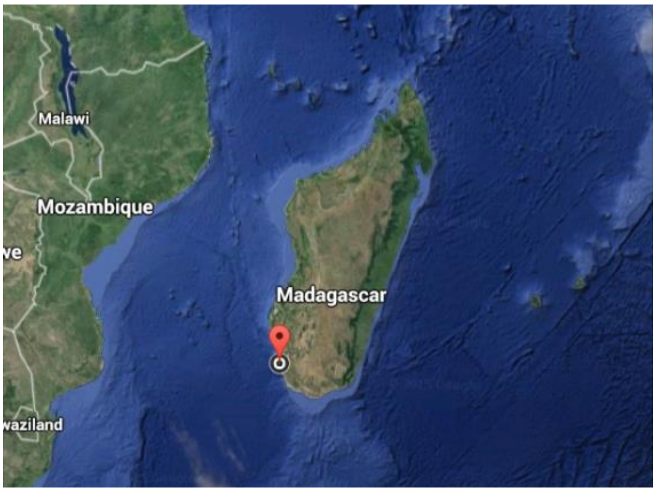
Simulated impacts of climate change adaption strategies on productivity in smallholder farms in Southwest Madagascar



By Andrew Dawson

Masters Thesis
FSE 80430

Farming Systems Ecology Group
Droevendaalsesteeg 1 – 6708 PB Wageningen - The Netherlands

WAGENINGEN UNIVERSITY
WAGENINGEN UR

Simulated impact of climate change adaption strategies on productivity in smallholder farms in Southwest Madagascar

Master Thesis

April 2016

Name student: Andrew Dawson
Registration number student: 891024173130
Credits: 36 ECTS
Code number: FSE-80436
Name course: MSc Thesis Farming Systems Ecology
Period: 2016
Supervisor(s): Dr. ing. Johannes Scholberg and Dr. Stéphanie Alvarez
Examiner: dr.ir. Jeroen Groot

Preface

This thesis explores the effects of agricultural interventions on crop productivity in southwest Madagascar. Crop modelling was used to simulate the impact of interventions over thirty years of weather data scenarios. Interventions were developed following discussion with local development organisations and farmers in order to determine "best bet" vs "best fit" opportunities. Furthermore, the study developed and used an expert typology for the area as basis to assess specific farming practices for representative farm types and how this relates to alternative interventions. Overall, the research helps to show the complex interplay of agronomic, social and environmental factors which provide both opportunities and constraints to the smallholders in southwest Madagascar.

The report was based on a collaborative effort of the Farming Systems Ecology Group (FSE) and a local research initiative and was part of the Master's degree program in Organic Agriculture at Wageningen University and Research Centre, the Netherlands. It was made possible by the local support of Big Red Earth, a development organisation cultivating agricultural capacity in southwest Madagascar.

My thanks go to the research team of the FSE group: Dr. ing. Johannes Scholberg, Dr. Stéphanie Alvarez and Hongkun Oh for their advice and support. We overcame many obstacles together, not just in the research, but also power failures, flat tires, and labour strikes at Air Madagascar. It has been a fascinating project that I sincerely hope will aid further development in the southwest region.

Thanks to the team at Big Red Earth: Dr. Susan Hanisch, Dustin Eirdosh, Fenohaja Babarezoto and Boris Romuald. In addition to local student and translator Christolain Andriniako. You all gave unwavering help and support throughout the research and helped me acclimatize to life in Madagascar. You have a great approach to development and I wish you every success. Further thanks to Hendrik Hänke of the University of Göttingen for providing data to help ground the study in reality. Your kindness will not be forgotten.

At the culmination of gratitude giving, thanks goes to my family and friends with whom I share all these adventures.

"The robin is not in the cage and nor should it be"

Best,

Andy

Executive Summary

This study was carried out to capture farm practices and explore opportunities for agricultural development in the context of variable weather conditions in Southwest Madagascar. To achieve this, a multi component study was carried out to account for the many factors influencing development in the region and provide context-relevant advice that is tailored to the views of local stakeholders as related to the local context. To begin with, an expert-based typology was developed in collaboration with local development organisations. This provided four main farm types which could be found in Efoetsy, a village in the Southwest of Madagascar. This featured poor, average and rich farmers along with farms where agriculture is complementing other activities and/or sources of income. These farm types were used to select representative farms for the farm surveys and thus assess the main characteristics and practices per farm type, and which interventions may be suitable for the farm type (best bet vs best fit approach). Generally the farms were found to be very similar in their cropping activity with only subtle differences related to sowing time, sowing density and weeding. Consequently one farm was used as the baseline for exploring interventions, but existing farm differences were used to contextualize model-based explorations further.

Best bet and best fit agricultural interventions were developed in collaboration with local development organisations and smallholders. The most popular of these interventions, or those with an interesting contrast between the development organisation and smallholder's opinions, were considered for investigation. Consequently crop cultivar, weeding and the use of manure and/or crop residues were investigated. These interventions, in addition to sowing time and sowing density, were modelled in APSIM (the Agricultural Production System Simulator) for millet, maize and mung bean which, besides cassava, farmers listed as being the most important crops. The simulation was performed using 30 years of weather data generated in MarkSim which allowed the efficacy of an intervention to be assessed over a large range of weather scenarios.

Results of the baseline simulation showed that the cumulative yields of millet, maize and sorghum, were substantially higher than those for beans, cowpea and mung bean, with millet being the most reliably yielding crop. Sowing density-based sensitivity analysis showed that the density of millet, maize and sorghum were close to optimal, but that mung bean and cowpea benefitted from a higher sowing density. Furthermore it showed that differences in the sowing density used by farmers are likely to affect crop yields. Based on the comparison of sowing times: October, December vs January it appears that sowing time did affect crop yields, though only marginally for millet, maize and sorghum. For mung bean and cowpea the effect was proportionally greater with both achieving moderate improvements from sowing in December. Thus showing that farmer differences in sowing time may affect the efficacy of interventions. For the intervention scenarios, the exploration of cultivars showed that some cultivars have much greater yield potential than others. Supporting cultivar introduction as one of the main ongoing development options of local NGO's. The different weeding scenarios demonstrated that weeding was essential to avoid crop failure in all scenarios and that there is an interaction between the timing and frequency of weeding. Under weed pressure, maize and mung bean achieved their highest yield when three weeding's occurred at a weed biomass threshold of 125 kg/ha, whereas millet had slightly higher yields when weeded twice at a weed biomass threshold of 250 kg/ha. Simulations also investigated the impact of crop residue retention and manure application. When residue was retained and 20 ton/ha of manure was applied, the probability of crop yields over 500 kg/ha

increased from 40% to 73% for maize and from 62% to 78% for millet, but mung bean showed no response. Thus showing that crops had a mixed response to manure amendment.

A final multiple factor yield-gap exploration compared the impact of crop density, irrigation and urea in conditions with weeds, and free from weeds, for millet. This simulation clearly shows that yields were most strongly defined by water limitation, once this limitation was overcome sowing density had the largest impact. Then at the higher sowing density the beneficial impact of urea on crop yields became more apparent. Thus the simulation shows that water imposes a severe limitation on crop yields, and that when this is overcome other factors become more important.

The simulations help to clarify the complex interplay of farmer management, interventions and local environmental conditions. Considerable differences were found in the crop response to changes in farmer management. For example some of the crops benefited from sowing in December while others in January and some crops benefit from a higher sowing density whereas others when it was lowered. This was also apparent for modelled interventions, large differences in response were observed for the different crops. Consequently, the study helps highlight that the success of agricultural development in improving agricultural productivity in the region will depend on crop specific approaches which adequately account for local practices and conditions.

Abbreviations

APSIM Agricultural production systems simulator

C Carbon

C:N Carbon: Nitrogen ratio

CO_2 Carbon dioxide

DUL Drained upper limit water content

FAO Food and Agriculture Organization

Fbiom Decomposable carbon

Finert Carbon not susceptible to decomposition

GDP Gross Domestic Product

GHG Green House Gas

Ha Hectare

Kg Kilogram

LL15 Lower limit water content

OC Organic Carbon

OM Organic Matter

% Percentage

SAT Saturated volumetric water content

m Meter

N Nitrogen

Table of Contents

Preface i
Executive Summary ii
Abbreviations iv
List of Figures vii
List of Tables x
1. Introduction 1
1.1. Global Context 1
1.1.1. Agriculture and Climate 1
1.1.2. Simulation Modelling 3
1.2. Local Context 3
1.2.1. General Description 3
1.2.2. Local Food Security 5
1.2.3. Biophysical Characteristics 6
1.2.4. Agricultural Systems 6
1.2.5. Agricultural Development 7
1.3. "*Best bet*"" vs "*Best fit*" Practices 8
1.4. Climate Change and Farming System 9
1.5. Farming System Typology 10
1.6. Purpose of the study and Research Objectives 12
2. Materials and Methods 13
2.1. Research Site 13
2.2. Conceptual Framework 14
2.3. Methodological Framework 15
2.4. Farm Typology 16
2.5. Farm Survey 17
2.6. Best Bet and Best Fit Interventions 17
2.7. The APSIM Model 18
2.8. APSIM Parameterisation 18
2.8.1. Crop Parameterisation 19
2.8.2. Soil Parameterisation 20
2.9. Weather data 22
2.10. APSIM Validation 24
2.11. Modelled Intervention Scenarios 24
2.12. Limitations 27

3. Results and Discussion **28**
3.1. Expert Farm Typology 28
3.2. Farm Characteristics 29
3.3. Farm management practices 30
3.4. Best Bet Options 32
3.5. Best Fit Options 32
3.6. Participatory-based Selection of Proposed Interventions 34
3.7. Baseline Model-based Yield Risk Assessment 34
3.8. Model-based evaluation of differing cropping practices 36
3.8.1. Sowing Density 36
3.8.2. Sowing Time 39
3.9. Model-based Exploration of Interventions 41
3.9.1. Cultivar 41
3.9.2. Time and Frequency of Weeding 45
3.9.3. Application of Crop Residues and Manure 52
3.9.4. Assessing Relevant Yield-limiting and Yield-defining Factors 57
4. Conclusion **59**
References 61
Appendix I 67
Appendix II 68
Appendix III 69

List of Figures

Figure 1 a) Projected change in average annual temperature for the period 2071-2099 as compared to 1970-1999 under RCP 2.6 (lower GHG concentrations) and RCP 8.5 (higher GHG concentrations). b) The projected change in average annual precipitation for the period 2071-2099 as compared to 1970-1999 under RCP 2.6 (lower GHG concentrations) and RCP 8.5 (higher GHG concentrations) (IPCC, 2013) 1

Figure 2 Projected changes in precipitation extremes for the period 2080-2099 as compared to 1980 and 1999 based on a multi-model simulations from nine coupled global climate models for the A1B Scenario. Precipitation intensity is defined as: “The annual total precipitation divided by the number of wet days”. Dry days are defined as: “the annual maximum number of consecutive dry days” (Bates et al., 2008)........ 2

Figure 3 The impact of climate change on agricultural yields (Cline, 2007) 2

Figure 4 Household food insecurity and poorest wealth quintiles Madagascar (from Rakotonirainy et al., 2011) 4

Figure 5 Map of Madagascar with the southwest region (Atsimo-Andrefana) highlighted red (d-maps.com, 2014). The communes (Brinkmann et al., 2014) 5

Figure 6 Soil types and elevation in the southern Atsimo-Andrefana region (adapted from Hanisch, 2015) 6

Figure 7 Two different approaches to innovation: the linear top down approach and the interactive participatory approach (Le Gal et al , 2011). 9

Figure 8 Frequency of drought events for maize and cassava during the period 1995-2009 (WFP, ND) 9

Figure 9 The yield change for rain-fed maize caused by climate change between 2000 and 2050 (Vololona et al., 2013) 10

Figure 10 Visual depiction of a farm typology. The initial diversity in a farming system is assessed based on distinguishing farm characteristics enabling the grouping into four distinct farm types. 11

Figure 11 The location of Efoetsy village within Madagascar (A) and an aerial view of the village with surrounding fields (B) (Google Earth Pro, 2015) 13

Figure 12 Left: A general overview of the original DEED framework (A,) adapted from Giller et al., 2008 along with the corresponding research components implemented during the current research (B). 14

Figure 13 The general operational and methodological framework employed for this research 15

Figure 14 Expert knowledge farm typology. A heterogeneous population of farms are grouped by criteria developed with local experts. 16

Figure 15 Schematic representation of APSIM engine and modules (Cox et al, 2001) 18

Figure 16 Screen shot for the soil database of HarvestChoice (2010) Efoetsy village is located on the map in an area which has three probable soil types: HC_GEN0026, HC_GEN0011 and HC_GEN0017. 21

Figure 17 Boxplot of average annual rainfall from 30 years of MarkSimGCM generated weather data for Efoetsy with range, median and quartiles with supporting of values. 22

Figure 18 Monthly distribution of precipitation from 30 years of weather data generated for Efoetsy using MarkSim. Note: outliers are shown for any point 1.5 times the interquartile range bellow the lower quartile or above the upper quartile, ... 23

Figure 19 Daily mean temperatures per month over 30 years of weather generated for Efoetsy using MarkSim. Note: outliers are shown for any point 1.5 times the interquartile range bellow the lower quartile or above the upper quartile, ... 23

Figure 20 Map of Efoetsy village and surrounding fields. Fields of the surveyed farms are highlighted. 30

Figure 21 The probability of exceeding a given yield of common crops in Efoetsy over 30 years based on the simulation parameters. The legend indicates the crop sown and the date of sowing (October) 34

Figure 22 The probability of exceeding a given yield of Millet, Maize, Mung bean, Cowpea and Sorghum based on 30 years of weather date for different sowing densities: Half density (hd) normal density (nd) double density (dd) and triple density (td) based on the simulation parameters. In addition to Farm D (FD) in which the sowing density and row spacing of Farm D was modelled. 38

Figure 23 The probability of exceeding a given yield of millet, maize, mungbean, cowpea and sorghum over 30 years for October (oct), December (dec) and January (jan) sowing dates, based on the simulation parameters.. 40

Figure 24 The probability of exceeding a given yield of millet over 30 years for different cultivars (Wrajpop, ZATIB and bj104), based on the simulation parameters. 41

Figure 25 The probability of exceeding a given yield of maize over 30 years for different cultivars (mwi_local, timor local and Pioneer_3237), based on the simulation parameters. 42

Figure 26 The probability of exceeding a given yield of mung bean over 30 years for different cultivars (Satin, Green diamond and Celera), based on the simulation parameters. 43

Figure 27 The impact of weeds on Millet yields under different weed management conditions. Millet 1 x 125 kg corresponds to one complete weeding at a weed biomass threshold of 125 kg/ha, Millet 2 x 250 kg corresponds to two complete weedings when weed biomass threshold reaches 250 kg/ha and so forth. 46

Figure 28 The impact of weeds on maize yields under different management conditions. Maize 1 x 125 kg corresponds to one complete weeding at a weed biomass threshold of

125 kg/ha, Maize 2 x 250 kg corresponds to two complete weedings when weed biomass threshold reaches 250 kg/ha and so forth. 48

Figure 29 The impact of weeds on mung bean yields under different management conditions. Mungbean 1 x 125 kg corresponds to one complete weeding at a weed biomass threshold of 125 kg/ha, Mungbean 2 x 250 kg corresponds to two complete weedings when weed biomass threshold reaches 250 kg/ha and so forth. 50

Figure 30 The probability of exceeding a given yield of millet over 30 years for different residue and manure scenarios: with residues (R) no residues (NR) with differing levels of manure (M) amendment. 52

Figure 31 The probability of exceeding a given yield of maize over 30 years for different residue and manure scenarios: with residues (R) no residues (NR) with differing levels of manure (M) amendment. 53

Figure 32 The probability of exceeding a given yield of mung bean over 30 years for different residue and manure scenarios: with residues (R) no residues (NR) with differing levels of manure (M) amendment.. 54

Figure 33 Exploration of the limiting factors to millet yields through the use of irrigation (IR), fertiliser (urea), and double density sowing rates (dd) 57

Figure 34 Exploration of the limiting factors to millet yields with weeds with different treatments of irrigation (IR), fertiliser (urea), and double density sowing rates (dd)......................... 57

List of Tables

Table 1 Smallholder coping strategies in South-West Madagascar (FAO, 2014b) 8

Table 2 Overview of the data necessary to parameterize APSIM 19

Table 3 Major crop parameters used for the baseline simulation 19

Table 4 Major crop parameters used for the Farm D simulation... 20

Table 5 APSIM soil parameters used for Efoetsy, soil HC_GEN0026 from HarvestChoice (2010) with LL15, DUL and SAT referring to volumetric soil moisture content at permanent wilting point, field capacity and saturation, OC to organic carbon content, FBiom the decomposable soil carbon, Finert the non-decomposing soil carbon and pH.................... 21

Table 6 Interventions modelled in APSIM, for baseline crop parameters and practices see table 3. 25

Table 7 Expert farm typology for Efoetsy village, bold text indicates factors indicated by experts to be most farm defining. 28

Table 8 The farm characteristics of the four farmers that were interviewed in Efoetsy. Bold text indicated factors which strongly define the farm type... 29

Table 9 Summary of farming practices of the four farmers surveyed in Efoetsy (Y – Yes, N – No).. 31

Table 10 Technical initiatives promoted by local agricultural development organisations to improve productivity in the Efoetsy area. 32

Table 11 Overview of farmers willingness to try several development options (Y: yes, N: No)........ 33

Table 12 Ranking score of crop importance by farmers interviewed in Efoetsy (a score of 4 implies the crop was ranked first, 3 it being ranked 2nd , 2 it being ranked 3rd, and a score of 1 implies it was ranked 4th). 33

Table 13 Yield data of several crops grown in Efoetsy 2014 provided by Hänke (2015). 35

1. Introduction

1.1. Global Context

1.1.1. Agriculture and Climate

Yearly changes in atmospheric conditions are known to account for more than 30% of the overall variation in global agricultural yields (Lobell et al., 2007) due to the impact of radiation, precipitation and temperature on crop growth. This shows that climate variability (the yearly fluctuation in climate above or below the long-term average) can result in large changes in crop yields and system performance. However, the climate not only varies in the short-term, but it also shows long-term changes in terms of temperature, precipitation, along with occurrence of extreme weather events (Houghton et al., 2001) which will greatly impact future agricultural production.

