use associations also required that LAIs build water-holding dams on their property. These restrictions led LAIs to supplement river irrigation by digging boreholes and implement rain water harvesting systems from greenhouse rooves. An irrigation schedule was compiled for the NLVF based on results from the semi-structured interviews, which included an average irrigation of 3 L m^{-2} day^{-1}, with 1 L m^{-2} day^{-1} for overcast conditions and 5 L m^{-2} day^{-1} on a hot, sunny day.

Fertilizer use

Interviews revealed that roses within the greenhouse system were continuously fertigated to meet their nutrient and water demands. According to the amount of fertilizer applied by the LAIs, the NLVF fertilized at a rate of 2 000 kg N ha^{-1}, 800 kg P ha^{-1}, 2 628 kg K ha^{-1} per year. This translated to approximately 100 kg ha^{-1} of fertilizer per bunch of roses (12 roses), which was 9% more than that used by Ethiopian rose cultivation (Sahle & Potting 2013).

Pesticide use

None of the aforementioned farm managers were willing to divulge the pesticide rates or types of sprays used for roses. Therefore, a study conducted by Sahle & Potting (2013) on the Ethiopian rose cultivation sector was used to estimate pesticide use in this study region. Sahle & Potting (2013) found that the sector used more than 212 types of pesticides, with multiple different active ingredients. Similarly, the rose farms in Nanyuki were heavily reliant on pesticides as pest control was deemed critical for success and was even described as the largest input cost. The NLVF therefore applied approximately 1.5 g of pesticides' active ingredient (AI) per bunch of roses, according to the findings by Sahle & Potting (2013).

Energy use

According to results from the semi-structured interviews, the average fuel consumption was estimated to be 5 L ha^{-1} per day of diesel, translating to an average 1880 L ha^{-1} per annum. This would have included fuel consumed for irrigation pumping, and diesel for tractors and other on-farm machinery.

7.3. Management practices discussion

The results from the household survey supported findings from previous studies that describe the typical Gurúè SSF system as a low input-low output production system. The majority of SSFs in the region relied on rainfed agriculture, had a low technological adoption rate, and the average yield was below the agro-ecological potential. Reasons for low utilization of agro-inputs were described as accessibility and affordability of inputs as well as the lack of extension services. Although it is understood that the promotion of these technologies was constrained by complex underlying social, political, and economic factors in the region.

The GLVF was classified as a high input-medium output system. Interpretation of semi-structured interviews supported the assumptions that the LAI systems applied conventional farming strategies and followed good management practices. This included applying quantities of fertilizer based on soil analyses and crop requirements, efficient weeding at optimal times, practising good soil management practices such as crop rotation and retaining soil residues, using high-yielding hybrid crop varieties, and sowing at optimal times.

The Nanyuki SSF production system was essentially a medium-input, medium-output system. Inputs were applied at sub-optimal to optimal rates and average yields were below agro-ecological potential. The majority of SSFs were employing efficient management practices as agro-inputs and infrastructure were relatively affordable and accessible compared to the Gurúè study site.

Large-investment rose farms in Nanyuki were classified as a high-input, high-output production system. The NSVF was a highly mechanized and controlled, input-intensive greenhouse system that produced highly profitable, globally-competitive roses. From a production perspective it was an efficient and well-managed system.

8. APSIM results

8.1. The Gurúè region

As a benchmark for the potential maize yield under the Gurúè weather and soil conditions, a monocrop of the early-medium maturing maize cultivar "sc_501" was simulated at a planting density of 5 plants ha^{-1} over a 50-year period. APSIM simulations estimated the mean agro-ecological yield at 0.63 tonnes ha^{-1}, according to GAEZ, under the rainfed and low-input use conditions the average potential maize yield was 3.4 tonnes ha^{-1} (FAO/IIASA, 2011). According to results from the APSIM simulation, the average water-limited yield was 2.69 tonnes ha^{-1}, GAEZ estimated that the potential maize yield under rainfed and intermediate input supply was 7.1 tonnes ha^{-1}. The average potential Nitrogen (N)-limited yield was estimated by APSIM at 1.07 tonnes ha^{-1}, GAEZ estimated that under irrigated and low-input management practices the potential maize yield in the region was 1.70 tonnes ha^{-1}. APSIM simulation results estimated the average potential yield in the region as 3.51 tonnes ha^{-1}, GAEZ estimated potential yield at almost double this value at 7.7 tonnes ha^{-1} under intermediate-input consumption and irrigated conditions. A possible explanation for the higher potential yield estimates by GAEZ was the potential differences in N input and the specific maize cultivar's response to N.

Results indicated that the Gurúè region was both a N- and water-limited environment for maize production. However, the addition of N to the system did more to improve yields than irrigation, which increased maize yield by 70% compared to the addition of N which increased maize yield by 327%. The addition of irrigation and N fertilization increased yield by 457%, indicating that maize production in the region responded positively from the addition of agro-inputs. Although it should be noted that the impact of weeds, pests, disease, and topographical constraints such as slope were not considered and could have significant impact on potential yield.

8.1.1. Gurúè small-scale virtual farm (GSVF)

8.1.1.1. GSVF yield

Results from the GSVF setup determined that the average yields were 1.2 tonnes ha^{-1} of maize, 1.6 tonnes ha^{-1} of soybean, and 0.76 tonnes ha^{-1} of pigeon pea. To simulate these yields in APSIM, the management practices described in the GSVF were applied to Gurúè weather and soil conditions over a 50-year period. These conditions resulted in simulated mean yields of 1.0 tonnes ha^{-1} maize, 1.7 tonnes ha^{-1} soybean, and 0.56 tonnes ha^{-1} pigeon pea (Figure 7 & 8).

Maize yields were used to analyze the production capabilities of the GSVF. Under these management practices, the maximum and minimum maize yields were 0.9 tonnes ha^{-1} and 0.4 tonnes ha^{-1}, respectively, the standard deviation was 0.5 tonnes ha^{-1} and there were no crop failures (<0.1 tonnes ha^{-1}) experienced over the 50- year period. Results of the investigation into the limiting factors to GSVF production are described below.

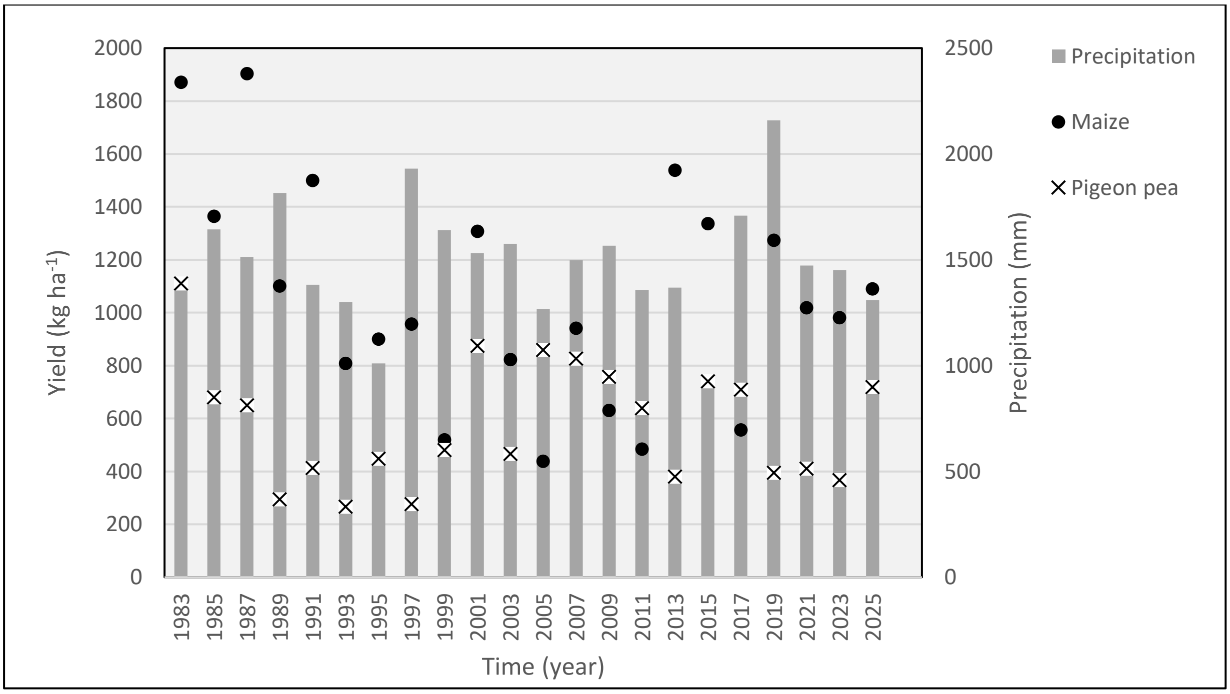

Fig. 7: Yields of maize (*Zea mays*) and pigeon pea (*Cajanus cajan*) intercrop under Gurúè small-scale virtual farm (GSVF) management practices and precipitation over 50 years of production

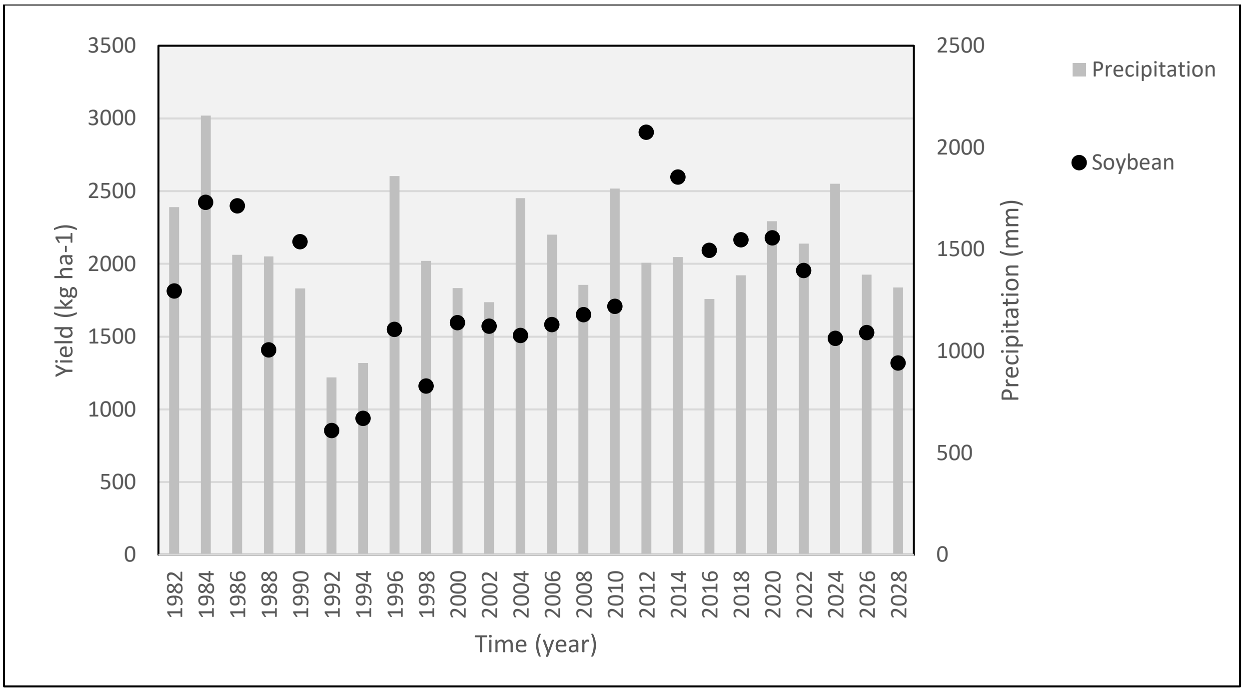

Fig. 8: Yield of soybean under rotation under Gurúè small-scale virtual farm (GSVF) management practices and precipitation over 50 years of production

8.1.1.2. GSVF soil degradation

In terms of soil degradation, SOC was found to decrease substantially after 50-years of productions. Soil layer 1 lost 0.24 % OC (15% of initial), layer 2 lost 0.66% OC (44% of initial), and layer 3 lost 0.45% OC (37% of initial) (Fig 9). Furthermore, the rate of soil N mineralization was found to decelerate over time under the GSVF management practices (Fig 11). This was explained by an insufficient supply of mineral-N from retained residues to meet the immobilization demands of the soil, indicating to a potentially N-limited soil environment. This is further iterated by the declining availability of total N in the soil illustrated in Figure 10. After 50 years of production, soil layer 1 was found to have lost an average 265.9 kg N ha^{-1} (15%), layer 2 lost 730.9 kg N ha^{-1} (45%) and layer 3 lost 522.3 kg N ha^{-1} (37%). These results were in line with Swanepoel *et al.*, (2016) that after 50 years of production the soil had almost lost an average of 50% of SOC.

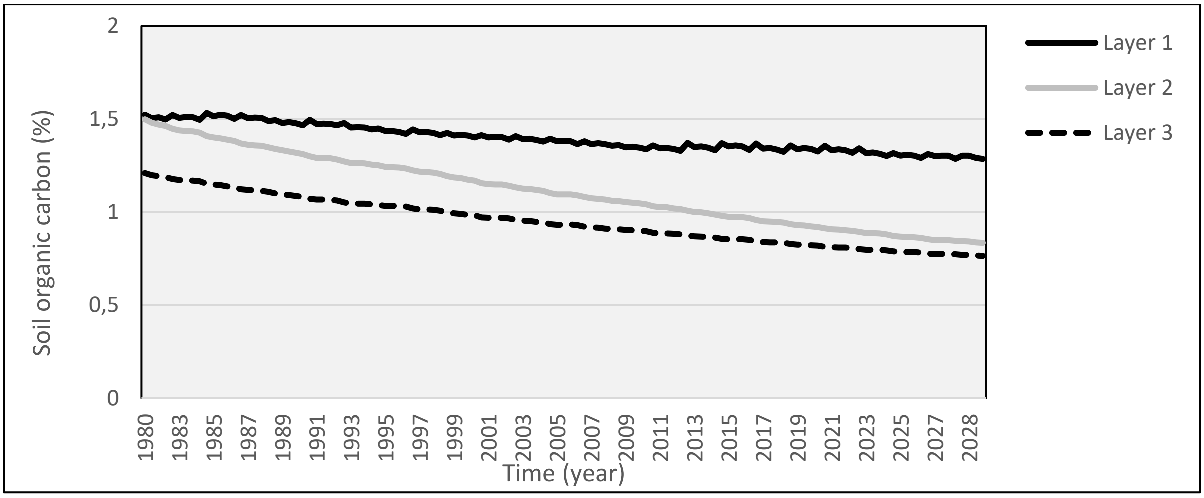

Fig. 9: Soil organic carbon (%) in soil layer 1 (0-0.1 m), 2 (0.1-0.2 m), and 3 (0.2-0.3 m) under Gurúè small-scale virtual farm (GSVF) management practices over 50-years of production

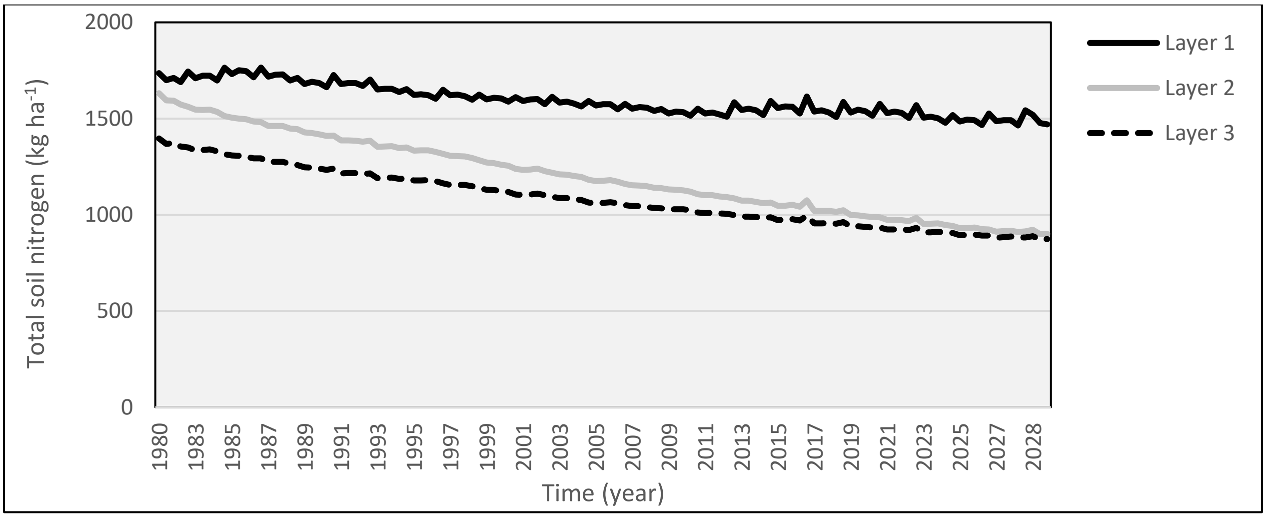

Fig. 10: Total nitrogen (N) in soil layer 1 (0-0.1 m), 2 (0.1-0.2 m) and 3 (0.2-0.3 m) under Gurúè small-scale virtual farm (GSVF) management practices over 50-years of production

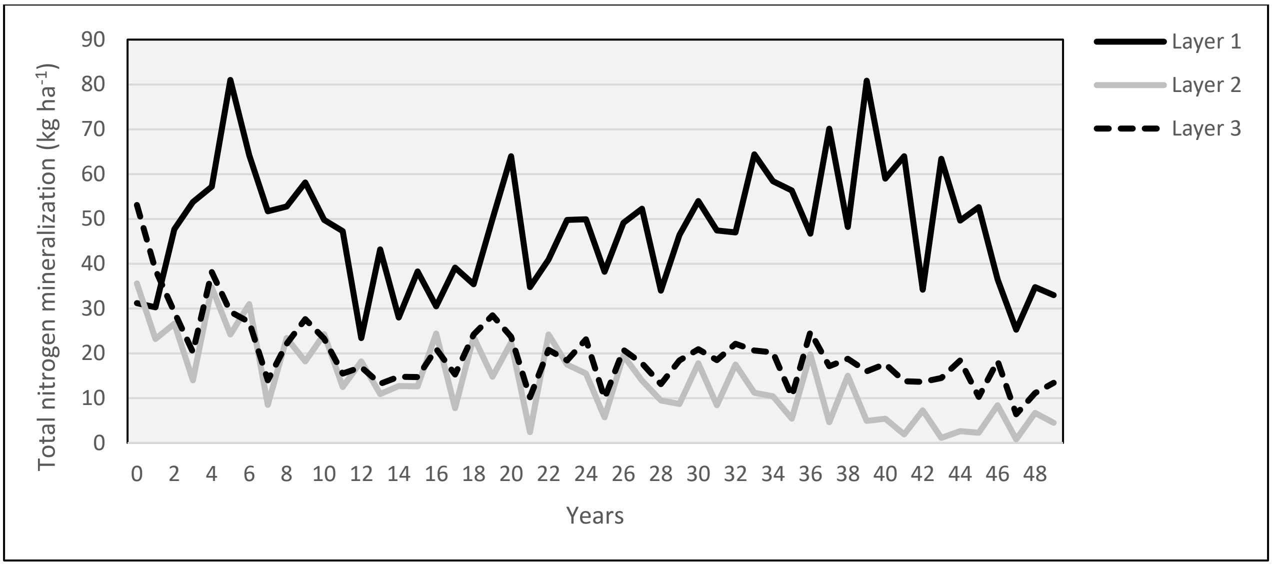

Fig. 11: Nitrogen mineralization in soil layer 1 (0-0.1 m), 2 (0.1-0.2 m), and 3 (0.2-0.3 m) under Gurúè small-scale virtual farm (GSVF) management practices over 50 years of production

8.1.1.3. Fertilization and yield

According to simulations under zero nitrogen fertilization, Nitrogen stress was found to limit yield affecting leaf expansion, grain filling, phenological development, photosynthesis, and tillering. This was corroborated by the addition of urea-N to the GSVF scenario which resulted in yields that were significantly different from the GSVF yields, at a 5% level using a paired samples *t*-test. As illustrated in Figure 12, the addition of 200 kg N to the GSVF scenario was found to consistently increase yield under the climactic conditions from 1980-2030, resulting in an average yield increase of 55% (0.57 tonnes ha^{-1}). The minimum yield increased by 85% (0.37 tonnes ha^{-1}) and maximum yield increased by 24% (0.5 tonnes ha^{-1}).

The Agronomic Efficiency of Nitrogen (NAE) at different N fertilization rates is captured in Table 10. The results ranged between 2-9 kg maize per kg of applied N. According to Whitbread *et al.,* (2013), an NAE below 15 kg grain per kg N applied is considered a low yield response. Although yield increase was statistically significant, the addition of N to the system was not an agronomically efficient use of N indicating that N was not the major limiting factor to production in the region. Although a cost-benefit analysis should be performed, due to the low NAE it was concluded that the sole addition of N to the GSVF system was not warranted without other management ameliorations.

Table 10: Descriptive statistics of maize yield under different nitrogen (N) rates over a 50-year period under the Gurúè small-scale virtual farm (GSVF) scenario

Scenario	Minimum (kg ha^{-1})	Maximum (kg ha^{-1})	Mean (kg ha^{-1})	Std. Deviation (kg ha^{-1})	NAE (kg ha^{-1})
0 kg urea-N ha^{-1}	438	1 904	1 020	454	-
15 kg urea-N ha^{-1}	500	2 098	1 158	499	9.14
50 kg urea-N ha^{-1}	566	2 242	1 307	544	5.74
100 kg urea-N ha^{-1}	661	2 237	1 429	560	4.09
200 kg urea-N ha^{-1}	811	2 361	1 586	569	2.83

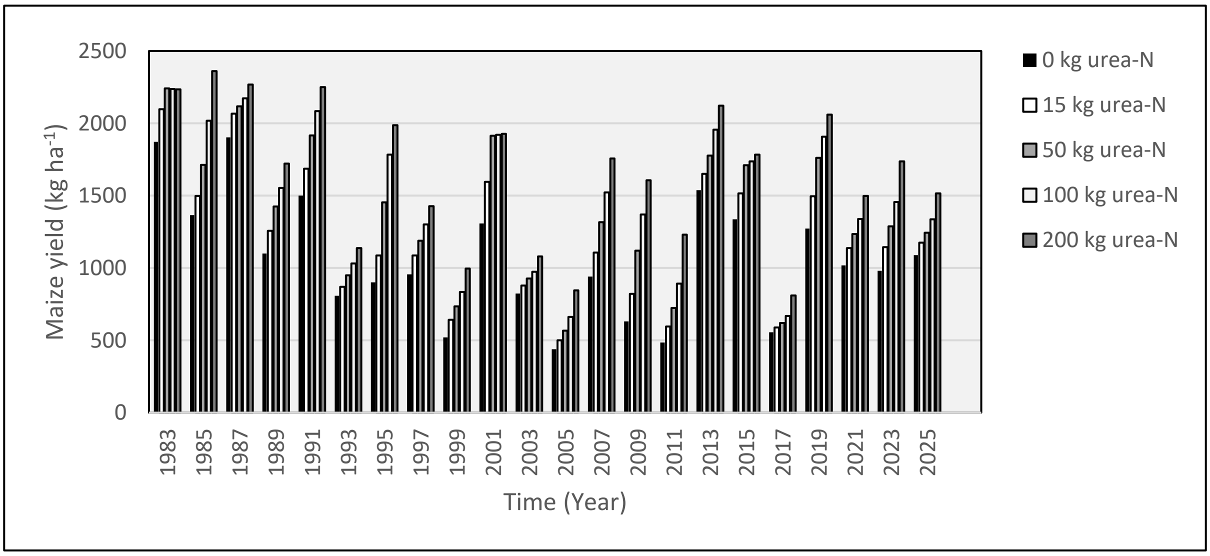

Fig. 12: Maize yields from the Gurúè small-scale virtual farm (GSVF) scenario from 1980 to 2030 under increasing fertilization rates

8.1.1.4. Fertilization and soil degradation

The addition of N fertilizer at different rates to the GSVF scenario was found to have a statistically significant impact on SOC and total soil N loss in all three soil layers at a 5% level using paired *t*-tests. Simulations revealed that the addition of 200 kg urea-N decreased total N loss by an average 0.32% (5,6 kg ha^{-1}) in the top soil layer, which is negligible.

In the two lower soil layers, however, increasing N fertilization lead to an increase in total N loss after 50 years (Table 11). The increase in soil N in the top layer was explained by the deposition of crop residues on the top soil layer while the decrease in lower layers was due to the increased N demand as a result of increased yields due to fertilization. Therefore, the addition of N fertilizer alone was not sufficient to decrease the rate of N loss within the root zone under the GSVF management practices under Gurúè's agro-ecological conditions. The impacts of N fertilization on SOC loss followed the same trend and conclusions as soil total N loss (Table 12).

Table 11: Soil nitrogen (N) loss in each soil layer after 50 years of Gurúè small-scale virtual farm (GSVF) production under different N rates

N rate (kg NH_4-N ha^{-1})	Soil layer 1 (kg N ha^{-1})	Soil layer 2 (kg N ha^{-1})	Soil layer 3 (kg N ha^{-1})
0 N	265.9 (15.32%)	730.9 (44.79%)	522.3 (37.39%)
15 N	265.4 (15.29%)	731.3 (44.82%)	522.5 (37.41%)
50 N	263.8 (15.2%)	732.0 (44.86%)	523.0 (37.45%)
100 N	262.7 (15.14%)	732.5 (44.89%)	523.3 (37.47%)
200 N	260.3 (15.00%)	733.5 (44.95%)	524.0 (37.52%)

Table 12: Soil organic carbon percentage (%SOC) loss in each soil layer after 50 years of Gurúè small-scale virtual farm (GSVF) production under different N rates

N rate (kg NH_4-N ha^{-1})	Soil layer (%SOC)	Soil layer 2 (%SOC)	Soil layer 3 (%SOC)
0 N	0.237	0.664	0.445
15 N	0.236	0.664	0.445
50 N	0.235	0.665	0.446
100 N	0.234	0.665	0.446
200 N	0.233	0.667	0.447

8.1.1.5. Planting density and yield

Using the paired *t*-test, the impact of a higher planting density on maize yield was found to be significantly different to the GSVF low planting density at a 5% level. The original GSVF scenario used a planting density of 2.5 plants ha^{-1}, if planting density was to double to 5 plants ha^{-1} it was shown that average yield decreased by 8% (0.08 tonnes ha^{-1}) and that there were two crop failures (<100 kg ha^{-1}) over a 50-year period (Table 13). The Wilcoxon Signed Ranks test shows that increasing planting density to 5 plants ha^{-1} would result in a decrease in yield 82% of the time and would only result in an increase in yield

18% of the time (Table 14). Similarly, increase planting density to 7.5 plants ha^{-1} resulted in an average yield decrease of 40% (0.40 tonnes ha^{-1}) and six consequent crop failures (<100 kg ha^{-1}) within a 50-year period (Figure 13). Increasing maize planting density to 7.5 plants ha^{-1} was found to decrease yield 91% of the time and only increase yield 8% of the time when conditions were favourable. These results indicated that, in most years, the agro-ecological conditions could not support the competition at higher planting densities without the addition of agro-inputs. This further supports the decision of SSFs in Gurúè to plant at low densities, because not only can they achieve higher average yields at lower planting densities, but yields are also more reliable as no crop failures were experienced.

Table 13: Descriptive statistics of maize yield under different planting densities over a 50-year period under the Gurúè small-scale virtual farm (GSVF) scenario

Scenario	Minimum (kg ha^{-1})	Maximum (kg ha^{-1})	Mean (kg ha^{-1})	Std. Deviation (kg ha^{-1})
2.5 plant m^{-2}	438	1 904	1 020	454
5 plants m^{-2}	73	2 505	937	605
7.5 plants m^{-2}	0	2 336	620	595

Table 14: Positive and negative ranks of the impact of maize planting densities on maize yield under the Gurúè small-scale virtual farm (GSVF) scenario using the Wilcoxon signed ranks test

		N	Mean Rank	Sum of Ranks
5 plants m^{-2} - 2.5 plants m^{-2}	**Negative Ranks**	18[a]	11.94	215.00
	Positive Ranks	4[b]	9.50	38.00
	Ties	0[c]		
	Total	22		
7.5 plants m^{-2} - 2.5 plants m^{-2}	**Negative Ranks**	20[d]	12.30	246.00
	Positive Ranks	2[e]	3.50	7.00
	Ties	0[f]		
	Total	22		

a. 5 plants m^{-2} < 2.5 plants m^{-2}
b. 5 plants m^{-2} > 2.5 plants m^{-2}
c. 5 plants m^{-2} = 2.5 plants m^{-2}
d. 7.5 plants m^{-2} < 2.5 plants m^{-2}
e. 7.5 plants m^{-2} > 2.5 plants m^{-2}
f. 7.5 plants m^{-2} = 2.5 plants m^{-2}

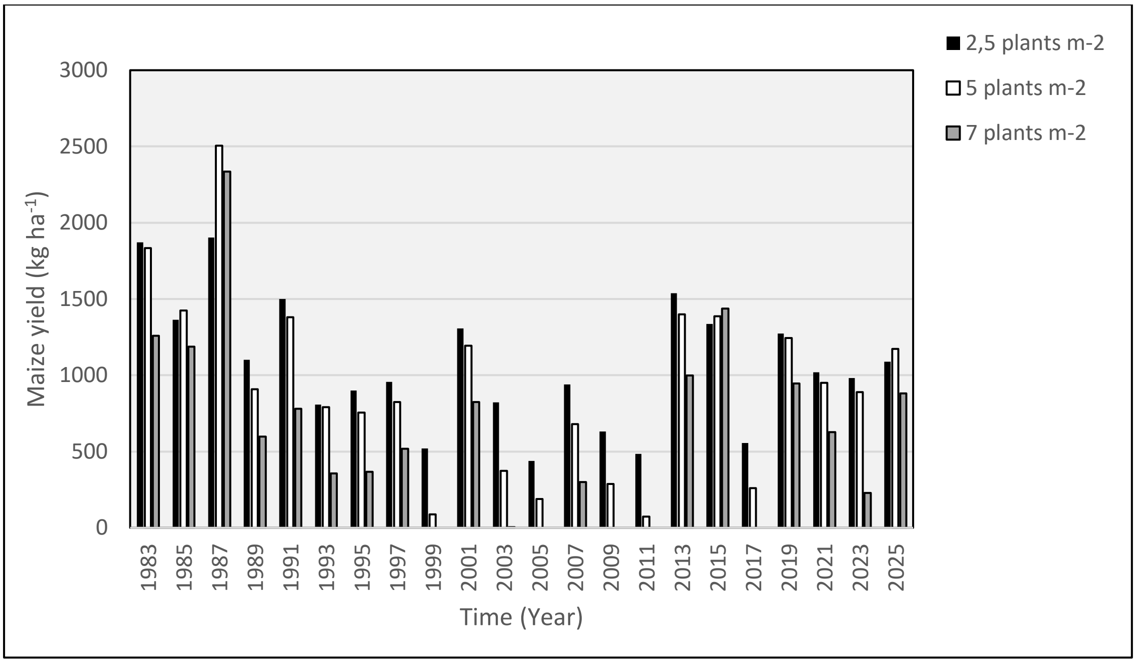

Fig. 13: The impact of different maize planting densities on maize yield over a 50-year period for the Gurúè small-scale virtual farm (GSVF) scenario

8.1.1.6. Planting density and soil degradation

According to the paired *t*-test, the impact of planting density on SOC and total soil N percentage was statistically significant at a 5% level. The total soil N loss after 50 years at a planting density of 5 plant ha^{-1} was found to decrease in the top soil layer (0-0.01m) but increase in soil layer two (0.01-0.02 m) and three (0.02-0.03 m) (Table 15). Similarly, the percentage of SOC loss decreased in the top soil layer and increased in the lower soil layers. The increased soil N in deeper layers was explained by the increased demand for N from the higher plant population while the decrease SOC and total soil N loss in the top soil layer was explained by the dynamics of N deposition from crop residues on the soil surface. However, these losses ranged from 0.4-1%, and therefore although statistically significant, the impact of planting density on SOC% and total N loss are negligible and do not decelerate or accelerate the rate of soil degradation.

Table 15: Soil organic carbon (SOC) and nitrogen (N) loss in each soil layer after 50 years of GSVF production under different planting densities

Scenario	N loss (kg ha^{-1})			SOC loss (%)		
	Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3
2,5 plants ha^{-1}	265.9 (15%)	730.9 (45%)	522.3 (37%)	0.237	0.664	0.445
5 plants ha^{-1}	258.5 (15%)	742.4 (45%)	532.9 (38%)	0.231	0.675	0.454
7,5 plants ha^{-1}	247.5 (14%)	748.8 (46%)	537.3 (38%)	0.221	0.681	0.458

8.1.1.7. Irrigation and yield

The impact of irrigating at soil water deficit of 90 mm between the 30th of November and the 1st of February on yield was not significant at a 5% level according to the paired *t*-test. The mean yield under irrigation was 1.11 tonnes ha^{-1} with a standard deviation of 0.44 tonnes ha^{-1}, this was a mean yield increase of 5% (0.05 tonnes ha^{-1}) (Table 16 and Figure 14). The increase in yield occurred in every season over the 50-year simulation and indicated that water stress was a consistent limiting factor in the region, however small. The increased N leaching due to irrigation was found to limit the percentage increase in maize yield. This means that the sole addition of irrigation to the GSVF was not sufficient to substantially increase maize yield.

Table 16: Descriptive statistics of maize yield under rainfed and irrigated conditions over a 50-year period under the Gurúè small-scale virtual farm (GSVF) scenario

Scenario	**Minimum (kg ha^{-1})**	**Maximum (kg ha^{-1})**	**Mean (kg ha^{-1})**	**Std. Deviation (kg ha^{-1})**
Rainfed	438.0	1903.7	1020.4	453.9
Irrigation	470.5	2035.2	1111.6	443.3

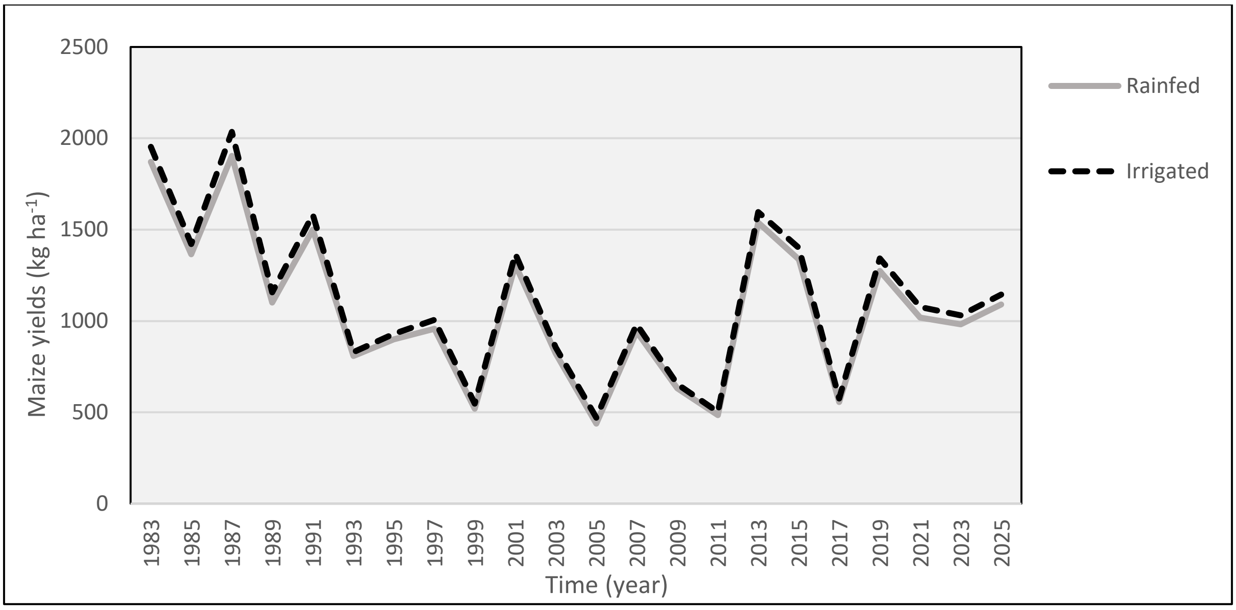

Fig. 14: Maize yield from 1980-2030 for the rainfed Gurúè small-scale virtual farm (GSVF) scenario and irrigated GSVF scenario over a 50-year period

8.1.1.8. Irrigation and soil degradation

The difference between irrigated SOC and total soil N loss and rainfed SOC and N loss was found to be statistically significant at a 5% level using the paired *t*-test. N loss was found to increase by an average 10% and an average 0.13% OC was lost in all soil layers when the GSVF was irrigated compared to rainfed conditions (Table 17). The increase in OC and total soil N loss was explained by increased leaching as result of irrigation. Due to the high seasonal climactic variability modelling the appropriate irrigation schedule to increase yield while combating soil degradation was challenging. However, although not in the capacity of this study, if irrigation was scheduled based on seasonal rainfall scenarios according to higher or lower average rainfall then leaching could potentially be mitigated while still increasing yield (Nape, 2011).

Table 17: Soil organic carbon (SOC) and nitrogen (N) loss after 50 years of rainfed GSVF versus irrigated Gurúè small-scale virtual farm (GSVF) scenarios

Scenario	N loss (kg ha^{-1})			SOC loss (%)		
	Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3
No Irrigation	265.9 (15%)	730.9 (45%)	522.3 (37%)	0.237	0.664	0.445
Irrigation	346.4 (20%)	970.4 (61%)	625.4 (45%)	0.316	0.891	0.537

8.1.1.9. Cultivar selection and yield

The impact of the maturity class of maize cultivars on yield was investigated and found to be statistically significant at a 5% level using paired *t*-tests. Simulations revealed that maize yield was highest when an early-medium maturity maize cultivar was cultivated (Figure 15). This indicated that, most of the time, the growing season was not long enough to sustain late maize cultivars.

Additionally, the yields of the high-yielding Pioneer 3237 hybrid cultivar were compared to those of the local Malawi cultivar used by the GSVF and found to be significantly different at a 5% level. The hybrid was fo0.und to increase average yield by 98% (1.05 tonnes ha^{-1}) and consistently outperformed the local cultivar (Table 18 and Figure 16). This indicates that yield can be increased by at least a tonne by improving cultivar selection. Considering this, it is still concluded that the genetic potential of the local cultivars was a major limiting factor to production in the region. However, a cost-benefit analysis would be necessary to warrant the purchase of an improved hybrid cultivar. Furthermore, it should be noted that the hybrid cultivars available to SSFs in the region may not have the same yield potential or adaptability as the cultivar used in this study.

Table 18: Descriptive statistics of maize yield under local cultivar compared to a high-potential cultivar over a 50-year period under the Gurúè small-scale virtual farm (GSVF) scenario

Scenario	Minimum (kg ha^{-1})	Maximum (kg ha^{-1})	Mean (kg ha^{-1})	Std. Deviation (kg ha^{-1})
Local cultivar	438.00	1903.70	1061.10	419.51
High-potential cultivar	1366.60	3504.70	2106.50	628.38

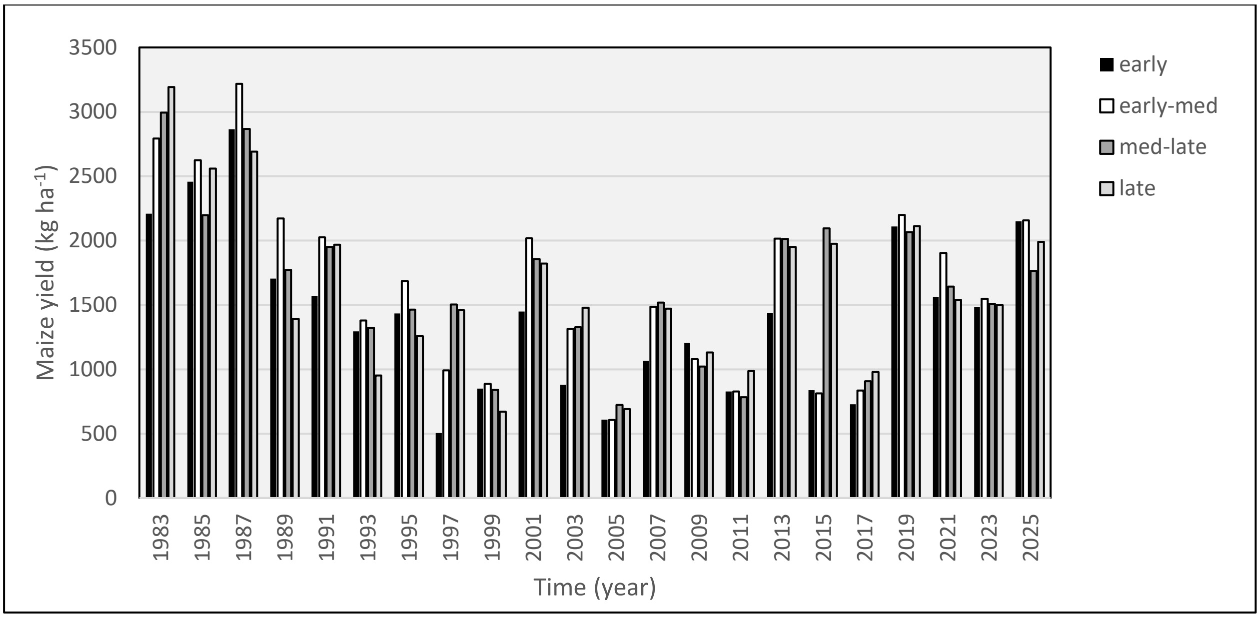

Fig. 15: Maize yield of a high-yielding cultivar (Pioneer 3237) compared to local cultivar over a 50-year period under the Gurúè small-scale virtual farm (GSVF) scenario

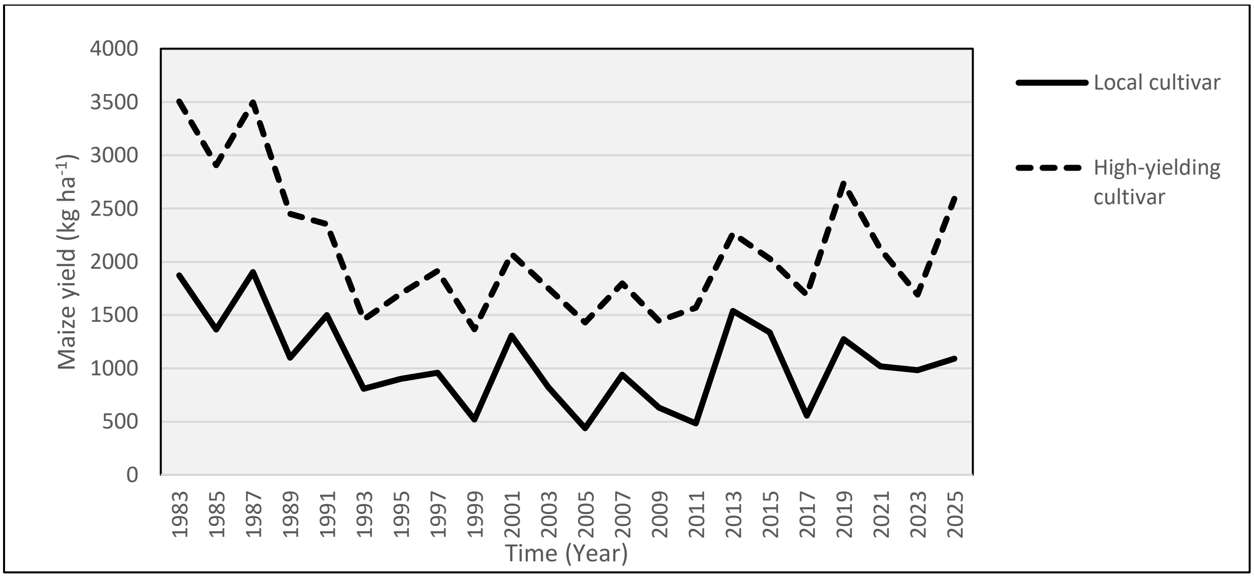

Fig. 16: Maize yield of a high-yielding cultivar (Pioneer 3237) compared to local cultivar over a 50-year period under the Gurúè small-scale virtual farm (GSVF) scenario

8.1.1.10. Cultivar selection and soil degradation

The difference between SOC and total soil N loss under a local maize cultivar (‘mwi_local’) versus hybrid maize cultivar (‘Pioneer 3237’) was found to be statistically significant at a 5% level. In the top soil layer, N loss was found to increase by an average 2% (0.02 kg ha^{-1}). In the lower two layers, total soil N decreased by 0.08 kg N ha^{-1} and 0.05 kg N ha^{-1}.

Similarly, SOC loss decreased in the top layer and increased in the two lower layers (Table 19).

Table 19: Soil organic carbon (SOC) and nitrogen (N) loss in each soil layer after 50 years of local cultivar compared to hybrid cultivar under the Gurúè small-scale virtual farm (GSVF) scenario

Scenario	N loss (kg ha^{-1})			SOC loss (%)		
	Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3
Local	265.9 (15%)	730.9 (45%)	522.3 (37%)	0.237	0.664	0.445
High-yielding	286.8(17%)	723.3 (44%)	517.6 (37%)	0.254	0.656	0.441

8.1.1.11. Sole cropping and maize yield

According to the paired *t*-test, there was significant difference between maize yields observed under an intercrop versus sole cropping cultivation. Changing from a legume intercrop to sole cropping maize decreased average maize yield by 45% (0.46 tonnes ha^{-1}) (Table 20). Therefore, the GSVF's practice of intercropping with legumes was shown to have improved maize yield (Figure 17). Although intercropping results in increased competition, the benefits of intercropping, such as N provided by the legume intercrop, was shown to outweigh the increased competition.

Table 20: Descriptive statistics of maize yield under sole cropping maize compared to a legume and maize intercrop over a 50-year period under the Gurúè small-scale virtual farm (GSVF) scenario

Scenario	Minimum (kg ha^{-1})	Maximum (kg ha^{-1})	Mean (kg ha^{-1})	Std. Deviation (kg ha^{-1})
Intercrop	438	1 904	1 020	454
Sole crop	316	996	563	311

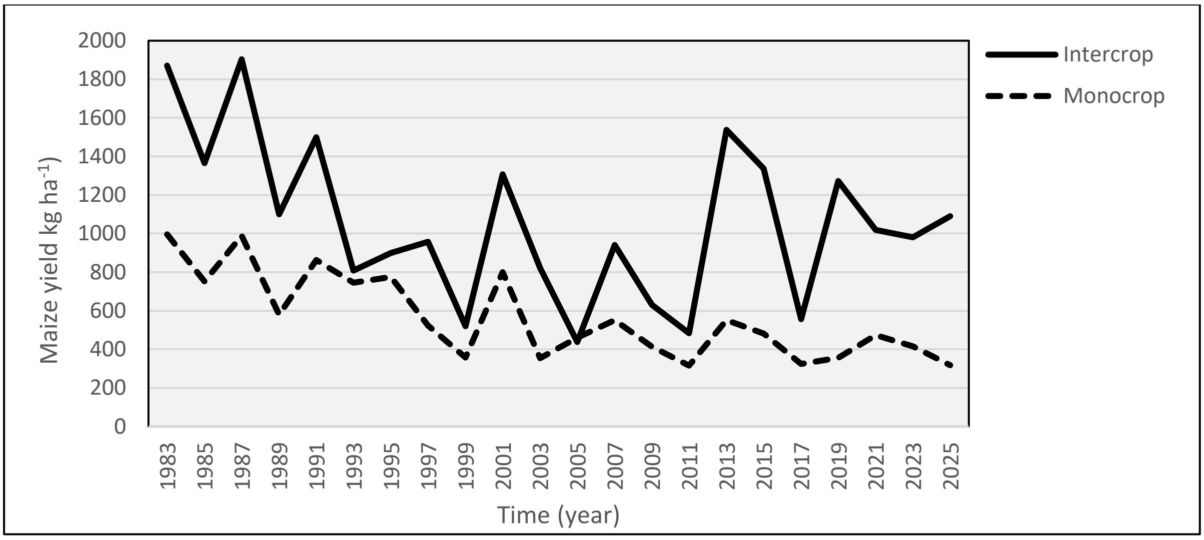

Fig. 17: Maize yield under sole cropping compared to an intercrop of legumes and maize over a 50-year period under the Gurúè small-scale virtual farm (GSVF) scenario

8.1.1.12. Sole cropping and soil degradation

The difference between SOC% and total soil N over a 50-year period was found to be significant at the 5% level between sole cropping maize and a maize and legume intercrop according to the paired *t*-test. It was found that under monocrop cultivation SOC% and total soil N loss increased in all soil layers (Table 21). This indicates that N from legume intercropping and the increased SOM from crop residues due to higher yields was effective in mitigating soil degradation in the GSVF scenario.

Table 21: Soil organic carbon (SOC) and nitrogen (N) loss in each soil layer after 50 years of maize sole cropping compared to a legume and maize intercrop under the Gurúè small-scale virtual farm (GSVF) scenario

Scenario	N loss (kg ha^{-1})			SOC loss (%)		
	Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3
Intercrop	265.9 (15%)	730.9 (45%)	522.3 (37%)	0.24	0.66	0.45
Monocrop	536.9 (31%)	808 (49%)	588.9 (42%)	0.46	0.74	0.51

8.1.1.13. Improved management and yield

To achieve the maximum potential maize yield, all the management variables discussed above were improved. Combinations of the above variables were simulated and found to be significant at a 5% level using paired *t*-tests against the GSVF. It was found that the highest average yield was achieved irrigating at 90 mm SW deficit, hybrid cultivar selection (Pioneer 3237), high planting density (7.5 plants ha^{-1}), and the addition of 200 kg urea-N ha^{-1} for all crops within the intercrop rotation. This improved management strategy resulted in an average yield of 6.1 tonnes ha^{-1}, a difference of 500% (5.0 tonnes ha^{-1}). The lowest yield experienced under improved management was 2.06 tonnes ha^{-1}, 106% more than the average yield under GSVF practices. Furthermore, the maximum potential yield under improved management was 337% (6.4 tonnes ha^{-1}) more than under GSVF practices. However, although yields were substantially improved, yield variability also increased. This indicated that the improved management scenario was more vulnerable to variability in climactic conditions.

Results showed that that increasing inputs would result in improved maize yields that could not be obtained under the natural agro-ecological conditions of the region. The amelioration of all management variables resulted in increases in maize yield 100% of the time in the 50-year simulation (Fig. 18). This means that all these variables contributed to limiting maize yield in the region, and improving each variable was required to achieve substantially improved maize yields.

Table 22: Descriptive statistics of maize yield over a 50-year period under improved management compared to the Gurúè small-scale virtual farm (GSVF) scenario

Scenario	Minimum (kg ha^{-1})	Maximum (kg ha^{-1})	Mean (kg ha^{-1})	Std. Deviation (kg ha^{-1})
GSVF	438	1 904	1 020	454
Improved	2 608	8312	6115	1 398

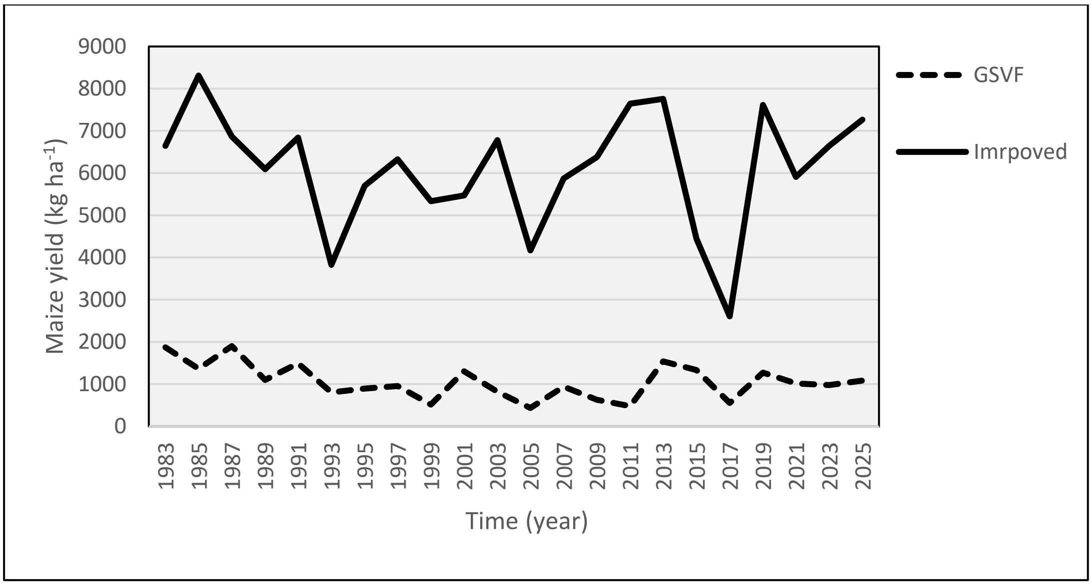

Fig. 18: Simulated maize yield of improved management compared to the Gurúè small-scale virtual farm (GSVF) scenario over a 50-year simulation

8.1.1.14. Improved management and soil degradation

The impacts of improved management on soil degradation were found to be significantly different compared to GSVF management practices at a 5% level. Average SOC and total soil N loss after 50-years of production was substantially accelerated in each soil layer under improved management compared to the GSVF scenario. In soil layer 2, 62% of total soil N was lost and 60% of OC after 50 years of production indicating to an unsustainable system (Table 23). This was mainly due to the addition of irrigation, which increased yield, but due to leaching it also accelerated soil degradation. It was further noted that the addition of N fertilizer was not sufficient to substantially decrease the rate of degradation of total soil N. N mineralization in the GSVF scenario versus the improved management practices was found to be statistically significant at a 5% level. However, after 50 years of production the improved management was not able to substantially alter the rate of N mineralization which remained low indicating that mineral-N was not sufficient to meet immobilization demand (Figure 19).

These results indicated that the increased yields due to improved management are potentially more damaging to SOC and total soil N than the lower yields from the GSVF scenario which did not apply any agro-inputs.

Table 23: Soil organic carbon (SOC) and nitrogen (N) loss in each soil layer after 50 years under improved management compared to the Gurúè small-scale virtual farm (GSVF) scenario

Scenario	N loss (kg ha^{-1})			SOC loss (%)		
	Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3
GSVF	265.9 (15%)	730.9 (45%)	522.3 (37%)	0.237 (16%)	0.664 (44%)	0.445 (37%)
Improved	621.1 (31%)	1083.2 (62%)	846.1 (51%)	0.336 (22%)	0.881 (60%)	0.532 (44%)

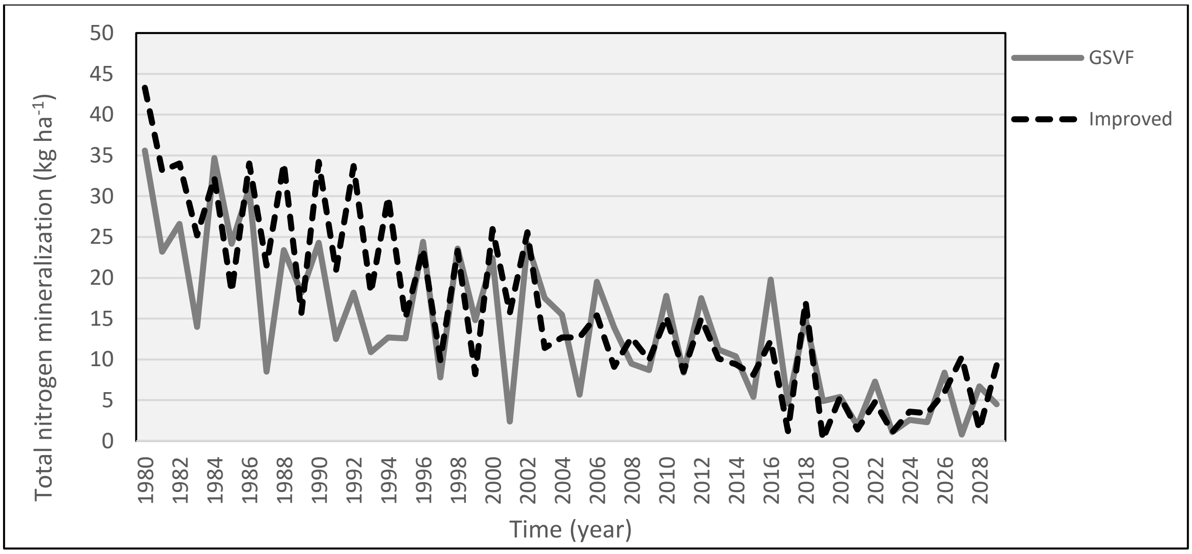

Fig. 19: Nitrogen mineralization in soil layer 2 under improved management practices compared to the Gurúè small-scale virtual farm (GSVF) scenario over 50 years of production

8.1.2. Gurúè large-scale virtual farm (GLVF)

8.1.2.1. GLVF and yield

The Gurúè large–scale farm achieved actual average yields of 3.1 tonnes ha^{-1} maize and 1.91 tonnes ha^{-1} soybean. The GLVF's management practices were simulated in APSIM over a 50-year period and achieved a mean yield of 2.99 ± 0.97 tonnes ha^{-1} of maize and 2.10 ± 0.59 tonnes ha^{-1} (Figure 20). The maximum and minimum maize yields achieved during this simulation period were 4.7 tonnes ha^{-1} in 2011 and 0.7 tonnes ha^{-1} in 1994, respectively. Additionally, there were no crop failures (<0.3 tonnes ha^{-1}) experienced over the 50-year period.

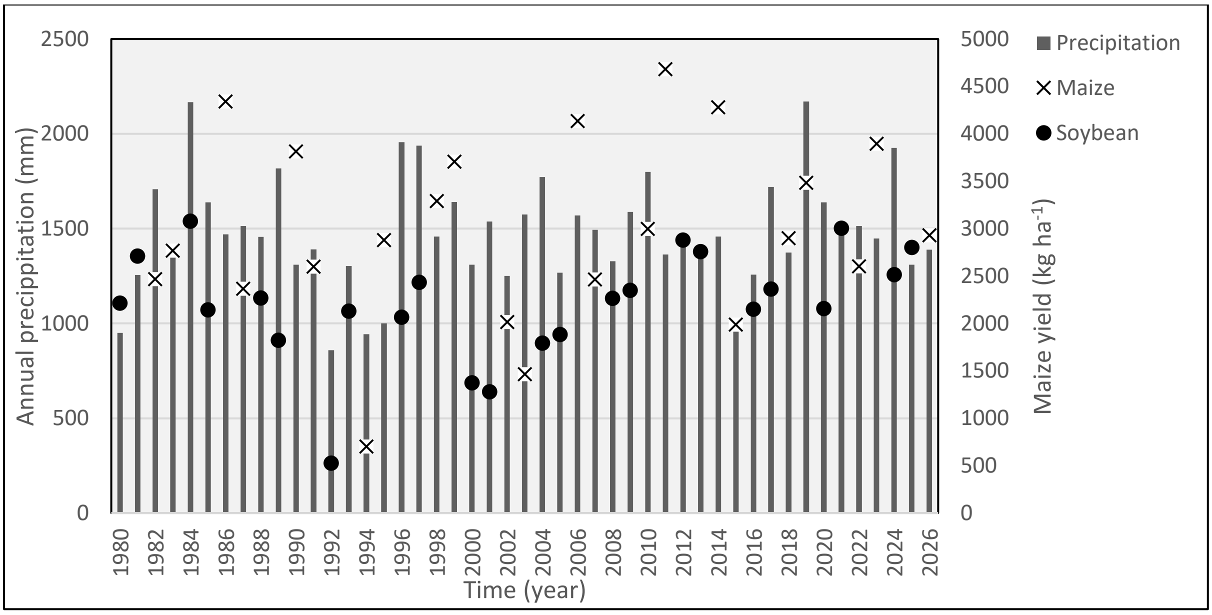

Fig. 20: Maize and soybean rotation yield under Gurúè large-scale virtual farm (GLVF) management practices over 50 years of production versus precipitation

8.1.2.2. GLVF and soil degradation

In terms of soil degradation, after 50 years of GLVF production the SOC pool gained 0.29% OC (19% of initial) in soil layer 1 and lost 0.73% OC (48% of initial) in soil layer 2 and 0.51% OC (42% of initial) in soil layer 3 (Figure 21). N loss after 50 years of production was also experienced in soil layer 2 and 3 by 804 kg N ha^{-1} (49%) and 593 kg N ha^{-1} (42%), respectively (Figure 22). However, total soil N increased in the top soil layer by 399 kg N ha^{-1} (23%) due to the deposition of crop residues and fertilizer on the soil surface. N mineralization was found to decelerate significantly in the two lower soil layers. After 40 years of production, N mineralization reached 0 kg N ha^{-1} in soil layer 2 indicating that there was insufficient N to meet the immobilization demand to the point where there was no soil N mineralization (Figure 23).

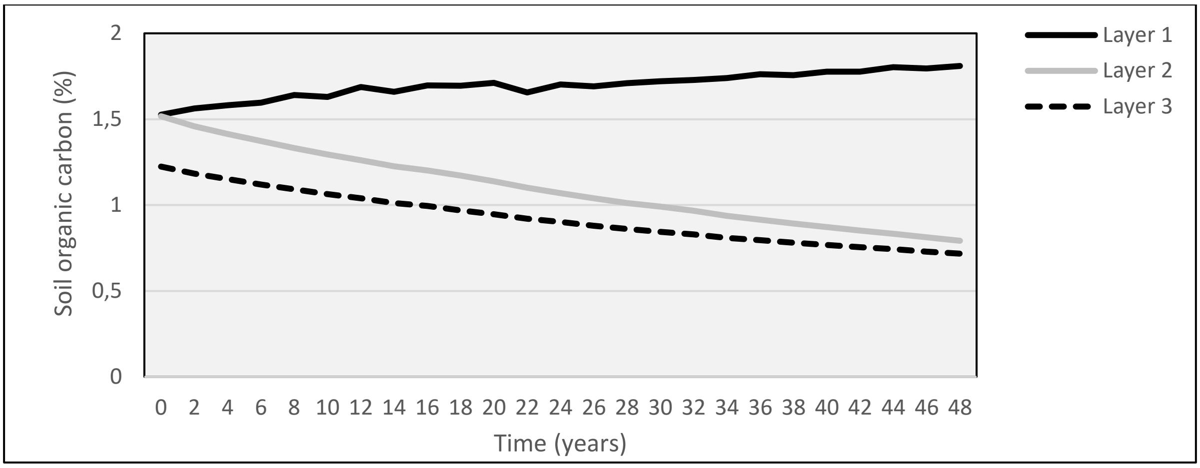

Fig. 21: Soil organic carbon (%) in soil layer 1 (0-0.1 m), 2 (0.1-0.2 m), and 3 (0.2-0.3 m) under Gurúè large-scale virtual farm (GLVF) management practices over 50-years of production

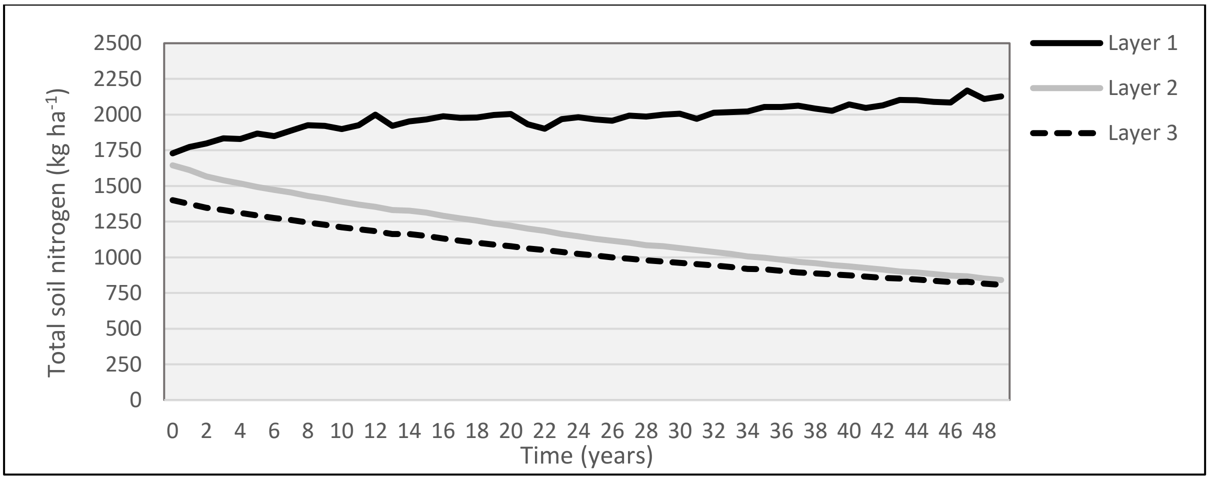

Fig. 22: Total nitrogen (N) in soil layer 1 (0-0.1 m), 2 (0.1-0.2 m), and 3 (0.2-0.3 m) under Gurúè large-scale virtual farm (GLVF) management practices over 50-years of production

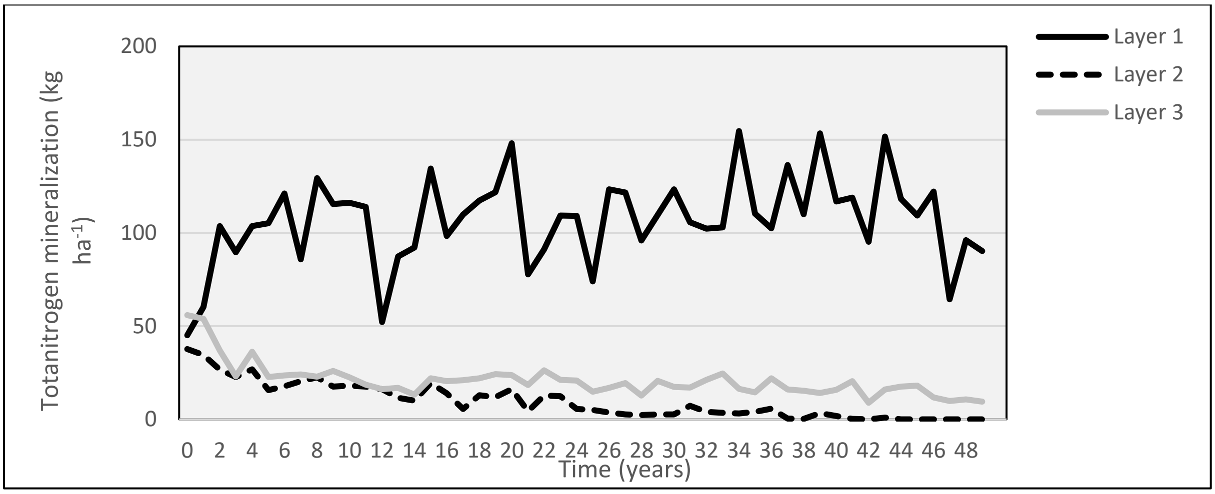

Fig. 23: Nitrogen mineralization in soil layer 1 (0-0.1 m), 2 (0.1-0.2 m), and 3 (0.2-0.3 m) under Gurúè large-scale virtual farm (GLVF) management practices over 50 years of production

8.1.2.3. Fertilizer and yield

It was found that fertilization was imperative under the GLVF management practices. If no fertilizer was added to the GLVF scenario there was a loss of 1.6 tonnes ha^{-1} of maize, more than half (54%) of the yield achieved with fertilizer. In addition, there were four crop failures (<300 kg ha-1) in the 50-year period when no fertilizer was utilized, indicating that there is a higher N demand from its higher yielding hybrid cultivars compared to the GSVF (Figure 26).