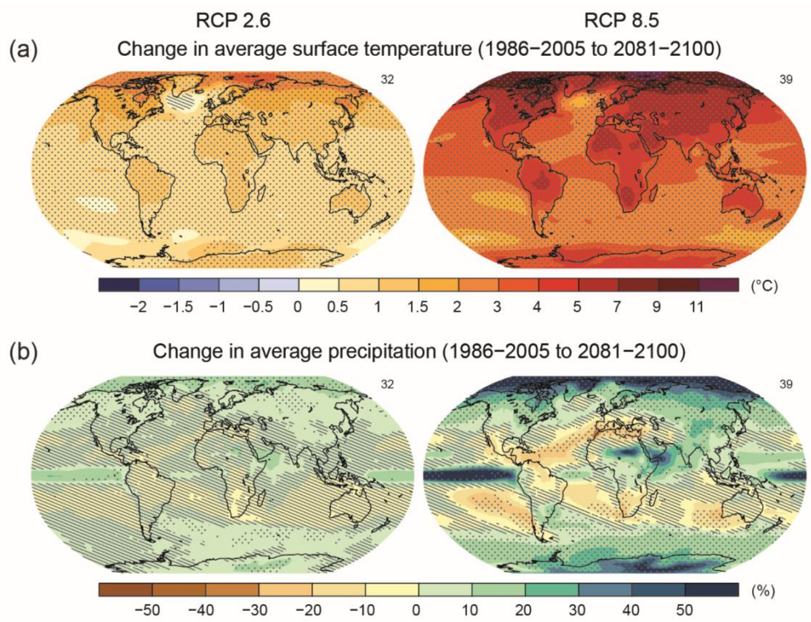


Figure 1: a) Projected change in average annual temperature for the period 2071-2099 as compared to 1970-1999 under RCP 2.6 (lower GHG concentrations) and RCP 8.5 (higher GHG concentrations). b) The projected change in average annual precipitation for the period 2071-2099 as compared to 1970-1999 under RCP 2.6 (lower GHG concentrations) and RCP 8.5 (higher GHG concentrations) (Source: IPCC, 2013)

Climate change and climate variability are caused by the increasing atmospheric concentration of greenhouse gases (GHGs), one of the most significant is carbon dioxide (CO_2). Since the 1750s the atmospheric concentrations have changed from 280 to 400 ppm in 2015. Currently, annual increases amount to 2 ppm and this increase is believed to be responsible for the increasing average global temperature during the 20th century (IPCC, 2013). This effect is expected to continue into the future due to the continued emissions of GHGs. Climate change and variability depend upon past, current and future GHG emissions, and a number of scenarios were developed based on projected trajectories for future GHG emissions. Four distinct scenarios are being used by the IPCC (Intergovernmental Panel on Climate Change), which are known as the Representative Concentration Pathways (RCPs). For instance RCP 2.6 is based on GHG emissions peaking between 2010 and 2020 and then declining thereafter. Conversely, RPC 8.5 is based on emissions continuing to rise throughout the 21st century (Meinshausen et al., 2011). The impacts of these two different scenarios on global temperatures and precipitation are shown in Figure 1.

It is clear from Figure 1 that the impact of GHG emissions on climate change will be region-specific, with latitude and landscape topography determining local impacts. Furthermore, it can be seen that there are large variations between the impacts of the RPC scenarios while pronounced changes in temperature may coincide with changes in precipitation. In addition to these average changes, the incidence of extreme weather events may change as well, as shown in Figure 2. Notably, the rainfall intensity and extreme weather events are likely to increase, in addition to the incidence, duration and severity of droughts (IPCC, 2013).

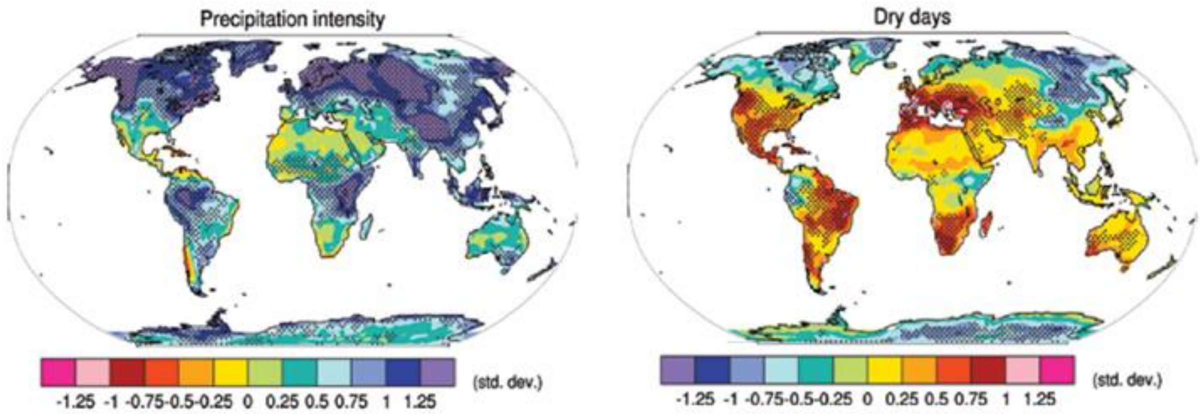


Figure 2: Projected changes in precipitation extremes for the period 2080-2099 as compared to 1980 and 1999 based on a multi-model simulations from nine coupled global climate models for the A1B Scenario. Precipitation intensity is defined as: "The annual total precipitation divided by the number of wet days". Dry days are defined as: "the annual maximum number of consecutive dry days" (Source: Bates et al., 2008)

The impact of climate changes on agricultural production will vary depending on the particular location and agro ecological zone (Gbetibouo et al., 2005). It can be seen in Figure 3 that the regions with cold winters during part of the year are expected to benefit while much of the global south will experience decreases of up to 25%.

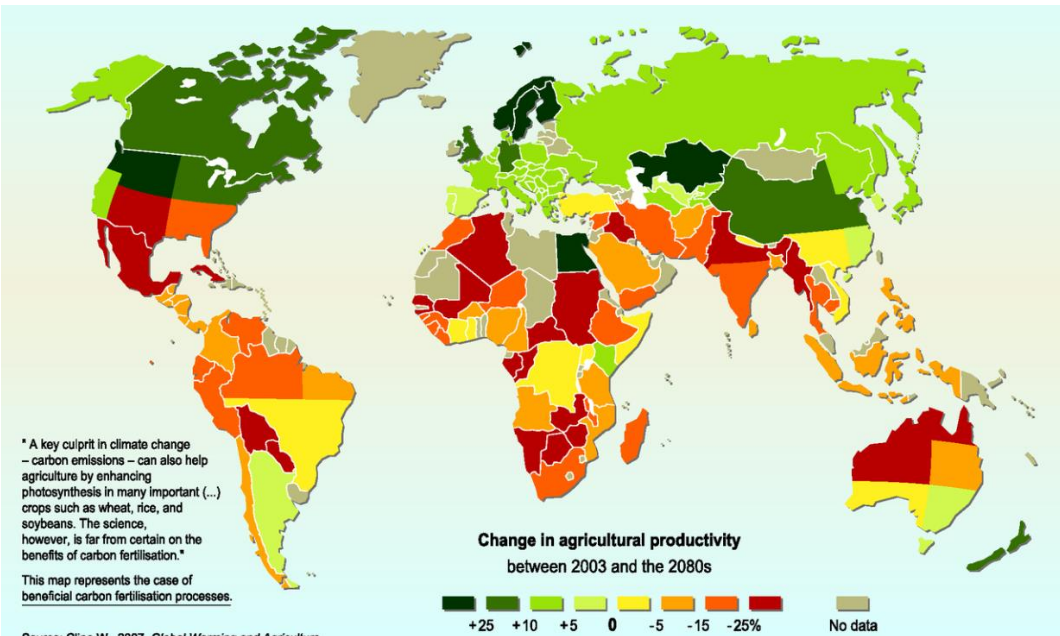


Figure 3 The impact of climate change on agricultural yields (Source: Cline, 2007)

Many of the areas expected to be negatively affected by climate change are also those that currently suffer from low agricultural production and widespread food insecurity. Consequently it becomes imperative to access local risk and develop interventions that take into account a changing and variable climate to ensure future agricultural production. However, knowing which interventions will succeed in a variable climate cannot easily be deduced from agronomic short-term field trials. To address this issue, the use of dynamic models may be desirable as they will allow improved assessment of changes in crop performance and food security across different regions over time (Rosenzweig and Iglesias, 1998).

1.1.2. Simulation Modelling

The Agricultural Production Systems Simulator (APSIM) is a commonly used simulation platform for cropping systems, which is designed to provide predictions of probable crop production using climate, soil, genotype, and management factors (Keating et al., 2003). Historic and/or generated long-term climate data may be used to assess long-term trends in crop production and to explore interventions that would buffer climate change and variability. This allows researchers to assess the probability of specific interventions being successful and to inform research, farm decision making and farm system design. For model-based simulations to be most useful to decision makers, the factors explored must be relevant to the local context both in terms of what is needed, and also viable strategies to achieve this (Meinke et al., 2001). Model-based explorations have been successfully used in Zimbabwe in terms of developing recommendations for fertiliser application (Twomlow et al., 2010). In this context, the standard recommendation of applying 52 kg N ha^{-1} was not feasible as local farmers indicated they could only afford to apply 17 kg N ha^{-1} so this appeared to be a more realistic application rate. A simulation using 46 years of local weather data then showed that rate of return was higher for the lower N dose in most years. Furthermore, almost all farmers achieved yield gains that more than covered the cost of investment. This indicates how simulation models may be used to help inform stakeholder decision making for on farm interventions.

1.2. Local Context

1.2.1. General Description

Madagascar is known as a hot-spot in terms of biodiversity and the prevalence of diverse and unique species. However, this natural richness contrasts starkly with the poverty prevailing throughout the country. Up to 75.3% of the population lives in poverty (World Bank, 2010) with insufficient resources, or capacity, to meet their current needs (Coudouel et al., 2002). Food insecurity is also experienced by 35.2% of the population and an additional 47.9% are considered vulnerable (Rakotonirainy et al., 2011). However, the distribution of poverty and food security is not uniform across the country with the southern area being the most food insecure (Figure 4)

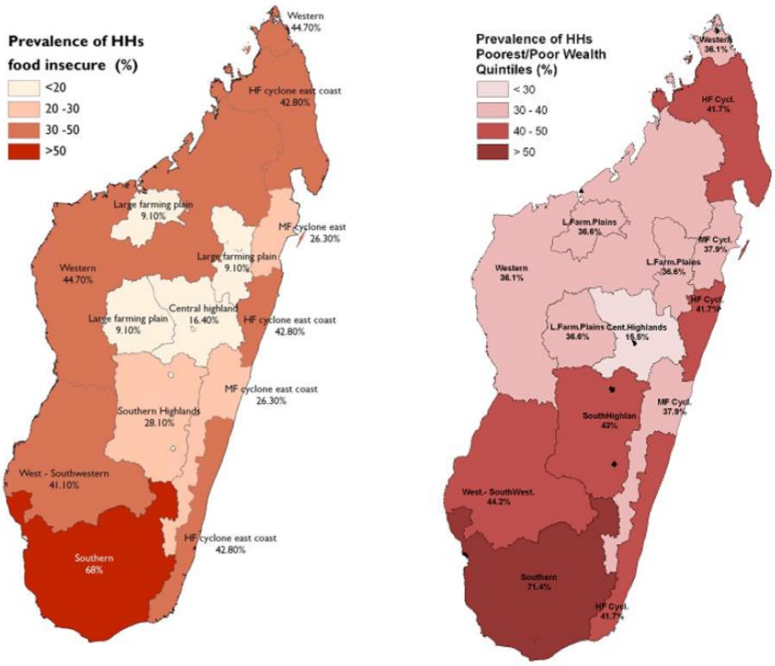


Figure 4 Household food insecurity and poorest wealth quintiles Madagascar (Source: Rakotonirainy et al., 2011)

The livelihood of local communities is often directly or indirectly dependent on agriculture which uses 82% of the total labour force (INSTAT, 2006). However, it is within farm communities that poverty is most acute and prevailing (World Bank, 1996) with one of the main drivers governing this poverty being low agricultural yields. Given the large proportion of the population relying on agriculture for both their livelihood and daily food it is clear that increasing agricultural yields could significantly reduce both poverty and food insecurity (Minten et al., 2008). Consequently, Madagascar has been a priority region for numerous international organizations (e.g. FAO, IFAD, UNICEF, WFP, WHO, UNIKO and UNDP) that implement agricultural development projects (FAO, 2014a).

Nevertheless, progress is slow and the southwest, regionally known as Atsimo-Andrefana, is one of the most vulnerable areas within Madagascar. The South West of Madagascar is subdivided into communes (municipalities); Soalara, Beheloka, Itampolo, Beahitse, Masiaboay, Beantake and Betioky-Sud which contain roughly 185 permanent settlements (villages) and a further 260 hamlets (Figure 5). The commune chosen for this study is Beheloka, located roughly 80 kilometres south of Tolaria and covers an area of 158,000 hectares. Here, there are three major landscape classes: coastal, savannah and plateau. The most densely populated areas are typically closest to the coast while densities on the inland limestone plateau of the Mahafaly are much lower.

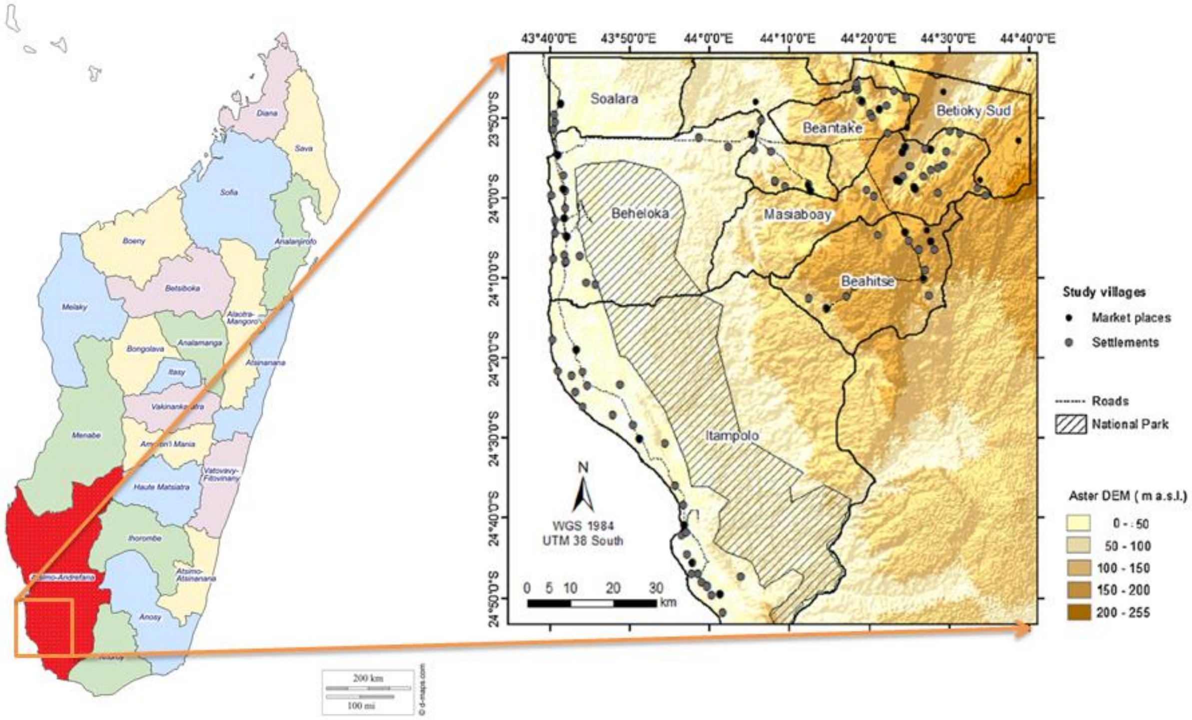


Figure 5 Map of Madagascar with the southwest region (Atsimo-Andrefana) highlighted red (Source: d-maps.com, 2014). The communes (Source: Brinkmann et al., 2014)

1.2.2. Local Food Security

Food security is being defined as "when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (FAO, 1996). When these conditions are not met then people are classed as food insecure. In Southern Madagascar 68% of the population are food insecure (Rakotonirainy et al., 2011) with significant seasonal variation which coincides with the cropping season. The worst period lasts roughly four and a half months and extends from November to February (Minten et al., 2008). Which can be attributed to the reliance on subsistence farming for household food security, and the often low harvests that cannot meet their families' yearly needs. A total of 54% of the households reported that the yields were never sufficient to meet family's needs (Neudert et al., 2014). In this context, one of the most promising interventions to improve food security is to increase the productivity of staple food crops, prevent increases in food prices, and increase farmer income (Dostie et al., 2002). Indeed, Minten et al. (2008) found that doubling rice production reduced food insecurity by 38% and the lean period by 1.7 months. This was attributed to improved farm profits, higher real wages (agricultural workers) and lower real food prices. Based on both direct and indirect impacts, agricultural development can be a promising method to alleviate food insecurity and improve local livelihoods. Nevertheless, in the context of southwest Madagascar it is challenging to overcome production constraints as related to the local biophysical environment.

1.2.3. Biophysical Characteristics

Climate

The climate in southwest Madagascar is classified as semi-arid and with three main seasons: a hot rainy season from December to March followed by a cool and dry season from April to July and hot dry weather from August to November (SuLaMa, 2011). Average rainfall varies with coastal areas receiving the least rain (300 to 350 mm) the savannah the most (500 to 600 mm) and the Mahafaly plateau having intermediate values (400 to 450mm). Average annual temperatures are 22.7°C, ranging from 24.7°C in hotter months to 18.8° C in cooler months. The low rainfall coupled with high evapotranspiration result in widespread water scarcity. Furthermore, rainfall is erratic and droughts can extend for several years (von Heland et al., 2014).

Soil

Prevailing soil types include Calcaric Regosols in the coast region, Lithosols on slopes and hilltops and Calcic Cambisols in depressions (Hillegeist, 2011). The location of these different soil types is shown in Fig 6. Soils on steep eroded slopes generally have low inherent soil fertility and are deficient in Phosphorous (P), Potassium (K), Calcium (Ca) and Magnesium (Mg) (Haut de sigy, 1970) while in the coastal areas soil salinity may occur due to seawater intrusion (Guyot, 2002). The main soil type of cultivated land is Calcaric Regosols which are poorly developed.

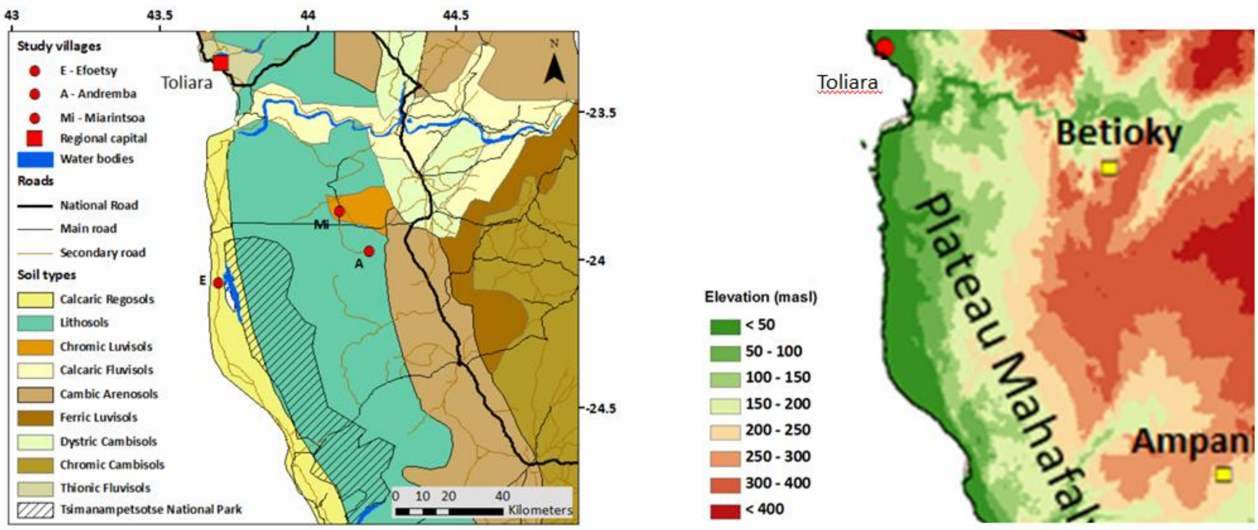


Figure 6 Soil types and elevation in the southern Atsimo-Andrefana region (Source: Hanisch, 2015a)

1.2.4. Agricultural Systems

Current agricultural practices in Beheloka are highly traditional with local varieties, manual labour and low-input used. Local farmers cultivate about 30 different crops and fodder species. The most commonly grown crops include cassava (Manihot esculenta Crantz, 99% of farmers), cowpea (Vigna unguiculata, 84% of farmers), maize (Zea mays L., 83% of farmers), mung bean (Vigna radiata, 69% of farmers) and sweet potatoes (Ipomoea batatas, 64% of farmers) (SuLaMa, 2014).

Long-term cultivated agricultural fields known as "*baiboho*" are located near the village (about a 2 km radius). Additional fields may be cropped temporarily using slash and burn techniques which are referred to as "*hatsaky*", and these fields tend to be more remote (Brinkmann et al., 2014). Temporary fields are continuously cultivated, often during five years, until reduced soil fertility or increasing weed pressure results in a large yield reduction. At this point the land traditionally was left fallow and a new patch of forest cleared and cultivated. However, as population pressures increased and national parks expanded, the area and scope for slash and burn agriculture has declined and farmers are becoming more dependent on permanent fields, which has negative implications for future crop productivity. Thus, crop choice depends largely on soil fertility. In *hatsaky* fields corn is often planted first followed by sweet potato or legumes up until the fifth year at which point the fertility is nearly depleted and only cassava may be grown, which may be maintained for several decades.

Cultivation is generally done manually by household members using simple hand tools, though wealthier farmers may use an ox-plough for fields in the plateau region. The area cultivated by smallholders is mainly governed by labour availably for weeding. Declining soil fertility generally leads to extensification to make up for reduced productivity as only 3% of farmers use fertiliser and it is uncommon for farmers to apply manure to their fields, even when it is available (SuLaMa, 2014). Estimates of crop yields for the area are difficult to obtain. This is likely due to the large intrinsic variability in yields, multiple harvests, and crop use for subsistence rather than sale. For the Mahafaly plateau reported that cassava yields ranged between 1-1.8 Mt DM ha^{-1} (Hanisch, 2015a).

Agriculture in the region suffers from many challenges and constrains including: droughts, flooding, cyclones, the incidence of pests (locusts) and diseases in addition to poor infrastructure (Günther et al., 2009). Other constraints include: poor inherent soil fertility (Battistini, 1964), land tenure, access to markets (Guerra et al., 2014), lack of access to capital and low levels of education (FAO, 2014b). Nevertheless, climactic factors are considered to be the main constraint by many authors. This is echoed by local households who consider lack of (reliable) rain to be their greatest constraint (Neudert et al., 2014). Furthermore, many farmers believe that rainfall has declined since the 1960s (SuLaMa, 2011). It appears that further reductions in rainfall and an increase in temperature across the region associated with climate change and increasing climactic variability will further aggravate this situation (Tadross et al., 2008).

1.2.5. Agricultural Development

In most cases, local agricultural development fails to introduce and support interventions that are relevant and feasible in terms of the local resource availability and inherent social structures. This is one of the primary reasons that the southwest region is being referred to as “The graveyard of development projects” (UNICEF, 2011, p. 1). Even the use of participatory development approaches had limited success as it can be at odds with traditional social structures (Blanc-Pamard & Fauroux, 2004). In terms of the local cultural context, 64% of household heads follow traditional beliefs and rules (UNICEF, 2011) while taboos and superstitions remain an integral part of local communities (Neudert et al., 2014). Thus, when interventions deviate from traditional practices, farmers face both the economic and social costs which deter them from adopting and implementing perspective innovations. Consequently farming systems’ innovation occurs in less than 9% of smallholder households (SuLaMa, 2014). Nevertheless, there are a range of coping strategies that are used by local farmers to cope with the climate related risks (Table 1).

Table 1 Smallholder coping strategies to poor crop yields in southwest Madagascar by prevalence of use by smallholders (Source: FAO, 2014b)

Coping Strategies	Prevalence (%)
Change sowing date	39.2
Crop variety	37.5
Change farmed land	10
Increase scale	9.1
Animal husbandry to cultivation	8.3
Adapted farming practices	8.3
Switch from cultivation to animal husbandry	6.7
Not using fertiliser manure or pesticides	2.5
Prayer	2.5
Off farm income	1.7
Agroforestry	1.7
Water conservation	0.8
Irrigation	0

1.3. "*Best bet*"" vs "*Best fit*" Practices

"Best bet" practices may be defined as: practices most likely to improve agricultural production in the region. "Best fit" practices may be defined as: practices most likely to be adopted by local farmers because they fit with the social, political and resource context of the farmer (Anderson, 2008; Birner et al., 2006; Ramalingam et al., 2014). Agricultural development programs historically focussed on "best bet" interventions which are commonly based on the best practices known to increase local crop productivity or food production. However, this approach has had only moderate impact as the adoption of best bet practices is often limited (Birner et al., 2009). This may be attributed to bias of this approach as it mainly targets increased production, while neglecting intrinsic decision drivers of local stakeholders. For example, farmer decision drivers may include: knowledge of the technique, willingness and ability to invest, labour availability, taste preferences and cultural taboos (FAO, 2014b; UNICEF, 2011). Consequently, there has been a move towards the development and use of "best fit" interventions which account for these additional decision drivers. In this regard the process has evolved from a top down approach, based on physical characteristics and production, to one which is more participatory (e.g. co-innovation) in which farmer's skills, knowledge and decision drivers shape farm innovation and corresponding interventions (Figure 7).

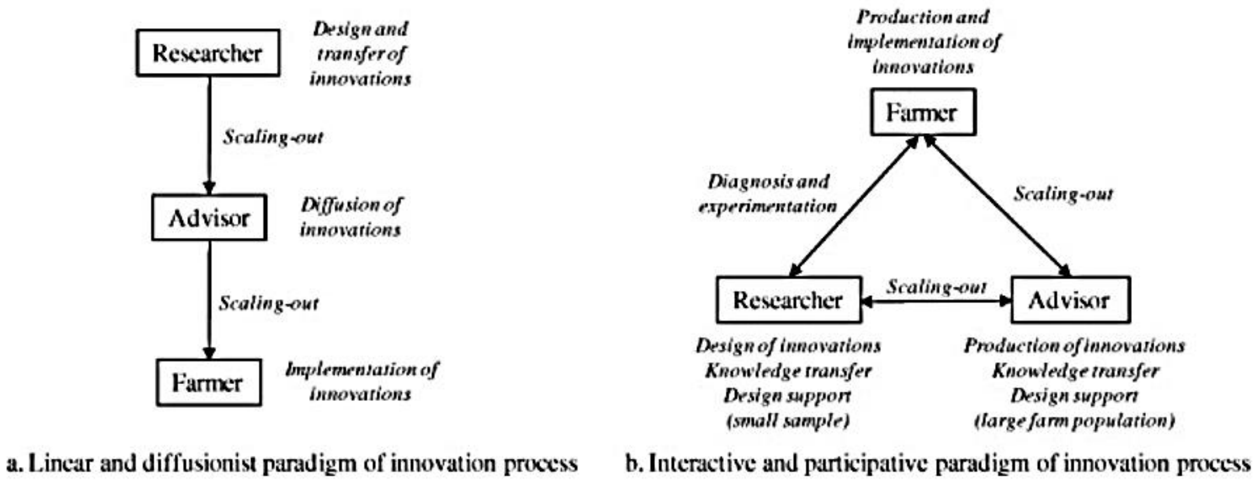


Figure 7 Two different approaches to innovation: the linear top down approach and the interactive participatory approach (Source: Le Gal et al , 2011).

1.4. Climate Change and Farming System

In southwest Madagascar rainfall may decline by 50 – 200mm by 2050, with an concurrent expected temperature increase of 0.5°C - 3°C (Vololona et al., 2011). Furthermore, the climate is expected to become more variable with an increase in extremes of daily temperature, precipitation and drought events (New et al., 2006). The most dominant effect on agriculture is likely to be increasingly negative water balances due to higher evapotranspiration and reduced precipitation rates. As shown in Figure 8 there is already a high probability of drought for the dominantly grown crops (maize and cassava).