Three alternative fertilization rates were investigated: increasing N at sowing from 18 kg N to 150 kg N, increasing N top-dress from 190 kg N to 250 kg N, and increasing both (Table 24). The yields obtained under these different fertilization rates were found to be significantly different at a 5% level using the paired *t*-test. Yield was highest when a combination of increased N at sowing and top-dress, but the NAE decreased from an average 8 kg grain kg N to an average low of 5 kg grain kg^{-1} N (Whitbread *et al.*, 2013). The NAE revealed that maize yield was not substantially responsive to increased N rates above the GLVF rates indicating that N was no longer limited above rates applied by the GLVF. Therefore, according to NAE the GLVF was fertilizing at ideal rates.

Furthermore, it was shown that under the GLVF fertilization rates the urea top-fertilizer contributed 1.5 tonnes ha^{-1} of the yield while the 18 kg pre-sow NH_4-N fertilization only contributed 0.07 tonnes ha^{-1} (2%) to yield. It is clear from the results that N fertilization, particularly the urea topdressing, was critical for achieving higher yields, but that increasing yields above the GLVF rates was not an agronomically efficient use of N.

It was also corroborated that the minimum yield obtained in 1994 during the GLVF simulation was not limited by N as the addition of N to the system did not significantly improve yield (Figure 24). However, the addition of more N to the system did increase the maximum GLVF yield, as predicted, even though on average over a 50-year period it is not an efficient use of N.

Table 24: Descriptive statistics of maize yield under different fertilization rates over a 50-year period under the Gurúè large-scale virtual farm (GLVF) scenario

Scenarios	**Minimum (kg ha^{-1})**	**Maximum (kg ha^{-1})**	**Mean (kg ha^{-1})**	**Std. Deviation (kg ha^{-1})**	**NAE**
GLVF	703	4 683	2 990	973	8.09
Increased N at sowing and top dress	717	5 270	3 236	971	4.82
Increased N top dress	703	5 152	3 149	962	6.87
Increased N at sowing	717	4 807	3 126	973	5.35
No N fertilizer	0	2 995	1 308	939	-

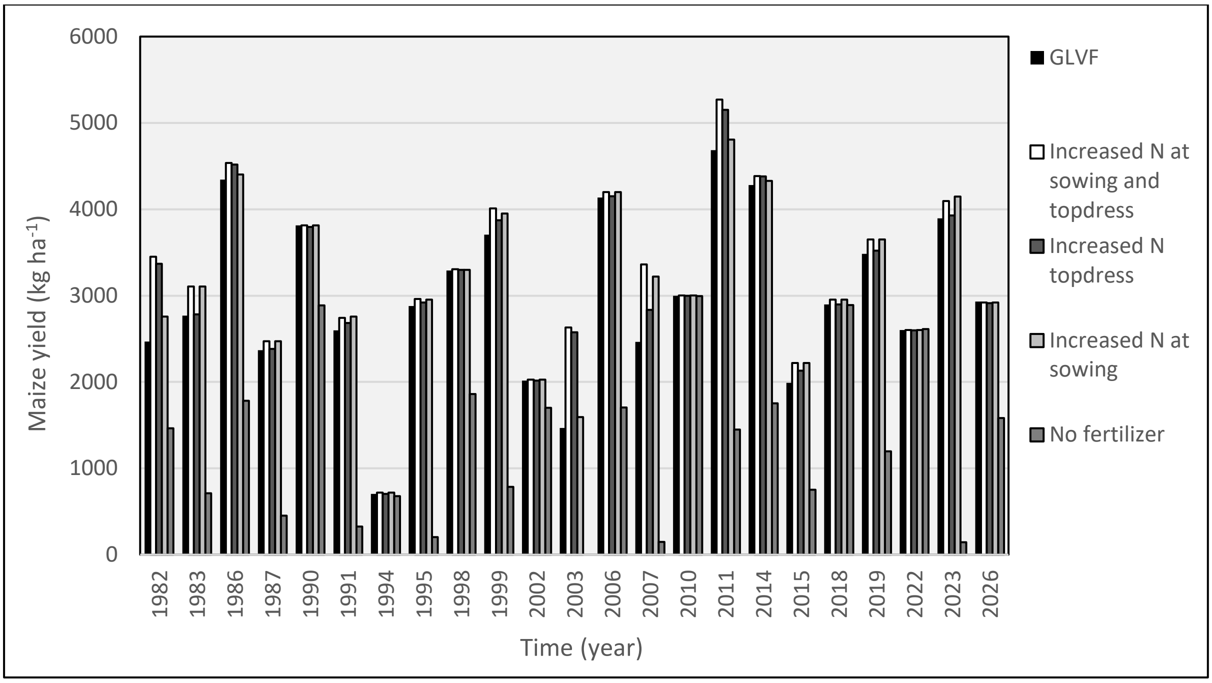

Fig. 24: Maize yield under different fertilization rates under the Gurúè large-scale virtual farm (GLVF) scenario over a 50-year simulation

8.1.2.4. Fertilization and soil degradation

The addition of N to the system did not significantly change the OC% in soil layer 2 and 3 according to the paired t-test. However, there was significant change in the top layer with an addition of 0.29 OC% (19% more than initial) showing that crop residues did replenish the OC pool in the top soil layer but failed to make a significant change in lower soil layers. Similarly, when the combination fertilizer scenario was run which included increased N at sowing to 150 kg NH_4-N ha^{-1} and a 250 kg Urea-N ha^{-1} top-dressing, SOC increased in the top layer but remained unchanged in the two lower soil layers.

N loss followed the same response as OC loss which was not significantly different at lower soil layers but increased significantly in the top soil layer indicating that the fertilization and larger quantity of crop residues from higher yields was able to replenish total soil N in the top soil layer (Table 25). However, when the combination fertilizer scenario was run, not only did N increase in the top soil layer, but N loss decreased by an average 51 kg ha^{-1} (3%) in soil layer 2 and 25 kg ha^{-1} (2%) in soil layer 3. This indicated that a substantially large addition of N would be required to meaningfully decelerate total soil N loss, according to the previous section this would however be agronomically inefficient.

Table 25: Soil organic carbon (SOC) and nitrogen (N) loss in each soil layer after 50 years of different fertilizer rates under the Gurúè large-scale virtual farm (GLVF) scenario

Scenario	**N loss (kg ha^{-1})**			**SOC loss (%)**		
	Layer 1	Layer 2	Layer 3	Layer 1	Layer 2	Layer 3
GLVF	-399 (23%)	804 (48%)	593 (42%)	-0 ,29 (-19%)	0,73 (48%)	0,51 (42%)
Increased N	-549 (32%)	753 (45%)	567 (40%)	-0.36 (-24%)	0.73 (48%)	0.51 (42%)
No N	-283 (16%)	793 (48%)	592 (42%)	-0,18 (-12%)	0,73 (48%)	0,52 (42%)

8.1.2.5. Irrigation and yield

The difference between yields under irrigation versus rainfed was found to be significantly different at a 5% level using the paired *t*-test. The irrigation schedule followed the rule that from 01-November to 31-January, if rainfall over the past 5 days was less than 20mm then 20mm of irrigation would be applied and that irrigation would not be applied until 7 days had passed. This schedule resulted in an average yield increase of 0.4 tonnes ha^{-1} (13%) over a 50-year simulation (Table 26 and Figure 25). Irrigation was also found to significantly decrease yield variability which according to the Two-related samples statistical test, indicating that water stress is the main contributor to yield variability in the region. When irrigation was added to the simulation the minimum yield in 1994 increased by 2.13 tonnes ha^{-1} (315%), indicating that irrigation was the major limiting factor to production when minimum yield was obtained.

However, using the Wilcoxon Signed Ranks test it was found that irrigation lead to increased maize yield 65% of the time and decreased maize yields 35% of the time over the 50-year simulation (Table 27). Negative ranks were potentially explained by the increased leaching of N which would have been required to increase yields. These results indicate that irrigation in the region requires careful scheduling and although it was not required to achieve high yields, it decreased yield variability and allowed for significant improvements of yield when the rainy season was delayed ensuring that yields remained above 2 tonnes ha^{-1}.

Table 26: Descriptive statistics of maize yield under rainfed compared to irrigated conditions over a 50-year period under the Gurúè large-scale virtual farm (GLVF) scenario

Scenario	Minimum (kg ha^{-1})	Maximum (kg ha^{-1})	Mean (kg ha^{-1})	Std. Deviation (kg ha^{-1})
GLVF rainfed	703	4 684	2 990	973
GLVF irrigated	2 048	4 569	3 388	665

Table 27: Positive and negative ranks of rainfed compared to irrigated maize yields under the Gurúè large-scale virtual farm (GLVF) scenario using the Wilcoxon signed ranks test

		N	Mean Rank	Sum of Ranks
GLVF irrigated - GLVF rainfed	**Negative Ranks**	8[a]	9.13	73.00
	Positive Ranks	15[b]	13.53	203.00
	Ties	0[c]		
	Total	23		

a. GLVF irrigated < GLVF rainfed

b. GLVF irrigated > GLVF rainfed

c. GLVF irrigated = GLVF rainfed

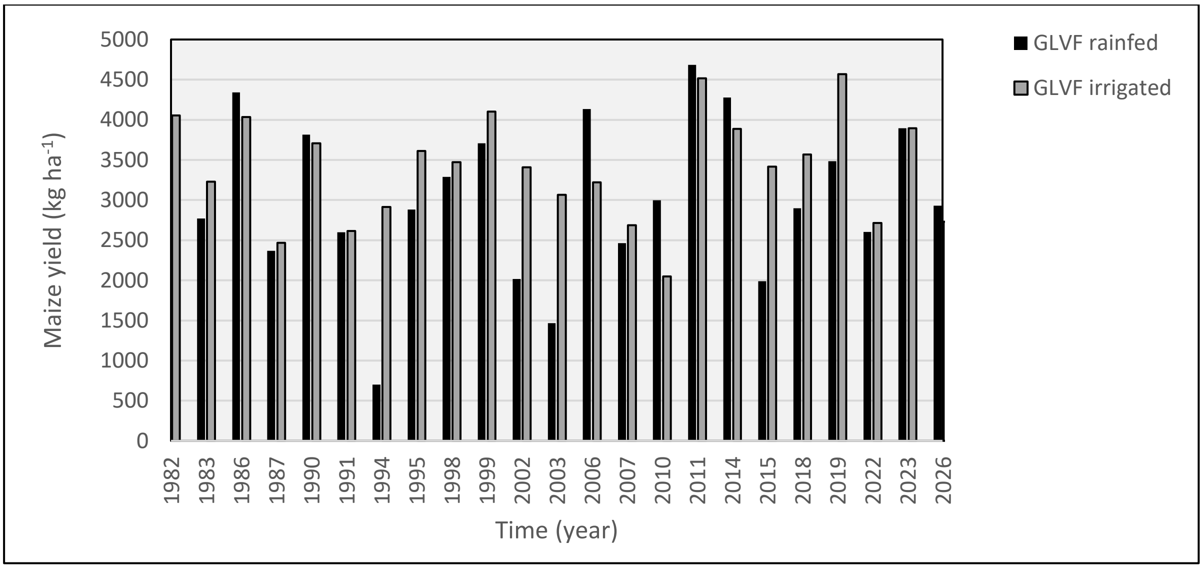

Fig. 25: Maize yield under rainfed and irrigated conditions under the Gurúè large-scale virtual farm (GLVF) scenario over a 50-year simulation

8.1.2.6. Irrigation and soil degradation

Irrigation was found to significantly impact total SOC and N loss compared to rainfed conditions at a 5% level according to a paired *t*-test. OC and N loss was accelerated due to irrigation. Under rainfed conditions the top soil layer benefited from the GLVF soil management increasing total SOC% and N, but under irrigation both SOC% and N decreased. Soil degradation was also aggravated in lower soil layers under irrigation compared to rainfed conditions due to increased leaching (Table 28). Therefore, although irrigation results in higher maize yields it accelerates soil degradation which in turn will eventually result in decreased yields if management stays the same.

Table 28: Soil organic carbon (SOC) and nitrogen (N) loss in each soil layer after 50 years of rainfed compared to irrigated production under the Gurúè large-scale virtual farm (GLVF) scenario

Scenario	**N loss (kg ha^{-1})**			**SOC loss (%)**		
	Layer 1	**Layer 2**	**Layer 3**	**Layer 1**	**Layer 2**	**Layer 3**
Rainfed	-399 (-23%)	804 (49%)	593 (42%)	-0 ,29 (-19%)	0,73 (48%)	0,51 (42%)
Irrigated	-342 (-19%)	838 (51%)	607 (43%)	-0.26 (-17%)	0.77 (51%)	0.53 (43%)

8.1.2.7. Cultivar selection and yield

According to the paired t-test the average maize yield of cultivar PAN 667 is significantly different to the average yield of cultivar Pioneer 3237 at a 5% level. The use of a high-yielding maize cultivar in the region resulted in an increase in average yield by 3.8 tonnes ha^{-1} (127%) (Table 29 and Figure 26). With minimum yield increased by an average 1.5 tonnes ha^{-1} (217%) and the maximum yield increased by an average 5 tonnes ha^{-1} (107%). Additionally, yield variability was found to increase under the improved cultivar due to water stress from the lack of irrigation. Increased maximum yields without additional N fertilization further illustrates that maize in the GLVF scenario is not N stressed and there is sufficient N in the soil profile to support the higher yields obtained by the improved cultivar. Access to improved seed varieties adapted to the region was a major issue perceived by farm managers to be limiting maize yields. Results show that this perception was accurate as maize yield improved every year of over the 50-year simulation under the improved cultivar.

Table 29: Descriptive statistics of maize yield under Gurúè large-scale virtual farm (GLVF) cultivar compared to the improved cultivar over a 50-year period under the GLVF scenario

Scenario	Minimum (kg ha^{-1})	Maximum (kg ha^{-1})	Mean (kg ha^{-1})	Std. Deviation (kg ha^{-1})
GLVF	703	4 684	2 990	973
Improved cultivar	2 227	9 701	6 814	1 544

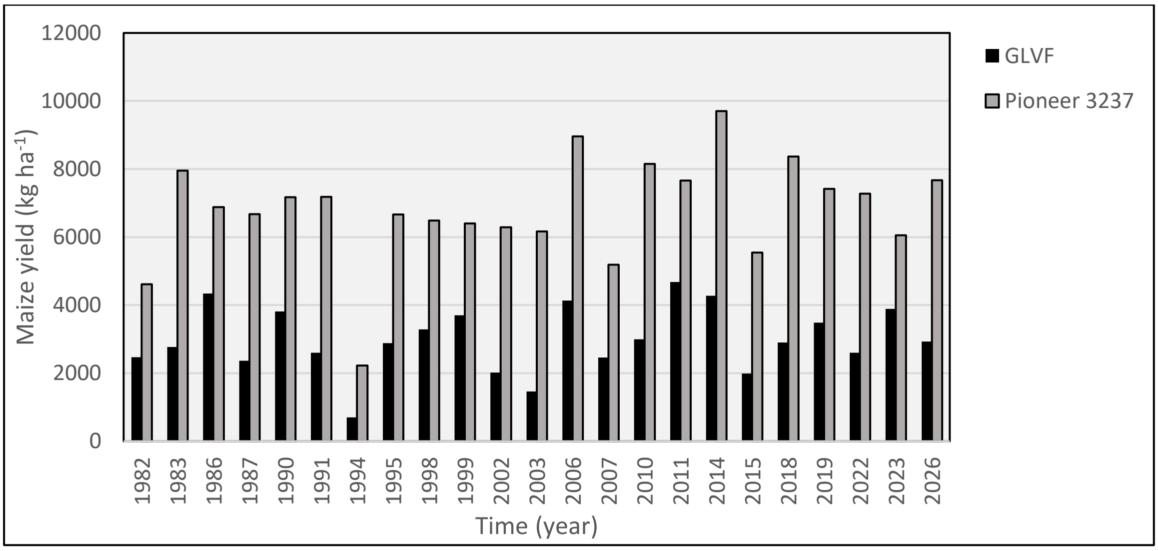

Fig. 26: Maize yield of a Gurúè large-scale virtual farm (GLVF) cultivar compared to improved cultivar over a 50-year period under the GLVF scenario

8.1.2.8. Cultivar selection and soil degradation

The impact of cultivar selection on maize yield was found to be significantly different at a 5% level using a paired t-test. The OC and N gained in the top soil layer was less under the improved cultivar than the GLVF cultivar (Table 30). However, in the lower soil layers soil degradation was decelerated as SOC and total soil N loss decreased by 1-3% under improved cultivar use.

Table 30: Soil organic carbon (SOC) and nitrogen (N) loss in each soil layer after 50 years of Gurúè large-scale virtual farm (GLVF) cultivar compared to the improved cultivar under the GLVF scenario

Scenario	**N loss (kg ha^{-1})**			**SOC loss (%)**		
	Layer 1	**Layer 2**	**Layer 3**	**Layer 1**	**Layer 2**	**Layer 3**
GLVF	-399 (-23%)	804 (49%)	593 (42%)	-0 .29 (-19%)	0.73 (48%)	0.51 (42%)
Improved cultivar	-326 (-19%)	763 (46%)	563 (40%)	-0.24 (-16%)	0.71 (46%)	0.50 (41%)

8.1.2.9. Improved management and yield

The GLVF is a comparatively well-managed system, with ideal planting dates tailored to rainfed conditions, with fertilization at optimal rates, and realistic planting density. Although increasing N rates were found to significantly increase yield, the low NAE meant that increasing N rates would not be beneficial to the system. Furthermore, it was found that fertilization rates did not need to be increased to account for the N demand of the higher yielding cultivar.

Ultimately, the improved management system included the addition of irrigation scheduling, as described previously, and the use of a higher yielding cultivar (Pioneer 3237). The improved management scenario increased average yield to 7.4 ± 1.1 tonnes ha^{-1} (148% increase). Minimum yield was improved from 0.7 tonnes ha^{-1} to 3.8 tonnes ha^{-1} mainly due to irrigation, and maximum yield was improved from 4.6 tonnes ha^{-1} to 9.5 tonnes ha^{-1} mainly due to the higher yielding potential of the improved cultivar.

Table 31: Descriptive statistics of maize yield under improved management compared to the Gurúè large-scale virtual farm (GLVF) scenario over a 50-year simulation

Scenario	**Minimum (kg ha^{-1})**	**Maximum (kg ha^{-1})**	**Mean (kg ha^{-1})**	**Std. Deviation (kg ha^{-1})**	**NAE (kg ha^{-1})**
GLVF	703	4 684	2 990	973	8
GLVF improved	3 815	9 532	7 426	1 165	29

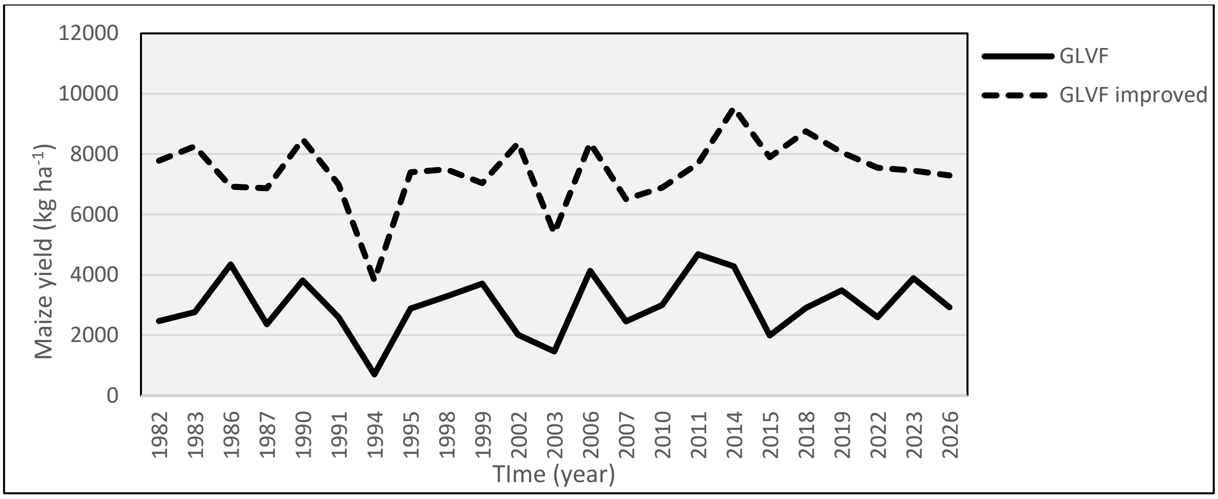

Fig. 27: Maize yield of improved management versus the Gurúè large-scale virtual farm (GLVF) scenario over a 50-year period

8.1.2.10. Improved management and soil degradation

Although improved management was found to substantially improve the yield potential of maize, it was found to significantly decrease soil OC and N at a 5% level. N mineralization under the GLVF versus improved management practices was also found to be significantly different at a 5% level using the paired t-test. It was found that with improved management N mineralization decelerated at a slower rate than under the GLVF management and avoided reaching a rate of 0 kg ha^{-1} after 50 years of production (Table 32). However, soil N and OC% loss were found to have increased under the GLVF management practices.

Table 32: Soil organic carbon (SOC) and nitrogen (N) loss in each soil layer after 50 years of improved management compared to the Gurúè large-scale virtual farm (GLVF) scenario

	N loss (kg ha-1)			**SOC loss (%)**		
Scenario	**Layer 1**	**Layer 2**	**Layer 3**	**Layer 1**	**Layer 2**	**Layer 3**
GLVF	-399 (-23%)	804 (49%)	593 (42%)	-0 ,29 (-19%)	0,73 (48%)	0,51 (42%)
Improved	-262 (-15%)	811 (49%)	585 (42%)	-0,18(-12%)	0,75(49%)	0,51 (42%)

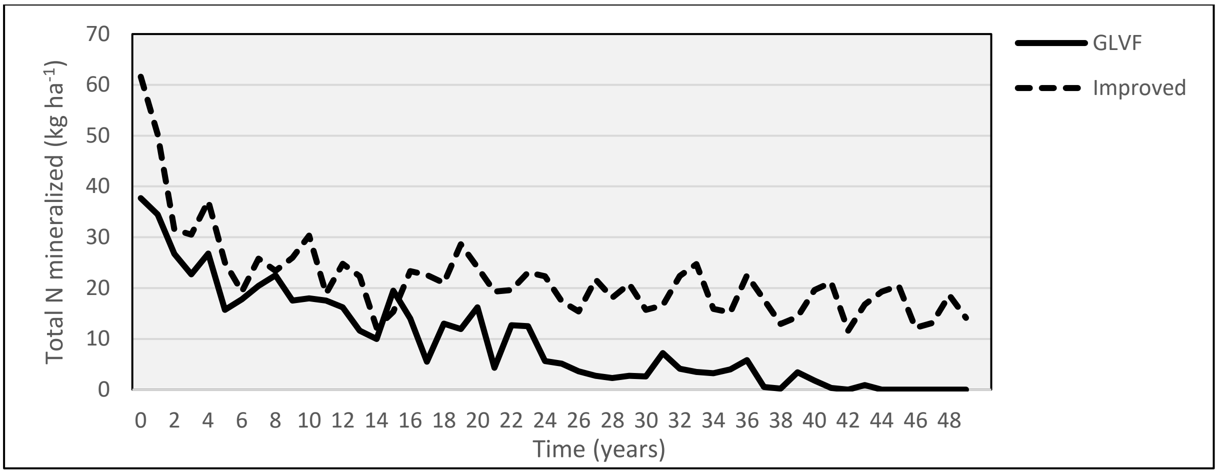

Fig. 28: Nitrogen mineralization in soil layer 2 (0.1-0..2 m)under improved management practices compared to the Gurúè large-scale virtual farm (GLVF) scenario over 50 years of production

8.2. The Nanyuki region

As a benchmark for the potential maize yield under the Nanyuki weather and soil conditions, a monocrop of the early-medium maturing maize cultivar "sc_501" was simulated at a planting density of 5 plants ha^{-1} over a 50-year period. According to this APSIM simulation the average potential yield was 6.12 tonnes ha^{-1}, this estimate was similar to the potential maize yields under irrigation and medium-input estimated by the Food and Agriculture Organization's (FAO) Global Agro-Ecological Zones (GAEZ) model, for the region, which was 6.4 tonnes ha^{-1}. The agro-ecological yield was 2.92 tonnes ha^{-1} according to the APSIM simulation, similarly GAEZ estimated a maize yield of 2.9 tonnes ha^{-1} under rainfed and low input use conditions. The average water-limited yield was 5.79 tonnes ha^{-1} according to APSIM simulations, GAEZ estimated that potential yield under rainfed conditions and intermediate input use was 5.7 kg ha^{-1} and rainfed conditions paired with high-input use was zero kg ha^{-1}. The average N-limited yield was simulated at 2.96 tonnes ha^{-1}, only 0.04 tonnes ha^{-1} more than the agro-ecological potential. Estimates from GAEZ predicted that under these conditions, there would be no maize yield. These baseline results indicated that the Nanyuki region was a N-stressed and water-stressed environment. However, the addition of N input improved maize yield by 98%, while irrigation only increased yield by 2%.

8.2.1. Nanyuki small-scale virtual farm (NSVF)

8.2.1.1. NSVF and crop yield

The Nanyuki small–scale farmers actual average yields were 3.02 tonnes ha^{-1} maize, 1.21 tonnes ha^{-1} legume and 3.65 tonnes ha^{-1} wheat. The NSVF's management practices were simulated in APSIM over a 50-year period and achieved an average yield of 3.06 ± 1.64 tonnes ha^{-1} of maize, 1.27 ± 1.1 tonnes ha^{-1} cowpea, and 3.23 ± 1.37 tonnes ha^{-1} wheat (Figure 29). The maximum and minimum (above crop failure) maize yields achieved during this simulation period were 4.3 tonnes ha^{-1} in 2008 and 5.41 tonnes ha^{-1} in 2002, respectively. Additionally, there were eight maize crop failures (<0.3 tonnes ha^{-1}) experienced over the 50-year period.

Crop failures in 1994, 2005, 2013, 2021, and 2024 were due to the failure to sow or germinate as there was no maize biomass production during these years. While crop failures in 2000, 2001, and 2011 successfully germinated the crop, however no grain was produced. Investigation into the reasons for crop failure, yield variability, and yield potential are investigated in the next section.

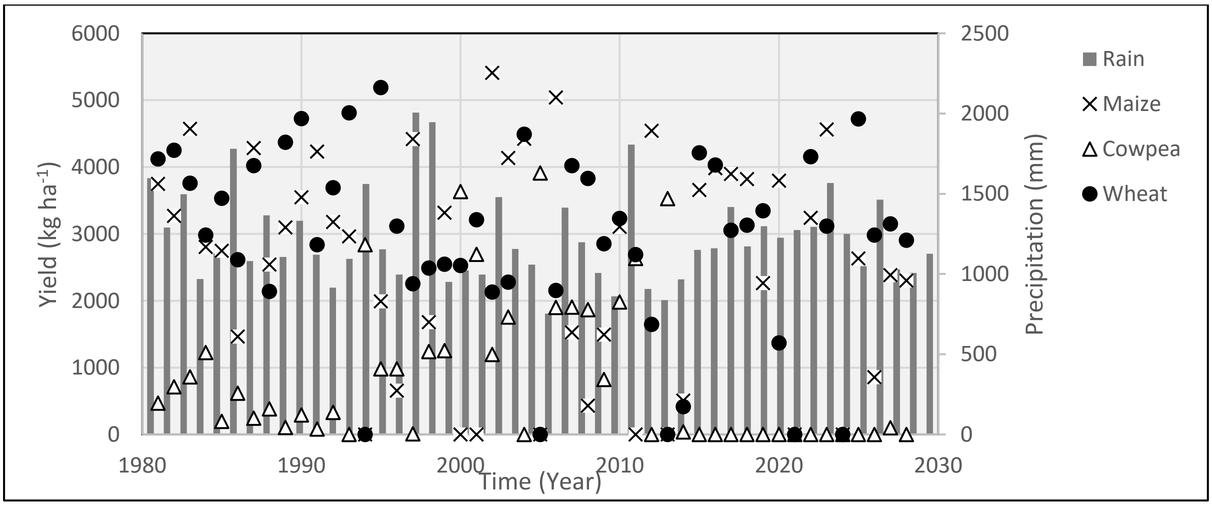

Fig. 29: Maize and cowpea intercrop rotating with wheat yield under Nanyuki small-scale virtual farm (NSVF) management practices over 50-years of production versus precipitation

8.2.1.2. NSVF and soil degradation

Results indicated that soil degradation, in terms of OC% and total soil N, was a potential environmental consequence of the NSVF management practices. Within the soil root zone (20-100 cm) soil organic carbon % (SOC%) decreased by an average range of 9-42%, with the most substantial SOC loss in soil layer 2 (20-45cm) which lost almost half of its SOC after 50 years of production (Figure 30). The SOC% increase in the top soil layer was due to the replenishment of OM from crop residues on the soil surface. Below the root zone an increase in SOC% was also observed as the soil was not disturbed by crop roots but benefited from the OM of their residues. A similar relationship was observed between NO_3 concentration and the soil layers (Figure 31). In the rooting zone (20-100cm) total soil N loss ranged from an average 10-42% with the largest loss occurring in soil layer 2 (20-45 cm). Crop residue and fertilization deposition on the soil surface benefitted the top soil layer which increase total soil N by 23%. While N leaching into soil layers below the root zone resulted in increases of total soil N in layers 6 to 8 by 1 to 5 %. Additionally, the rate of N mineralization was found to decelerate over time within the rootzone layers under the NSVF management practices, indicating that there was insufficient mineral-N to meet the soil immobilization demand (Figure 32).