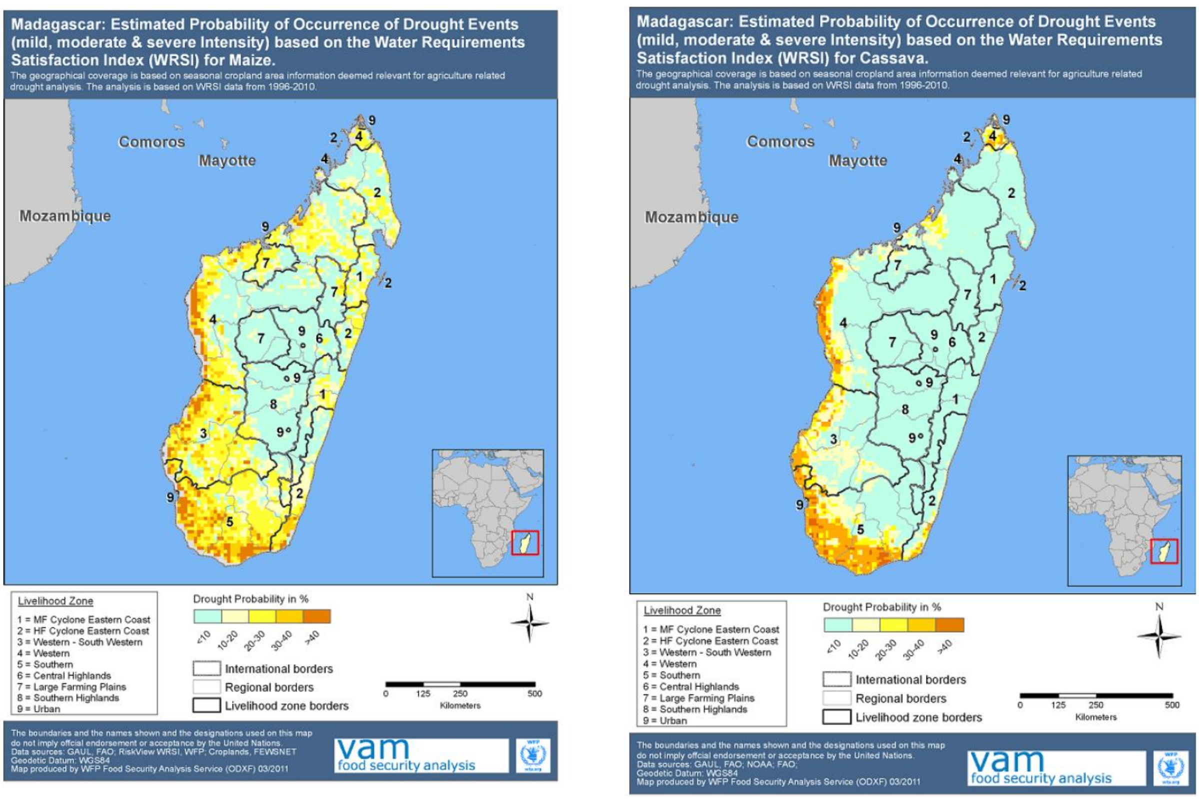


Figure 8 Frequency of drought events for maize and cassava during the period 1995-2009 (Source: WFP, ND)

Climate change will further exacerbate inherent risks and these challenges to production resulting in yield losses in many parts of the southern regions (Figure 9). However, actual crop response to climate change is likely to vary considerably for different crop species and cultivars. In addition to this, environmental variables such as temperature, water stress, soil properties, mineral nutrition, pathogens, pests and plant adaptive responses may also impact potential yield reductions (McCarthy, 2001)

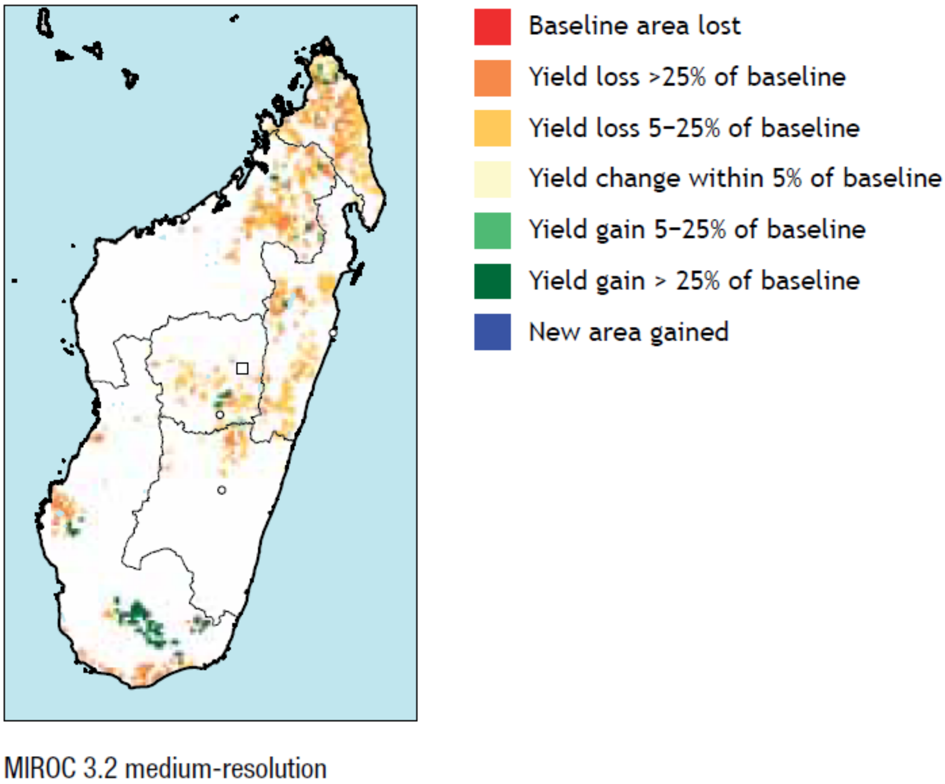


Figure 9 The yield change for rain-fed maize caused by climate change between 2000 and 2050 (Source: Vololona et al., 2013)

1.5. Farming System Typology

A farm typology provides a description of distinct farm types based on distinguishing characteristics, traits or strategies (Kostrowicki, 1977, see Figure 10). Farms may then be classified into a type that best captures key farm characteristics. Thus the main purpose of a typology is to map farming system diversity and categorise a diverse population of farms into a few groups of farm that share key structural and/or operational features (Alvarez et al., 2014). The typology may also be used to support the selection of farms based on representativeness, prevalence or specific needs. In this way a particular farm type can be targeted for an intervention (Daskalopoulou et al., 2002). Consequently, proposed interventions and/or extension domains can be based on a particular farm type and could be generalizable to other farms within that farm type, thus allowing the research to be applicable to make recommendations to a larger group of farms that share certain traits. A typology can be distinguished as being structural, or functional (ICRA, 2015). A structural typology is based on farm resources, and a functional typology on how these resources are allocated and managed. The method used should be based on which component appears to be most relevant in terms of explaining farm management and farm performance and/or attaining a certain goal based on specific research objectives. Many different methods exist for constructing the typology including: step by step comparison, expert knowledge, participatory ranking and statistical analysis (Alvarez et al., 2014). The most suitable method depends on the research objectives, and the need for reproducibility and standardisation. Furthermore, when used in development work, the types should be easily distinguished by local stakeholders so they can be conveyed and used to define effective extension realms (Landais, 1998).

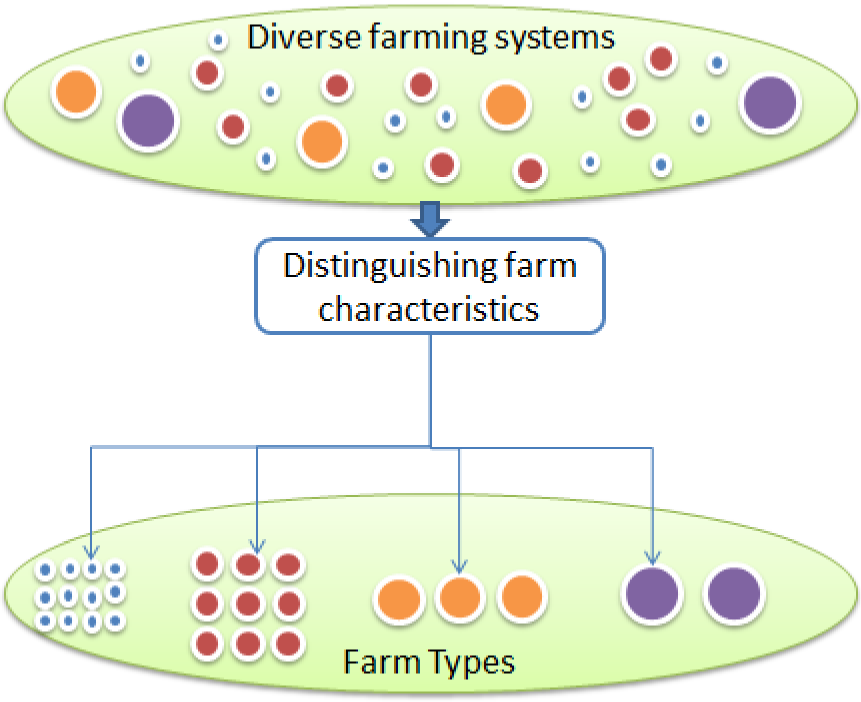


Figure 10 Visual depiction of a farm typology. The initial diversity in a farming system is assessed based on distinguishing farm characteristics enabling the grouping into four distinct farm types.

1.6. Purpose of the study and Research Objectives

Current agricultural practices cannot effectively support household food security in Southwest Madagascar. One of the major limitations is the yield reductions associated with low and unreliable rainfall coupled with soils with limited water and nutrient retention capacities. Given that climate change is expected to aggravate the frequency and intensity of extreme climactic events (in particular droughts) it is expected that this will further reduce future yields and greatly jeopardise food security. In order to avoid future food security catastrophes, modification of current practices and the design of suitable interventions is necessary that more effectively take into account climate risks. As part of such effort, model-based simulations using multiple years of weather data appears to be warranted as a means for more effective ad-hoc assessment of the probability an intervention to be successful for different scenarios. The objective of this research therefore is to assess crop production in a variable climate based on current prevailing farm practices. Furthermore, the crop production risk or benefit associated with plausible interventions will be assessed to inform local researchers and policy makers on the impacts of a suite of different technical interventions and to aid farm decision making.

The research objectives of this study are:

1) Determine farm types in the Beheloka region of southwest Madagascar.
2) Compile insights of local experts on what “best bet” and “best fit” interventions may be most effective in reducing crop risk associated with climate change.
3) Use model-based explorations to determine how different best bet vs best fit interventions impact probable future yield for a combination of different crops and management options based on expert-based knowledge.

To meet the study objectives, the following research questions were defined:

1) What are the prevailing farm types in Beheloka? Are there differences in their farming practices?
2) What are the best bet interventions recommended by local stakeholders to improve agricultural productivity?
3) Which agricultural interventions are most likely to be implemented by smallholders?
4) What is the impact of suggested interventions on crop productivity in highly variable annual weather conditions?

Thus, the following hypothesis were associated to this study:

1) There are distinct local farm types in Beheloka, which may be differentiated based on structural farm characteristics.
2) There is a suite of context-appropriate “best bet” solutions that can effectively improve crop performance in a variable climate.
3) Although expert-derived interventions may positively impact crop yield, recommendations will differ across crops and farm types.

2. Materials and Methods

2.1. Research Site

After consulting with a local expert from the SuLaMa research group and consecutive field visits to a number of villages in the Beheloka region, Efoetsy village was chosen as the case study community for this thesis. Several factors contributed to this decision. Firstly, though this village was deemed to be slightly richer than some of the others in the region, its farming system was considered to be representative of the methods of production, and the challenges faced, by smallholders in the targeted region. Secondly, background information was available for this village which could support the research both in terms of implementation but also in terms of contextualization. Thirdly, this village had participated in previous research so it appeared that the community was open to working with foreign researchers. Finally, Efoetsy appeared to be an appropriate choice based on time, access, personal safety and budgetary constraints.

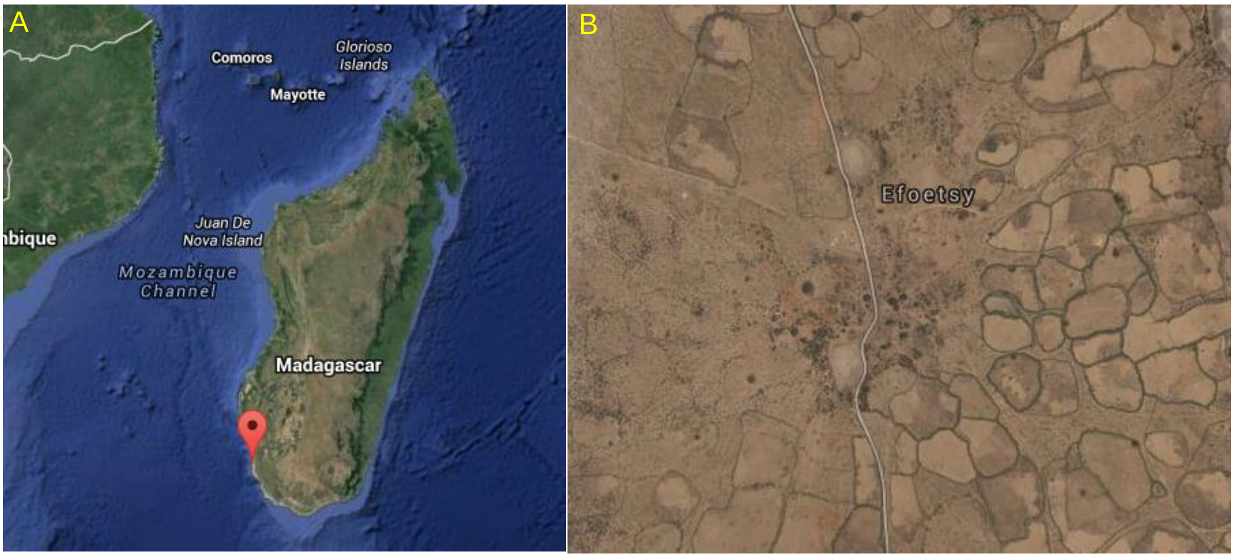


Figure 11 The location of Efoetsy village within Madagascar (A) and an aerial view of the village with surrounding fields (B) (Source: GoogleEarthPro, 2015)

Efoetsy is located in the littoral region in southwest Madagascar (latitude 24°4'44"N, longitude 43°41'57"E), about 2.5 km from the sea. The last population census counted 205 households and 1294 inhabitants (SuLaMa, 2014). Most families depend on agriculture and livestock in terms of their livelihood, while 85% consider themselves as farmers. Both men and women work in the fields, though the men are often responsible for the more physical tasks such as hedgerow construction and keeping livestock, particularly zebu. Currently there is no mechanisation, or use of animal traction and all field work is done manually using hand tools. Generally, all members of a household engage in and/or assist with farming activities such as: seeding, weeding, harvesting, or the clearing of new fields. Though if the man leaves during transhumance then these tasks would be managed by the rest of the household. Most households own one or more fields, which are delineated by hedges that indicate ownership of the land. These hedges are often made up of sisal (Agave sisalana) and prickly pear cactus (Opuntia). In some cases the field is divided into plots and cultivated by different households (often extended family). In addition to farming some households supplement their food needs with foraging, hunting and fishing, or obtain income from charcoal making or ox-cart production (SuLaMa, 2011).

Ensuring food security in this area is difficult, with the majority of households reporting that their food production was never enough to meet their food needs, or only enough during high rainfall years (SuLaMa, 2014) with several bio-physical and socio-economic factors contributing to this. Firstly, sandy soils tend to prevail (>95% sand) while the average precipitation is 360mm with a range of 200mm to 500mm (Hanisch, 2015a). Furthermore, the area experiences cyclones during which crops and animals may be lost and destroyed due to heavy rains and strong winds. Pests such as birds and insects pose an additional constraint. In 2013 locust swarms were reported to destroy 50% of crops in the local area (CCD, 2015). Furthermore, birds may eat the seeds that are being sown while also scavenging grain crops, such as millet and sorghum, before they can be harvested.

2.2. Conceptual Framework

The DEED framework (Giller et al., 2008) was used as a conceptual framework to structure different consequential research components within this study. This framework facilitated the development of viable interventions at the field scale using participatory research techniques to realistically include local priorities, practices, resources and constraints. As shown in Figure 12. The DEED framework contains four distinct phases: Describe, Explain, Explore and Design. During the "Describe" phase the farming system was characterised based on expert-views of prevailing farm types. Based on this typology, representative farms were selected and physical, management and socioeconomic data for these farms was compiled. This information was then used to verify proposed farm types while also being used to model farms during model-based explorations during the "Explain" phase. During this phase a better understanding of the crop and yield formation processes was developed. The "Explore" phase investigated different interventions based on recommendations by local experts, to assess and evaluate their impact on farm performance. Finally, during the "Design" phase choices were made regarding what type of intervention was most likely to fulfil specific research objectives.

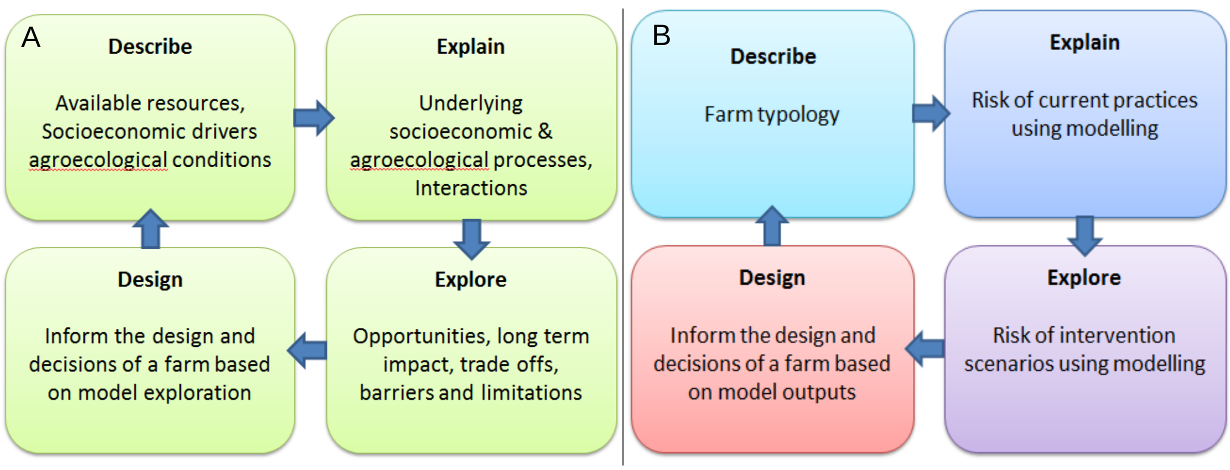


Figure 12 Left: A general overview of the original DEED framework (A,) adapted from Giller et al., 2008 along with the corresponding research components implemented during the current research (B).

2.3. Methodological Framework

An outline of the overall steps and system analysis sub-components of the research, in addition to the sequence of events is outlined in Figure 12, a more detailed description is provided in Figure 13. The five main components of this research included i) the development of a farm typology, ii) the compilation of input data required for APSIM calibration, iii) the simulation of current practices via APSIM, iv) the development and ranking of “best bet” and “best fit” interventions and v) the simulation of the impacts of chosen interventions on crop performance using APSIM. A detailed account of these steps is given in the proceeding paragraphs.

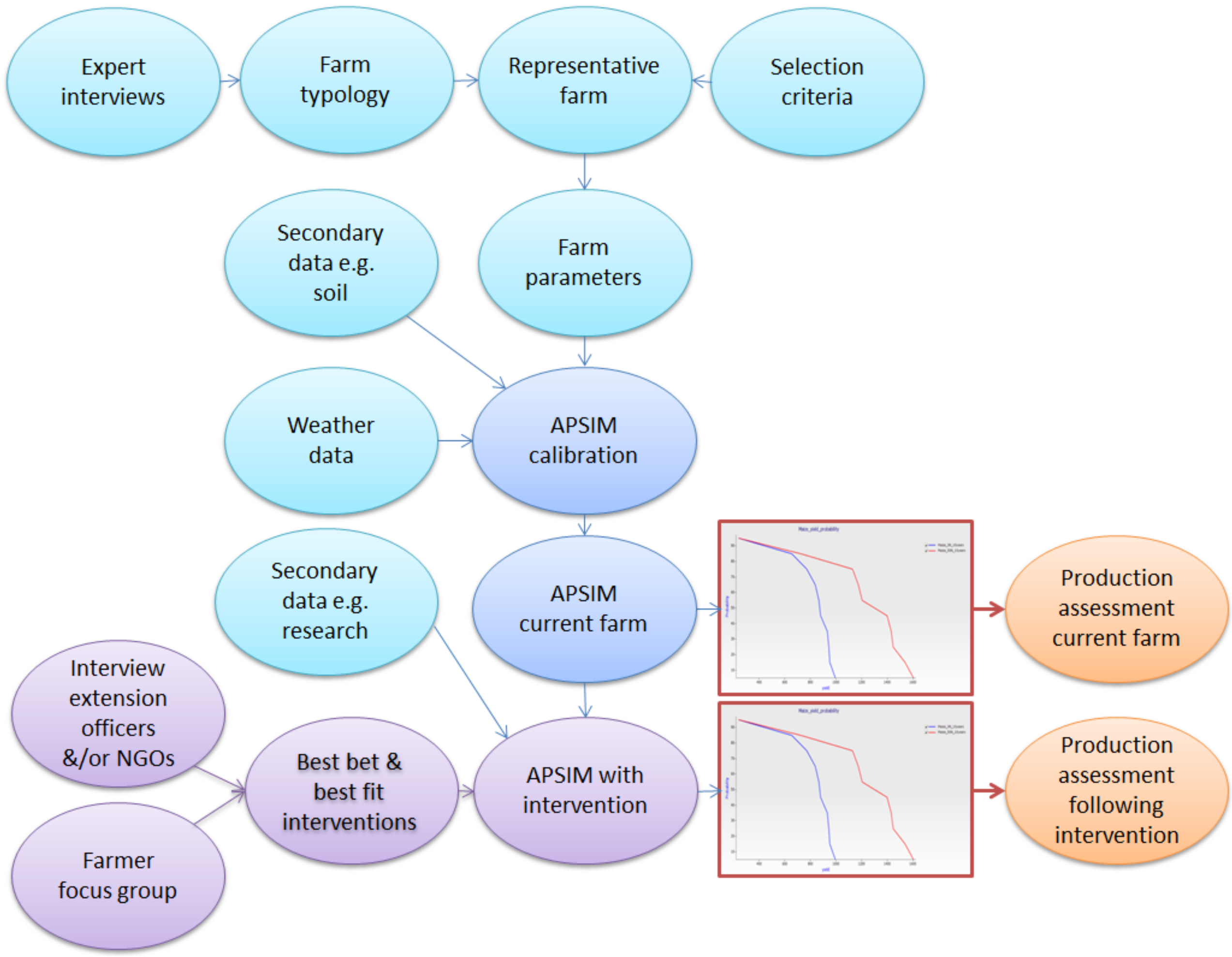


Figure 13 The general operational and methodological framework employed for this research

2.4. Farm Typology

An expert knowledge-based typology (Figure 14) was used to aggregate farms into groups based on inputs provided by local experts (Giller et al., 2011). This method was chosen as it balances utility, accuracy and the data requirements for actual implementation.

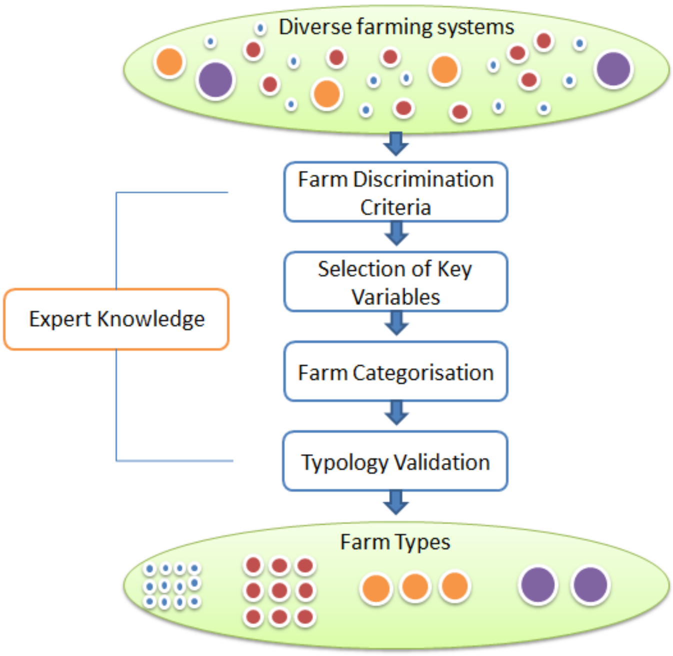


Figure 14 Expert knowledge farm typology. A heterogeneous population of farms are grouped by criteria developed with local experts.

In terms of the local context, farms mainly included households engaged in subsistence agriculture. Here a household is being defined as: "a group of people related in most cases by blood or marriage, who eat normally from the same cooking pot and share income, expenses and agricultural production." (SuLaMa, pp 9, 2014). Local experts (N=3) were interviewed using a semi-structured questionnaire (Appendix II). Experts were chosen based on their knowledge of the area following interviews at several local organisations known to facilitate agricultural development in the region (DRDA, CDD, FOFIFA, MDP, GIZ, SuLaMa). Only a few of these organisations (SuLaMa, GIZ, MDP) had direct working experience in Efoetsy, or the surrounding villages, thus these organisations provided the inputs for the farm typology. During the interviews the relevant criteria to differentiate local farm types was determined and utilised to define distinct farm types. These criteria were both spontaneously suggested by the local expert, or alternatively were based on commonly used variables used to distinguish farm types, such as: farm size, labour, capital, soil quality, production pattern, land use, managerial ability, productivity, purpose of production (Escobar et al., 1990). Additionally, the interviews were used to determine which of these criteria were relevant to the local farm types, and which characteristics strongly differentiated the different farm types.

2.5. Farm Survey

The typology distinguished four main farm types in Efoetsy which were then used as a reference point for further investigation. To determine if farm types resulted in differing practices and thus differences in the best fit or best bet intervention options, the intention was to survey representative farmers from each of the four farm types. However, in keeping with local customs, it was necessary to obtain permission from the village president to work in the village, and the president selected the households to survey based on the obtained typology. Although, the president said that the four selected farm represented the four farms types best, one farm type (Type 2) appeared to be missing while one other (Type 1) was repeated twice. Subsequently farm surveys and field visits were conducted to obtain the baseline data necessary for APSIM (Appendix III). This included agronomic practices such as: tillage, sowing, weeding and harvesting. In addition to basic crop management information, farmer yield estimates along with information regarding the use of soil amendments and residue use. This was achieved through individual interviews conducted with each farmer at the presidents' house. Prior to conducting the interviews the survey was pretested with a local translator. During the interviews each question was first asked in English by the interviewer and then translated into Malagasy by the local translator. Responses were directly translated into English and recorded by the interviewer and verified by the translator such that any discrepancies or misunderstandings could be immediately corrected.

2.6. Best Bet and Best Fit Interventions

Both best bet, and bet fit interventions were investigated based on the multiple perspectives of different stakeholders (DRDA, CDD, FOFIFA, MDP, GIZ, SuLaMa, and farmers). Best bet interventions were developed through semi-structured interviews with local departments, research institutes, NGOs and extension officers (N=6, DRDA, CDD, FOFIFA, MDP, GIZ, SuLaMa, Appendix I). The interventions recommended by these institutes were considered to be the best bet options for farmers. These suggested best bet interventions were then ranked based on the number of organisations that recommended them. Best fit options were developed to account for local: social, cultural, economic, knowledge, governance, resources and understanding of reality as outlined in previous research (Birner et al., 2009; Birner et al., 2006; Ramalingam et al., 2014). This was achieved using farmer interviews and field visits. Farmers who took part in the farm survey (N=4) were also interviewed to ascertain practices they utilise to improve their yields. Additionally, farmers were asked their opinion on best bet interventions to ascertain if these were feasible given the farmers situation. Farmers responded *Yes* (I would) or *No* (I would not) while additional comments regarding use of best bet interventions were also denoted. These options were then ranked based on the number of yes votes by participating farmers. The assumption being that the options with the greatest number of yes votes were most likely to be appropriate and potentially adopted by local farmers. To further focus the intervention scenarios. Farmers were also asked to rank their most important crops from 1 to 4. To aggregate the results across farmers, the first crop was given 4 points, 3 points to the second, 2 points to the third and 1 point to the fourth. These were summed across farmers to give the crops voted overall the most important by the four farmers.

2.7. The APSIM Model

APSIM is a computer based modelling environment that can simulate the growth and yield of crops based on biological, environmental and managerial modules (Figure 15). These modules are further differentiated into component modules. The biological module includes: Crop characteristics such as phenology and growth, which are influenced by the environmental module which includes: soil characteristics and daily weather data. Both of these are influenced by the management module which covers factors such as the timing of operations, tillage and amendments. Importantly, APSIM does not account for pest or disease pressure. Thus, the models predicted yields represent the maximum attainable production for the site, based on the limiting factors of water and nutrients, and not the yield reducing factors such as pests and disease, though weeds can be modelled.

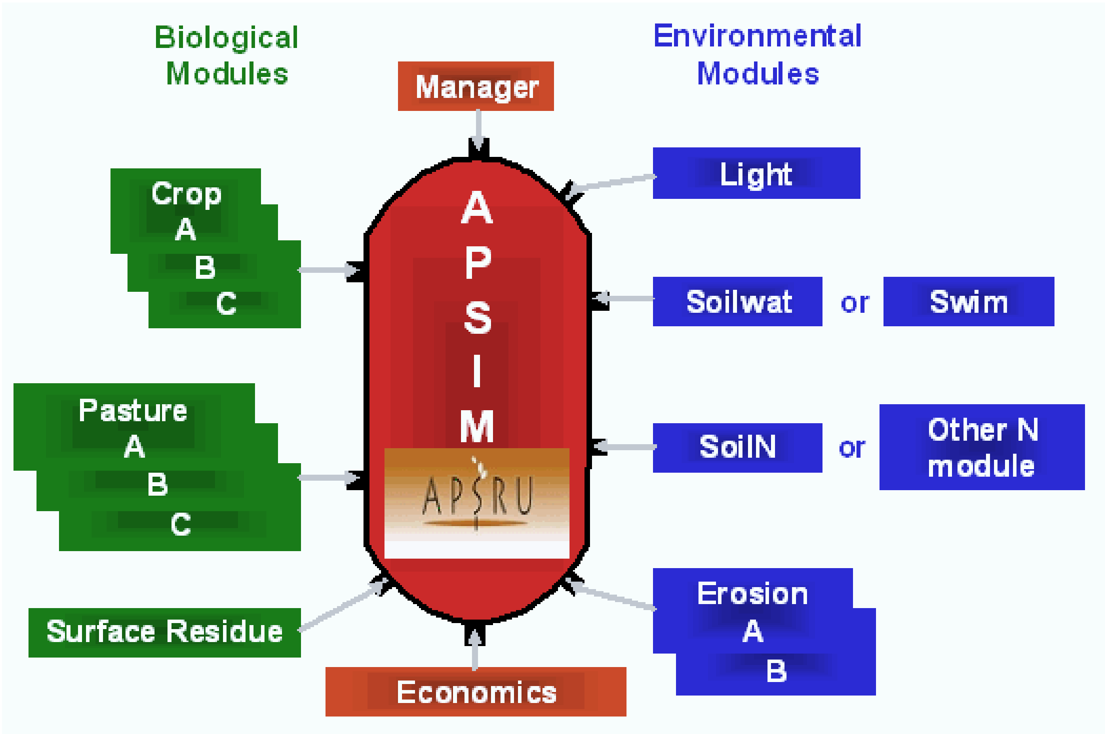


Figure 15 Schematic representation of APSIM engine and modules (Source: Cox et al, 2001)

2.8. APSIM Parameterisation

APSIM was parameterized using data collected from the farm survey, field visits, data made available by local organisations and previous research (Table 2). Based on the results from the farm survey, the discussion with local experts and personal experience in the field, it appeared that the four farms had similar cultivation practices. Thus, one farm (Farm A from Type 1) was chosen for the modelling of interventions in APSIM, and constitute the baseline simulation (Table 3). Beside, Farm A belongs to a farm type representing the majority of households in Efoetsy, i.e. relatively poor.

Furthermore, the main two practice differences observed between the four surveyed farms were sowing density and sowing date; this was particularly pronounced for Farm D. Consequently, these factors were also modelled and Farm D cropping density was added as an intervention (Table 4), so that their impact could also be ascertained.

Table 2 Overview of the data necessary to parameterize APSIM

General	Details	Information source
Site	Latitude Slope	GPS, GoogleEarthPro (2015)
Climate	Daily: Radiation, minimum and maximum temperature and rainfall.	MarkSIMGCM (CGIAR, 2015)
Soil and soil water	Soil: texture, depth, Per layer soil water contents, soil bulk density, NO3, Soil Carbon, total soil N, P sorption and extraction	Hanisch, 2015b; HarvestChoice, 2010
Surface residues	Type: crop/ manure Characteristics, C, N and P % ground cover	Field visits and interviews and Hanisch, 2015a
Management	Dates of all operations, plant density, sowing depth, use of amendments/fertiliser, tillage, irrigation, weeding	Field visits and interviews
Crop	Type, cultivar, sowing date, emergence, panicle initiation, flowering, grain maturity, yield (grain and above-ground biomass)	Field visits, interviews, local experts, Hänke, 2015 and SuLaMa, 2011

2.8.1. Crop Parameterisation

Crops were parameterised using data collected during the farmer interviews, the more important features are shown in Table 3.

Table 3: Major crop parameters used for the baseline simulation

	Millet	Maize	Mung bean	Cowpea	Sorghum
Cultivar	Wrajpop	Mwi_local	Celera	Spreading	Medium
Sowing time	October	October	October	October	October
Harvest	when ripe	when ripe	when ripe	when ripe	when ripe
Chemical fertilisation	None	None	None	None	None
Organic fertilisation	None	None	None	None	None
Crop residue	Removed	Removed	Removed	Removed	Removed
Sowing depth (mm)	60	60	60	60	60
Row spacing (cm)	120	110	100	130	110
Sowing density (plants/m^2)	6.9	2.5	3.0	1.8	2.5
Weeds	None	None	None	None	None
Sown as	Monocrop	Monocrop	Monocrop	Monocrop	Monocrop
Irrigation	None	None	None	None	None

For the simulation exploring the impact of the different row spacing and sowing density practices of Farm D the crops were parameterised as shown in Table 4.