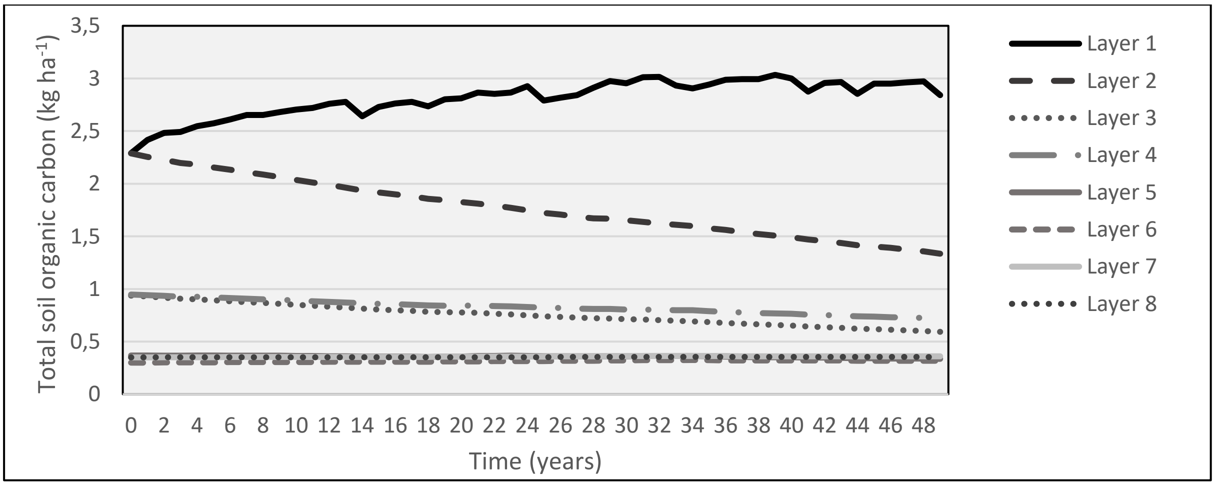

Fig. 30: Soil organic carbon (%) in soil layer 1-8 (0-1 m) under Nanyuki small-scale virtual farm (NSVF) management practices over 50-years of production

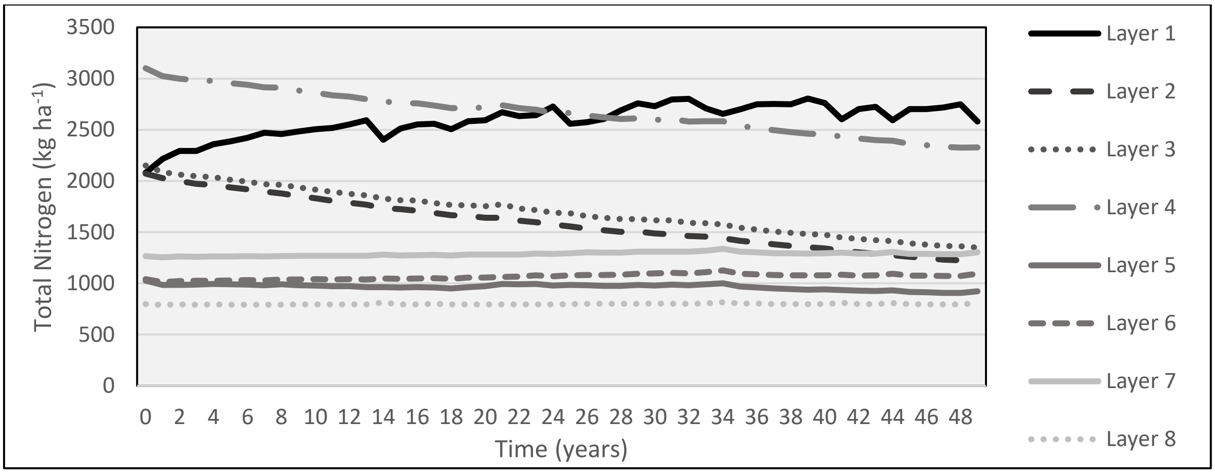

Fig. 31: Total nitrogen (N) in soil layer 1-8 (0-1 m) under Nanyuki small-scale virtual farm (NSVF) management practices over 50-years of production

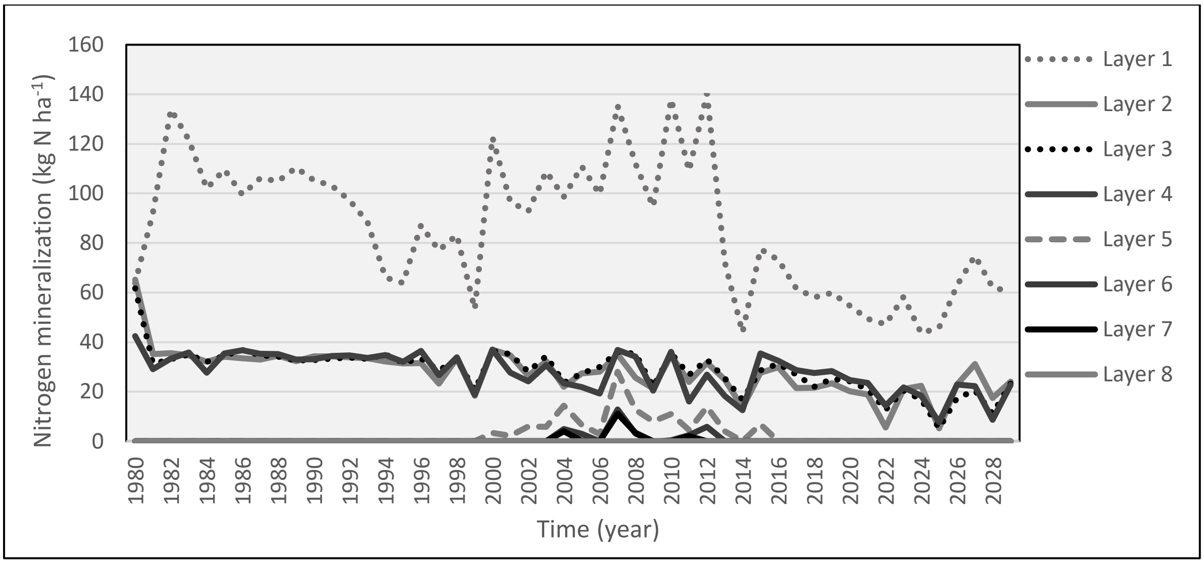

Fig. 32: Nitrogen mineralization in soil layer 1-8 (0-1 m) under the Nanyuki small-scale virtual farm (NSVF) management practices over 50-years of production

8.2.1.3. Fertilization and yield

Simulating the NSVF management practices with no N fertilization indicated that supplementary N was critical to achieving productivity. When no N was applied yield decreased by 1.7 tonnes ha^{-1} (57%) and there were 21 crop failures (<0.3 tonnes ha^{-1}) during the 50-year simulation. This was 13 more crop failures than under the NSVF fertilization schedule. Therefore, it was clear that the total soil N in Nanyuki was insufficient to meet the crop N demands of the NSVF system and that the addition of N fertilizer by the NSVF was warranted as it ensured higher crop productivity. Furthermore the fertilization rate used by the NSVF had an NAE of 39 kg grain kg^{-1} N, which according to Whitbread *et al.* (2013) is considered to be a high N response and therefore an agronomically efficient use of N (Table 33 and Figure 33).

Scenarios that increased the NH_4-N topdressing by 100kg and 200 kg was simulated and the difference between means was found to be statistically significant at 5% level using paired *t*-tests. The addition of 100 kg NH_4-N to the top-dressing increased the average yield by 0.70 tonnes ha^{-1} (23%), the maximum yield by 0.63 tonnes ha^{-1} (12%) and the minimum yield by 0.05 tonnes ha^{-1} (12%). However, this increased N rate did not result in less crop failures compared to the NSVF fertilization rate. The NAE at this N rate decreased to 17 kg grain kg^{-1} N which is considered to be a an intermediate N response (Whitbread *et al.,* 2013).

The addition of 200 kg NH_4-N to the topdressing compared to the 100 kg NH_4-N addition only resulted in a further average yield increase of 0.04 tonnes ha^{-1} (1%) and resulted in an NAE of 10 kg grain kg^{-1} N which is considered a low N response(Whitbread *et al*., 2013). increasing N did result in increased average yield, the N use efficiency of the system decreased. These results were in line with findings by Whitbread who showed that moderate N rates (15-30 kg N ha^{-1}) resulted in the highest NAE values (30-80 kg grain kg^{-1} N). Results indicated that the NSVF was fertilizing at ideal rates for their current management practices, and that maize yield was not N-limited. If increasing N fertilizer was to be recommended a cost-benefit analysis would be necessary to warrant the additional use of N.

Table 33: Descriptive statistics of maize yield under different fertilization rates over a 50-year simulation under the Nanyuki small-scale virtual farm (NSVF) scenario

Scenario	**Minimum (kg ha^{-1})**	**Maximum (kg ha^{-1})**	**Mean (kg ha^{-1})**	**Std. Deviation (kg ha^{-1})**	**NAE (kg ha^{-1})**
No fertilizer	0.00	3 149	1 292	905	-
NSVF 44 kg N	0.00	5 410	3 062	1 644	39
144kg N	0.00	6 041	3 683	1 985	17
244kg N	0.00	6 086	3 727	1 994	10

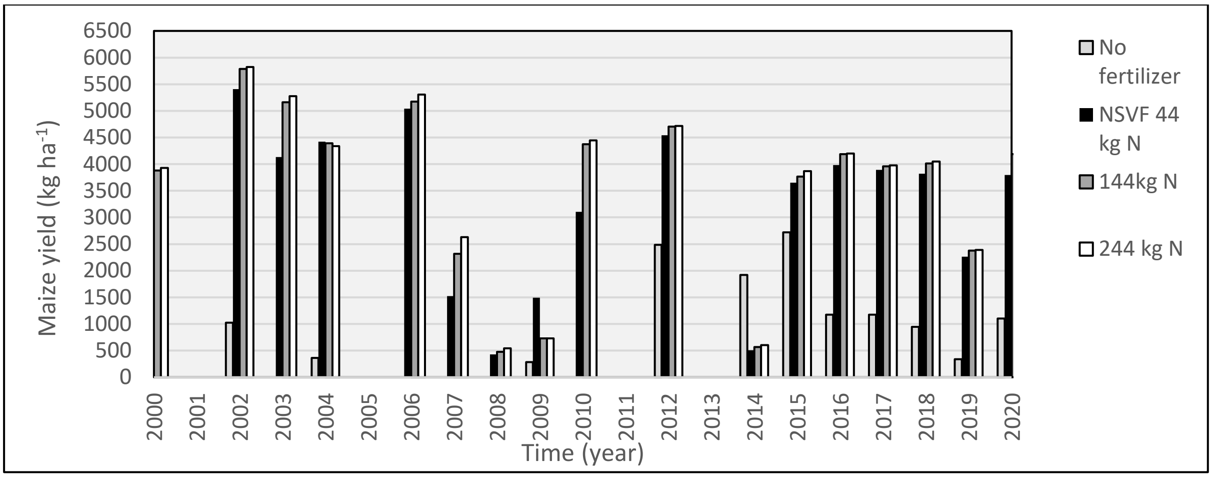

Fig. 33: Maize yield from 2000-2020 under different fertilization rates under the Nanyuki small-scale virtual farm (NSVF) scenario over a 50-year simulation

8.2.1.4. Fertilization and soil degradation

Increasing N fertilization was found to mitigate soil degradation by decelerating the rate of OC and total soil N loss in the root zone (Layers 2-5) and by increasing their concentration in the top soil layer (Layer 1) and below-root zone layers (Layers 6-8). The additional 200 kg NH_4-N resulted in an increase of 10% soil OC and 11% total soil N in the top soil layer after 50 years of production compared to the NSVF (Table 34 and 35). Below the root zone the increase in OC and total soil N was not statistically significant according to the paired *t*-test. However, the improvement in soil layers 2-5 (0.2-1.0 m) was statistically significant with OC loss decreasing by an average range of 1-2% and total soil N loss decreasing by an average range of 2-8%. Although the addition of N to the system has been shown to mitigate soil degradation, it does not prevent it as a decrease towards 0 % SOC and 0 kg ha^{-1} N was observed within the root zone. A much larger addition of OM and N would be required to replenish the degradation done by the NSVF system.

Table 34: Total soil organic carbon percentage (%) loss in each soil layer after 50 years of Nanyuki small-scale virtual farm (NSVF) production under different nitrogen fertilization rates

Scenario	Total SOC loss (%)							
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8
0kg N	0,23 (10%)	1,00 (44%)	0,38 (40%)	0,27 (28%)	0,05 (14%)	-0,02 (-5%)	-0,01 (-3%)	-0,00 (-1%)
NSVF 44 kg N	-0,55 (-24%)	0,95 (42%)	0,34 (37%)	0,23 (24%)	0,03 (9%)	-0,02 (-6%)	-0,01 (-3%)	-0,00 (-1%)
144 kg N	-0,78 (-29%)	0,93 (41%)	0,33 (41%)	0,22 (25%)	0,03 (7%)	-0,02 (-7%)	-0,01 (-3%)	-0,00 (-1%)
244 kg N	-0,78 (-34%)	0,93 (41%)	0,33 (36%)	0,22 (23%)	0,03 (7%)	-0,02 (-7%)	-0,01 (-3%)	-0,00 (-1%)

Table 35: Soil nitrogen (N) loss in each soil layer after 50 years of Nanyuki small-scale virtual farm (NSVF) production under different nitrogen fertilization rates

Scenario	Total N loss (kg ha^{-1})							
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8
0 kg N	217 (11%)	914 (44%)	882 (41%)	904 (29%)	168 (16%)	-23 (-2%)	-22 (-2%)	-6.1 (-1%)
NSVF 44 kg N	-499 (-23%)	868 (42%)	801 (37%)	773 (25%)	105 (10%)	-54 (-5%)	-38 (-3%)	-10 (-1%)
144 kg N	-719 (-34%)	846 (41%)	755 (35%)	699 (22%)	57 (5%)	-95 (-10%)	-70 (-5%)	-27 (-3%)
244 kg N	-731 (-34%)	841 (40%)	733 (34%)	657 (21%)	15 (2%)	-158 (-15%)	-153 (-12%)	-93 (-12%)

8.2.1.5. Sole cropping and yield

According to multiple paired *t*-tests, simulated maize yields were significantly different under each cropping system (Table 36). The NSVF scenario consisted of one intercrop with a legume and two growing seasons (GS) within a year. Results indicated that the number of growing seasons and whether the cropping system was an intercrop, or a monocrop significantly impacted maize yield within the NSVF management scenario. Compared to the NSVF scenario, having only one GS a year was found to significantly improve maize yield by 0.2 tonnes ha^{-1} (8%), however there were the same amount of crop failures over the 50-year period under both cropping systems, although they occurred during different years (Table 36). The change from an intercrop to sole cropping was also found to significantly improve yield as the ‘Sole crop and one GS’ scenario resulted in the highest average maize yields and resulted in no crop failures over the 50-year simulation. Compared to the ‘Intercrop and one GS’ scenario, maize yield increased by 1.6 tonnes ha^{-1} (48%). However, the 'Sole crop and two GS' scenario had the lowest maize yield and 29 crop failures over a 50-year period. This poor performance indicated that the sole cropping scenario was not suited to two growing seasons within a year.

Table 36: Descriptive statistics of maize yield under different cropping systems over a 50-year simulation under the Nanyuki small-scale virtual farm (NSVF) scenario

Scenario	Minimum (kg ha^{-1})	Maximum (kg ha^{-1})	Mean (kg ha^{-1})	Std. Deviation (kg ha^{-1})
NSVF Intercrop two GS	.00	5410	3061	1644
Intercrop one GS	.00	6009	3295	1871
Sole crop two GS	.00	4559	2939	1422
Sole crop one GS	1993	7250	4872	1142

8.2.1.6. Monocrop and soil degradation

Within the root zone (Layers 2-5), the NSVF scenario, which included a legume intercrop and two growing seasons, had the least soil degradation (Table 37 and 38). This was explained by the addition of N by the legume intercrop compared to the monocrop scenario. Also, due to the two GS, the NSVF had a lower maize yield which in turn demanded less N. The 'Intercrop and one GS scenario' also benefitted from the addition of N by the legume and therefore had less degradation than the monocrop scenarios. However, because it had a higher yield than the NSVF scenario, it also had a higher soil degradation rate than the within the root zone. Since the 'Monocrop and 2 GS' scenario had the lowest average maize yield and 29 crop failures over the 50-year simulation, the rate of soil degradation was significantly less than the highest yielding scenario, the 'Monocrop and 1 GS'. However, since the monocrop has no additional N from legume, it exhibited a faster soil degradation than the intercrop scenarios. Therefore, the addition of a N-fixing legume into the cropping system was critical for mitigating both OC% and total soil N loss within the root zone. The 'Monocrop and 1 GS' scenario had the highest rate of soil degradation as it lacked the addition of a legume and displayed the highest yields.

Table 37: Soil organic carbon percentage (%SOC) loss in each soil layer after 50 years of Nanyuki small-scale virtual farm (NSVF) production under different cropping systems

Scenario	Total SOC loss (%)							
	Layer 1	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**	**Layer 6**	**Layer 7**	**Layer 8**
NSVF	-0,55 (-24%)	0,95 (42%)	0,34 (37%)	0,23 (24%)	0,03 (9%)	-0,02 (-6%)	-0,01 (-3%)	-0,00 (-1%)
Intercrop and one GS	0.95 (41%)	1.06 (46%)	0.39 (41%)	0.27 (28%)	0.05 (12%)	-0.02 (-6)	-0.01 (-4%)	-0.01 (-1%)
Monocrop and two GS	-0.75 (-32%)	1.00 (44%)	0.39 (41%)	0.27 (28%)	0.06 (15%)	-0.01 (-2%)	-0.02 (-1%)	0.00 (0%)
Monocrop and one GS	1.04 (45%)	1.10 (49%)	0.42 (44%)	0.30 (31%)	0.06 (17%)	-0.01 (-4%)	-0.01 (-3%)	0.00 (-1%)

Table 38: Soil nitrogen (N) loss in each soil layer after 50 years of Nanyuki small-scale virtual farm (NSVF) production under different cropping systems

Scenario	Total N loss (kg N ha^{-1})							
	Layer 1	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**	**Layer 6**	**Layer 7**	**Layer 8**
NSVF	-499 (-23%)	868 (42%)	801 (37%)	773 (25%)	105 (10%)	-54 (-5%)	-38 (-3%)	-10 (-1%)
Intercrop and one GS	861 (41%)	966 (46%)	884 (41%)	871 (28%)	123 (12%)	-63 (-6%)	-49 (-4%)	-11 (-1%)
Monocrop and two GS	-699 (-34%)	910 (44%)	910 (42%)	907 (29%)	184 (18%)	3.5 (0.3%)	2.6 (0.2%)	3.2 (0.4%)
Monocrop and one GS	942 (45%)	1028 (49%)	947 (44%)	973 (32%)	177 (18%)	-31 (-3%)	-26 (-2%)	-5 (-1%)

8.2.1.7. Irrigation and yield

According to the paired *t*-test and two-related samples test there was no significant difference between the average yields produced under rainfed and irrigated conditions. The most beneficial APSIM irrigation schedule to increase the average maize yield in the Nanyuki region was to irrigate based on the soil water deficit in the window between the 1st March and the 30th September when there was a 90 mm deficit. These conditions resulted in an average yield increase of 0.12 tonnes ha^{-1} (5%), with minimum yield (above crop failure) increasing by 2.25 tonnes ha^{-1} (526%) and a decrease in maximum yield by 1.7 tonnes ha^{-1} (31%). Additionally, crop failures in 2000 and 2011 under rainfed conditions managed to produce yields of 4.2 and 4.99 tonnes ha^{-1} respectively once irrigation was added.

Results from the Wilcoxon signed ranks test noted that in 50 years irrigation only improved yield 27% of the time (Table 40). Water stress was found to be extremely variable due to the highly variable nature of rainfall in the region (Figure 34). When average annual rainfall was low, maize productivity was extremely limited by water stress, under these conditions the addition of irrigation was critical for obtaining productive yields. When average annual rainfall was high, water stress was negligible and N stress along with other growing condition variables were the limiting factors, under these conditions the addition of irrigation resulted in an increase in N leaching which in turn decreased yield. Consequently, a more adaptive and precise irrigation schedule would be required to respond to the crop water demand based on annual soil water conditions so that irrigation is not used unnecessarily.

Table 39: Descriptive statistics of maize yield under rainfed compared to irrigated production over a 50-year period under the Nanyuki small-scale virtual farm (NSVF) scenario

Scenario	Minimum (kg ha^{-1})	Maximum (kg ha^{-1})	Mean (kg ha^{-1})	Std. Deviation (kg ha^{-1})
Rainfed	0	5 410	3 062	1 644
Irrigated	0	6 524	3 228	1 488

Table 40: Positive and negative ranks of the impact of rainfed versus irrigated production on maize yields under the Nanyuki small-scale virtual farm (NSVF) scenario using the Wilcoxon signed ranks test

		N	Mean Rank	Sum of Ranks
Rainfed - Irrigated	**Negative Ranks**	13[a]	31.08	404.00
	Positive Ranks	29[b]	17.21	499.00
	Ties	6[c]		
	Total	48		

a. Rainfed < Irrigated

b. Rainfed > Irrigated

c. Rainfed = Irrigated

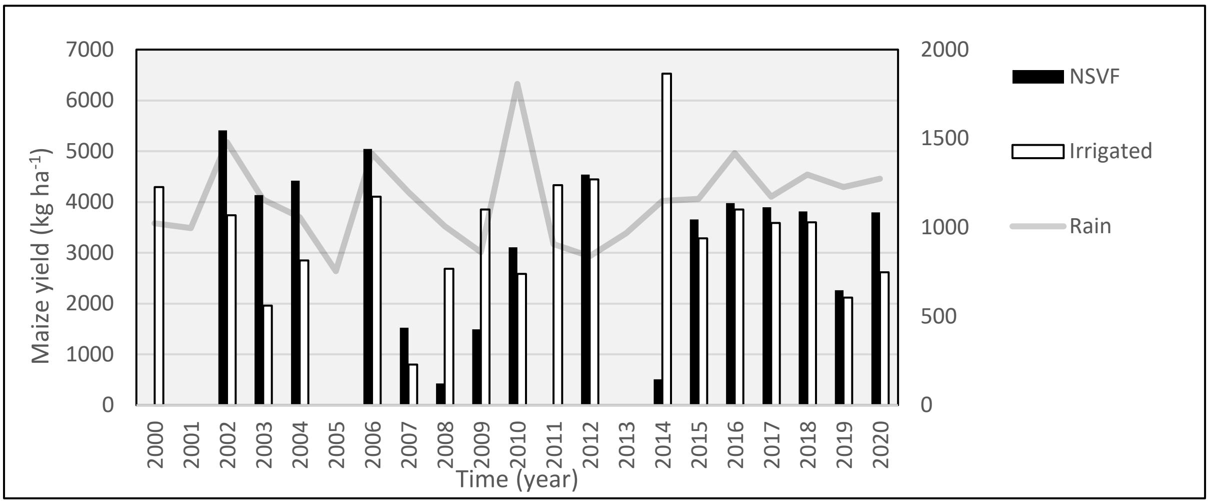

Fig. 34: Maize yield under rainfed and irrigated conditions under the Nanyuki small-scale virtual farm (NSVF) scenario over a 50-year period with corresponding annual rainfall

8.2.1.8. Irrigation and soil degradation

Irrigation was found to significantly impact soil layers 2-5 according to the paired *t*-test. The top soil layers and the layers below the root zone were not significantly impacted by the addition of irrigation. Within the root zone soil OC% loss increased by an average range of 3-4% and, similarly, total soil N loss increased by an average range of 3-4% (Table 41). Results indicate that the addition of irrigation to the NSVF scenario would increase the rate of soil degradation within the root zone.

Table 41: Soil organic carbon percentage (%SOC) loss in each soil layer after 50 years of rainfed compared to irrigated production under the Nanyuki small-scale virtual farm (NSVF) scenario

	Soil organic carbon loss (%)							
Scenario	**Layer 1**	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**	**Layer 6**	**Layer 7**	**Layer 8**
Rainfed	-0,55 (-24%)	0,95 (42%)	0,34 (37%)	0,23 (24%)	0,03 (9%)	-0,02 (-6%)	-0,01 (-3%)	-0,00 (-1%)
Irrigated	-0,52 (-23%)	1,03 (45%)	0,37 (40%)	0,27 (28%)	0,05 (13%)	-0,02 (-7%)	-0,01 (-3%)	-0,00 (-1%)

Table 42: Soil nitrogen (N) loss in each soil layer after 50 years of rainfed compared to irrigated production under the Nanyuki small-scale virtual farm (NSVF) scenario

	Total N loss (kg ha^{-1})							
Scenario	**Layer 1**	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**	**Layer 6**	**Layer 7**	**Layer 8**
Rainfed	-499 (-23%)	868 (42%)	801 (37%)	773 (25%)	105 (10%)	-54 (-5%)	-38 (-3%)	-10 (-1%)
Irrigated	-475 (-23%)	942 (46%)	862 (40%)	896 (29%)	148 (14%)	-53 (-5%)	-34 (-3%)	-8 (-1%)

8.2.1.9. Cultivar selection and yield

The impact of cultivars with different lengths to maturation on maize yield was found to be significant at a 5% level using paired *t*-tests. Simulations revealed that the early maturation cultivar (sc401) used in the NSVF was most suited to the management conditions as it resulted in the most reliable yields with the least crop failures. The late maturing cultivar (sc709) reached a maximum yield of 7.5 tonnes ha-1, 39% more than the early cultivar. However, as time to maturity increased, so did the number of crop failures. In the 50-year simulation the late cultivar experienced 18 crop failures, 10 more than the early cultivar (Figure 35). Alternative scenarios were simulated to include fertilization and irrigation to supplement the higher yields produced by the late maturing cultivar to mitigate crop failure. However, there were still 14 crop failures indicating that late maturing cultivars are unsuited to the climactic growing conditions, specifically temperatures, of the Nanyuki region.

Additionally, the yields produced by the NSVF early cultivar were compared to the yields of the high-yielding Pioneer 3237 cultivar and found to be significantly different using the paired *t*-test. Under a 'good year' when growing conditions were ideal, the cultivar was able to reach a maximum yield of 10.84 tonnes ha^{-1} of production (Figure 36). However, the cultivar also experienced 18 crop failures as its long duration to maturity made it vulnerable to unfavourable temperatures. Though it should be noted that at least four of these crop failures were due to inadequate N and irrigation supply by the NSVF management scenario to meet the cultivars N and water demands. When there was zero fertilization, therefore under agro-ecological conditions, the average maize yield of the Pioneer 3237 cultivar was 3.44 tonnes ha^{-1} and there were 25 crop failures indicating that the cultivar was unsuited to these conditions.

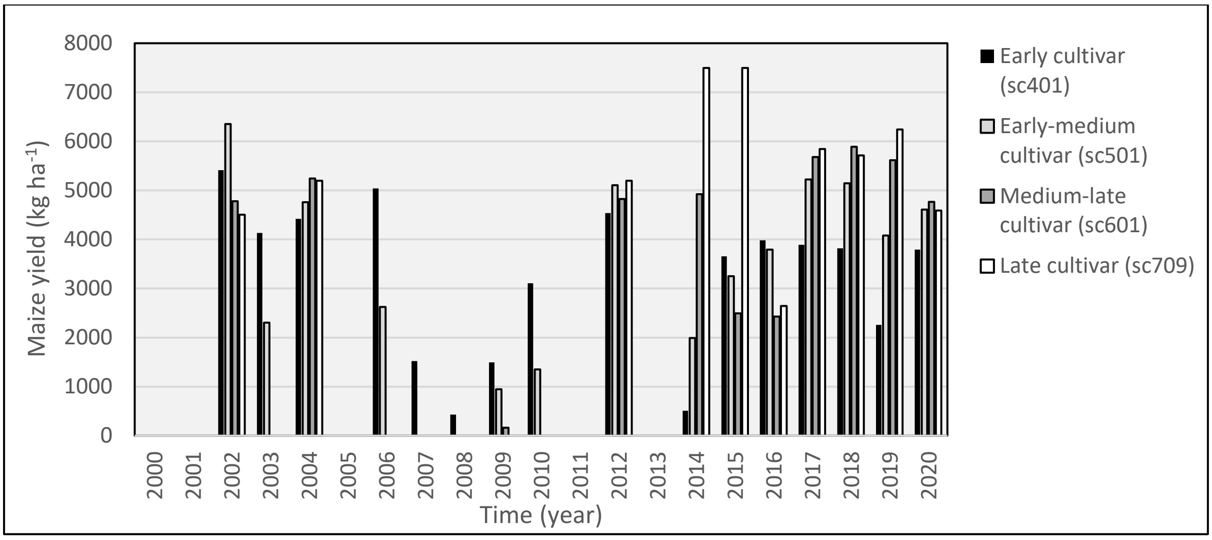

Fig. 35: Maize yields of cultivars of different maturity classes from 2000-2020 under the Nanyuki small-scale virtual farm (NSVF) 50-year simulation

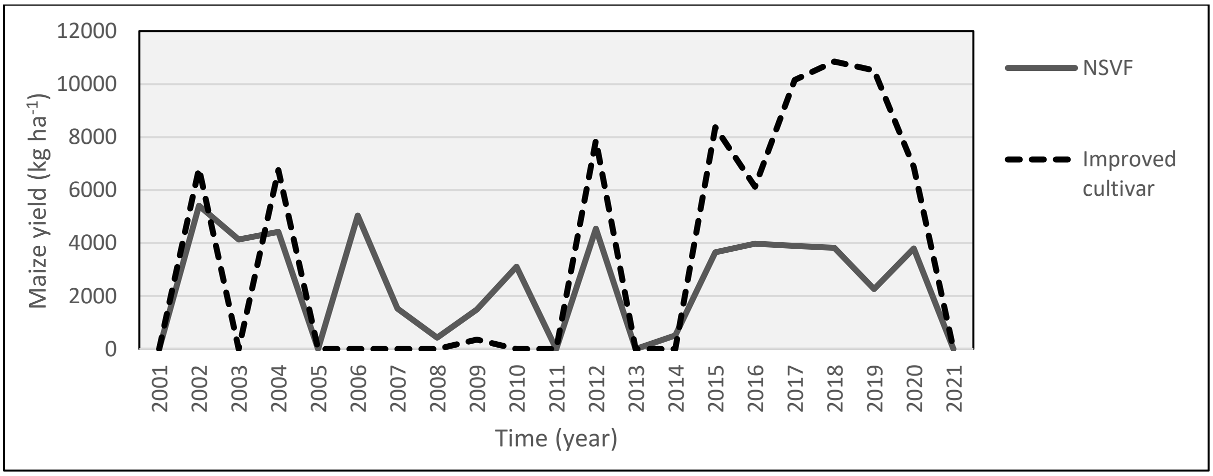

Fig. 36: Maize yields of a high-yielding improved cultivar versus the early maturing Nanyuki small-scale virtual farm (NSVF) cultivar from 2000-2020 under the NSVF 50-year simulation

8.2.1.10. Improved cultivar and soil degradation

According to the paired t-test there was no significant difference in SOC and N loss in soil layer 2-8 between the improved, high-yielding Pioneer 3237 cultivar and the early maturing cultivar used by the NSVF (Table 43 and 44). However, in the top soil layer there was a significant difference between the two treatments. After 50 years of production under the improved cultivar scenario, there was less of an increase in OC% and total soil N in the top soil layer. This was explained by the increased crop failures experienced under the improved cultivar production over the 50-yer simulation resulting in fallow periods when there was no OM deposition on the soil surface. Therefore, due to the presence of crop failures and the statistically insignificant average yield differences in lower soil layers, the impact of an improved cultivar on mitigating soil degradation in the NSVF context was inconclusive.

Table 43: Soil organic carbon percentage (%SOC) loss after 50 years of improved cultivar compared to Nanyuki small-scale virtual farm (NSVF) cultivar production under the NSVF scenario

Scenario	Soil organic carbon (%)							
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8
NSVF cultivar	-0,55 (-24)	0,95 (42%)	0,34 (37%)	0,23 (24%)	0,03 (9%)	-0,02 (-6%)	-0,01 (-3%)	-0,00 (-1%)
Improved cultivar	-0,19 (-8%)	0,97 (42%)	0,35 (37%)	0,23 (25%)	0,03 (8%)	-0,02 (-7%)	-0,01 (-3%)	-0,01 (-2%)

Table 44: Soil nitrogen (N) loss in each soil layer after 50 years of improved cultivar compared to Nanyuki small-scale virtual farm (NSVF) cultivar production under the NSVF scenario

Scenario	Soil nitrogen (kg ha^{-1})							
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8
NSVF cultivar	-499 (-23%)	868 (42%)	801 (37%)	773 (25%)	105 (10%)	-54 (-5%)	-38 (-3%)	-10 (1%)
Improved cultivar	-163 (-7%)	888 (42%)	826 (38%)	805 (26%)	114 (11%)	-50 (-5%)	-38 (-3%)	-14 (-2%)

8.2.1.11. Improved management and yield

Considering the agro-ecological conditions of the Nanyuki region, the NSVF management practices are a safe strategy that ensures annual maize production. However, the simulations under improved cultivars, increased N, and irrigation indicated that higher yields can be obtained (Table 45). The 'improved strategy' used in the study included increasing topdressing by 100kg ha^{-1}, the addition of irrigation to SW deficit, and the use of the high-yielding cultivar Pioneer 3237. Under these conditions the average maize yield was 10.37 tonne ha^{-1}, an increase of 7.3 tonnes ha-^{1} (237%), considering that average yield does not include crop failures 9 (Figure 37). Due to the unsuitability of a late maturing cultivar to the region, there were 14 crop failures of 0 tonnes ha^{-1}. However maximum yield under improved management was a high 17 tonnes ha^{-1}, indicating that when conditions are favourable the yield potential of the region is extremely high. Due to extremely variable seasonality, these high yields are not consistent, the Wilcoxon signed ranks test indicated that Improved management only improved yields 63% of the time (Table 46). Although improved management has the potential to radically improve yields, the high variation in climactic seasonality is a significant threat to maize productivity and consequently to economic and food security. A cost-benefit analysis would be necessary to warrant the recommendation of any of these inputs to SSFs. Additionally, readers are advised that the simulations presented here cannot be used to advise farmers directly as they were not parameterized to their specific growing conditions.

Table 45: Descriptive statistics of maize yield under Nanyuki small-scale virtual farm (NSVF) management versus improved management over a 50-year period

Scenario	Mean (kg ha^{-1})	Std. Deviation (kg ha^{-1})	Minimum (kg ha^{-1})	Maximum (kg ha^{-1})
NSVF	3 061	1 644	0	5 410
Improved	10 346	6 290	0	17 037

Table 46: Positive and negative ranks of the impact of improved cultivar compared to the Nanyuki small-scale virtual farm (NSVF) cultivars on maize yield using Wilcoxon signed ranks test

		N	Mean Rank	Sum of Ranks
Improved - NSVF	**Negative Ranks**	12[a]	8.42	101.00
	Positive Ranks	30[b]	26.73	802.00
	Ties	6[c]		
	Total	48		

a. Improved < NSVF

b. Improved > NSVF

c. Improved = NSVF

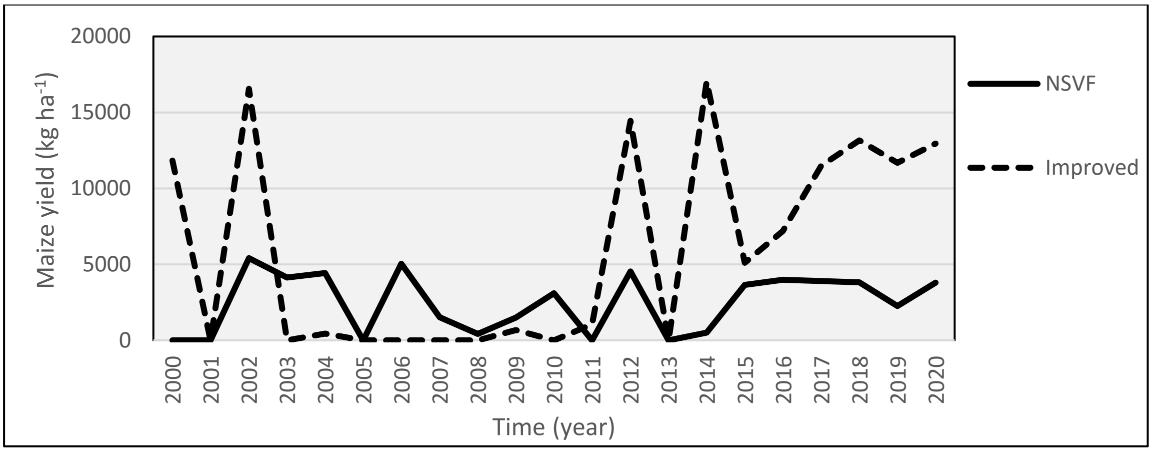

Fig. 37: Maize yield of improved management compared to the Nanyuki small-scale virtual farm (NSVF) scenario from 2000-2020 as a snapshot of a 50-year simulation period

8.2.1.12. Improved management and soil degradation

The difference between soil OC% loss and total soil N under the NSVF versus the improved management scenario was found to be significantly different at a 5% level using the paired *t*-test. Improved management resulted in increased soil OC% and N after 50 years of production compared to the NSVF. This was explained by the increase in N fertilization and the increased OM deposition from the higher maize yields of the improved management scenario. Within the rooting zone soil OC% and N loss was higher under improved management than under the NSVF scenario due to the increased nutrient demands by the high-yielding cultivar. In lower soil layers 6-8 the improved management strategy resulted in higher soil OC% and N increases due to the additional OM deposition from the increased root biomass and due to increased N fertilization and leaching from irrigation. Although some soil layers benefitted from the improved management scenario, within the rooting zone where OC% and soil N is essential for crop development, soil degradation was accelerated. Additionally, under improved management, N mineralization decelerated significantly compared to the NSVF scenario, indicating that it was a more N-limited environment (Figure 38). Therefore, the high yields under the improved management scenario resulted in consequently higher soil degradation which was not ameliorated by the increased addition of N fertilizer compared to the NSVF.

Table 47: Soil organic carbon percentage (%SOC) loss after 50 years under improved management compared to the Nanyuki small-scale virtual farm (NSVF) scenario

Scenario	Soil organic carbon loss (%)							
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8
NSVF	-0,55 (-24%)	0,95 (42%)	0,34 (37%)	0,23 (24%)	0,03 (9%)	-0,02 (-6%)	-0,01 (-3%)	-0,00 (-1%)
Improved	-0,58 (-26%)	1,04 (46%)	0,37 (39%)	0,26 (28%)	0,04 (11%)	-0,03 (-8%)	-0,02 (-5%)	-0,01 (-3%)

Table 48: Soil nitrogen (N) loss in each soil layer after 50 years of improved management compared to the Nanyuki small-scale virtual farm (NSVF) scenario

Scenario	Total soil N loss (kg ha^{-1})							
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7	Layer 8
NSVF	-499 (-23%)	868 (42%)	801 (37%)	773 (25%)	105 (10%)	-54 (-5%)	-38 (-3%)	-10 (-1%)
Improved	-531 (-25%)	945 (45%)	837 (39%)	852 (27%)	113 (11%)	-84 (-8%)	-64 (-5%)	-25 (-3%)

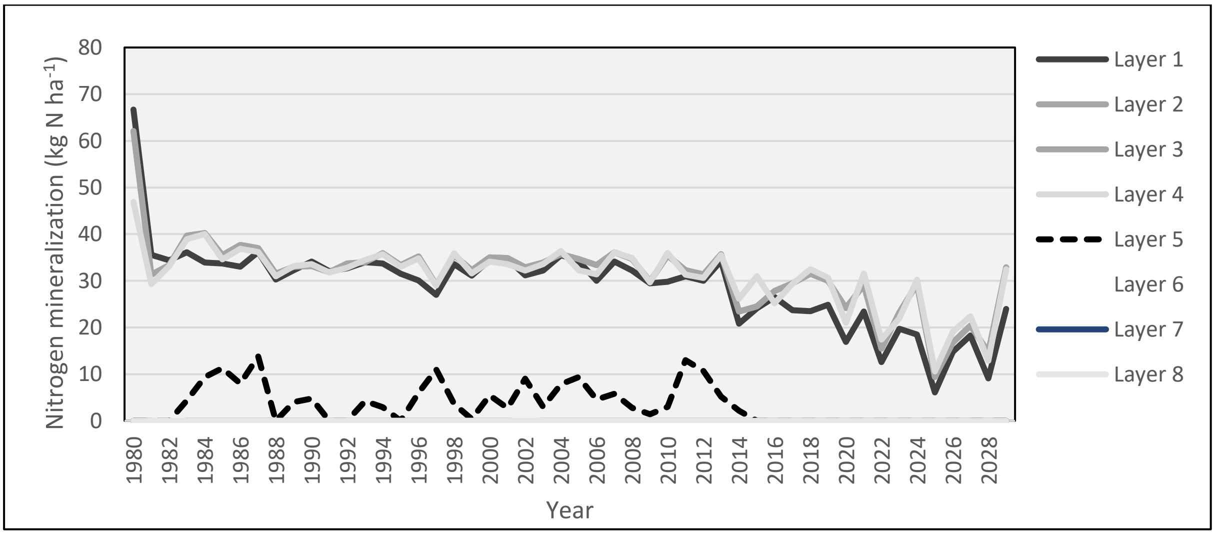

Fig. 38: Annual nitrogen mineralized in soil layer 1-8 (0-1 m) under the improved management scenario over a 50-year period

8.3. Discussion for APSIM results

8.3.1. The Gurúè region

8.3.1.1 Agronomic efficiency

The classification of the smallholder system in the Gurúè district as low-input low-output is corroborated in this study (FAO, 2010; MAE, 2005). The poor accessibility and availability of improved cultivars and fertilizers reported by Hanlon & Smart (2013) have been shown to result in unproductively low yields. The GSVF simulation produced average maize yields above the agro-ecological potential of the region, however the actual average maize yield was considered agronomically low at 1.2 tonne ha^{-1}. Nitrogen (N) availability and cultivar selection were identified as the two major limiting factors to production, followed by planting density and water stress limiting yield at a lesser extent.

The incorporation of two legumes into the cropping system allowed for N to be added back into the soil system. Since N was a major limiting factor to production in the region and there was no N fertilization in the GSVF scenario, this was critical to achieving yields above agro-ecological potential. However, the addition of N alone did not result in yields above 3 tonnes ha^{-1} due to the low-yielding potential of the cultivar selected. The change from a local cultivar to a hybrid cultivar was essential for improving maize yield and, without any other improvements, allowed for a maximum potential yield of 3.5 tonnes ha^{-1} to be obtained. However, only when planting density and irrigation were improved in combination with the use of a hybrid cultivar and the addition of N fertilizer, were yields increased to an average potential of 6 tonnes ha^{-1}. This means that the GSVF had a low agronomic efficiency, only achieving 16% of its potential yield and to achieve potential yield, a combination of management factors would need to be improved. Although, considering the poor access to agro-inputs in the region, the GSVF was still able to significantly improve yield above the agro-ecological potential through the use of legumes and ensure annual production by sustaining a low planting density. It should also be noted that the impact of weeds and pests on crop yield wasn't investigated in the simulations but that they would be additional challenges that SSFs would have to overcome, which they do mainly through manual weeding and the burning of crop residues.

In the literature review it was unclear as to why LAIs in Mozambique were unable to achieve higher crop yields. In comparison to the GSVF, the GLVF had a higher average yield potential by 1.3 tonnes ha^{-1}. Indicating that when inputs are intensified under Gurúè agro-ecological conditions, maize has a higher yield potential under a monocrop rotation (GLVF scenario) than under an intercrop rotation (GSVF scenario). The agronomic efficiency of the GLVF was also higher, as actual average maize yield was 40% of the potential average maize yield (Table 49). This meant that the GLVF cropping system had a higher actual and potential agronomic efficiency than the GSVF system. The main limiting factor under the GLVF management practices was cultivar selection as N rate was enough to meet crop demands and water was not a major limiting factor in the region. It was shown that the Agronomic Nitrogen-use Efficiency (NAE) was low, indicating that the GLVF was over-fertilizing. However, once cultivar selection was improved and irrigation added to the scenario, the same fertilization rate had an NAE of 29 kg grain per kg N, which is considered to be a high N response and an efficient use of N (Whitbread *et al.,* 2013). Even if the GLVF only improves its cultivar selection and does not add irrigation, it would have an average potential yield of 6.8 tonnes ha^{-1} with a high NAE of 26 kg grain per kg N. Therefore, if LAIs are given more time by the Mozambican government for trial and error and change their focus from short-term to long-term investment goals, then there is higher probability that they will achieve the correct combination of agro-inputs to attain higher crop yields. Not only do LAIs have fewer limiting factors to overcome to achieve yield potential compared to SSFs, but their systems are also more agronomically efficient.

Table 49: Average maize yield potentials in the Gurúè region under different management scenarios over a 50-year simulation

Scenario	Agro-ecological (tonnes ha^{-1})	Actual (tonnes ha^{-1})	VF Potential (tonnes ha^{-1})
GSVF	0.6	1.2	6.1
GLVF	0.6	3.1	7.4
NSVF	2.9	3.0	10.4

8.3.1.2. Soil degradation

In the root zone layers, soil layer 2 and 3 lost an average 45% of SOC under the GSVF scenario (Table 50). This increased to 46% SOC loss under improved management indicating that the increased amount of crop residues due to higher yields was not enough OM to compensate for the OC lost through cultivation. This was similar to findings reported by Swanepoel *et al.,* (2016) that 50% SOC was lost after 50 years of cultivation in a long-term maize field trial in Pretoria, RSA. Temporally, SOC loss had different rates of decline throughout the 50-year simulation with an apparent start to an equilibrium occurring 40 years after cultivation. Nitrogen loss followed a similar pattern, the new equilibrium forming after 40 years of cultivation as N mineralization reached a rate of 0 kg N ha^{-1} in soil layer 3. The remaining N was organic-N that could no longer be mineralized as the immobilization demand was too high. Although the inclusion of N-fixing legumes in the cropping system allowed for higher yields to be obtained, it did not significantly improve OC and total soil N loss as crops were still dependant on newly mineralised N from organic-N. In soil layer 2 and 3, SOC and total soil N loss occurred at a faster rate under the GLVF scenario than the GSVF scenario. Therefore, even though there was an increase in crop residue deposition and N fertilization in the GLVF, the higher yields resulted in an increased rate of soil degradation compared to the GSVF.

Table 50: Soil organic carbon percentage (SOC%) and nitrogen (N) loss in each soil layer after 50 years of Gurúè small-scale virtual farm (GSVF) production compared to Gurúè large-scale virtual farm (GLVF) production

Scenario	**Soil N loss**			**Soil OC loss**		
	Layer 1 (kg N ha^{-1})	**Layer 2 (kg N ha^{-1})**	**Layer 3 (kg N ha^{-1})**	**Layer 1 (OC%)**	**Layer 2 (OC%)**	**Layer 3 (OC%)**
GSVF	266 (15%)	731 (45%)	522 (37%)	0,24 (16%)	0,66 (44%)	0,45 (37%)
GLVF	-399 (-23%)	804 (49%)	593 (42%)	-0 ,29 (-19%)	0,73 (48%)	0,51 (42%)

8.3.2. The Nanyuki region

8.3.2.1 Agronomic efficiency

In comparison to the average potential yield obtainable, the NSVF system was found to have a low agronomic efficiency as it was producing maize at 29% of its potential (Table

51). However, the average potential yield was only achieved when a high-yielding late maturity cultivar was used. Due to variable climatic conditions in the region, late maturing cultivars were not consistently suited to the region and only achieved improved yields 63% of the time. It was found that the most suited cultivar to the region was the early maturing cultivar used by the NSVF. Although the early cultivar resulted in less crop failures, it also had an inherently lower yield potential resulting in an average yield similar to the agro-ecological potential. Additionally, the intercropping system with two growing seasons utilized by the NSVF was found to have an inherently lower yield potential than a monocrop of maize with only one growing season a year, which was the cropping system used to estimate the agro-ecological potential of the region.

The Nanyuki region was found to be a highly variable environment, consequently maize growth and yield was constrained by rainfall distribution. Results indicated that irrigation was not always necessary to achieve high yield under the NSVF scenario and would potentially result in decreased yields 60% of the time due to increased N-leaching. However, 29% of the time maize productivity was limited by water stress, and the addition of irrigation was critical for obtaining productive yields. Therefore, although irrigation was not always warranted, its availability was fundamental when climactic conditions aggravated water stress. APSIM simulations revealed that the addition of N fertilizer to the NSVF scenario was imperative for achieving productive maize yields. However, the fertilization rate applied in the NSVF scenario was found to be a high agronomically-efficient use of nitrogen (NAE) and increasing N input only decreased the NAE. Although the NSVF was not reaching its full maximum potential and its cropping system was not the most productive for the region, its cultivar choice and management practices allowed for more consistent yields to be achieved over very variable climactic conditions.

8.3.2.2. Soil degradation

In comparison to the alternative cropping systems simulated, the NSVF had the lowest rate of soil degradation in terms of both SOC% and total soil N loss. This was due to its incorporation of a legume intercrop into the cropping system and lower average yields due to the impacts of two growing seasons in a year. Although the NSVF was not the most agronomically efficient system, it is because of its lower average yields and its incorporation of a legume intercrop that allowed for the mitigation of the rate of soil degradation. However, it was apparent that the NSVF was not replenishing total soil N and OM at a rate that was sufficient to prevent soil degradation within the root zone. Additionally, there was no indication of an equilibrium being reached in SOC% or total soil N, within the simulated window, within the rootzone soil layers.

9. Life Cycle Assessments (LCA) results

The values estimated here should be interpreted as orders of magnitude rather than specific figures, due to the dependence of the calculations on interview specifications about input consumption and various general assumptions made based on management-related interview specifications.

9.1. Inventory analysis

The input inventory was based on the virtual farms and reports the organization of this collection of data into the LCA input inventory format, which dictates the average input consumption and relevant emissions during the growing season of each crop.

9.1.1. Gurúè small-scale virtual farm (GSVF)

In terms of inputs consumed, the GSVF did not irrigate or fertilize any of the crops under analysis (Table 51). Farm activities were not mechanized and therefore no diesel or electricity was consumed. This means that there were no emissions related to these activities (Table 52). However, the decomposition and burning of crop residues and the application of pesticides were two categories that potentially resulted in harmful emissions into the environment.

The rate of insecticide application for soybean was estimated at 100 ml Bandit 350 SC containing 0.04 kg ha^{-1} of the active ingredient (AI) Imidacloprid. This resulted in an average 0.004 kg AI ha^{-1} potentially emitted into the air and 0.03 kg AI ha^{-1} into water sources in a growing season. Furthermore, the manufacture of the insecticide resulted in potential average emissions of 0.52 kg CO_2-e ha^{-1} and consumed 4.8 MJ ha^{-1} of non-renewable energy in a growing season.

Crop residues from maize contained 0.7 kg N ha^{-1}, soybean residues contained 1.4 kg N ha^{-1}, and pigeon pea residues contained 0.23 kg N ha^{-1}. In one growing season, this translated to 4.1 kg CO_2-e ha^{-1} for maize, 8.2 kg CO_2-e ha^{-1} for soybean, and 1.6 kg CO_2-e ha^{-1} for pigeon pea. Crop residue burning emitted CH_4 and N_2O which contributed an additional 11.3 kg CO_2-e ha^{-1} for maize cultivation, 10.0 kg CO_2-e ha^{-1} for soybean cultivation, and 2.4 kg CO_2-e ha^{-1} for pigeon pea cultivation. The total greenhouse gas emissions related to the burning of one hectare of land are displayed in Table 51 for each crop.

Table 51: Input inventory for chemical, diesel and irrigation consumption under the Gurúè small-scale virtual farm (GSVF) scenario

Inputs		**Units**	**Rate**			**Comment**
			Maize	**Soybean**	**Pigeon pea**	
Fertiliser						
	N	**kg ha^{-1}**	0	0	0	None used
	P	**kg ha^{-1}**	0	0	0	None used
	K	**kg ha^{-1}**	0	0	0	None used
Crop residues						
	N content	**kg N ha^{-1}**	0.72	1.43	0.23	Above- and below-ground
Pesticide						
	Nematicide	**kg AI^{a} ha^{-1}**	0	0	0	None used
	Herbicide	**kg AI ha^{-1}**	0	0	0	None used
	Insecticide	**kg AI ha^{-1}**	0	0.04	0	Imidaclopride
	Fungicide	**kg AI ha^{-1}**	0	0	0	None used
Fuel						
	Diesel (machinery)	**L ha^{-1}**	0	0	0	None used
Irrigation water						
	Irrigation applied	**mm**	0	0	0	None used

a: AI is Active ingredient

Table 52: Pollutant emissions and non-renewable energy consumption under the Gurúè small-scale virtual farm (GSVF) scenario

Emission description	Units/ha/growing season	Maize	Soybean	Pigeon pea	Emission factor & reference
Input emissions to air					
Fertilizer					
NH_3	**kg**	0	0	0	0.08 kg NH_3 kg^{-1} applied N (Sahle, 2013)
NO_x	**kg**	0	0	0	0.02 kg NO_x kg^{-1} applied N (Sahle, 2013)
N_2O direct	**kg**	0	0	0	0.01 kg N_2O kg^{-1} N input (IPCC, 2006)
N_2O indirect	**kg**	0	0	0	0.3 kg N_2O kg^{-1} N leach & runoff (IPCC, 2006)
Total CO_2-e	**kg CO_2-e**	0	0	0	298 kg CO_2-e kg^{-1} N_20 (IPCC, 2006)
Crop residues decomposition					
N_2O direct	**kg**	0.01	0.02	0.004	0.01 kg N_2O kg^{-1} kg $^{-1}$ N (IPCC, 2006)
N_2O indirect	**kg**	0.00	0.01	0.001	0.3 kg N_2O kg^{-1} N leached (IPCC, 2006)
Total CO_2-e	**kg CO_2-e**	4.12	8.20	1.50	298 kg CO_2-e kg^{-1} N_20 (IPCC, 2006)
Crop residue burning					
CH_4	**kg**	0.18	0.28	0.09	2.7 g CH_4 kg^{-1} Bb[b] (IPCC, 2006)
N_2O	**kg**	0.01	0.01	0.00	0.07 g N_2O kg^{-1} Bb (IPCC, 2006)
NO_x	**kg**	2.50	3.92	1.31	2.80 g NO_x kg^{-1} Bb (McCarty, 2011)
SO_2	**kg**	0.12	0.19	0.06	1.17 g SO_2 kg^{-1} Bb (McCarty, 2011)
NH_3	**kg**	1.77	2.78	0.93	2.4 g NH_3 kg^{-1} Bb (Jenkins *et al*, 1996)
Energy use					
CO_2 (diesel)	**kg**	0	0	0	0.94 kg CO_2 kg^{-1} diesel (Lal, 2004)
CH_4 (diesel)	**kg**	0	0	0	3.9 kg CH_4 TJ^{-1} diesel (IPCC, 2006
N_20 (diesel)	**kg**	0	0	0	3.9 kg N_20 TJ^{-1} (IPCC, 2006.)
NO_x (diesel)	**kg**	0	0	0	0.042 kg NO_x kg^{-1} diesel (Sahle, 2013)
Pesticide use					
Active ingredient	**kg AI**	0	0.004	0	0.1 kg AI kg^{-1} AI[a] (Margni *et al.*, 2002)
Herbicide (manuf.)	**kg CO_2-e**	0	0	0	6.3 kg CO_2-e kg^{-1} product (Lal, 2004)
Insecticide (manuf.)	**kg CO_2-e**	0	0.52	0	5.1 kg CO_2-e kg^{-1} product (Lal, 2004)
Fungicide (manuf.)	**kg CO_2-e**	0	0	0	3.9 kg CO_2-e kg^{-1} product (Lal, 2004)
Field emissions to water					
N-NO_3 leaching	**kg**	0	0	0	0.3 kg N kg $^{-1}$ N applied (IPCC, 2006)
P leaching	**g**	0	0	0	0.18 g P mm^{-1} drainage (Thompson, 1991)
Pesticide leaching	**kg**	0	0.04	0	0.015 kg AI kg^{-1} AI (Renouf *et al.*, 2008)
Non-renewable energy consumption					
Fertilizer (manuf.)	**MJ**	0	0	0	(Lal, 2004)
Pesticide (manuf.)	**MJ**	0	4.8	0	120 MJ kg^{-1} AI (Mashoko *et al.* 2010)
Diesel	**MJ**	0	0	0	43 MJ kg^{-1} Diesel (IPCC, 2006)

a: AI is Active Ingredient
b: Bb is Biomass burned

9.1.2. Gurúè large-scale virtual farm (GLVF)

The division of agro-inputs for maize and soybean were summarized in Table 53. GLVF cropping system applied fertilizer at a rate of 94 kg N ha^{-1} (applied as ammonium and urea) and 83 kg P ha^{-1} for maize, while 10 kg N ha^{-1} and 50 kg P ha^{-1} was applied during the production of soybean in one growing season. In a growing season, this resulted in potential emissions of 644 kg CO_2-e ha^{-1} from maize and 48 kg CO_2-e ha^{-1} from soybean as a consequence of direct and indirect N_2O emissions. Furthermore, in a growing season 4.95 kg N ha^{-1} and 8.25 kg P ha^{-1} were estimated to be leached during maize cultivation, while 2.31 kg N ha^{-1} and 2.1 kg P ha^{-1} were leached during soybean cultivation. The non-renewable energy consumption related to the manufacture of the fertilizers consumed for each crop was 3 064 MJ ha^{-1} for maize and 18 MJ ha^{-1} for soybean in one growing season. Fertilizer manufacturing also emitted 575 kg CO_2-e ha^{-1} to sustain maize cultivation and 85 kg CO_2-e ha^{-1} to sustain soybean cultivation for a growing season.

The maize and soybean crop residues left on the field contained 2.51 kg N ha^{-1} and 1.81 kg N ha^{-1}, respectively. These crop residues emitted N_2O into the atmosphere equivalent to an estimated 14.42 kg CO_2 ha^{-1} and 10.41 kg CO_2 ha^{-1}, respectively, over a growing season of production.

Pesticide use resulted in a total potential AI emission into the atmosphere of 0.05 kg AI ha^{-1} during maize cultivation and 0.04 kg AI ha^{-1} during soybean cultivation over one growing season. While emissions into water were 0.01 kg AI ha^{-1} for both crops. The non-renewable energy consumed during the manufacturing of pesticides required for a growing season of maize was estimated at a potential 60 MJ ha^{-1} and 42 MJ ha^{-1} for a growing season of soybean cultivation.

According to calculations based on fuel consumption for maize cultivation an average of 91 L ha^{-1} of diesel was consumed and a growing season of soybean cultivation, consumed an average of 73 L ha^{-1} of diesel per growing season. Maize consumed more diesel as it required an additional top-dress of N fertilizer, while soybean was only fertilized at sowing. Greenhouse gas emissions during fuel combustion are summarized in Table 54 and the non-renewable energy consumed was equivalent to 3 244 MJ ha^{-1} during maize cultivation and 2 624 MJ ha^{-1} during soybean cultivation.

Table 53: Input inventory for agrochemical, diesel and irrigation consumption under Gurúè large-scale virtual farm (GLVF) scenario

Inputs	Units	Rate		Comments
Fertiliser		**Maize**	**Soy**	
N (NH_4^+)	**kg ha^{-1}**	17	10	Applied as MAP
N (Urea)	**kg ha^{-1}**	87	0	Applied as Urea 46%
P (P_2O_5)	**kg ha^{-1}**	83	50	Applied as MAP
K	**kg ha^{-1}**	0	0	None applied
Crop residues				
N content	**kg N ha^{-1}**	2.51	1.81	Above and below-ground residues
Pesticides				
Nematicide	**kg AI ha^{-1}**	0	0	None used
Herbicide	**kg AI ha^{-1}**	0	0	None used
Insecticide	**kg AI ha^{-1}**	0.10	0.10	Cyfluthrin (Pyrethroid)
Fungicide	**kg AI ha^{-1}**	0.40	0.25	Tebuconazole, Trifloxystrobin, Azoxystrobin
Fuel				
Diesel (machinery)	**L ha^{-1}**	90.69	73.36	Own figures
Irrigation water				
Irrigation applied	**mm**	0	0	None used

a: AI is Active ingredient

Table 54: Pollutant emissions and non-renewable energy consumption under the Gurúè large-scale virtual farm (GLVF) scenario

Emission description	Unit/ha/growing season	Maize	Soy	Emission factor & reference
Input emissions to air				
Fertilizer				
NH_3	**Kg**	9.35	1.41	0.08 kg NH_3 kg^{-1} N (Sahle, 2013)
NO_x	**Kg**	1.77	0.27	0.02 kg NO_x kg^{-1} applied N (Sahle, 2013)
N_2O direct	**Kg**	1.84	0.28	0.01 kg N_2O kg^{-1} N input (IPCC, 2006)
N_2O indirect	**Kg**	0.60	0.09	0.3 kg N_2O kg^{-1} N leachate & runoff (IPCC, 2006)
Total CO_2-e	**kg CO_2-e**	644.24	47.70	298 kg CO_2-e kg^{-1} N20 direct & indirect (IPCC, 2006)
N (manuf.)	**kg CO_2-e**	514.30	49.01	4.95 kg CO_2-e kg^{-1} N (Lal, 2004)
P (manuf.)	**kg CO_2-e**	60.23	36.14	0.73 kg CO_2-e kg^{-1} P (Lal, 2004)
K (manuf.)	**kg CO_2-e**	0	0	0.15 kg CO_2-e kg^{-1} P (Lal, 2004)
Crop residues decomposition				
N_2O direct	**kg**	0.04	0.03	0.01 kg N_2O kg^{-1} kg $^{-1}$ N in crop residues (IPCC, 2006)
N_2O indirect	**kg**	0.01	0.01	0.3 kg N_2O kg^{-1} N leached crop residues (IPCC, 2006)

Total CO_2-e	**kg CO_2-e**	14.42	10.41	298 kg CO_2-e kg^{-1} N20 direct and indirect (IPCC, 2006)
Crop residue burning				
CH_4	**kg**	0	0	2.7 g CH_4 kg^{-1} Bb^{b} (IPCC, 2006)
N_2O	**kg**	0	0	0.07 g N_2O kg^{-1} Bb (IPCC, 2006)
NO_x	**kg**	0	0	2.80 g NO_x kg^{-1} Bb (McCarty, 2011)
SO_2	**kg**	0	0	1.17 g SO_2 kg^{-1} Bb (McCarty, 2011)
NH_3	**kg**	0	0	2.4 g NH_3 kg^{-1} Bb (Jenkins *et al*, 1996)
Energy use				
CO_2 (diesel)	**kg**	70.92	57.37	0.94 kg CO_2 kg^{-1} diesel (Lal, 2004)
N_20 (diesel)	**kg**	0.01	0.01	3.9 kg N_20 TJ^{-1} (IPCC, 2006.)
CH_4 (diesel)	**kg**	0.01	0.01	3.9 kg CH_4 TJ^{-1} diesel (IPCC, 2006)
NO_x (diesel)	**kg**	4.36	3.75	42 g NO_x kg^{-1} diesel (Sahle, 2013)
Pesticide use				
Active ingredient	**kg AI**	0.05	0.04	0.1 kg AI kg^{-1} AI (Margni *et al.*, 2002)
Herbicide (manuf.)	**kg CO_2-e**	0	0	6.3 kg CO_2-e kg^{-1} product (Lal, 2004)
Insecticide (manuf.)	**kg CO_2-e**	4.18	4.18	5.1 kg CO_2-e kg^{-1} product (Lal, 2004)
Fungicide (manuf.)	**kg CO_2-e**	5.46	3.51	3.9 kg CO_2-e kg^{-1} product (Lal, 2004)
Input emissions to water				
N-NO_3 leaching	**kg**	4.95	2.31	0.3 kg N kg^{-1} N applied (IPCC, 2006)
P leaching	**kg**	0.01	0.00	0.18 g P mm^{-1} drainage (Thompson, 1991)
Pesticide leaching	**kg**	0.01	0.01	0.015 kg AI kg^{-1} AI (Renouf *et al.*, 2008)
Non-renewable energy consumption				
Urea (manuf.)	**MJ**	2049.53	0	23.45 MJ kg^{-1} Urea (Brentrup & Pallière, 2008)
DAP (manuf.)	**MJ**	1014.00	197.89	6.76 MJ kg^{-1} DAP (Brentrup & Pallière, 2008)
Pesticide (manuf.)	**MJ**	60.00	42.00	120 MJ kg^{-1} AI (Mashoko *et al.* 2010)
Diesel	**MJ**	3244.32	2624.36	43 MJ kg^{-1} Diesel (IPCC, 2006)

a: AI is Active Ingredient
b: Bb is Biomass burned

9.1.3. Nanyuki small-scale virtual farm (NSVF)

The NSVF system applied a mixture of equal amounts of DAP and NPK at a rate of 250 kg ha^{-1} per crop in one growing season (Table 55). This translated into 44 kg N ha^{-1}, 34 kg P ha^{-1}, and 18 kg K ha^{-1} per crop. The potential release of N_2O into the environment due to fertilization was 271 kg CO_2-e ha^{-1} for each crop in the production system over one growing season. Fertilizer manufacture to sustain a growing season of production for each crop consumed an estimated 1 794 MJ of non-renewable energy and emitted 250 kg CO_2-e ha^{-1}.

Pesticide rates were applied according to label instructions which were 500 ml ha^{-1} Adama Dimethoate 400 for all crops that amounted to 0.20 kg AI ha^{-1}. The AI potentially emitted into the air was estimated at 0.02 kg ha^{-1} and 0.17 kg ha^{-1} emitted into water sources per growing season (Table 56). Additionally, 2.55 kg CO_2-e ha^{-1} was emitted and 24 MJ ha^{-1} consumed during insecticide manufacture to support a growing season of production.