Table 4: Major crop parameters used for the Farm D simulation

	Millet	Maize	Mung bean	Cowpea	Sorghum
Cultivar	Wrajpop	Mwi_local	Celera	Spreading	Medium
Sowing time	October	October	October	October	October
Harvest	when ripe	when ripe	when ripe	when ripe	when ripe
Chemical fertilisation	None	None	None	None	None
Organic fertilisation	None	None	None	None	None
Crop residue	Removed	Removed	Removed	Removed	Removed
Sowing depth (mm)	60	60	60	60	60
Row spacing (cm)	30	100	55	55	30
Sowing density (plants/m^2)	33.3	3	9.9	9.9	33.3
Weeds	None	None	None	None	None
Sown as	Monocrop	Monocrop	Monocrop	Monocrop	Monocrop
Irrigation	None	None	None	None	None

Due to the lack of available local data regarding cultivars used, detailed growth characteristics and corresponding genetic yield coefficients, comparable cultivars were chosen from the APSIM database which most closely matched the known characteristics of the crops. These included seed characteristics, crop growth durations and cultivars which were unimproved and open pollinated.

2.8.2. Soil Parameterisation

APSIM soil data for Efoetsy was obtained from the HarvestChoice (2010) database (Figure 16 and Table 5). The database is developed to provide soil data for modelling where local soil data is not readily available. By inputting the latitude and longitude of the research location the database provide the most probable soils for the area (Figure 16).

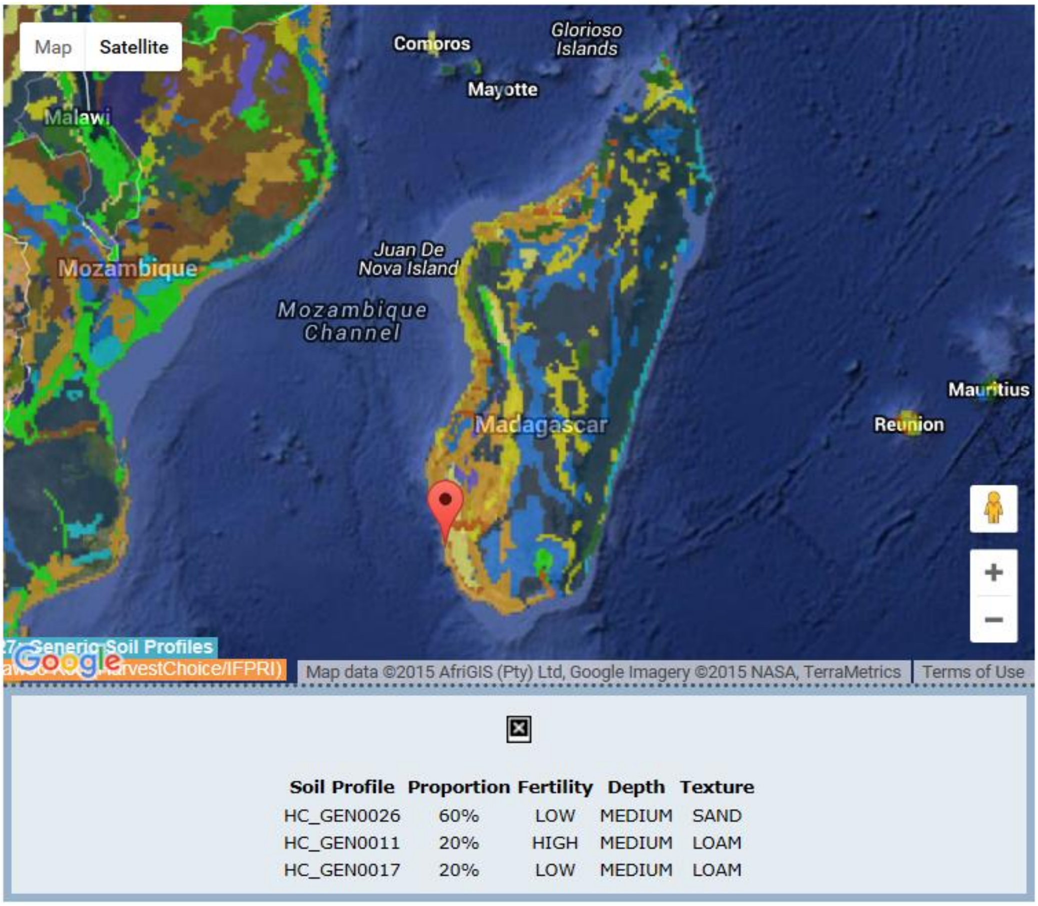


Figure 16: Soil database of HarvestChoice (2010) Efoetsy village is located on the map in an area which has three probable soil types: HC_GEN0026, HC_GEN0011 and HC_GEN0017.

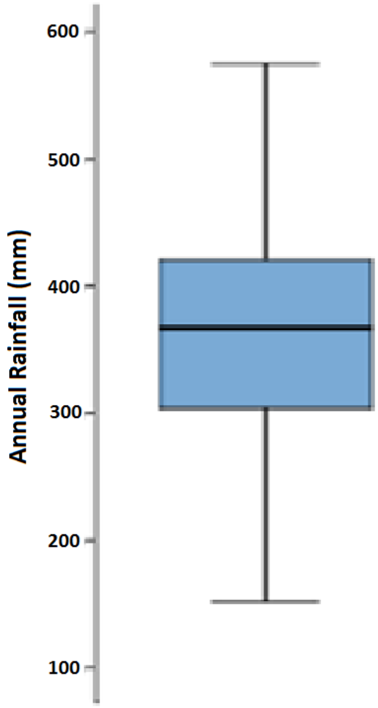
In Efoetsy village, the HC_GEN0026 default soil type was the most prevalent soil according to HarvestChoice (Figure 16). This concurred with field observations and soil characteristics from soil samples collected in Efoetsy by Hanisch (2015b) which were determined in a laboratory. The values used for the simulations are shown in Table 5.

Table 5 APSIM soil parameters used for Efoetsy, soil HC_GEN0026 from HarvestChoice (2010) with the volumetric soil moisture content at permanent wilting point (LL15), the field capacity (DUL), the saturation (SAT), the soil organic carbon content (OC), the decomposable soil carbon (FBiom), the non-decomposing soil carbon (Finert) and pH.

Depth	Bulk Density	LL15	DUL	SAT	OC	FBiom	Finert	pH
(cm)	(g/cc)	(mm/mm)	(mm/mm)	(mm/mm)	(total %)	(0-1)	(0-1)	6.5
0-10	1.6	0.06	0.165	0.36	0.4	0.04	0.4	6.5
10-30	1.6	0.07	0.17	0.365	0.25	0.03	0.45	6.5
30-60	1.6	0.09	0.172	0.37	0.2	0.02	0.5	6.5
60-90	1.6	0.11	0.175	0.37	0.18	0.015	0.75	6.5
90-120	1.6	0.13	0.18	0.37	0.17	0.01	0.9	6.5

2.9. Weather data

Weather parameters for APSIM were generated using MarkSimGCM (CGIAR, 2015). This is a stochastic weather generator that simulates daily sunshine hours, rainfall in addition to minimum and maximum temperatures. Due to the remoteness of the research site only a few years of historical rainfall records were available and several months of data were missing. Previous research stated that the average annual rainfall of the littoral area, where the village is located, was 360mm with values ranging between 200mm and 500mm (Hanisch, 2015a). Multiple simulation were run using MarkSim based on different combinations of the 17 available GCM models for the year 2015 with the latitude and longitude of Efoetsy village (-24.079, 43.703) in RCP 4.5. After consultation with local experts weather data generated using MIROC-ESM-CHEM and MIROC-ESM (Watanabe et al., 2011) were used, as these produced weather data that appeared most representative and realistic for the case study area based on overall average annual average rainfall and rainfall variability. Consequently, thirty years of weather data were generated using the MIROC-ESM-CHEM and MIROC-ESM GCMs in RCP 4.5 for the year 2020. This resulted in the weather data shown in Figure 17, Figure 18 and Figure 19.



Statistic	Rainfall (mm)
Mean	363
Median	367
Range	424
Minimum	151
Maximum	575
25th percentile	304
50th percentile	367
75th percentile	421

Figure 17 Boxplot of average annual rainfall from 30 years of MarkSimGCM generated weather data for Efoetsy with range, median and quartiles with supporting of values.

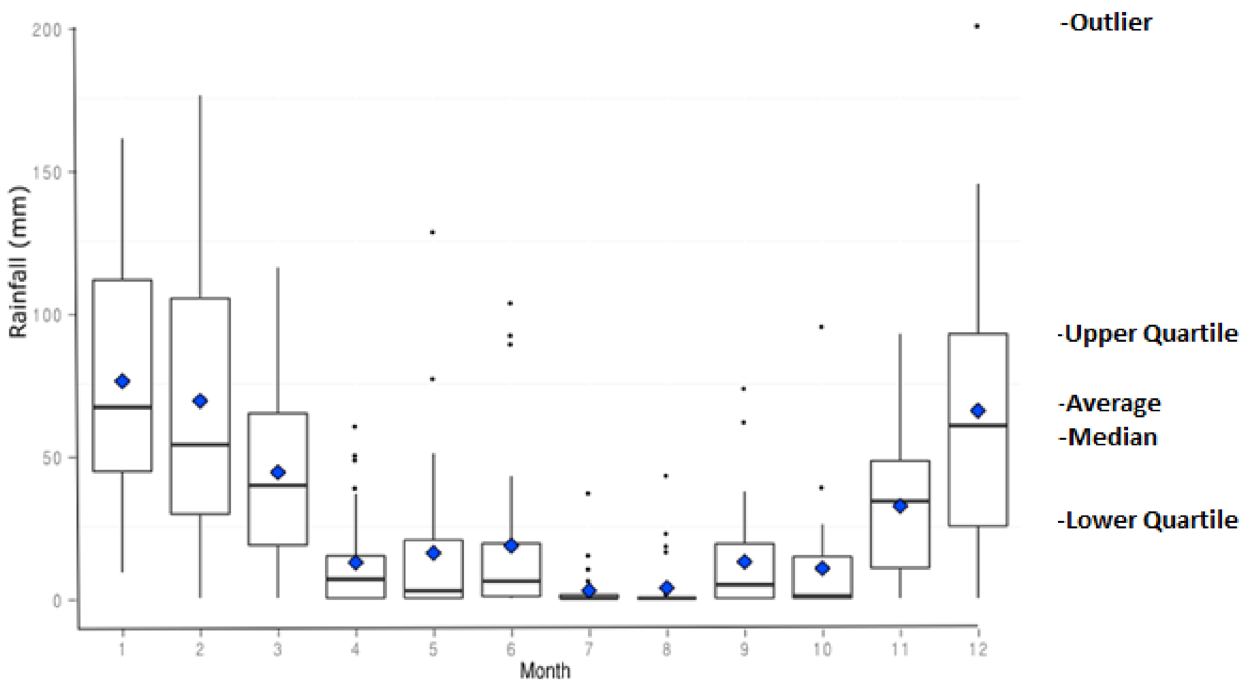


Figure 18 Monthly distribution of precipitation from 30 years of weather data generated for Efoetsy using MarkSim. Note: outliers are shown for any point 1.5 times the interquartile range bellow the lower quartile or above the upper quartile,

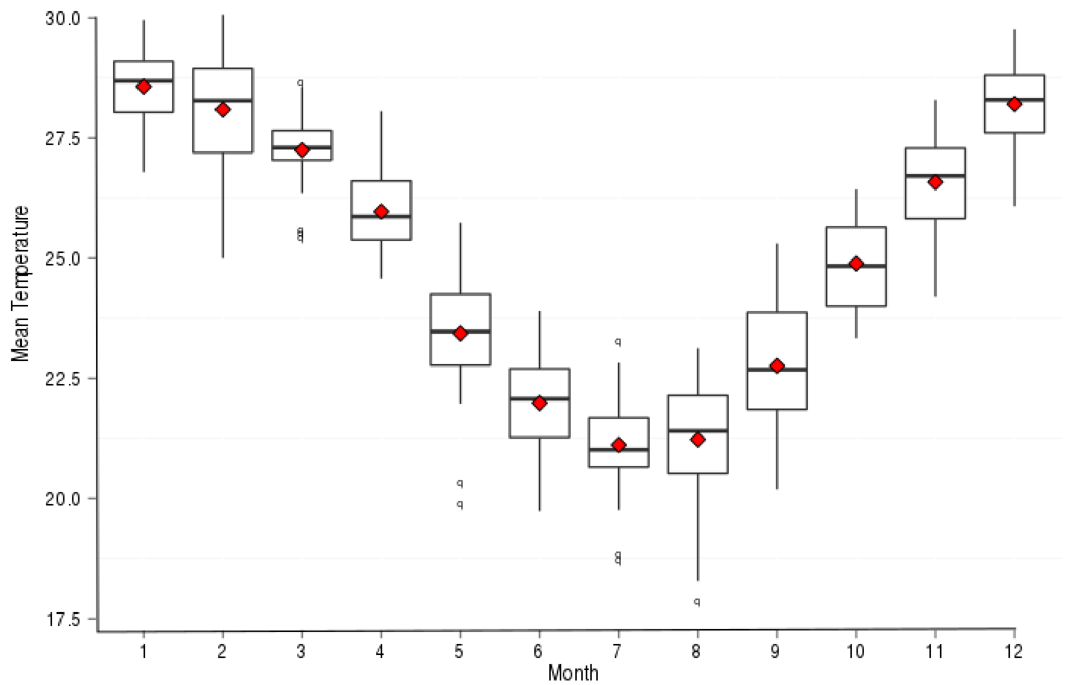


Figure 19 Daily mean temperatures per month over 30 years of weather generated for Efoetsy using MarkSim. Note: outliers are shown for any point 1.5 times the interquartile range bellow the lower quartile or above the upper quartile,

2.10. APSIM Validation

The APSIM model could not be validated in the conventional manner as accurate crop data for Efoetsy was not available. Thus the measured yield and simulated yields could not be compared via standard regression and model fit assessment procedures (e.g. MSEP). Nevertheless, based on the accounts of local experts, smallholders, and available yield data (Hänke, 2015) model predictions for standard practices appear to concur with expected and observed values for the included crops (millet, maize, cowpea, sorghum and mungbean).

2.11. Modelled Intervention Scenarios

Several scenarios were modelled in APSIM (Table 6). The baseline scenario modelled crop performance of millet, maize, mung bean, sorghum and cowpea under normal farming practices (Table 3). Two further scenarios modelled the impact of planting density and planting date on the crop yields of millet, maize, mung bean, sorghum and cowpea. Finally, three interventions were chosen for model-based explorations with APSIM: Crop cultivar, weed management, manure and residues. These were chosen based on: the results of the best bet and best fit interventions, the feasibility to model the intervention in APSIM and the researchers' field observation and impressions of relevant areas for exploration. The interventions were modelled for three crops, millet, maize and mung bean, as farmers reported these crops were among their most important cultivated crops (excluding cassava, which cannot currently be modelled in APSIM). A summary of all the simulations is shown in Table 6.

Table 6 Interventions modelled in APSIM (for baseline crop parameters and practices see Table 3).

Scenario	Crops	Treatments
Baseline	Millet Maize Mung bean Sorghum Cowpea	Baseline parameters
Planting Density	Millet Maize Mung bean Sorghum Cowpea	Half Normal (baseline) Double Triple Farm D (cf. Table 4)
Planting Date	Millet Maize Mung bean Sorghum Cowpea	October (baseline) December January
Crop Cultivar	Millet Maize Mung bean	3 Cultivars of Millet: Wrajpop (baseline), ZATIB and bj104 3 Cultivars of Maize: mwi_local (baseline), timor local and Pioneer_3237 3 Cultivars of Mung bean: Satin (baseline), Green diamond and Celera
Weeding	Millet Maize Mung bean	No weeds (baseline) Weeding 1 time at weed biomass: 1x 250kg/ha, 1x500kg/ha and 1x1000kg/ha Weeding 2 times at weed biomass: 2x 250kg/ha, 2x500kg/ha, and 2x1000kg/ha Weeding 3 times at weed biomass: 3x 250kg/ha, 3x500kg/ha, 3x1000kg/ha No weeding
Manure and residues	Millet Maize Mung bean	No crop residue (baseline) Crop residue No crop residue + 5 t of manure Crop residue + 5 t of manure No crop residue + 20 t manure Crop residue + 20 t manure

The baseline scenario was developed using the data collected during the farm interviews and parameterised in APSIM accordingly (Table 3). This represents the normal farming practices used based on the survey of four farmers in Efoetsy. This was used as the basis to construct other scenarios and to compare the impact using simple sensitivity analysis during which parameter values were modified for a realistic range of values.