Table 55: Input inventory for agrochemical, diesel and irrigation consumption under the Nanyuki small-scale virtual farm (NSVF) management practices

Inputs		Units	Rates			Comments
			Maize	Bean	Wheat	
Fertiliser						
	N (NH_4^+)	**kg ha^{-1}**	44	44	44	Applied as DAP and NPK
	P (P_2O_5)	**kg ha^{-1}**	34	34	34	Applied as DAP and NPK
	K (K_2O)	**kg ha^{-1}**	18	18	18	Applied as DAP and NPK
Crop residues						
	N content	**kg ha^{-1}**	0	0	0	None used
Pesticide						
	Nematicide	**kg AI ha^{-1}**	0	0	0	None used
	Herbicide	**kg AI ha^{-1}**	0	0	0	None used
	Insecticide	**kg AI ha^{-1}**	0.20	0.20	0.20	Dimethoate
Energy/Fuel						
	Fuel consumption (diesel)	**L ha^{-1}**	0	0	0	Own figures
Irrigation water						
	Irrigation applied	**mm**	0	0	0	None used

a: AI is Active ingredient

Table 56: Pollutant emissions and non-renewable energy consumption for the Nanyuki small-scale virtual farm (NSVF)

Emission description	Units/ha/growing season	Crop	Emission factor & reference
Input emissions to air			
Fertilizer			
NH_3 (volatilization)	**kg**	3.5	0.08 kg NH_3 kg^{-1} N (Sahle, 2013)
NO_x (nitrification + denitrification)	**kg**	0.66	0.02 kg NO_x kg^{-1} applied N (Sahle, 2013)
N_2O direct	**kg**	0.68	0.01 kg N_2O kg^{-1} N input (IPCC, 2006)
N_2O indirect	**kg**	0.22	0.3 kg N_2O kg^{-1} N leachate & runoff (IPCC, 2006)
Total CO_2-e	**kg CO_2-e**	271.27	298 kg CO_2-e kg^{-1} N20 direct & indirect (IPCC, 2006)

N (manuf.)	**kg CO_2-e**	216.56	4.95 kg CO_2-e kg^{-1} N (Lal, 2004)
P (manuf.)	**kg CO_2-e**	24.64	0.73 kg CO_2-e kg^{-1} P (Lal, 2004)
K (manuf.)	**kg CO_2-e**	9.63	0.15 kg CO_2-e kg^{-1} P (Lal, 2004)
Crop residues			
N_2O direct emissions	kg	0	0.01 kg N_2O kg^{-1} kg^{-1} N in crop residues (IPCC, 2006)
N_2O indirect emissions	kg	0	0.3 kg N_2O kg^{-1} N leached from crop residues (IPCC, 2006)
Total emissions CO_2-e	kg CO_2-e	0	298 kg CO_2-e kg^{-1} N20 direct and indirect (IPCC, 2006)
Crop residue burning			
CH_4	kg	0	2.7 g CH_4 kg^{-1} Bb[b] (IPCC, 2006)
N_2O	kg	0	0.07 g N_2O kg^{-1} Bb (IPCC, 2006)
NO_x	kg	0	2.80 g NO_x kg^{-1} Bb (McCarty, 2011)
SO_2	kg	0	1.17 g SO_2 kg^{-1} Bb (McCarty, 2011)
NH_3	kg	0	2.4 g NH_3 kg^{-1} Bb (Jenkins *et al*, 1996)
Energy use			
CO_2 (diesel)	kg	0	0.94 kg CO_2 kg^{-1} diesel (Lal, 2004)
CH_4 (diesel)	kg	0	3.9 kg N_20 TJ^{-1} (IPCC, 2006.)
N_20 (diesel)	kg	0	3.9 kg CH_4 TJ^{-1} diesel (IPCC, 2006)
NO_x (diesel)	kg	0	42 g NO_x kg^{-1} diesel (Sahle, 2013)
Pesticide use			
Active ingredient	kg AI	0.02	0.1 kg AI kg^{-1} AI (Margni *et al.*, 2002)
Herbicide (manuf.)	kg CO_2-e	0	6.3 kg CO_2-e kg^{-1} product (Lal, 2004)
Insecticide (manuf.)	kg CO_2-e	2.55	5.1 kg CO_2-e kg^{-1} product (Lal, 2004)
Fungicide (manuf.)	kg CO_2-e	0	3.9 kg CO_2-e kg^{-1} product (Lal, 2004)
Field emissions to water			
N-NO_3 leaching	kg	13.125	0.3 kg N kg^{-1} N applied (IPCC, 2006)
P leaching	kg	0.01	0.18 g P mm^{-1} drainage (Thompson, 1991)
Pesticide leaching	kg	0.17	0.015 kg AI kg^{-1} AI (Renouf *et al.*, 2008)
Non-renewable energy consumption			
DAP (manuf.)	MJ	845	6.76 MJ kg^{-1} DAP (Brentrup & Pallière, 2008)
NPK (manuf.)	MJ	949	7.59 MJ kg^{-1} NPK (Brentrup & Pallière, 2008)
Pesticide (manuf.)	MJ	24	120 MJ kg^{-1} AI (Mashoko *et al.* 2010)
Diesel	MJ	0	43 MJ kg^{-1} Diesel (IPCC V.2., 2006)

a: AI is Active Ingredient
b: Bb is Biomass burned

9.1.4. Nanyuki large-scale virtual farm (NLVF)

The NLVF applied fertilizer at a rate of 200 mg L^{-1} N, 75 mg L^{-1} P, and 240 mg L^{-1} of K in a fertigation system that irrigated at 3 mm day^{-1}. Since the NSVF growing season is a year, according to the fertilizer ratios, this translated into 2 190 kg N ha^{-1}, 820 kg P ha^{-1}, and 2 630 kg K ha^{-1} per annum (Table 57). Therefore, a year of rose production would potentially emit as much as 13 579.16 kg CO$_2$-e ha^{-1} due to fertilizer application. Furthermore, it was estimated that 657 kg N and 0.082 kg P would leach from fertilization. To support a year of fertilizer application, fertilizer manufacturing consumed an estimated 124 409 MJ ha^{-1} and emitted an estimated 12 885 kg CO$_2$-e ha^{-1}.

Over a year of production, the NLVF consumed 75 kg AI ha^{-1}. It was estimated that this would result in 7.5 kg ha^{-1} AI emitted into the atmosphere and 1.15 kg ha^{-1} AI emitted into bodies of water. Additionally, the manufacture of enough pesticides to sustain a year of rose production was found to emit a potential 383 kg CO$_2$-eq ha^{-1} and consume 18.38 MJ ha^{-1} of non-renewable energy.

The average fuel consumption to support a year of production was estimated at 5 L ha^{-1} day^{-1} of diesel, this amounted to an average 1 880 L ha^{-1} annum^{-1}. The non-renewable energy consumption related to fuel combustion in a year was estimated at 7 393 MJ ha^{-1} and the related greenhouse gas emissions are illustrated in Table 58.

Table 57: Input inventory for agrochemical, diesel and irrigation consumption under Nanyuki large-scale virtual farm (NLVF) management practices

Inputs		Units	Roses	Comments
Fertiliser				
	N (NH_4^+)	**kg ha^{-1}**	2190	Applied in fertigation
	P (P_2O_5)	**kg ha^{-1}**	820	Applied in fertigation
	K (K_2O)	**kg ha^{-1}**	2630	Applied in fertigation
Pesticide				
	Nematicide	**kg AI ha^{-1}**	0	None applied
	Herbicide	**kg AI ha^{-1}**	0	None applied
	Insecticide	**kg AI ha^{-1}**	75	Sahle & Potting (2013)
Energy/Fuel				
	Fuel consumption	**L ha^{-1}**	1880	Diesel
Irrigation water				
	Irrigation applied	**mm**	1095	Applied at rate 3 L m^{-2} day^{-1}

a: AI is Active ingredient

Table 58: Pollutant emissions and non-renewable energy consumption under the Nanyuki large-scale virtual farm (NLVF)

Emission description	Units/ha/year	Roses	Emission factor & reference
Input emissions to air			
Fertilizer			
NH_3	**kg**	175.2	0.08 kg NH_3 kg^{-1} N (Sahle, 2013)
NO_x	**kg**	33.18	0.02 kg NO_x kg^{-1} applied N (Sahle, 2013)
N_2O direct	**kg**	34.38	0.01 kg N_2O kg^{-1} N input (IPCC, 2006)
N_2O indirect	**kg**	11.18	0.3 kg N_2O kg^{-1} N leachate & runoff (IPCC, 2006)
Total emissions CO_2-e	**kg CO_2-e**	13 579.16	298 kg CO_2-e kg^{-1} N20 direct & indirect (IPCC, 2006)
N (manuf.)	**kg CO_2-e**	10 840.50	4.95 kg CO_2-e kg^{-1} N (Lal, 2004)
P (manuf.)	**kg CO_2-e**	598.60	0.73 kg CO_2-e kg^{-1} P (Lal, 2004)
K (manuf.)	**kg CO_2-e**	1 446.50	0.15 kg CO_2-e kg^{-1} P (Lal, 2004)
Crop residues decomposition			
N_2O direct	**kg**	0	0.01 kg N_2O kg^{-1} kg^{-1} N in crop residues (IPCC, 2006)
N_2O indirect	**kg**	0	0.3 kg N_2O kg^{-1} N leached from crop residues (IPCC, 2006)
Total CO_2-e	**kg CO_2-e**	0	298 kg CO_2-e kg^{-1} N20 direct and indirect (IPCC, 2006)
Crop residues burning			
CH_4	**kg**	0	2.7 g CH_4 kg^{-1} Bb^b (IPCC, 2006)
N_2O	**kg**	0	0.07 g N_2O kg^{-1} Bb (IPCC, 2006)
NO_x	**kg**	0	2.80 g NO_x kg^{-1} Bb (McCarty, 2011)
SO_2	**kg**	0	1.17 g SO_2 kg^{-1} Bb (McCarty, 2011)
NH_3	**kg**	0	2.4 g NH_3 kg^{-1} Bb (Jenkins *et al*, 1996)
Energy use			
CO_2 (diesel)	**kg**	1473.24	0.94 kg CO_2 kg^{-1} diesel (Lal, 2004)
CH_4 (diesel)	**kg**	0.26	3.9 kg N20 TJ^{-1} (IPCC, 2006.)
$N_2$0 (diesel)	**kg**	0.26	3.9 kg CH_4 TJ^{-1} diesel (IPCC, 2006)
NO_x (diesel)	**kg**	65.83	42 g NO_x kg^{-1} diesel (Sahle, 2013)
Pesticide use			
Active ingredient	**kg AI**	7.5	0.1 kg AI kg^{-1} AI (Margni *et al.*, 2002)
Herbicide (manuf.)	**kg CO_2-e**	0	6.3 kg CO_2-e kg^{-1} product (Lal, 2004)
Pesticide (manuf.)	**kg CO_2-e**	383	5.1 kg CO_2-e kg^{-1} product (Lal, 2004)
Fungicide (manuf.)	**kg CO_2-e**	0	3.9 kg CO_2-e kg^{-1} product (Lal, 2004)
Field emissions to water			
N-NO_3 leaching	**kg**	657	0.3 kg N kg^{-1} N applied (IPCC, 2006)
P leaching	**kg**	0.08	0.18 g P mm^{-1} drainage (Thompson, 1991)
Pesticide leaching	**kg**	1.13	0.015 kg AI kg^{-1} AI (Renouf *et al.*, 2008)
Non-renewable energy consumption			

Ammonium nitrate (manuf.)	**MJ**	91 653	14.02 MJ kg^{-1} AN (Brentrup & Pallière, 2008)
Triple super Phosphate (manuf.)	**MJ**	1 102.99	7.59 MJ kg^{-1} TSP (Brentrup & Pallière, 2008)
Muriate of potash (manuf.)	**MJ**	31 654.26	3 MJ kg^{-1} MOP (Brentrup & Pallière, 2008)
Pesticide (manuf.)	**MJ**	18.38	120 MJ kg^{-1} AI (Mashoko *et al.* 2010)
Diesel	**MJ**	7 393	43 MJ kg^{-1} Diesel (IPCC, 2006)

a: AI is Active Ingredient
b: Bb is Biomass burned

9.2. Impact assessment results

The LCA inventory results are related to each crop over a year of production. According to the percentage contribution guidelines based on cropping systems growing cycles, the allocation of the percentage contribution of each crop species to the final environmental impacts related to the VFs average year of production is displayed in Table 59. The GSVF cropping system was made up of a two-year cycle, with maize and pigeon pea intercropped in year one and soybean in year two. This resulted in maize contributing 25%, pigeon pea contributing 25%, and wheat contributing 50% to an average growing year. The GLVF was based on a four-year cycle with the first two years producing maize and final two-years producing soybean, resulting in maize contributing 50% and soybean contributing 50% to an average growing year of GLVF production. The NSVF cropping system was a one-year cycle containing two growing seasons where maize and a legume were intercropped in the first growing season and wheat was grown in the second growing season. To account for both growing systems, the assumed contribution of maize to the system was 25%, the legume was 25%, and wheat was 50%.

Table 59: Percentage contribution of each crop to the representative virtual farm (VF) system

Crop		% Weighted Contribution
GSVF		
	maize	25
	soybean	50
	pigeon pea	25
GLVF		
	maize	50
	soybean	50
NSVF		
	maize	25
	legume	25
	wheat	50
NLVF		
	roses	100

9.2.1. Gurúè small-scale virtual farm (GSVF)

GSVF farming practices did not consume NRE 'directly', the only source of energy consumption was from the manufacturing of pesticides applied to soybean resulting in an estimated total 0.004 MJ ha^{-1} of non-renewable energy consumption during one year of soybean cultivation (Figure 39). However, soybean was cultivated in rotation with other crops in the GSVF and therefore its impacts only contributed 50% to the GSVF. Consequently, the GSVF system consumed a negligible 0.002 MJ ha^{-1} of non-renewable energy during an average year of production, exclusively due to manufacturing of pesticide used.

The Global Warming Potential (GWP) was estimated at a total of 14 kg CO_2-e ha^{-1} emitted during an average year under GSVF management practices. An estimated 39% was attributed to crop residues being left on the soil surface and a further 59% was from burning the crop residues. The remaining 2% occurred during manufacturing of pesticide used. The GWP of each individual crop over a year of production is displayed in Figure 49. Soybean had the highest GWP followed by maize and the pigeon pea. This was attributed to soybean's higher yields which resulted in more crop residues and the higher N content of its residues. Additionally, soybean was the only crop that applied pesticides.

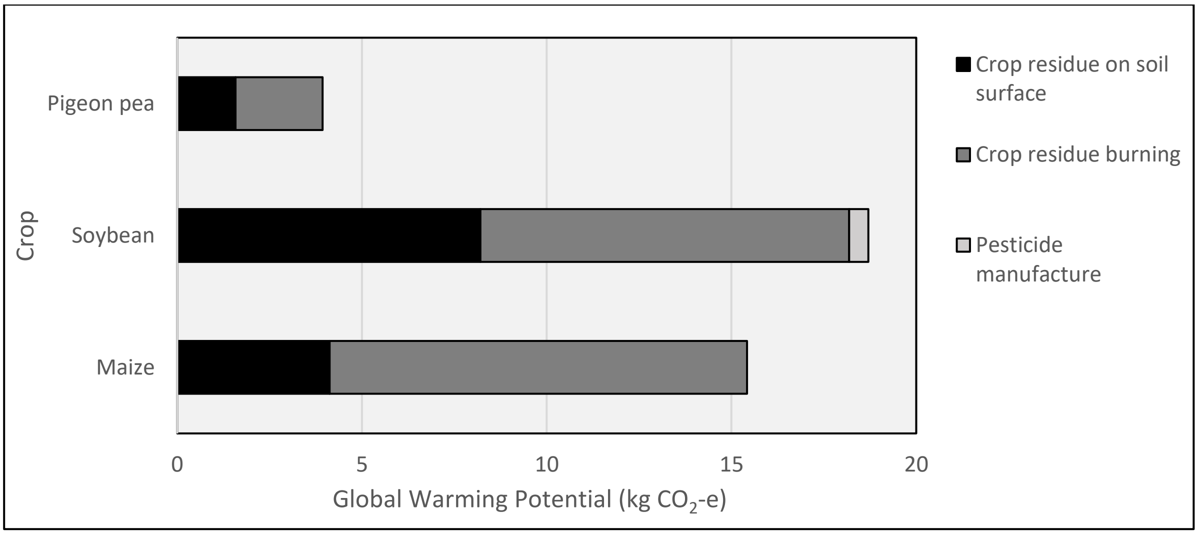

Fig. 39: Annual Global Warming Potential (GWP) of individual crops under the Gurúè small-scale virtual farm (GSVF) management scenario

The GSVF system released NO_x, SO_2, and NH_3 via crop residue burning which resulted in an estimated AP of 4.69 kg SO_2-e ha^{-1} over a year (Figure 40). Additionally, crop residue burning also emitted NO_x and NH_3 with an annual EP estimated at 0.81 kg PO_4-e ha^{-1} (Figure 41). The quantity of each emission that contributed to the AP of each crop over a year of production is illustrated in Figure 50. Soybean had the highest AP and EP as it had more crop residues with a higher N content compared to the maize and pigeon pea cropping system.

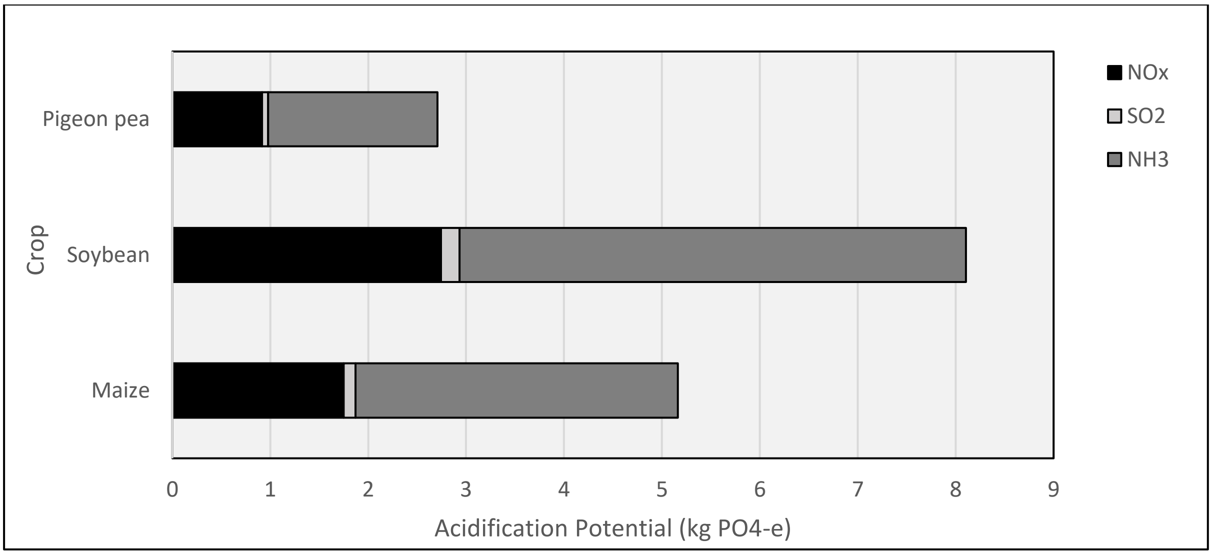

Fig. 40: Annual Acidification Potential (AP) of individual crops under the Gurúè small-scale virtual farm (GSVF) management scenario

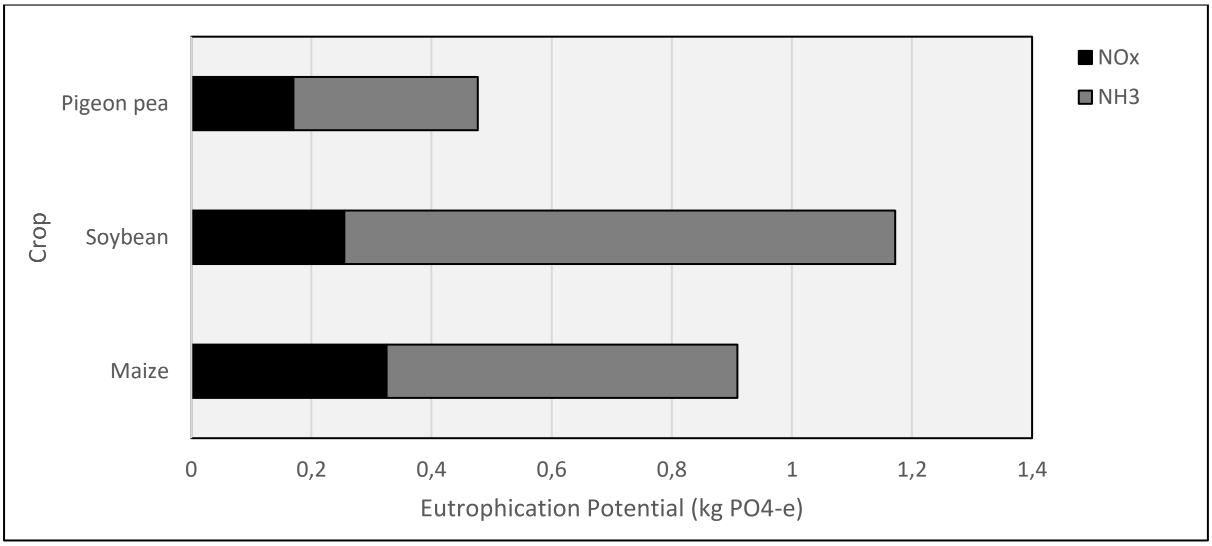

Fig. 41: Annual Eutrophication Potential (EP) of individual crops under the Gurúè small-scale virtual farm (GSVF) management scenario

9.2.2. Gurúè large-scale virtual farm (GLVF)

The GLVF production system consumed an estimated 2 675 MJ ha^{-1} in a year of production (Figure 42). This was dominated by fertilizer manufacturing and diesel combustion which consumed an estimated 1 630 MJ ha^{-1} and 5 349 MJ ha^{-1}, respectively. Non-renewable Energy (NRE) consumption from pesticide manufacturing was substantially lower at a negligible 0.20 MJ ha^{-1}. Figure 50 illustrates the NRE consumption of each crop over a year of production, it shows that maize had a higher NRE consumption compared to soybean, predominantly due to its higher N fertilization rate.

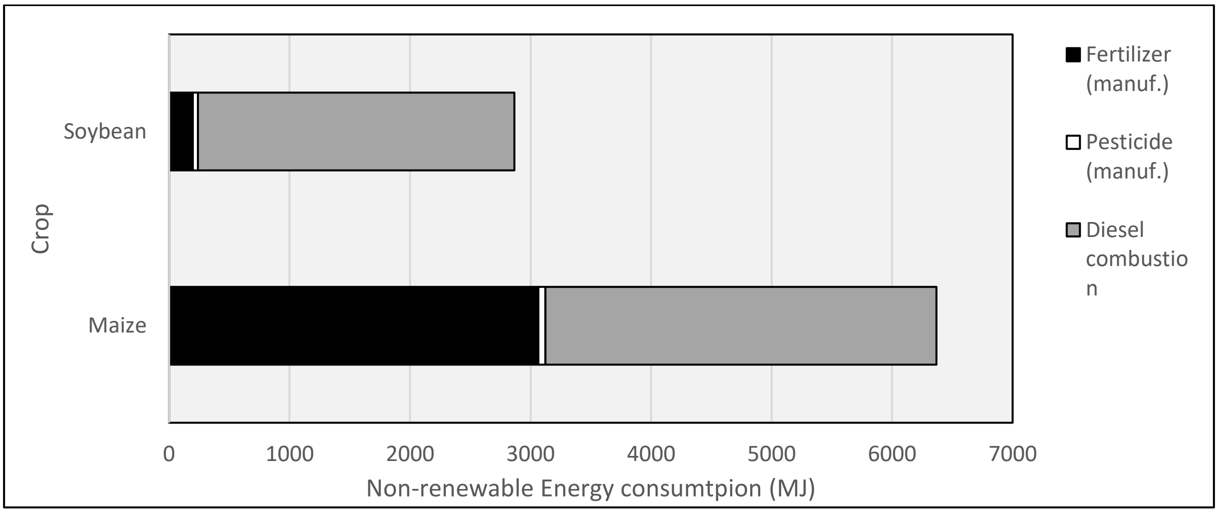

Fig. 42: Annual Non-renewable Energy Consumption (NRE) of individual crops under the Gurúè large-scale virtual farm (GLVF) management scenario

The GWP under a year GLVF production was an estimated 761 kg CO_2-e ha^{-1}. Fertilization was the largest contributor to the GWP with an estimated 346 kg CO_2-e ha^{-1} emitted during nitrogen volatilization, nitrification, denitrification, leaching and runoff. Fertilizer manufacture was the second largest contributor, emitting an averaged 330 kg CO_2-e ha^{-1} as CO_2, N_2O and CH_4. Diesel combustion emitted an estimated 58 kg CO_2-e ha^{-1}. The amount of nitrogen emitted from crop residues left on the soil surface also contributed to GWP at an estimated 12 kg CO_2-e ha^{-1}. Pesticide manufacturing played a small part in GWP with estimated emissions amounting to 9 kg CO_2-e ha^{-1}. According to Figure 43, which illustrated the GWP of each crop over one year of production, maize had a higher GWP than soybean, this was predominantly due to its higher fertilization rate which resulted in more N_20 emissions and more CO_2-e emissions during manufacturing.

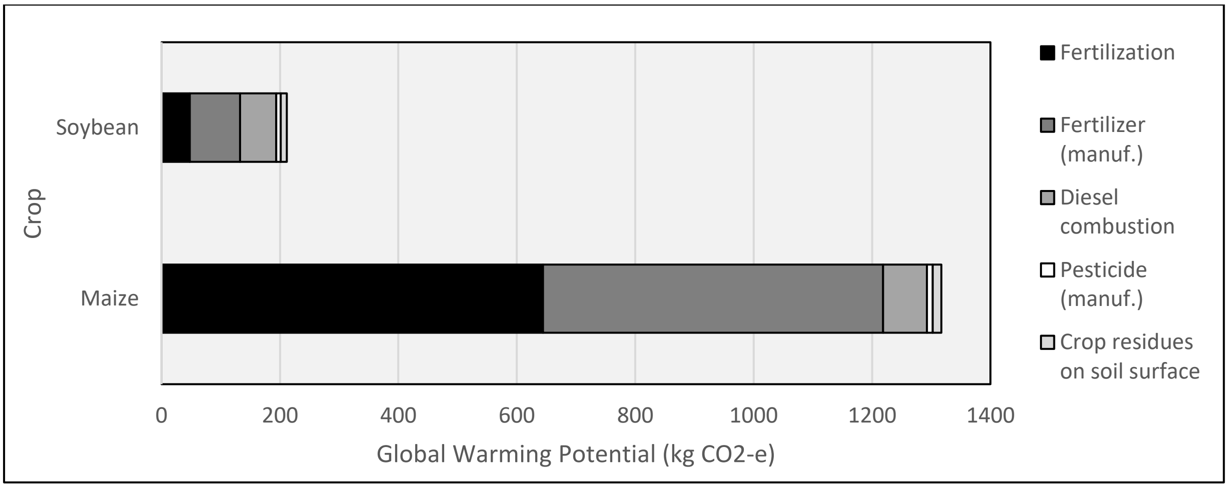

Fig. 43: Annual Global Warming Potential (GWP) of individual crops under the Gurúè large-scale virtual farm (GLVF) management scenario

The acidification potential of the GLVF system was distributed between fertilization-based emissions and diesel combustion, which in total resulted in 14 kg SO_2-e ha^{-1}. Fertilization contributed an estimated 11 kg SO_2-e ha^{-1} due to NH_3 and NO_x emissions, and diesel combustion contributed an estimated 3 kg SO_2-e ha^{-1} as NO_x emissions. Results illustrated in Figure 44 indicate that maize had a higher AP than soybean, the majority of this increase was due to higher NH_3 emissions due to its higher fertilization rates.

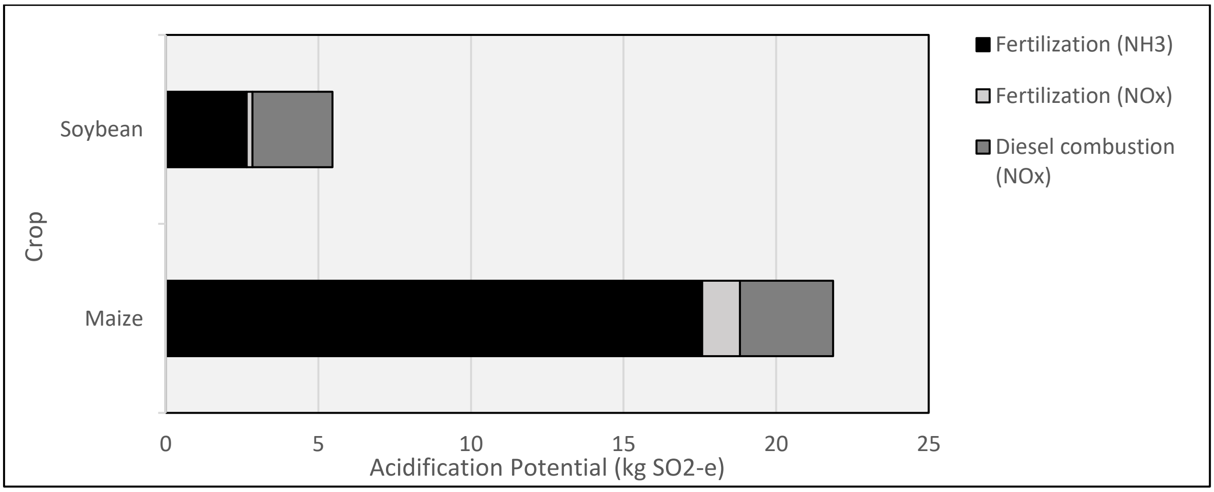

Fig. 44: Annual Acidification Potential (AP) of individual crops under the Gurúè small-scale virtual farm (GSVF) management scenario

Fertilization related emissions, specifically NH_3 and NO_x, emitted an estimated 1.78 kg PO_4 ha^{-1}, while N and P leaching led to an estimated 17 kg PO_4^{3-} ha^{-1}. Diesel combustion also contributed an estimated 0.53 kg PO_4^{3-} ha^{-1} to the EP of the system through its emission of NO_x during combustion. The total EP of the GLVF was therefore equivalent to 20 kg PO_4 ha^{-1}. The EP of each individual crop over a year of production is illustrated in Figure 45, results indicated that maize had a higher EP than soybean. This was predominantly due to the higher fertilization rates applied to maize which resulted in more N and P leaching than for soybean.

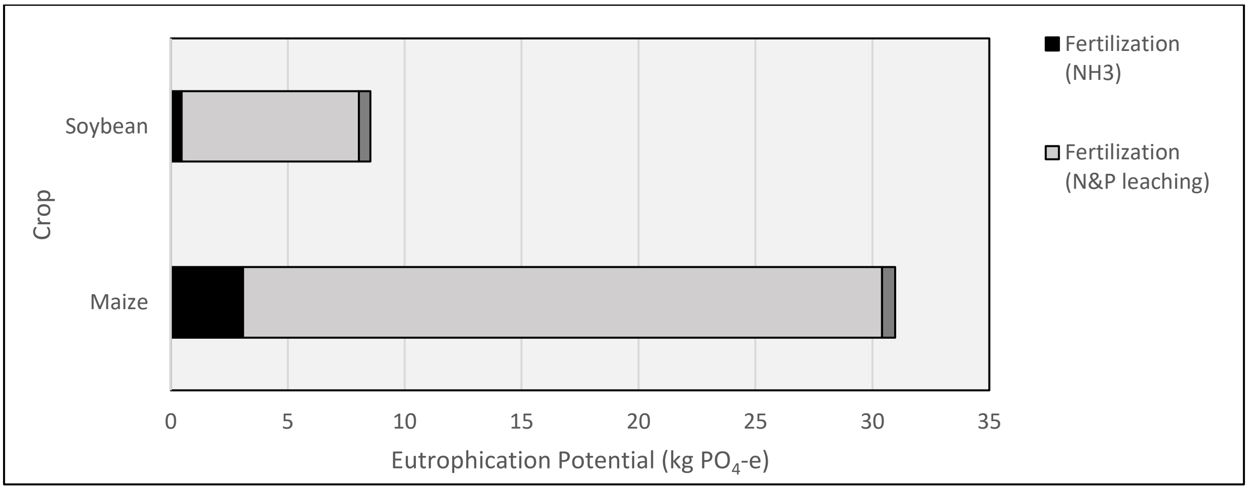

Fig. 45: Annual Eutrophication Potential (EP) of individual crops under the Gurúè small-scale virtual farm (GSVF) management scenario

9.2.3. Nanyuki small-scale virtual farm (NSVF)

The total energy consumption by the NSVF to support a year of production was estimated at 3 636 MJ ha^{-1}. This was dominated by fertilizer manufacture which contributed an estimated 3 588 MJ ha^{-1}, while pesticide manufacture only contributed an estimated 48 MJ ha^{-1}. The management practices for each crop were not differentiated so there were no differences between the EI indicators of each crop.

An estimated 1 048 kg CO_2-e ha^{-1} was emitted during pesticide and fertilizer manufacturing and following fertilization. The N_2O emissions from fertilization resulted in an average annual emission as high as 542 kg CO_2-e ha^{-1}. Due to the low quantities of pesticide applied, its manufacturing only contributed an estimated 5 kg CO_2-e ha^{-1}, while fertilizer manufacturing emitted an estimated 502 kg CO_2-e ha^{-1}.

The AP of the NSVF system was solely generated from fertilization-based emissions, which in total resulted in 14 kg SO_2-e ha^{-1} over an average year of production. This was exclusively due to NH_3 emissions during volatilization and NO_x emissions during nitrification and denitrification. The EP of the GSVF was similar due to the fertilization practices which resulted in an estimated potential of 14 kg PO_4-e ha^{-1} in an average year of production through N leaching, volatilization, nitrification, and denitrification.

9.2.4. Nanyuki large-scale virtual farm (NLVF)

The main contributors to NRE consumption in the NLVF case study were fertilizer manufacture and diesel combustion. The energy required to manufacture the system's annual fertilizer demands was estimated at 124 410 MJ ha^{-1}, while 67 393 MJ ha^{-1} of energy was consumed during diesel combustion (Figure 46). Pesticide manufacturing also played a role resulting in the total non-renewable energy consumption of 191 821 MJ ha^{-1} for a year of NLVF production. As there was only one crop produced in the NLVF scenario, there was no comparison between the emissions of different crops.

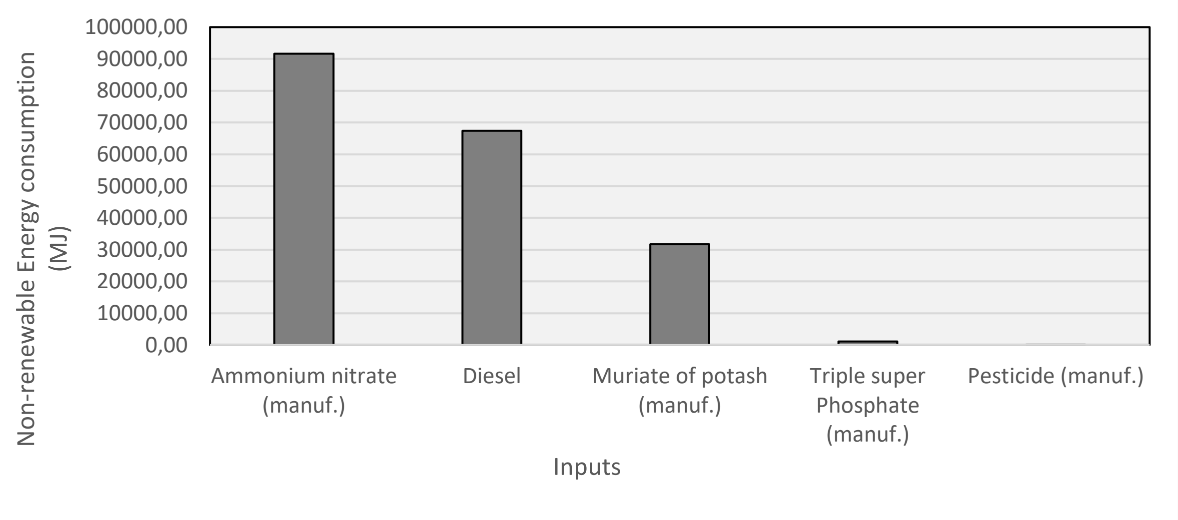

Fig. 46: The contribution of each input to the total annual Non-renewable Energy (NRE) consumption of roses under the Nanyuki large-scale virtual farm (NLVF) management scenario

The total GWP for NLVF rose production was the highest out of the four case studies with estimated emissions of 28 321 kg CO_2-e ha^{-1}. Due to the continuous application of fertilizer through an open fertigation system, fertilization's contribution to GWP is extremely high with estimated emissions of 13 579 kg CO_2-e ha^{-1} (Figure 47). Additionally, fertilizer manufacturing to sustain a year of production emitted an estimated 12 886 kg CO_2-e ha^{-1}. Non-renewable energy consumption in the form of diesel combustion during on-farm activities resulted in a sizeable contribution of 1 473 kg CO_2-e ha^{-1}. Lastly, pesticide manufacturing emitted an estimated 383 kg CO_2-e ha^{-1}.

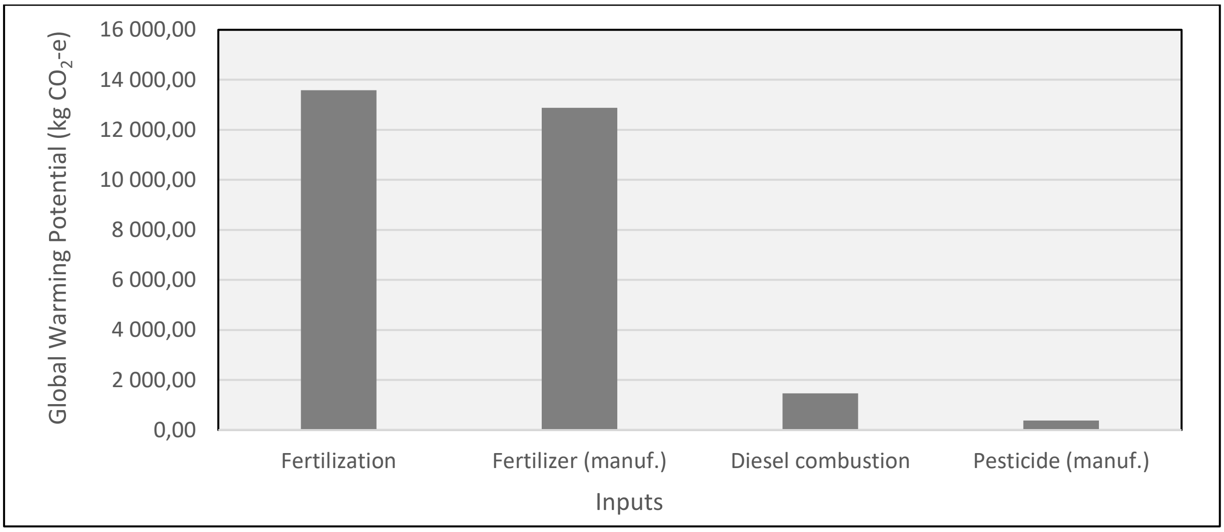

Fig. 47: The contribution of each input to the total annual Global Warming Potential (GWP) of roses under the Nanyuki large-scale virtual farm (NLVF) management scenario

The total acidification potential of the system was estimated at 399 kg SO_2-e ha^{-1} (Figure 48). This was due to the relatively high inputs of fertilizer resulting in 329 kg SO_2-e ha^{-1} from NH_3 emissions and 23 kg SO_2-e ha^{-1} from NO_x emissions. Additionally, the combustion of diesel emitted NO_x equivalent to 46 kg SO_2-e ha^{-1}. The total EP was estimated at 593 kg PO_4-e ha^{-1}, with the main contribution from fertigation which produced 58 kg PO_4-e ha^{-1} through NH_3 emissions and 527 kg PO_4-e ha^{-1} through N and P leaching (Figure 49). Diesel combustion emitted a further estimated 46 kg PO_4-e ha^{-1}.

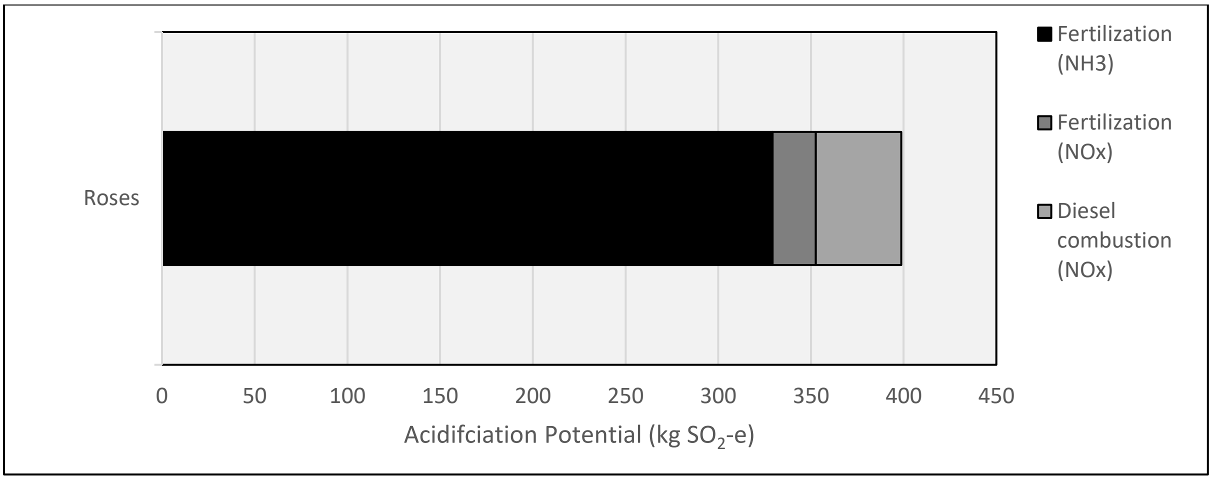

Fig. 48: The contribution of each input emission to the total annual Acidification Potential of roses under the Nanyuki large-scale virtual farm (NLVF) management scenario

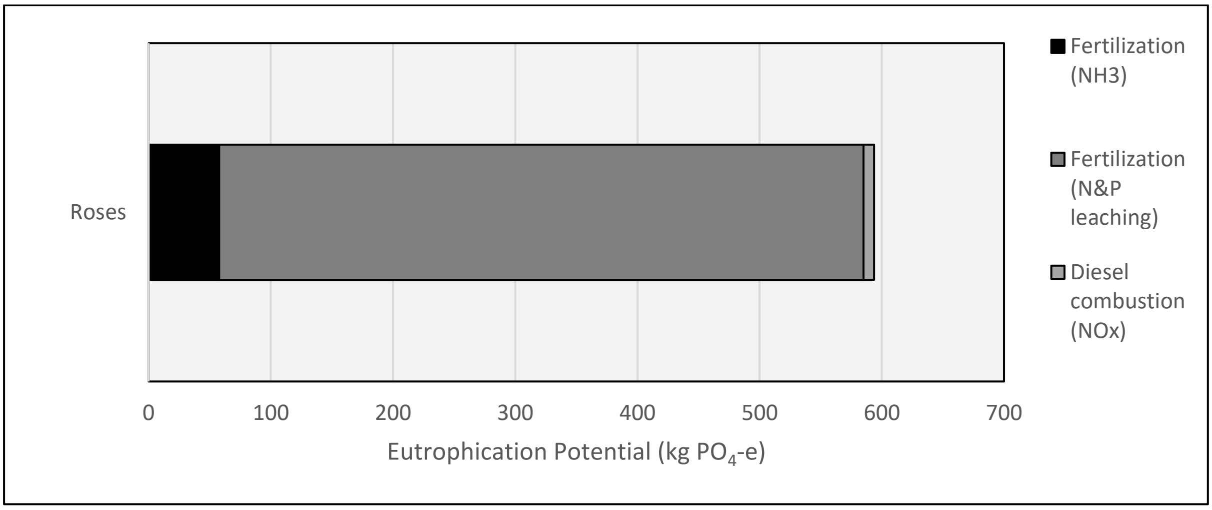

Fig. 49: The contribution of each input emission to the total annual Eutrophication Potential of roses under the Nanyuki large-scale virtual farm (NLVF) management scenario

9.3. Life Cycle Assessment (LCA) discussion

The chosen EI indicators for each VF system related to 1 ha of land and a 50 kg bag of maize, or in the NLVF case one rose stem, are shown in Table 60 and 61. The highest values over all indicators were observed under the management practices of the NLVF. All inputs, including fertilization, pesticide, and fuel, were highest under the NLVF management scenario for roses. In the NLVF case, it was not the type of inputs used that resulted in a higher EI, but rather the quantity, as intensive production occurred throughout the year. However, the higher productivity of the system substantially improved the EI per bunch of roses (12 roses) over all indicators to negligible levels.

Relative to the NLVF, the NSVF had a negligible EI, however when compared to the Mozambican virtual farms, the NSVF's EIs was substantial. Since the NSVF had two growing seasons within a year this meant that soil preparation, fertilization, and pesticide application occurred biannually, which in turn meant double the EI. Although a the NSVF may apply a moderate rate of agricultural inputs during one growing season, because they have two growing seasons within a year their EI becomes more substantial per hectare per year.

When considering the EI per kg of maize, however, the two growing seasons are not accounted for and the EIs become substantially less for the NSVF. Compared to the GLVF, the NSVF used less fertilizers, pesticides and fuel, but achieved the same yield, which resulted in a lower EI over all indicators. This meant that per 50 kg bag of maize the NSVF was a more environmentally-friendly system while still achieving the same level of productivity as the GLVF. Therefore, in one growing season the NSVF has a lower EI than the GLVF because it uses less inputs while achieving the same yield, but due to its back to back seasons in an average year of production the SSF system in Nanyuki has a similar EI to the LAIs in Gurúè. Although it should be noted that a limitation of the LCA methodology utilized in this study is that it does not consider site-specific conditions and the Nanyuki region has higher agro-ecological potential than the Gurúè region.

Results indicated that the higher the input intensification the higher the EIs per annum. Accordingly, due to the higher input consumption by the GLVF compared to the GSVF, their EIs were also higher. However, because of the intensive use of inputs the GLVF was able to produce higher yields, which meant that the EIs of the GLVF were lower than the GSVF per kg of maize. So much so that a 50 kg bag of maize produced by the GLVF had an AP and EP below 1 kg SO_2-e and 1kg PO_4-e, respectively. This means that per ha the GLVFs EIs may seem much higher than the GSVF, but per unit yield the EIs, specifically AP and EP, become almost negligible.

Against most standards the GSVF had lowest EIs over all of the EI indicators. The lack of input use and mechanization meant that there were relatively no emissions. The emissions that did occur were due to leaving crop residues on the soil surface which was done to return fertility to the soil and then burning the crop residues to clear the land for planting. When assessing the EI of a bag of maize produced under the GSVF management scenario, even though their yields were low, the EIs over all indicators were negligible. Therefore, the GSVF scenario had the lowest environmental impact over all indicators per ha and per kg maize.

Table 60: Environmental impacts of Gurúè Small-scale virtual farm (GSVF) and Gurúè large-scale virtual farm (GLVF) production systems in a year of production

Impact category	**Unit yr^{-1}**	**1 ha GSVF**	**50kg maize GSVF**	**1 ha GLVF**	**50kg maize GLVF**
Non-renewable Energy consumption	**MJ**	0	0.00	4 305	106
Global Warming Potential	**kg CO2-e**	14	0.77	1 049	22
Acidification Potential	**kg SO2-e**	5	0.26	14	0.36
Eutrophication Potential	**kg PO4-e**	1	0.05	20	0.52

Table 61: Environmental impacts of Nanyuki small-scale virtual farm (NSVF) and Nanyuki large-scale virtual farm (NLVF) production systems in a year of production

Impact category	**Unit yr^{-1}**	**1 ha NSVF**	**50kg maize NSVF**	**1 ha NLVF**	**1 bunch of roses NLVF**
Non-renewable energy consumption	**MJ**	3 636	30	191 822	2.3
Greenhouse gas emissions	**kg CO_2-e**	1 048	17	15 435	0.19
Acidification potential	**kg SO_2-e**	14	0.12	399	0.00
Eutrophication potential	**kg PO_4-e**	14	0.11	593	0.01

10. Water footprint results

10.1. Gurúè small-scale virtual farm (GSVF) water footprint

The cropping system of the GSVF consists of the annual rotation of a maize-bean intercrop with a soybean monocrop. Using APSIM to model evaporation and transpiration under the GSVF scenario, it was found that one year of soybean had an average transpiration of 38 mm yr^{-1}, the mixture of maize and pigeon pea transpired an average 49 mm yr^{-1}. The total average ET_c was computed at 44 mm yr^{-1} for the entire production system. Evaporation was found to be substantially higher than transpiration at 625 mm yr^{-1}, alluding to the extremely low yield of the crops and their inefficient water use. The sum of these two components resulted in a notably low average ET of 669 mm yr^{-1} (2 mm day^{-1}) of which only 7% was due to crop transpiration.

Alternatively, CROPWAT was used to investigate the water requirements of generic maize, dry beans, and soybean crops in the Gurúè region when water stress was null. A year of production under these irrigated conditions resulted in an average ET_c of 233 mm (Table 62). According to CROPWAT the GSVF would require an additional 56 mm yr^{-1} of irrigation to avoid water stress, meaning that an average 24% of ET_c would be considered as blue water.

Table 62: Crop water use (ETc) and irrigation requirement of the Gurúè small-scale virtual farm (GSVF) scenario in the Gurúè region

Crop	Potential ET_c (mm)	Irrigation requirement (mm)
Maize-Bean intercrop	254	66
Soybean	212	45
Average year of production	233	56

10.2. Gurúè large-scale virtual farm (GLVF) water footprint

The cropping system of the GLVF consists of two years of soybean production followed by two years of maize according to interview results. Using the APSIM model to calculate crop water use it was found that within the GLVF cropping system, maize transpired an average 113 mm yr^{-1} and soybean an average 81 mm yr^{-1}. The average total transpiration rate for a cropping year under the GLVF was calculated at 97 mm yr^{-1}. It was estimated that over a year of production there would be 554 mm yr^{-1} of evaporation, resulting in a total ET of 651 mm yr^{-1} (2 mm day^{-1}). A considerably low water footprint that was attributed to poor crop growth and low annual yields compared to potential maize and soybean growth and development.

In the scenario where water stress was zero, maize would require 263 mm yr^{-1} and soybean would require 212 mm yr^{-1} of water, resulting in an average ET_c of 238 mm yr^{-1}. According to CROPWAT simulations, to meet this crop water requirement the GLVF would need to fully utilize effective rainfall and an additional 56 mm yr^{-1} of irrigation (Table 63).

Table 63: Crop water use (ETc) and irrigation requirement of the Gurúè large-scale virtual farm (GLVF) scenario in the Gurúè region

Crop	**Potential ET_c (mm)**	**Irrigation requirement (mm)**
Maize	263	67
Soybean	212	45
Average year of production	238	56

10.3. Nanyuki small-scale virtual farm (NSVF) water footprint

Transpiration from the NSVF annual production of wheat and a mixed cropping system of maize and pigeon pea was computed using APSIM. The average transpiration was found to be 171 mm yr^{-1} during the maize-bean intercrop and 110 mm yr^{-1} during the wheat rotation. The total average transpiration in a year of NSVF crop production as modelled by APSIM was calculated at an average rate of 141 mm yr^{-1}. Evaporation from the soil surface was steady throughout the year due to the proximity of the study site to the equator. Using APSIM, soil evaporation was calculated at an average 615 mm yr^{-1} bringing the total ET to 756 mm yr^{-1} (2 mm day^{-1}). Mutiga *et al.* (2010) found similar results using remote sensing to estimate the ET rates of small-scale farms, and estimated it at 3-4 mm day^{-1}, this value would most likely have been a mixture of irrigated and dryland practices occurring in the pixels analysed.

CROPWAT was used to estimate the amount of water required so that yield is not water-limited which is equivalent to ET_c for this theoretical cropping system (Table 64). The amount of irrigation water needed was also computed based on rainfall patterns from the Kalalu weather station. According to CROPWAT results the total production system's ET_c under zero water stress, is 1 066 mm (2.92 mm day^{-1}). The total irrigation requirement for the maize-bean intercrop was estimated at 115 mm, and the rotation of wheat required 214.8 mm. An average full year of production under the current NSVF cropping calendar would therefore require an additional 330 mm of irrigation. This scenario would then have a blue water footprint of 31% (330 mm) and a green water footprint of 69% (736 mm).

Table 64: Crop water use (ET_c) and irrigation requirement of the Nanyuki small-scale virtual farm (NSVF) scenario in the Nanyuki region

Crop	**Potential ET_c (mm)**	**Irrigation requirement (mm)**
Maize-Bean intercrop	328	115
Wheat	737	215
Year of production	1 066	330

10.4. Nanyuki large-scale virtual farm (NLVF) water footprint

Continuous NLVF rose production under greenhouse conditions for a total farm area of 9 ha would consume an average 99 ML yr^{-1} (11 ML ha^{-1}) of irrigation water. Achieving a yield of 100 stems m^{-2} yr^{-1} would then result in an average 11 L of irrigation water applied per rose stem. It should be noted that this value is not necessarily equivalent to the WF as a return flow via runoff and drainage would occur. To more accurately estimate the WF of the crop, ET of the NLVF roses was calculated at 65% of ET_o outdoor and with a K_c value of 0.81. Using these variables, the average ET was 6.2 ML ha^{-1} yr^{-1} or 625 mm yr^{-1} (2mm day^{-1}). Adopting the water footprint calculation, where the yield was 100 stems m^2, the WF_{produc} was calculated at an average 6.2 L stem^{-1}.

Irrigation water that did not transpire or evaporate was returned to the environment via drainage and runoff. The drainage-runoff fraction of irrigation water was initially based on Hoekstra and Chapagain (2008) who estimated at 10% of irrigation. If the NSVF was irrigating at 11 ML ha^{-1} yr^{-1}, then Hoekstra and Chapagain (2008) would predict that an average 1.1 ML ha^{-1} yr^{-1} was lost through deep drainage. However, *ET* was estimated at 6.2 ML ha^{-1} yr^{-1}, which means there would be a consequential return flow of 4.8 ML ha^{-1} yr^{-1}, 44% of irrigation.

The claim by the NLVF that they could sustain production using harvested rainwater during the three-month dry season from July to September was investigated using the WF methodology. Average rainfall over a 50-year period was used to estimate how much water the LAI could harvest from its 4 ha dam and 9 ha greenhouse roofs and how much water would be available for irrigation after evaporation. Results were calculated on a monthly time-step and shown in Table 65. The irrigation demand for one month of 9 ha of rose production was calculated at 8 ML, to sustain three months of production would require 25 ML. The water available after evaporation from the dam from April to June, alone, was 38 ML. This was enough to sustain production during the three-month dry period.

The total amount of rainfall harvested from the 4 ha dam surface as well as the 9 ha greenhouse roofs was an average 104 ML yr^{-1} which was then stored in a 157 ML capacity dam. Evaporation from the dam surface was estimated at 52 ML yr^{-1}, this means that out of the 104 ML harvested in a year, 50% of it would potentially be lost through evaporation. The estimated $WF_{storage}$ was 5.21 L $stem^{-1}$ which brings the total consumptive *WF* to an average of 12 L $stem^{-1}$ (1 200 mm yr^{-1}). Consequently, 52% of the WF is due to ET during production and a substantial 48% is attributed to evaporation from water storage. This is a significant loss that could potentially be addressed by reducing evaporation from the dams, for example, through the use of some type of cover (Hassan *et al.,* 2015).

The WF was then split into blue and green water consumption. The blue water definition by Hoekstra *et al.* (2011) states that any irrigation water should be considered as blue water. This is problematic for the NLVF case because even though the system was fully dependant on irrigation, 57% was potentially supplied by rainwater harvesting, which this dissertation debates should partly be considered as green water. Hoekstra *et al.* (2011) argues that harvested rainwater would otherwise become run-off, replenishing groundwater and surface water and should, therefore, be considered as blue water consumption. For a greenhouse production system which harvests and stores rainfall from the greenhouse roof above its crop, attributing all crop *ET* to blue water may be a misrepresentation of the pressure such a system places on blue water resources. Water conflicts are particularly significant in the Nanyuki region as water is scarce during the dry season and competition for the resource is high. By defining harvested rain water as blue water only, implies that it would be otherwise available to water users and ecosystems downstream. While acknowledging that a fraction of rainwater could runoff to become blue water, the rainfall that infiltrated the soil below would become green water. The pressures on blue water resources are then not as high as what the methodology of Hoekstra *et al.*, (2011) would estimate, as it would not recharge blue water and would not be available to downstream users. If evaporation from dam surfaces are mitigated, then rainwater harvesting during the rainy season should be considered an agronomically productive use of blue and green water resources that alleviates the pressures on blue water during the dry season.

Table 65: Rainfall harvesting potential over a 13 ha water harvesting area in the Nanyuki region using weather data from Kalalu Weather Station

Month	Rainfall (mm)	ET_0 (mm)	Total rainwater harvest (ML)	Dam evaporation (ML)	Plant available water (ML)
Jan	77	128	10	5	5
Feb	50	133	7	5	1
Mar	72	130	9	5	4
Apr	121	103	16	4	12
May	120	101	16	4	12
Jun	146	101	19	4	15
Jul	93	100	12	4	8
Aug	61	87	8	3	4

Sep	39	113	5	5	1
Oct	99	111	13	4	8
Nov	211	92	27	4	24
Dec	118	105	15	4	11
Totals	1207	1304	157	51	105

Mekonnen et al. (2012) calculated that the Lake Naivasha cut flower industry attributed 33% (123 m^3 $tonnes^{-1}$) of the total water footprint to grey water to assimilate the N fertilizers that enter the waterway systems due to leaching and runoff. Although not estimated here, the grey WF is expected to be relatively high due to the intensive applications of N, P, and various pesticides to the system. There is also potentially an increased threat during the dry season when there is less water available to assimilate the load of pollutants to ambient water quality standards. The water transport from the dams to the field was unknown and could therefore not be quantified. This issue is recommended for future research.

10.5. Water Footprint (WF) discussion

10.5.1 Gurúè region

A 50 kg bag of maize produced under the GSVF scenario was found to have a higher WF compared to a 50 kg bag of maize produced under the GLVF scenario. The GSVF was shown to be an inefficient and unproductive use of green water due to its high evaporation and low transpiration rates. This indicated that the GSVF was not fully utilizing the green water available to it, which means that management practices are limiting the full utilization of rainfall. This was supported by APSIM simulation results which indicated that the sole addition of irrigation to the GSVF scenario was not sufficient to significantly increase yields.

The GLVF was shown to be a more efficient use of green water due to its higher transpiration and lower evaporation rates compared to the GSVF. It was estimated that over a year of production there would be 554 mm yr^{-1} of evaporation, this was 20% less evaporation than what was observed for the GSVF system. Evaporation is considered an unproductive loss of water; therefore, the results suggest that the GLVF system was a more water use efficient than the GSVF. This was further confirmed by the higher yields obtained under the GLVF scenario which resulted in higher transpiration rates and a combination of quicker canopy establishment and improved crop residue management which results in less bare soil exposed to evaporation. However, the WF per unit area, does not capture the differences between productive (transpiration) and unproductive (evaporation) water use thus resulting in a similar WF per unit area for the GSVF and GLVF.

Irrigation requirement results from the GSVF scenario indicated that an average 56 mm yr^{-1} would be needed to support an average year of production to reach the potential maize yield when water stress is null. This is a relatively low value that could potentially be met by harvesting rainwater from water storage systems (Musayev *et al.* 2018). Heavy rains are common in the region and harvesting flood water has the potential to address this water deficit. Infrastructure is the major challenge for irrigation in the region as financial constraints, poor management, and low availability limit access to equipment, skilled labour, and necessary materials. SSFs also do not believe that irrigation is necessary and are accustomed to rainfed cultivation. There does not seem to be immediate plans for investment into irrigation by government or non-governmental organizations. According to the FAO, Mozambique has only equipped 38% of potentially irrigable areas with infrastructure, and only 1.3% of the 38% are actually irrigated (Beekman *et al.* 2014). Dryland agriculture is currently productive in the region, as it was found that water was not a major limitation to yield. However, it is recommended that further research be done into the potential risks of climate change on crop productivity as the lack of irrigation infrastructure places SSFs in a position of risk due to low adaptability towards climate change. Beekman *et al*. (2014) observed an emergence of an irrigation culture amongst SSFs in Central Mozambique. Most of these systems were developed without government or technical support and include furrow irrigation along slopes, pumped irrigation in valleys and floodplain water management along the coast.

These forms or farmer-led irrigation development should be encouraged and incentivised as a way of creating a sustainable water management scheme to better prepare SSFs to changing rainfall patterns. Research into the identification of perennial rivers and flow rates is also recommended to support the management of future irrigation schemes

The enterprises interviewed to build the GLVF did not have imminent plans for investing in irrigation as it believed it could attain profitable yields under rainfed conditions. This is understandable as the high evaporation rates indicate that the GLVF was not fully utilizing effective rainfall. Therefore, it is recommended that improvements be made to maximize the crop use of rainfall before investing in irrigation systems. Although, as with the SSF case, if rainfall continues to become increasingly unpredictable due to climate change, managing rainfall use could become more challenging and profitability could be at risk. A benefit is that the LAIs are better equipped to react to changes in rainfall patterns than the SSFs, they have the financial means to invest in expertise, equipment, construction, and energy to adapt to potential climate change. If there is future investment into irrigation infrastructure, discussions with nearby communities will be critical to minimize potential water conflicts and create a sustainable system that can meet everyone's needs. It would also be an advantageous opportunity for technology transfer between LAI and SSF so that both systems have suitable access to the shared water resources.

Table 66: The consumptive Water Footprint (WF) of the Gurúè small-scale virtual farm (GSVF) scenario compared to the Gurúè large-scale virtual farm (GLVF) scenario per unit area and per unit maize yield

Scenario	**Total WF per ha ($ML\ yr^{-1}$)**	**Total WF per 50kg bag of maize ($ML\ yr^{-1}$)**
GSVF	7	0.33
GLVF	7	0.11

10.5.2. The Nanyuki region

Compared to the Gurúè region, the Nanyuki region has an inherently higher evaporative demand. Due to its higher transpiration rates, however, the NSVF was considered a more productive use of green water than the GSVF and GLVF scenarios. In comparison to the NLVF, the consumptive WF of the NSVF was similar to the WF of the Kenyan rose production system during the production phase. However, the total WF of the NLVF was substantially higher due to the additional unproductive evaporation losses during water storage. Although the NLVF has a considerably higher total WF per unit area, the WF per stem was significantly lower than that of a bag of maize produced by the NSVF. According to the results, the total WF of 10 833 roses was equivalent to the total WF one 50 kg bag of maize.

Although the WF of the NLVF was low per rose stem, it was found that the NLVF was irrigating more than the crop water requirement, with a drainage fraction possibly as high as 44%. Tipis & Mpusia (2006) explain that in their case study of roses under greenhouse conditions, irrigation was applied with a 30-50% leaching fraction. This was done to avoid the build-up of salts in the root zone by flushing them out of the soil. Similarly, since the NLVF scenario applied high rates of fertilizers it would have to take steps to prevent salt accumulation in the soil. However, the Tipis & Mpusia (2006) greenhouse case study was under a complete re-circulating system while the NSVF case is an open-system. This open-system allowed for runoff and drainage to return to blue water sources where they could potentially be available to downstream users, but with the consequence of potential water pollution due to leaching into sub-surface and surface water. Therefore, in addition to minimizing the drainage fraction, the NLVF could modify its operations to a closed irrigation system so that the extraction of irrigation water from blue water sources could potentially be minimized. This is particularly crucial in the context of Nanyuki as water-scarce region.

According to blue water definition by Hoekstra *et al.,* 2011, all irrigation water is considered as blue water. Therefore, the total WF of the NLVF scenario was considered as the blue water footprint, although it should be noted that 57% of irrigation was supplied by rainwater harvesting. It was found that although ET from water storage was a large portion of the WF and rainwater harvesting was not sufficient to support year-round production, the amount of rainwater stored during the rainy season did have the potential to alleviate competition for scarce blue water during the dry season. However, the WF from water storage indicated to a significant loss that could potentially be addressed by reducing evaporation from the dams, for example, through the use of some type of cover (Hassan et al., 2015).

The household survey results indicated that the majority of SSFs in the Nanyuki region were not irrigating as only 37% of SSFs were using some form of irrigation. Although not the practices of the majority, this 37% could consume a substantial portion of blue water in the area. Results indicated that irrigation and improving water use efficiency has the potential to increase yields and provide year-round food production in the basin. However, this would require more abstraction from rivers which would result in further reduction of downstream water availability. Increasing water use efficiency by mitigating runoff also has the potential of reducing return flows that were previously available to downstream users. These potential impacts could be magnified as climate change occurs and rainfall patterns change, forcing more SSFs to shift from rainfed to irrigated agriculture. If water resources are not managed correctly to meet the needs and expectations of water users, illegal water abstractions could increase and conflicts worsen (Liniger et al., 2005). Even if SSFs do not fully irrigate to satisfy crop water demand, the collective increase in consumption could create a water crisis, not only for the agricultural sector but for wildlife, communities, and forestry alike. Authors such Mekonnen et al. (2012), Notter *et al.*, (2007) and Liniger *et al.* (2005) have stressed the importance of sustainable management and careful negotiation of water resources to mitigate the growing water crises and conflicts. This study iterates that point and highlights the importance of acknowledging water as a shared resource. These results and the relatively simple WF methodology provide some quantitative data and a framework for key stakeholders to better manage water allocation within the basin.

Chapter IV: Conclusions

In this final chapter, selected key findings of the study are presented within the context its aims. In-depth discussions on the results were presented at the end of each chapter, these should therefore be consulted for further analysis on the following sections.

11. Cropping system productivity and yield gaps

11.1. The Gurúè study region in Mozambique

This study supported the classification of a typical Gurúè SSF system as a low input-low output production system (FAO, 2011). Household survey results indicated that none (0% of n=50) of SSFs were using fertilizer, irrigation and mechanization, and that only 12% (n=50) were using pesticides which was only utilized for soybean production. This low technological adoption was attributed to the poor accessibility and affordability of inputs as well as the lack of extension services in the Gurúè region. The lack of fertilizer use was particularly problematic for maize growth since nitrogen (N) was identified as a major limiting factor to production in the region. The average agro-ecological yield was estimated at 0.63 tonnes ha^{-1}, and the addition of 100 kg NH_4-N ha^{-1} had the potential to increase yield by 327% (to 2.06 tonnes ha^{-1}).

SSFs are able to circumvent this N-limitation and ensure continuous annual production, however, by intercropping with legumes and cultivating at a low plant density of 2.5 plants ha^{-1}. If maize planting density doubled to 5 plants ha^{-1}, maize yield was estimated by the APSIM model to decrease by 8% and the likelihood of crop failures increased to 4%. The change from the SSFs practice of intercropping maize and pigeon pea to a maize monocrop in the context of the GSVF management practices, was estimated to decrease average maize yield by 45%. Although these practices resulted in low average yields, the lower N-demand was able to be met by total soil N. Additionally, the majority of SSFs in the region relied on rainfed agriculture, which was a perceived as favourable to yield according to APSIM simulations due to the low soil fertility. It was estimated that the sole addition of irrigation only increased maize yield by 5% (0.05 tonnes ha^{-1}). Conversely, since the Gurúè soils were N-limited, the addition of irrigation actually increased N leaching which was detrimental to improving maize yields. Therefore, within the SSF resource-availability context, their management practices allowed them to avoid crop failures and attain yields higher than the agro-ecological potential of the region. These results support observations by Smart & Hanlon (2014) that SSFs do not invest in agro-inputs because they consider it to be a risky investment whereas if they continue traditional practices they are ensured that they will produce something at the end of the season.

SSFs, however, are only producing at 16% of the potential yield which is achieved when agro-inputs are utilized. By cultivating improved hybrid cultivars instead of using saved local seed varieties, SSF average yield can be increased by 98% (1.05 tonnes ha^{-1}) as the hybrid consistently outperformed the local cultivar even during years of low rainfall. It is, however, noted that APSIM modelling was not able to capture the loss in yields by pests and diseases. These along with other factors such as the storage performance, grain/cob size, and taste are important traits that determine the adoption of improved cultivars (Antonio *et al.,* 2016). Therefore, although it was demonstrated here that improved genetics has the potential to increase maize yield drastically, there are other factors that may impede its adoption.