In the case of sowing density, the baseline density was halved, doubled, and tripled to see the effect of plant spacing (seeding rate) on crop production. Since it was observed that farmers tended to use relatively low sowing densities, it was not expected that a lower density would increase yields. Therefore, only one simulation was run at below the current density (Table 5). The final treatment explored the sowing density and row spacing practices of Farm D (Table 4) as these deviated from the practices of the other farmers.

For sowing date, the baseline was run, but the sowing date was changed to either December or January (the other main months of sowing practiced by farmers) to determine if sowing date resulted in substantial changes to crop production.

For the intervention scenarios different crop cultivars were modelled, as they represented both the best bet and best fit option of different stakeholders. Cultivars were chosen from those available in APSIM based on differences in their characteristics from the baseline crop (such as phenology and growth).

Weeding was modelled mostly as a best fit scenario, as it represented the only technique that all farmers participated in. Furthermore, the village president noted that the farmer that consistently got the highest yields in the village was the one who spent the most time weeding. Thus, the impact of weeds, and different weed management was explored. In this scenario, to represent the weed growth, summer grass was sown four times at monthly intervals beginning when the main crop was sown. The weeds were sown at a density of 10 plants/m^2 , a depth of 15 mm and row spacing of 200 mm (based on field experience). Weed control was achieved using “weeding at threshold weed biomass” option and in this case weeding occurred, when weed biomass reached a determined level, which seems a realistic approach. The number of weedings and the threshold to commence weeding were both altered to produce different scenarios. For instance Maize 1 X 250 kg refers to maize being the main crop, that it was weeded once when the weed biomass reached 250 kg ha^{-1}. The number of weedings ranged from one to three as this represented the farmer differences in weed management practices. The assumed threshold for weeding were 125, 250 or 500 kg weeds ha^{-1}. These were chosen after initial exploration which showed that sensitivity was reduced at higher thresholds, as weed pressure would not become sufficient to initiate weeding.

The final intervention which was simulated related to the application of manure and crop residues, this was the second highest ranking best bet intervention, but had no current use in Efoetsy by farmers. Residues were generally removed for zebu, or burnt to maintain a clean field, and manure wasn’t used due to labour limitations, lack of access to manure, or a general perception that manure would not improve crop productivity. Thus, it represented more of a researcher-based intervention. The quantity of manure chosen was based on viable quantities that may be collected given the number of zebu. In addition to previous research in the area exploring the effect of manure amendments on yields (Hanisch, 2015a). This research also quantified the C:N ratio of cattle manure as 25, though it varied with the season and year. This ratio was used for the manure in the simulation. An additional parameter for manure was the application time. Given no field examples were available to base this upon it was assumed to be 30 days prior to crop sowing. This was chosen as a realistic time given the labour constraints of the farmers to fulfil other agronomic and household duties.

2.12. Limitations

The study was undertaken in the littoral area of southwest Madagascar with the particular weather and soil characteristics for this location. These differ significantly from the savannah and Mahafaly plateau. Consequently the finding of this study are location specific and may not be generalizable to these other areas despite their close proximity. The study used expert knowledge to develop the farm typology and the consent of the president was required for farmer interviews. These methods are known to experience selection bias. Nevertheless, this was the most feasible and culturally acceptable approach for this study. Overall, the simulation results provide an initial risk-based exploration of the possible impacts of different interventions on crop production in Efoetsy. This should aid local stakeholders in the development of future field research and highlight the important determining parameters which should be recognised when generalising findings to other farmers.

3. Results and Discussion

3.1. Expert Farm Typology

Discussion with local experts resulted in four farm main types in Efoetsy Village: "*Poor*", "*Average*", "*Rich*" farms and farms with "*Alternative income*" sources. The characteristics of each type are shown in Table 7. The experts chose to primarily structure the farm types based on wealth, locally expressed via the number of zebu that farmers own. Additionally, there is a clear difference in cultivated crop area, however experts noted that in practice this was not a reliable defining factor for these farm types due to the ability to claim lands in the traditional manner (slash and burn).

Table 7 Expert farm typology for Efoetsy village, bold text indicates factors indicated by experts to be most farm defining.

Category	Characteristic	Type 1: Poor	Type 2: Average	Type 3: Rich	Type 4: Alternative income
Household size	People	6	6	6	6
Education	**None, Primary, secondary**	**None**	**None, maybe visited primary**	**Primary**	**Primary, maybe visited secondary**
Operational characteristics	Land Cultivated (ha)	0.2-0.5	1-2	3	2
	Hired Labour	**None**	**Small**	**High**	**High**
	Capital inputs	Seed	Seed	Seed Hired labour	Seed
	Tools	Hoe, machete	Hoe, machete	Hoe, machete, **charrette**	Hoe, machete, **charrette**
Production Characteristics	Production type	Arable crops	Arable crops, livestock	Arable crops, livestock	Arable crops, livestock
	Crops	All* except sorghum, millet,	All*	All*	All*
	Livestock	**No zebu**	**Some zebu and goats**	**Big zebu and goat herds**	**Some zebu and goats**
Economic	Production orientation	Subsistence	Subsistence	Subsistence and sale	Subsistence and sale
	Market access	Village market	Village market	Greater have a charrette	Greater have a charrette
	Wealth	1-2 houses	2-3 houses	3-4 houses	3-4 houses
	Off farm activities	**Low**	**Medium (weeding for richer households)**	**Medium (e.g. temporary emigration)**	**High**

*Cassava, maize, mung bean, cowpea, lablab, sweet potatoes, sorghum, millet, melon, pumpkin

It can be seen that wealthy households (Type 3 and Type 4) were defined by their ownership of livestock and a charrette both of which are key local wealth indicators. Farmers belonging to these types are more likely to have attended primary and/or secondary school. Furthermore, they are likely to be engaged in off-farm activities, while in turn they also hire labour to assist with farm activities (for tasks such as weeding and livestock care). The poorer households (Types 1 and 2) are much less likely to have livestock, and will never have a charrette. Education level tends to be low and there is lower off farm activities while they are also unlikely to hire labour. With regards to the distribution of different farm types in Efoetsy, the experts expressed that the majority of households were poor to average types, with only a minority being either rich or having alternative activity as a major source of family income. This is in keeping with previous research in the area which classified 39% of households as being poor, 46% as average and 15% as wealthy (Neudert et al., in press).

3.2. Farm Characteristics

An overview of the farm characteristics of the four farms surveyed, Farm A, Farm B, Farm C and Farm D, are shown in Table 8.

Table 8 The farm characteristics of the four farmers that were interviewed in Efoetsy. Bold text indicates factors which strongly define the farm type.

Farm characteristic	Unit	Farm A Type 1	Farm B Type 1	Farm C Type 3	Farm D Type 4
Land Cultivated	ha	3.9	3.84	2.42	1.82
Distance to field	km	0.88	1.62	0.32	0.1
Household size	Core (extended)	3 (42)	7 (4)	8	6 (5)
Education	**School level**	**None**	**None**	**Primary**	**Secondary**
Hired Labour		**none**	**2 weeks**	**None**	**All year**
Capital inputs		seeds	seeds	seeds	seeds
Tools	Hoe	9	4	6	2
	Machete	5	4	1	2
	Rake	0	2	1	2
	Plough	0	0	0	0
Crops		All*	All*	All* no millet	All*
Production orientation	Subsistence or sale	Bad year eat all. Good year sell some	Bad year eat all. Good year sell some	Bad year eat all. Good year sell some	Subsistence and sale
Market access		Local market	Local market	Local market, Tulear	Local market, Tulear
House	#	4	2	3	6
Livestock	**Zebu**	**0**	**0**	**8**	**11**
	Goats/sheep	**0**	**0**	**19**	**30**
	Chickens	6 (10)	2	1 (11)	8 (2)
	Charrette	**0**	**0**	**1**	**1**
Off farm activities	**Importance**	**No**	**no**	**no**	**high**

All* Cassava, maize, mung bean, cowpea, lablab, sweet potatoes, sorghum, millet, melon, pumpkin

Of the four farms surveyed Farm A and Farm B had characteristics both fitting farm Type 1 (poor), whilst Farm C resembled farm Type 3 (rich) and Farm D, Type 4 (alternative income). Thus, despite our initial request, no surveyed farm was really representative of Type 2.

The main characteristics that differentiated farms included number/presence of zebu, goats or sheep, charrette along with education level and off-farm employment. Interestingly the poorer farms (Farm A and B) had the largest area available for cultivation which, though not expected based on the typology, it is in keeping with local accounts of the difficulty in using land size as a criteria to determine farm type. Furthermore, though poor farms farmed larger amounts of land, the distance to their fields range from 1-2 km compared to 300-700 m for the richer farms (Farm C and D, Figure 20). So poor farmers invest more time to move to and from their fields during land preparation, weeding and harvesting.

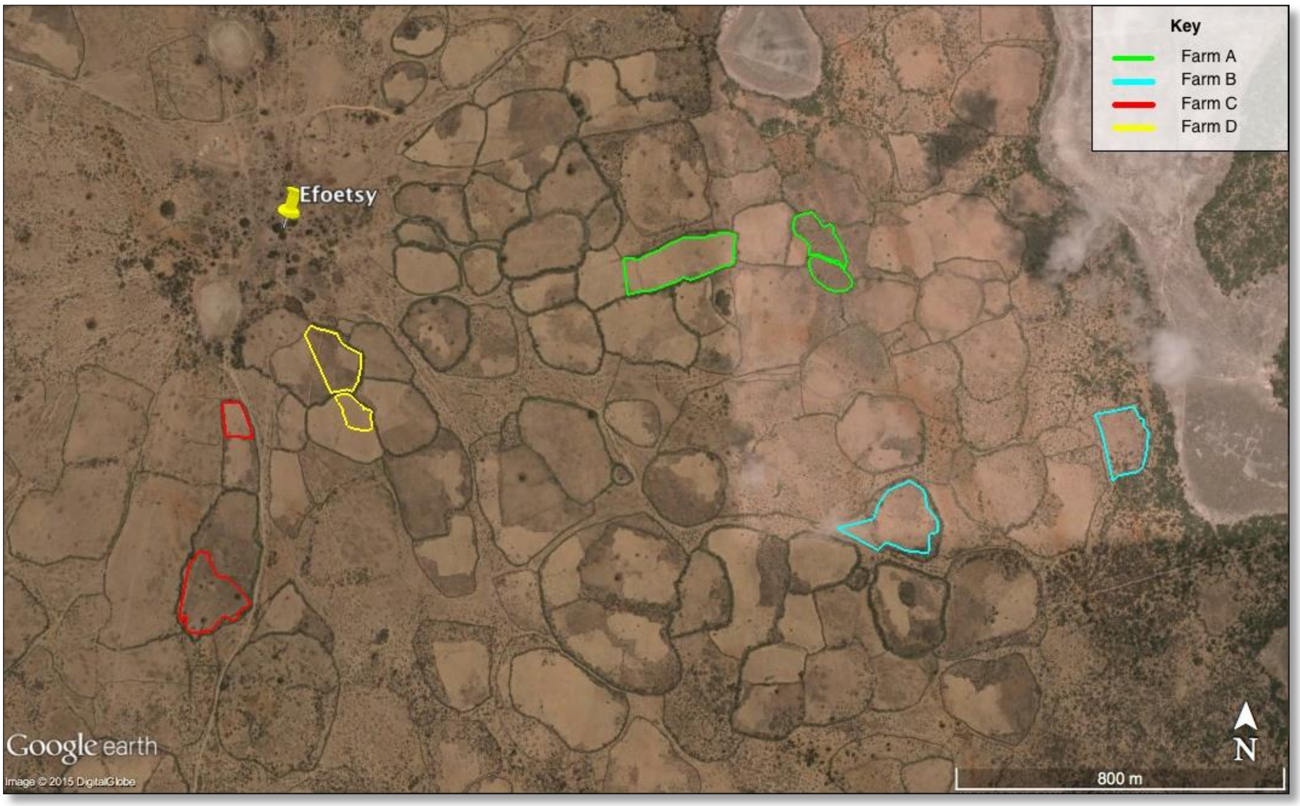


Figure 20 Map of Efoetsy village and surrounding fields. Fields of the surveyed farms are highlighted (Source: GoogleEarthPro, 2015).

3.3. Farm Management Practices

A summary of the findings of the farm survey is presented in Table 9. The main crops included cassava, sweet potato, maize, sorghum, millet, cowpea, lablab, mung bean, and melon. Farm B and D sowed crops once per year whilst Farm A and C sowed twice (if the rains failed). Some differences were observed in terms of the actual sowing time of the different farms with preferences for October, December and January (though cassava and sweet potato were planted at a different time). Farm C and Farm D would wait for rain before sowing whereas Farm A and Farm B planted crops in anticipation of rain due to labour limitations. Interestingly all farmers said they would plant opportunistically after a heavy rain regardless of the time of year. Field preparation techniques used were the same across all farms. Before sowing the fields would be completely cleared of weeds using a hand hoe. This would result in a superficial tillage to a depth of 4-5 cm. None of the farmers applied manure, fertilisers or herbicides. Plant density and sowing density varied with the crop but were fairly similar across farms, except for Farm D whose sowing density was approximately twice as high compared to the others farmers. During the growing season crops were weeded 1-3 times, depending on weed growth and labour availability. Then after three months most crops would be harvested. Crop residues would then be removed and either fed to zebu or burnt, though Farm C indicated that lablab and mung bean residues were left in the field.

Table 9 Summary of farming practices of the four farmers surveyed in Efoetsy (Y – Yes, N – No).

Farming Practices	Farm A Type 1 (poor)	Farm B Type 1 (poor)	Farm C Type 3 (rich)	Farm D Type 4 (alternative)
Crops	All*	All*	All* except millet	All*
Field weeded before Sowing	Y	Y	Y	Y
Sowing after rain	N	N	Y	Y
Sowing time 1	October	October	December	January
Sowing time 2	January	N	January	N
Opportunistic Sowing	Y	Y	Y	Y
Growing season weeding	3	2	1-2	2
Residue use	N	N	N	N
Chemical fertiliser	N	N	N	N
Organic fertiliser	N	N	N	N
Herbicides	N	N	N	N

* Cassava, sweet potato, cowpea, lablab, sorghum, millet, melon, maize, mung bean.

Despite the differing resource endowment of the farm types this did not translate into substantially differing agricultural practices or investment. This is consistent with the knowledge of local experts that cropping practices were generally very similar. The differences observed were subtle, concerning: the area of each crop planted, the sowing density, sowing after rain, the sowing time, and the number of weedings per crop. Thus, the greater resources of Farm C and Farm D were not used to invest in improved seeds, fertility or pest control. Though the greater sowing density of Farm D would involve a higher investment in seeds.

The reasons for the homogeneity in cropping practices are numerous. Discussion with a local expert (from GIZ) indicated that Efoetsy does not have a strong history of farming and that their level of innovation and technical agronomic skills are relatively low. Furthermore, chosen practices conform to their cultural beliefs. A common response when asked why they use, or do not use, a certain agricultural practice was: “this is how the ancestors did it”, or “the ancestors didn’t use manure, and they had high yields, so why should we need it?”. Additionally, many of the common barriers to agricultural innovation were present including limited access to credit, information, risk aversion, insufficient labour, lack of equipment, poor resource supply and poor infrastructure (Feder et al., 1985).

3.4. Best Bet Options

A summary of the practices advocated by local organisations is shown in Table 10, along with a listing of the actual organisations that explicitly stated this practice as being part of their recommendation for agricultural development in the region.

Table 10 Technical initiatives promoted by local agricultural development organisations to improve productivity in the Efoetsy area.

Interventions	Advocated by:
Provision of crop varieties	DRDA, CDD, FOFIFA, MDP, GIZ, SuLaMa[1]
Apply manure and compost	DRDA, MDP, GIZ, SuLaMa,
Use crop rotation	CDD, IST, MDP
improve weeding efficiency	MDP, GIZ, SuLaMa
Use clay pot / small scale irrigation	MDP, GIZ, SuLaMa
Use agroforestry tree crops	MDP, GIZ, SuLaMa
Use Intercropping	IST, FOFIFA, GIZ
Apply spot mulching (1m rows)	CDD, MDP
Use Zai planting pits	MDP, GIZ
Encourage legume use	MDP
Use keyhole vegetable gardens	CCD
Have fallow fields	MDP
Substitute high risk crops such as maize to lower risk crops, such as sorghum	GIZ
Use conservation agriculture techniques	GIZ
Change crop sowing date	GIZ

[1] Direction Régionale pour le Développement Agricole (DRDA), Conseil Diocesian de Developpment (CDD), Centre National de la Recherche Appliquée du Développement Rural (FOFIFA), Maison des paysans (MDP), Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Sustainable Landmanagement in southwest Madagascar (SULaMa)

The most commonly advocated intervention was the provision of new crop varieties (n=6), followed by the use of manure, or composting (n=4). Following this, the use of crop rotation, weeding techniques, small scale irrigation, agroforestry and intercropping (n=3) which were being proposed by three organisations.