In terms of N fertilizer, even if SSFs were to add 200 kg NH_4-N ha^{-1} to their cropping system without improving any other management practice, yield was found to only increase by 55% (0.57 tonnes ha^{-1}), which is considered an inefficient agronomic use of N with an increase of only 2.83 kg maize grain per kg N. In fact, after the addition of 50 kg NH4-N ha^{-1}, maize yields did not significantly increase indicating that growth was then limited by other factors, specifically cultivar selection, planting density and to a lesser extent water stress. For the SSF system to reach the maximum yield potential, when there is no water or N stress, of 6.1 tones ha^{-1} would require that all of these factors be improved incrementally as each improved variable, when combined, result in exponential yield improvements.

Compared to the SSF scenario, the LAI scenario was classified as a high input-medium output system. LAIs were found to apply standard commercial agricultural practices for soybean-maize cultivation that included applying fertilizer quantities based on soil analyses and crop requirements and applying pesticides according to label instructions. In addition, the LAI scenario also applied management practices associated with conservation agriculture (CA), specifically: zero tillage, crop rotation, and retaining crop residues on the soil surface. These practices allowed for an average yield of 3 tonnes ha^{-1} to be achieved, which was triple the average yield obtained under the SSF management practices.

The LAI scenario was found to be achieving 40% of its potential maize yield, which was estimated at 7.4 tonnes ha^{-1}. The major limiting factor to achieving their potential yield was the genetic potential of the maize cultivar utilized. When an improved hybrid cultivar with almost double the maximum number of head grain was utilized, the average maize yield was estimated to increase by 3.8 tonnes ha^{-1} (127%). In addition, the LAI was found to be over-fertilizing for the yield it was obtaining, but once the improved cultivar was utilized the fertilization rate was estimated to result in the agronomically efficient use of N (NAE). In terms of water stress, the LAI system benefitted from the addition of irrigation. The LAI scenario did not have imminent plans for investing in irrigation as it believed it could attain profitable yields under dryland conditions. APSIM modelling results indicated that the use of irrigation increased average yield by 13% (0.4 tonnes ha^{-1}) and significantly decreased yield variability. However, it was also found that the GLVF was not fully utilizing effective rainfall exhibiting high evaporation rates, representing an unproductive loss of water during cultivation.

In the Gurúè context, not only was yield gap smaller for LAIs than for SSFs, but the cropping system design utilized by the LAI system, which comprised of sole cropping of maize rotated with sole cropping of soybean, had a higher yield potential than the SSF intercropping system. In addition, the SSF scenario had more factors affecting the yield gap between actual and potential yield that would also be more challenging to overcome compared to the fewer limitations experienced by the LAI system. For SSFs to invest in fertilization and improved seeds would require serious intervention strategies that require a change of perspective towards the use of agro-inputs by SSFs and for a reliable and affordable agro-input market to develop in the region. Strategies that include technology transfer are critical as it was recognized that many SSFs lacked the crop and land management skills to use agro-inputs efficiently, as was seen with the pesticide use case. Generation of research in the region is also required to identify location-specific combinations of agro-input practices that could be adapted by farmers from different socio-economic backgrounds and risk preferences. However, the most critical factor may be government commitment to supportive public investment, pro-SSF policy choices, and the development of a practical agro-input market.

In comparison, LAIs have fewer limitations to overcome. With more time to investigate higher-yielding cultivars more suited to the region through trial and error, LAIs would be able to drastically improve their yields. If governments and investors focus more on long-term profit goals, not only can higher yields be obtained but the negative perception by SSFs could also be improved through the generation of stable employment and technology transfer.

11.2. The Nanyuki study region in Kenya

The Nanyuki SSF production scenario was essentially a medium input-medium output system. Unlike the SSFs in the Mozambican case study, agro-inputs were more accessible and affordable in the Nanyuki region. Therefore, the majority of SSFs were found to be applying fertilizers, pesticides, and using hybrid cultivars which resulted in higher yields than the agro-ecological potential. It is noted, however, that the cropping system utilized by the GSVF identified as two growing seasons in a year comprising of an intercrop of maize and legume rotated with wheat, was not best suited to the region according to APSIM results. Higher maize yields were obtained when maize was cultivated as a monocrop and cultivation only occurred during the long rains. It is recognised that SSFs do not necessarily prioritize maximizing maize yield over crop diversification which is a method of diversifying risk, preventing disease build-up, and improving soil fertility.

In general, the Nanyuki region has highly variable weather conditions resulting in variable maize yields ranging from 0-5.4 tonnes ha^{-1}. In a study by Njeru & Gitonga (2004) the chance of maize cultivation experiencing crop failure was 21% in the Nanyuki region, under the SSF scenario in this study, the chance of crop failure was 16%. This supported the description by various authors of Nanyuki as a risky environment for maize production (McCord *et al.,* 2015; Njeru & Gitonga, 2004; Ulrich *et al.,* 2012). It was further agreed that yield variability was primarily due to rainfall variability (Njeru & Gitonga, 2004). During seasons with good rainfall, the use of irrigation was estimated to decrease maize yields as a result of N leaching, however, during seasons of poor rainfall, applying irrigation was critical for maize production. Simulations for 'no N fertilization' indicated that applying at least some fertilizer N is critical for improving productivity in the region. The fertilization rates applied by the SSFs had an NAE of 39 kg grain kg^{-1} N, which according to Whitbread *et al.,* (2013) is considered to be a high N response and therefore an agronomically efficient use of N. Results indicated that the NSVF was fertilizing at ideal rates for their current management practices, and that maize yield was not N-limited under the SSF practices.

Although water stress severely constrained maize yields, model results indicate that high potential for maize production exists in the study area. Under improved management, average maize yields of 10 tonnes ha^{-1} could be reached, which means that SSFs are currently only reaching 29% of the potential maize yield. Increased yields were estimated when late-maturing cultivars were used, however, these cultivars experienced 20% more crop failures than early-maturing hybrids. This indicated that higher yielding late-maturing cultivars were not always suited to the length of the growing season. Although improved management has the potential to radically improve yields, the high variation in climactic seasonality is a significant threat to maize productivity and consequently to economic and food security. Since agro-inputs are already used by the majority of SSFs in the region, finding the optimal quantity for each farmer's needs would be the next step to improving yields in the region. This would require support from extension services and the policies that enable them. Commercial agro-chemical companies also have an important role to play, Nyakundi *et al.,* (2017) reported high rates of pesticide misuse by SSFs in Kenya and Sheahan *et al.,* (2013) observed that the majority of SSFs in the Rift Valley were over-fertilizing. The main focus for improving productivity should therefore remain on addressing the major limiting factor to production, which was water stress, through improving water conservation and optimizing irrigation practices.

The Nanyuki LAI scenario was classified as a high input-high output production system by this study. The LAI system was estimated to produce 100 roses m^{-2}yr^{-1} which is low compared to other countries and areas in Kenya that are reported to produced more than 200 roses m^{-2} (Mekonnen & Hoekstra, 2014a; Sahle & Potting, 2013). This is explained by the comparably colder climate in the region and cooler night temperatures that result in slower growth, but also allow for longer stems and larger heads to be produced, which fetch higher market prices. To obtain this high quality all year-round and meet the stringent quality regulations of international trade, high rates of nutrients are applied through an open fertigation system and high rates of pesticides are utilized to prevent and combat diseases and pests.

Since the potential yield of the Nanyuki LAI scenario couldn't be investigated, its agronomic efficiency and the determinants of yield could not be estimated. However, in comparison with the medium agronomic efficiency of the SSF system, the highly controlled greenhouse environment utilized by the LAIs was speculated to have higher agronomic efficiency than the SSF production system.

12. Cropping system characteristics and on-site environmental impacts

12.1. The Gurúè study region

Under SSF practices soil lost an average of 41% soil organic carbon (SOC) and total soil nitrogen (N) after 50-years of production. Under LAI practices soil lost an average of 45% SOC and 46% total soil N after 50-years of production. These results were similar to findings reported by Swanepoel *et al.*, (2016) that 50% of SOC was lost after 50 years of cultivation in a long-term maize field trial in Pretoria, South Africa. In our modelling study, soil degradation in lower soil layers, in terms of SOC and total soil N loss, occurred at a faster rate under LAI than under SSF management practices due to the higher N-demands as a result of higher yields from improved LAI management practices. However, both soil OC and N increased in the top soil layer (0-0.1 m) by 19% and 23%, respectively, after 50-years under LAI production, while under SSF practices both soil OC and N decreased. This was explained by the deposition of soil OC and N from crop residues left on the soil surface and increased fertilization rates by LAIs. Although the LAI scenario had a higher soil degradation rate than the SSF scenario, both systems were shown to be detrimental as they did not replenish soil OC and N at a rate that could prevent soil degradation within the root zone.

12.2. The Nanyuki study region

Within the lower soil root zone (0.2-1 m) soil OC% decreased by an average range of 9-42% and 10-42% of total soil N was lost. In the top soil layer (0-0.2 m), SOC% increased by 24% and total soil N increased by 23% due to the replenishment of OM from crop residues on the soil surface and the addition of N fertilizer. Below the root zone there was an increase in SOC% and total soil N by 3% since the soil was not disturbed by crop roots but benefited from the OM of their residues. During the semi-structured interviews with LAI rose farm representatives, they estimated that due to intensive fertigation, the top soil layer would need to be replaced after six or seven years of production. If these projections are accurate then the LAI would have more accelerated rate of soil degradation compared to the SSF scenario, which was still productive after 50 years of production.

13. Management practices and off-site environmental impacts

13.1. The Gurúè study region

Due to negligible agro-chemical input consumption and mechanization use by SSFs in the Gurúè region, the environmental impacts (EIs), specifically Non-Renewable Energy consumption (NRE), Global Warming Potential (GWP), Acidification Potential (AP), and Eutrophication Potential (EP) ranged from low to negligible. The emissions that did occur were driven by retaining crop residues on the soil surface, which was done to return fertility to the soil, and then burning the crop residues to clear the land for planting, as well as from pesticide manufacturing.

Comparatively, the LAI scenario had a higher EI across all indicators per ha as well as per kg of maize produced. This was due to increased fertilizer, fuel, and pesticide consumption. This intensification also resulted in improved yields which meant that EIs were substantially decreased per kg of maize. In terms of the water footprint (WF), the SSF and LAI scenarios had similar WFs per unit ha, but the SSF system had a higher water footprint per kg of maize. This further confirmed that the SSF system was an inefficient use of green water. Overall, due to the LAI's input intensification strategy, the LAI scenario had a significantly higher off-site environmental impact than the SSF scenario.

13.2. The Nanyuki study region

The highest values over all EI indicators were observed for the Nanyuki LAI system due to the year-round input intensive production of roses. When analyzing the EIs per unit area, relative to the LAI in Nanyuki, the SSF production system results in negligible EIs. Compared to the production systems in the Gurúè region, due to the two growing seasons within a year, the EIs of the SSF in Nanyuki were substantial per ha per year. However due to the increased maize yields from input use and improved management practices, this value diminishes per kg maize. Additionally, due to the high yields obtained by the LAI, the EI per bunch of roses becomes negligible. In terms of WF, the LAI production of roses was more water efficient than SSF production of maize. According to the results, the total WF of 10 833 roses was similar to the total WF one 50kg bag of maize produced under the SSFs management practices. In the context of Nanyuki as a water-limited area, the higher potential WF of the SSF system could be seen as more detrimental and problematic than the higher NRE, GWP, AP, and EP of the LAI system.

14. Synthesis and recommendations

14.1. The Gurúè region

Within the Gurúè study region, literature has reported conflict between SSFs and LAIs, particularly over the competition for land (Aalerud, 2010). This raised questions and claims around which management system, SSFs or LAIs, could best utilize the scarce land resource (Smart & Hanlon, 2014). Modelling results indicated that under their current management practices, LAIs have a higher agronomic efficiency and a better potential for achieving higher yields than SSF cropping systems. However, it was found that global concerns over the LAIs environmental impacts are legitimate as input intensification resulted in higher on- and off-site environmental impacts (Dell'Angelo *et al.,* 2017). On-site soil degradation is particularly problematic since land was scarce, however results indicated that both systems were shown to degrade soil organic matter at a rate beyond what they could replenish. In terms of off-site impacts, Mozambique has stated its intent to implement climate change actions by reducing CO_2-e emissions (Cunguara & Garrett, 2011). In this context, the SSF system would be a more suited system to the government's mitigation goals since it has a lower GWP. However, if the government is also dedicated to improving SSF crop yields, then the use of agro-inputs needs to be promoted, which in turn would also increase GWP. A higher acidification and eutrophication potential were also a consequence of applying agro-inputs and consuming fuel. However, without agro-inputs, the higher yields produced by the LAI can simply not be achieved due to the agro-ecological conditions of the region.

Due to the SSFs high dependence on and a traditional connection to agricultural production, it is understood that SSF systems will persist, regardless of intrusions by LAIs. Alternatively, LAIs have the potential to increase crop productivity in the region which the Mozambican government argues is a key driver for agricultural development in Mozambique (Joala *et al.*, 2016). Currently, due to the poor governance structures in the region, there is little to no positive spill-over from the re-introduction of LAIs to the region. Therefore, it is felt that long-term investments should be made into both of these types of systems, with focuses on capturing positive impacts from both LAIs and SSFs, as there is high potential for substantial improvements in yields in both systems.

To realistically increase SSF productivity, more research needs to be done into identifying and breeding high-potential maize cultivars suited to the agro-ecological conditions of the region that display key traits desired by SSFs. The use of hybrid cultivars would need to be accompanied by the use of agro-inputs, specifically N fertilizer and pesticides. This would be an investment that the majority of SSFs in the region are unwilling to make without long-term interventions into the accessibility and affordability of agro-inputs coupled with improved support from extension services. Accessible information on production improvement strategies would be critical for SSFs to appropriately utilize agro-inputs, which would correspondingly mitigate potential on- and off-site environmental impacts. However, it is understood that there are numerous political factors limiting government intervention and numerous challenges for private companies to establish themselves in rural area and also to change the sceptical perceptions SSFs have of agro-input use.

The major limiting factor to production was identified to be logistical challenges more than agronomic challenges. The remote location of the LAI limited access to agro-inputs and services and resulted in the use of cultivars unsuited to the region. Therefore, it is recommended that LAIs in the region invest in diversifying improved cultivars use to identify those best suited to the agro-ecological conditions of the region and that the knowledge gained from these trials be shared with the local community. It is further recommended that LAIs invest in water conservation to maximize crop water use, for example maintaining soil surface cover to decrease evaporation losses before investing in irrigation.

14.2. The Nanyuki region

The Nanyuki SSFs were achieving resource-efficient yields for the level of input resources they used within the context of Nanyuki as a climactically variable region with a high likelihood of crop failures. The LAIs technological adoption of fertigation and greenhouse climate-control allow for a higher level of agronomic precision to be met that is not possible under the field conditions of SSFs. The most constraining factor identified by both production systems was the unpredictability of climate and water availability. Results indicate that the LAIs have a higher WF per ha, but due to their high yields, they had a lower WF per unit yield. Water conflicts are particularly significant in the Nanyuki region as water is scarce during the dry season and competition for the resource is high. A sustainable solution that guarantees the future continuation of both sectors would require that the pressures on rivers, particularly during the dry season, be minimized and water use efficiency improved by both production systems.

To mitigate pressures on shared blue water resources, LAIs are investing in boreholes for groundwater abstraction as well as rain water harvesting. Our results show that the irrigation demands during the three-month dry season could be fully met by harvesting rainfall off the greenhouse roofs and dams during three months of the rainy season. However, the harvested water is then considered as blue water, and although the impact of this abstraction on river flow is unknown it is expected that rain water harvesting will have some impact on blue water resource availability. It is recommended that LAIs invest in a type of cover to decrease evaporation from their dams' water storage surface, this has the potential to substantially decrease WF by almost half. The conversion from an open-fertigation system to a closed-fertigation system also has the potential of decreasing WF as well as decreasing Eutrophication Potential (EP). The impact of borehole abstractions could not be quantified in this study, but warnings by Lanari (2014) that the excessive use of borehole water could have potentially devastating consequences in the long-term as the interactions between aquifers and river replenishment are unknown, are supported. Although water stress was a major limiting factor to SSF production in the region, SSFs were not fully utilizing green water, as their crop water use was low and evaporation rates high. It was therefore recommended that water conservation such as those proposed by Njeru & Gitonga (2004) for the Nanyuki region be implemented.

In terms of GWP, EP, AP, and NRE, the LAIs in Nanyuki had the highest environmental impacts per unit area. This was due to the high rated of agro-input and fuel consumption which it is argued were critical to achieving high-quality roses. Comparatively, the SSF scenario had a negligible EI over all indicators, except WF. It was concluded that the input intensification by LAIs significantly increased EIs per ha to a point where EIs by SSFs became negligible. Therefore, further research focusing on decreasing the EIs of LAI systems and on increasing the agronomic efficiency of SSF systems in the Nanyuki region is advised in order to ensure the growth of both these sectors and their ability to co-exist.

14.3. The Nanyuki region versus the Gurúè region

A case-study comparison between the production systems in Gurúè and Nanyuki highlight the importance of viewing agronomic efficiency and EIs within a regional context. Both regions experienced conflict between SSFs and LAIs over limited resources, in Gurúè the major conflict is around land while in Nanyuki the conflict primarily is over water resources. These resources were shown to be either inefficiently utilized or degraded by both SSFs and LAIs. For Gurúè, both SSFs and LAIs production systems resulted in unsustainable soil degradation and both production systems were producing crops yields at less than half of their yield potential under optimal growing conditions. In Nanyuki, both SSF and LAI production systems were inefficiently utilizing green water resources. Therefore, although fair resource allocation should be a priority under these limiting environments, it is recommended that there be continued research and extension efforts emphasised on improving resource-use efficiency in both production systems as part of the solution to mitigating conflict between them.

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ZAEHRINGER, J. G., WAMBUGU, G., KITEME, B., ECKERT, S., 2018. How do large-investment agricultural investments affect land use and the environment on the western slopes of Mount Kenya? Empirical evidence based on small-scale farmers' perceptions and remote sensing. *Journal of Environmental Management* 213:79–89.

Appendix

Appendix A: Additional details concerning the AFGROLAND research project

WP3 team members

- Dr. Julie Zaehringer (University of Bern)
- Dr. Sandra Eckertt (University of Bern)
- Prof. Michael van der Laan (University of Pretoria)
- Prof. John Annandale (University of Pretoria)
- Maya da Silva (University of Pretoria)

Partner institutions

- CIRAD (French Agricultural Research Centre for International Development), France; Ward Answeeu (Lead), Perrine Burnod, Magalie Bourblanc, Even Fouilleux
- CDE (Centre for Development and Environment, University of Bern), Switzerland; Peter Messerli, Julie Zaehringer, Sandra Eckert, Markus Giger
- University of Pretoria, South Africa. Johann Kirsten, Sheryl Hendriks, John Annandale, Michael van der Laan, Lorenzo Fioramonti, Camilla Adelle, Maya da Silva
- Malagasy Land Observatory, Madagascar, Rivo Andrianirina-Ratsialonana
- CETRAD (Centre for Training and Integrated Research in ASAL Development), Nanyuki, Kenya, Boniface Kiteme
- Universidade Católica de Moçambique - Facultade de Agricultura de Cuamba, Mozambique
- ILC (International Land Coalition), Mike Taylor
- NEPAD Business Foundation, Henri Minnaar

Research papers from the project

- ECKERT, S., KITEME, B., NJUGUNA, E., ZAEHRINGER, J. G., 2017. Agricultural expansion and intensification in the foothills of Mount Kenya: A Landscape Perspective. *Remote Sensing* 9:784-804.
- ZAEHRINGER, J. G., WAMBUGU, G., KITEME, B., ECKERT, S., 2018. How do large-investment agricultural investments affect land use and the environment on the western slopes of Mount Kenya? Empirical evidence based on small-scale farmers' perceptions and remote sensing. *Journal of Environmental Management* 213:79–89.
- A second report on the farm inventory was completed in June 2017. Interviews with key decisions makers on investments policies and awareness of and application of international guidelines were conducted in early 2017.The respective report is in preparation.

Appendix B: Large-scale agricultural investment (LAI) semi-structured interview guide created by Maya da Silva with the guidance of Prof. Michael van der Laan

1. Interview number / code	
2. Name of interviewer	
3. Is there an on-site weather station with data that you could share?	
4. If a soil analysis or farmer's analysis has been performed, could the results be shared?	
4.1. How do you prepare your soil before planting (e.g. tillage)?	
4.2. Do you leave any crop residues on the soil surface after harvesting?	
4.3. In your opinion what is the major soil weakness? (e.g. fertility, acidity, water holding capacity etc.)	
5. What crops (and cultivars) are produced, and on how many ha of land?	
5.1. What is the sowing and harvesting dates c for each crop?	
5.2. What is the cropping density for each crop?	
6. Do you use irrigation? If so what equipment and scheduling routine is utilized?	
7. Could the following information on fertilization be provided:	
7.1. What **type** of fertilizers do you apply to the soil and at what **quantity** and **frequency**, if a fertilization schedule is available, could it be provided?	
8. Could the following information on pest and disease control be provided:	
8.1. What pests and diseases are an economic problem for each of the crops grown on the farm	
8.2. How are those pests and diseases managed, if chemical control is used, how often are the crops	

sprayed and what products are used (is there a schedule that can be provided?)	
8. Could the following information on mechanization be provided:	
8.1 What mechanization is currently used at the farm in terms of tractors and trucks etc 8.2. How much fuel is used per acre or per month or year on the farm?	
8.3. Do you hope to increase the technology and mechanization of your farm?	
9. Could the following information on structures be provided:	
9.1. Do you have any storage structures on the farm (e.g. silo)?	
10. What are the major challenges to production at the farm, and in your opinion, what is the most limiting factor to yields and production	
11. Additional comments	

Appendix C: Small-scale farmer (SSF) semi-structured interview guide created by Maya da Silva with the guidance of Prof. Michael van der Laan

1. Interview number / code	
2. Name of interviewer	
3. Town and GPS coordinated	
4. Crops	
5. Sowing and harvesting date	
6. Weeding date	
7. Fertilization (Y/N)	
7.1. Fertilizer type and quantity	
7.2. Fertilizer application date	
8. Pesticide use (Y/N)	
8.1. Pesticide type and quantity	
8.2. Pesticide application date	
9. Seed source and seeding rate	
10. Harvest method	
10.1. Post-harvest treatment?	
10.2. Post-harvest storage	
12. Yield for each crop	
13. Do you rotate crops?	
13.1. Length of rotation cycle	
14. Do you practice mixed cropping?	
15. What do you do with crop residues?	
16. Are there problems with pest and diseases? Can you identify them?	

Appendix D: Household survey interview guide created by WP3 researchers

Interview number / code	
Name of interviewer	
Name and contact of interviewee (if agree)	
Gender of interviewee	
Age of interviewee	
Date and Time of interview	
Place of interview *(e.g. homestead, field, a public place etc.)*	
Coordinates of place of interview	
Coordinates of interviewees fields (if possible)	

Part 1: Household characteristics and involvement with LAIx[1]

1.1	Is (or was) your household engaged in any activities using cropland? (Yes, go to 1.1.2) (No, go to 1.1.1)	
1.1.1	If no, why, and what are your households' activities for income generation?	
1.1.2	If yes, what is your main source of income generation?	

1.2.	What crops do you plant?	
1.2.1.	Which of them do you sell?	
1.2.1.1	Who are you selling to? (contract farmer, market, LAIx)?	
1.2.1.2	If you are selling to LAIx, how regularly and do you get a higher price from LAIx than on the usual market?	
1.2.2	Which of them do you keep for own consumption?	

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[1] LAIx is the investment / agribusiness in whose neighbourhood the interviewed farmer lives

1.3	How big is the total area of your cropland? (in hectares) How many machambas do you have? How big is each one?	
1.3.1	How long does it take to get to each machamba (walking)?	
1.3.2	How often do you go to your machamba? (every day, once a week etc)	
1.3.3	Are any of your machambas located near a river? Which one and how far away from the river?	

1.4	How long have you been living in this place?	
1.4.1	If moved here from somewhere else: why?	
1.4.2	How long do you use a machamba before moving? (Is it different for the machambas next to the river?)	
1.5	How many people belong to your household[2]?	

1.6	Is any household member working for LAIx at the moment (with our without contract, temporary, through contract farming etc.)?	
1.6.1	If no, was this the case earlier and why was it stopped?	
1.6.2	If no, why not?	
1.6.3	If yes, what kind of job?	
1.6.4	If yes, what kind of contractual arrangement? (*e.g. permanent contract, temporary, contract farming*)	
1.6.5	If yes, do you have enough labour force for your own cropland?	

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[2] All people that are financially supported including children living in the city for schooling etc.

1.7	Do you own livestock? If yes, how many heads of each type (cows, goats, sheep, pigs)?	
1.7.1	Do you own grazing land for your livestock or do you use communal land for grazing?	
1.7.2	How big is the grazing land you own (hectares)?	
1.7.3	What do you use the livestock for (sell, consume animal products, work on farms)?	

Part 2: Land use and land (including soil and water) management change due to LAIx Cropland change

2.1	Since what year do you cultivate or own your current area of cropland?	
2.2	Did you have any cropland which was taken by the LAIx? (If yes, ask 2.2.1-2.2.7) (If no, go to 2.3.)	
2.2.1	How big was this cropland (in hectares)?	
2.2.2	Which crops did you plant on that land?	
2.2.3	Were you compensated by LAIx for the cropland they took and if yes how much Meticals per hectare?	
2.2.4	Did you acquire new cropland when your cropland was taken by LAIx? (If yes, ask 2.2.5-2.2.7)	
2.2.5	How much (in hectares)?	
2.2.6	What kind of land use was on this new cropland when you acquired it (e.g. forest / bush, grazing land, cropland)?	
2.2.7	What are the differences between the new cropland and the cropland which was taken by LAIx (e.g. soil quality, suitability for mechanization, rainfall etc.)?	

2.3	Has the size of your cropland changed in the last 10 years? (If yes, ask 2.3.1-2.3.4) (If no, go to 2.4)	

2.3.1	Increased / decreased by how many hectares?	Increased: Decreased:
2.3.2	What land use was present before the increase? What land use was present after the decrease?	Before: After:
2.3.3	In which year did the size change?	
2.3.4	Why did the size change?	

2.4	Have you changed anything with respect to your cropland management and what? (*e.g. crops planted, agricultural practices used, change in irrigation frequency / quantity, new tools, new inputs etc.*) (If yes, ask 2.4.1 – 2.4.4) (If no, go to 2.5)	
2.4.1	In which year did this change happen?	
2.4.2	Why did this change happen?	
2.4.3	Do these changes have any impact on the following:	Please circle: -2 strong decrease, -1 decrease, 0 no change, +1 increase, +2 strong increase
2.4.3.1	Crop yield	-2, -1, 0, 1, 2
2.4.3.2	Crop production	-2, -1, 0, 1, 2
2.4.3.3	Crop diversity	-2, -1, 0, 1, 2
2.4.3.4	Soil quality (fertility, structure etc.)	-2, -1, 0, 1, 2
2.4.3.5	Irrigation water use	-2, -1, 0, 1, 2
2.4.4	Did the LAIx have anything to do with these changes?[3] (if not mentioned yet)	

Grazing land change

Interviewer: For households using grazing land today (see 1.7.1) ask the following questions. For households not using grazing land today go to 2.7.

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[3] e.g. less labour available because household member working with LAI, trainings, availability of new tools or inputs due to CSR projects, new market opportunities, less land available because taken by investors etc.

2.5.	Has the area available for grazing changed? (If yes, ask 2.5.1-2.5.4) (If no, go to 2.6)	
2.5.1	Increased / decreased by how many hectares?	
2.5.2	What land use was present before the increase? What land use was present after the decrease?	Before: After:
2.5.3	In which year did the area change?	
2.5.4	Why did the area change?	
2.6.	Has anything changed with respect to your use of grazing land and what? *(e.g. new places for grazing, new grazing times, new practices such as stall feeding, new types (or abandonment) of cattle*) (If yes, ask 2.6.1-2.6.3) (If no, go to 2.7)	
2.6.1	In which year did the change happen?	
2.6.2	Why did the change happen?	
2.6.3	Did the LAIx have anything to do with these changes (size or use) and what? (if not already mentioned)	

Forest change

2.7.	Has the area of forest or tree cover in the area changed? (If yes, ask 2.7.1-2.7.4) (If no, go to 2.7.5)	
2.7.1	Increased / decreased?	
2.7.2	Are you talking about natural tree cover or planted trees (e.g. eucalyptus, mango etc.)?	
2.7.3	Why did it happen?	
2.7.4	In which year (or decade) did it happen?	

2.7.5	Is there still some forest / natural tree cover available in your area? (If yes, ask 2.7.6-2.7.8) (If no, go to 2.7.9)	
2.7.6	Which of the following benefits does the forest provide to you?	
2.7.6.1	Timber / construction wood?	
2.7.6.2	Firewood	
2.7.6.3	Medicinal plants	
2.7.6.4	Wild fruits / foods	
2.7.6.5	Freshwater source	
2.7.6.6	Wild animals for hunting	
2.7.7	How far do you have to go to collect these products (km or hours spent walking)?	
2.7.8	Apart from these products, do you think the forest is important for anything else and what? (Go to 3.1.)	

2.7.9	How do you obtain the following products today?	
2.7.9.1	Timber / construction wood?	
2.7.9.2	Firewood	
2.7.10	Do you think that the disappearance of forest has any other consequences / impacts for you?	

Part 3: Perceptions of direct impacts of LAIx on the environment and on human well-being

3.1.	Does the LAIx have any positive impacts for your household and which ones?	
3.2.	Does the LAIx have any negative impacts for your household and which ones?	
3.3.	Does the LAIx have any environmental impacts? (maybe give some examples of environmental impacts because they might not know what it means?)	

3.4.	Do you apply irrigation for your own cropland?	
3.4.1.	What is your source of irrigation water (e.g. river, borehole, well, dam etc.)?	

3.4.2	Do you have sufficient irrigation water and if not, why?	
3.4.3	How is the quality of your irrigation water and if bad, why?	
3.4.4	Where did you obtain the knowledge about how to irrigate?	
3.4.5	Where did you get equipment for irrigation from?	

3.5.	What is your source of drinking water?	
3.5.1	Do you have sufficient drinking water and if not, why?	
3.5.2	How is the quality of your drinking water and if bad, why?	

3.6	Do you apply any fertilizers to your crops and if yes, where do you get them from?	
3.6.1	If no, why not?	
3.6.2	Can you get fertilizers from LAIx, and if yes, are they cheaper than in the shops?	
3.6.3	How do you make decisions about which fertilizers to apply, the quantity and when to apply them?	

3.7.	Do you apply any chemicals (pesticides/herbicide) to your crops and if yes, where do you get them from?	
3.7.1	If no, why not?	
3.7.2	Can you get chemicals from LAIx, and if yes, are they cheaper than in the shops?	
3.7.3	How do you make decisions about which chemicals to use, what quantity to apply and when to apply?	

3.8	Do you think LAIx has any impact (positive or negative) on the health of	

	this community and if yes, what impact?	
3.9	Has LAIx provided any infrastructure to this community?	
3.10	Are there any conflicts between members of the community due to LAIx?	
3.11	Are there any conflicts between members of the community and the LAIx?	
3.12	In general, do you find it good that LAIx is here or would you prefer them to leave?	

Interviewer: If the interviewee stated (under 1.6) that he used to work or currently works for LAIx ask the following questions.

3.13	What were the positive and negative aspects when you worked for LAIx?	
3.14	When you worked for LAIx, did you work with chemicals?	
3.14.1	Did you get protective clothing?	
3.14.2	Did you experience any health issues?	
3.15	Did you learn something from LAIx that you can use for your own crop cultivation and if yes, what?	

Part 4: Detailed information on crop production

4.1 For each of your crops, could you give an average of the area planted for each crop and an average production per year?

Crop	Subsistence (S) or commercial (C) use	Average area planted	Unit	Average production per year	Unit

4.2 What agricultural management practices do you use?	Explain
a) How do you prepare your soil before planting? (burning, tillage, ridges etc)	
b) Crop rotation? Yes____ No____	
c) Fallows / resting periods? Yes____ No____	
d) Tractors or any other machinery? Yes____ No____	
e) Do you ever leave crop residues on the soil surface? Yes____ No____	
f) Weeding? Yes____ No____ If so, is it mechanical, manual, or chemical control?	
How do you make decisions on planting dates? (e.g. extension officer, rainfall, time of year)	
Do you have any storage facilities/structures that you use? Yes____ No____	
How much time do you spend in the field per day? (man hours/ha)	
What is your perception of the soil quality? Good or bad soil?	
If bad, what is the problem with your soil?	
What is the biggest problem for production on your farm?	

4.3 If the household uses irrigation for his own crop production, fill the following table.

Crop	Irrigated (tick if yes)	Irrigation type (sprinkler, furrow, drip…)

4.4 If the household uses pesticides/herbicides fill the following table.

Crop	Pest/Weed	Pesticide/Herbicide type	Quantity used during growing season	Applied before or after the pest / weed appears?

4.5 If the household uses fertilizers, please fill the following table.

Crop	Fertiliser type	Quantity used during growing season (unit/season)