3.5. Best Fit Options

Captured during the farm survey, the willingness of farmers to utilise different interventions is summarised in Table 11. The four farmers interviewed were willing to: change their crop varieties, plant more than once per year, weed more frequently, use intercropping and grow trees. The least popular intervention was the use fertilisers. Currently the primary practices used by farmers to improve their crop production are weeding (one to three times per crop) and extending the cultivated area.

Table 11 Overview of farmers willingness to try several development options (Y: Yes, N: No)

Would you:	Farm A	Farm B	Farm C	Farm D	Notes
Change your crop varieties	Y	Y	Y	Y	Prefer tall varieties
Plant more than once per year	Y	Y	Y	Y	For some crops
Weed more frequently	Y	Y	Y	Y	But time constraints
Use intercropping	Y	Y	Y	Y	For some crops
Grow trees	Y	Y	Y	Y	Do fodder and fruit trees
Use compost/mulch/manure	N	Y	Y	N	Doesn't work, time constraints, only if irrigated
Use herbicides	Y	Y	N	N	Don't like, not available
Change your crop species	N	Y	N/Y	N	Keep own and try new
Change your sowing dates	N	Y	N	N	This is when the rain comes, follow rain
Use fertilisers	N	N	N	N	Not favourable, ancestors didn't use it

Despite the positive response of the farmers to many of these options their capacity and ability to effectively implement them determined whether an intervention could be carried out successfully. In some cases farmers were willing to try an intervention, such as increased weeding, but they cited constraints of time and labour diminished their capacity to achieve this. Other constraints included access to obtain new/improved crop varieties from commercial sources in absence of support from outside organisations.

In order to assess which crops to investigate in greater depth, farmers were asked to rank their most important crops (Table 12). The preferences were based on the quantity and reliability of the crops yield, and its importance for household food provision. Cassava was clearly the most important crop for farmers as 3 out 4 farmers ranked it highest, followed by millet which was ranked by one farmer as being most important, followed by maize, then sweet potato, sorghum and mung bean came in joint 4th. As it is not possible to model cassava or sweet potato in APSIM, millet, maize and mung bean were chosen for the modelling in the intervention scenarios.

Table 12 Ranking score of crop importance by farmers interviewed in Efoetsy (a score of 4 implies the crop was ranked first, 3 it being ranked 2nd , 2 it being ranked 3rd, and a score of 1 implies it was ranked 4th).

Farm	Cassava	Sweet potato	Cowpea	Lablab	Sorghum	Millet	Melon	Maize	Mung bean
Farm A	2	1	0	0	3	4	0	0	0
Farm B	4	0	2	0	0	1	0	0	3
Farm C	4	3	0	0	0	0	0	2	1
Farm D	4	0	0	0	1	2	0	3	0
Total	***14***	***4***	***2***	***0***	***4***	***7***	***0***	***5***	***4***

3.6. Participatory-based Selection of Proposed Interventions

Based on the results of the interviews of local experts regarding their short list of best bet vs best fit interventions, and the farmer preferences indicated during the farm surveys, a number of interventions were selected to be modelled using APSIM: crop cultivar, weeding, and manure-residue amendment. Crop cultivar was chosen as an intervention because it was the most highly recommended by development organisations and additionally, all farmers were willing to implement this strategy. Thus, making crop cultivars the most relevant overall best fit and best bet intervention. Weeding was modelled predominantly as a best fit scenario. This since all the farmers currently practiced weeding, and besides extending the area cultivated, it was the only practice consistently used by farmers to improve their production. Additionally, three of the development organisations advocated increased, or improved weeding. For instance, sowing in rows, and the provision of rakes to improve weeding efficiency. The final interventions chosen for modelling was manure and residue amendments as this was the second most frequently advocated intervention by organisations, but was currently not utilised by the surveyed farmers, and only two of the farmers expressed that they would be willing to explore using this technique. The contrast between what was advocated and what was practiced thus made this an interesting scenario to explore.

3.7. Baseline Model-based Yield Risk Assessment

The probability of exceedance graph shown in Figure 21 can be used in two ways; firstly, for a given minimum yield the probability of attaining this yield can be obtained. Conversely yield variation dispersal may also be assessed in terms of range (minimum vs maximum) and different percentile distribution values.

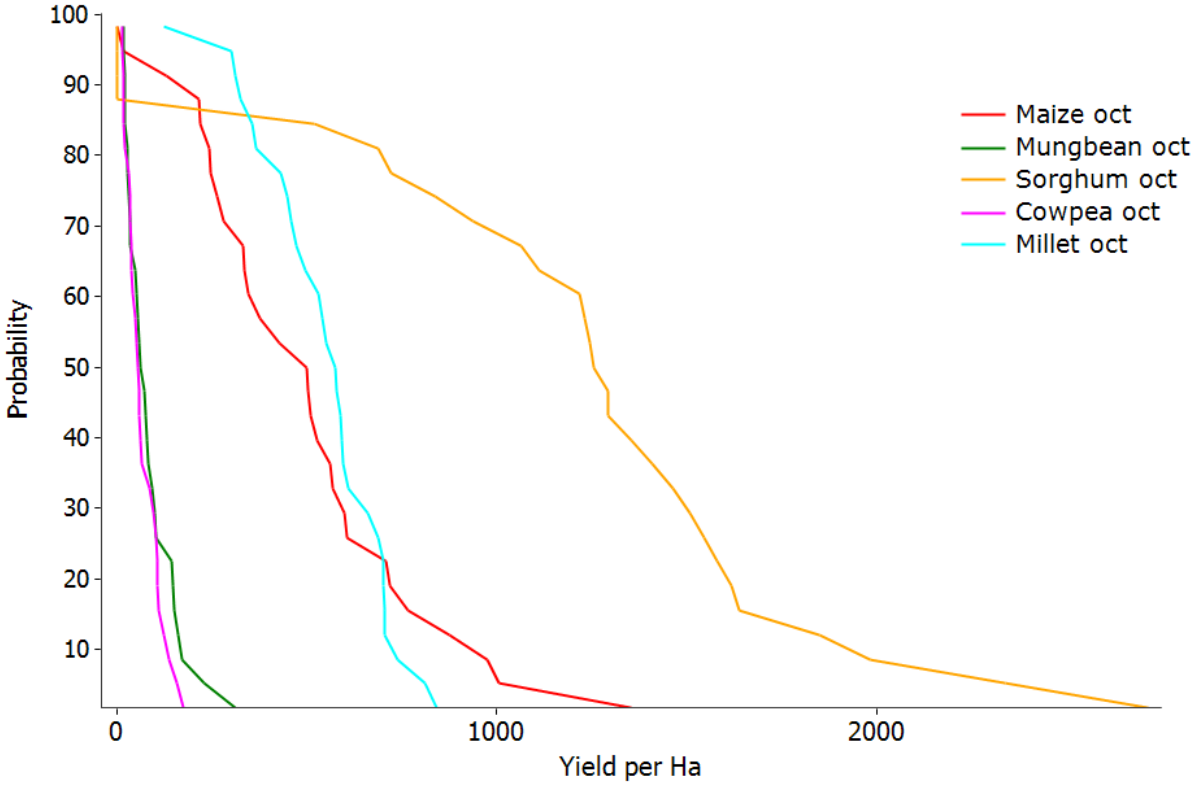


Figure 21 The probability of exceeding a given yield of common crops in Efoetsy over 30 years based on the baseline simulation parameters. The legend indicates the crop sown and the date of sowing (October) .

Figure 21 shows that the crops differ substantially in their probable yields. The bean crops cowpea and mung bean have a 50% chance of yields greater than 61 kg/ha and 55 kg/ha, respectively, meaning that in 5 out of 10 years yields would be expected to be less than that. Over the 30 year period the maximal yield (i.e. yield at the intercept of the curve with the X-axe) for cowpea was about 173 kg/ha and 311 kg/ha for mung bean. At 50% probability of exceedance, the grain crops; millet, maize and sorghum show a much greater attainable yield of 575 kg/ha 499 kg/ha and 1256 kg/ha respectively. Additionally maximal yields were higher: 843 kg/ha for millet, 1354 kg/ha for maize and for sorghum 2716 kg/ha.

The crops were cultivated with local smallholder management practices and field conditions. The only local data available for comparison was provided by Hänke (2015) which consisted of 23 sampled households in Efoetsy during 2014 (Table 13). That year was considered by locals as a poor rainfall year though actual rainfall data was unavailable. Large differences in the crop yields obtained by the different households were observed. For instance, some farms experienced a crop failure whilst others had an equivalent yield of over 1 ton/ha. The cause of these differences is not known from the dataset but is expected to be due to pest, disease and weed effects, in addition to, differences in smallholder practices. These yields show that the model predictions fall within the range of crop yields experienced by farmers in Efoetsy. The main difference occurred for median mung bean yields which were higher in the sampled farmer fields than predicted by the model, though the modelled yields do fall within the range of those obtained by farmers. Further exploration within the mung bean model found equivalent yields were obtained when the row spacing was changed from 100cm to 55cm. Which was a difference noticed between the interviewed Farm A (used as the baseline) and Farm D (Figure 22).

Table 13 Yield data of several crops grown in Efoetsy 2014 provided by Hänke (2015).

	Millet Yield (kg/ha)	Maize Yield (kg/ha)	Mung bean Yield (kg/ha)	Sorghum Yield (kg/ha)	Cowpea Yield (kg/ha)
Mean	138	8	216	238	57
Std. Deviation	124	11	308	511	60
25th percentile	68	0	21	0	12
Median	97	0	112	3	31
75th percentile	228	19	462	593	115
Minimum	65	0	13	0	0
Maximum	359	23	754	1151	153

The model predicted that sorghum was most likely to provide crop yields over 1000 kg/ha (Figure 21). At 50% probability of exceedance the yield of sorghum was double that of the next highest yielding crop (millet), indicating a large advantage of sorghum production in the context of climate change. Given the higher overall yields of sorghum it may be suggested that a larger cropping area of sorghum could be beneficial. However, given that the farmers produce food for their subsistence their diet preferences should also be considered. Furthermore, in some years sorghum is likely to experience a crop failure whereas the chance of a crop failure for millet is lower (Figure 21). Thus, the farmers current strategy of sowing multiple crops from a risk-avoidance perspective makes sense, for example given the current scenario millet has a 95% chance of exceeding a yield of 300 kg/ha, thus providing some yields even in the years that sorghum may fail. An alternative strategy to concentrate effort, resources and cropping area on sorghum and sell the surplus yields in the good years to develop savings for the years, may be possible. Or else store grain for the following year. However, in the local context many of the smallholders rely on basic storage facilities which may experience excessively high post-harvest losses. Furthermore, most smallholders only have access to the local market and thus have a limited market to which to sell their produce.

3.8. Model-based evaluation of differing cropping practices

3.8.1. Sowing Density

The impact of changing sowing density varied with each crop (Figure 22). Increasing the density improved the cumulative yields of millet, mung bean, cowpea and sorghum but decreased the yield of maize when compared to normal sowing density. Conversely, reducing the sowing density slightly increased the yield of maize, but decreased the yields of millet, mung bean, cowpea and sorghum. The crops respond differently to the differing plant densities. For millet a trade-off can be seen with using double and triple seed densities. There were higher yields at the lowest probabilities, but lower yields at the highest probabilities when compared to the normal planting density. For maize a higher density reduced the yield at each level of probability when compared to the normal scenario. This was particularly pronounced at triple density where there was only a 42% chance of exceeding 100kg/ha whereas at normal density there was a 92% chance of this. Interestingly for mung bean and cowpea a higher sowing density improved yields consistently although for cowpea at a triple density there was a slight decrease in yields at the very highest level of probability. Sorghum also benefited from a greater sowing density, but the effect was mainly to increase the number of productive years from 88% to 95%. Importantly, the lower density had a very negative effect on sorghum yields, resulting in only 12% of years being productive.

An additional comparison of the baseline scenario, based on Farm A, with Farm D is also shown in Figure 22. The management differences in sowing density and row spacing between these two farms are shown in Table 4. The model predicted that under the sowing conditions of Farm D there was a 38% chance of millet yields exceeding 500 kg/ha compared to 62% for Farm A. For maize the probability of exceeding 500kg/ha was 36% for Farm D but 46% for Farm A. These results suggest that millet and maize performed better under the conditions of Farm A. Conversely, for mung bean, cowpea and sorghum the sowing condition of Farm D performed better. For mung bean the probability of exceeding 500 kg/ha was 0% for Farm A, but 75% for Farm D. Cowpea showed a similar difference, with the probability of exceeding 250 kg/ha being 0% for Farm A but 80% for Farm D. For sorghum the differences were less pronounced, with the probability of exceeding 1000 kg/ha being 74% for Farm A but 79% for Farm D. The drastic changes in probable yield for cowpea and mung bean are largely accounted for by the thinner row spacing used by Farm D, though the higher sowing density also contributes, as is visible for mung bean triple density (td) and cowpea td.

The model-based exploration provides a systematic assessment of the potentially optimal sowing densities of the different crops based on the model parameters. Millet and maize appeared to be very close to their optimal sowing densities as increasing or decreasing the density resulted in a decrease of the yield. In the years with better growing conditions (i.e. favourable distribution and amount of rainfall) the increased density results in higher grain yields. Conversely during unfavourable years the increased densities reduced yields, likely due to increased interplant crop water competition inducing more rapid soil water depletion and increased crop water stress. This is in agreement with results for plant density trials in Sub Saharan Africa which showed that the optimal sowing density for maize was 16,670 plants/ha with significant reductions in yield at higher plant densities (Mashiqa et al., ND). In the Sahel the optimal density for Millet was 45-60,000 plants/ha (Bationo et al., 1990). These reports and findings are consistent with the model-based exploration. Both mung bean and cowpea benefited from an increased sowing density in most cases without yield penalties. Field trials in dry land conditions have shown cowpea yields to increase with densities up to 120,000 plants/ha (El Naim et al., 2012) and to 566,000 plants/ha for mung bean (Jan et al., 2000). This is much higher than the current sowing density used by local farmers. Sorghum also responded positively to increased density. Trials by Rees (1986) showed that the optimal density varied depending on the rainfall conditions, from 120,000 plants/ha at 597 mm, to just 10,000 when rainfall was 126 mm. In this case long term production was maximised when a sowing density between 40,000 and 80,000 plants/ha was used (Rees, 1986).

Interestingly, when the practices of Farm A (nd) were compared to Farm D (FD) the effect of plant spacing becomes apparent, particularly for mung bean and cowpea (Figure 22). Between row spacing is known to significantly affect the crop performance of mung bean and cowpea. A smaller between row spacing allows for more uniform distribution of plants, thus reducing within crop competition for light, nutrients and space (Jakusko et al., 2013; Taj et al., 2002). This factor may account for a large portion of the differences in actual farmer yields indicated in Table 13.

The simulations provide an indication as to the potentially optimal sowing densities for a variety of crops in Efoetsy. Though some crops are cropped at close to their optimal density (maize, millet) others may benefit from an increased sowing density and changes to their row spacing (mung bean, cowpea). Results are consistent with previous research on sowing density in dryland areas of Africa (Bationo et al., 1990; El Naim et al., 2012; Jakusko et al., 2013; Jan et al., 2000; Mashiqa et al., ND; Rees, 1986; Taj et al., 2002). The findings also highlight how farmer differences in row spacing may have a large impact on yields, particularly for mung bean and cowpea yields.

The results also help to show the trade-offs which smallholders face, in which a higher sowing density improves yields in favourable years, but reduces yields in unfavourable years. This was particularly apparent for millet. In this case, net yield gains in the favourable years more than compensates for reduced yields in the unfavourable years and the greater investment in seed (not shown). However, such a strategy of increasing density would only pay off in the long term. Thus showing the importance of longer-term modelling, or field trials. With such highly variable weather conditions short-term trials may fail to show the potential range of possible crop yield responses, nor may they allow effective assessment of yield risk for different strategies. The results also verify that the higher sowing density employed by Farm D may pay off for some crops (Figure 22). And that farmer differences in sowing density and row spacing should be accounted for when considering interventions and implementing them as the model shows these may have a large impact on crop performance.

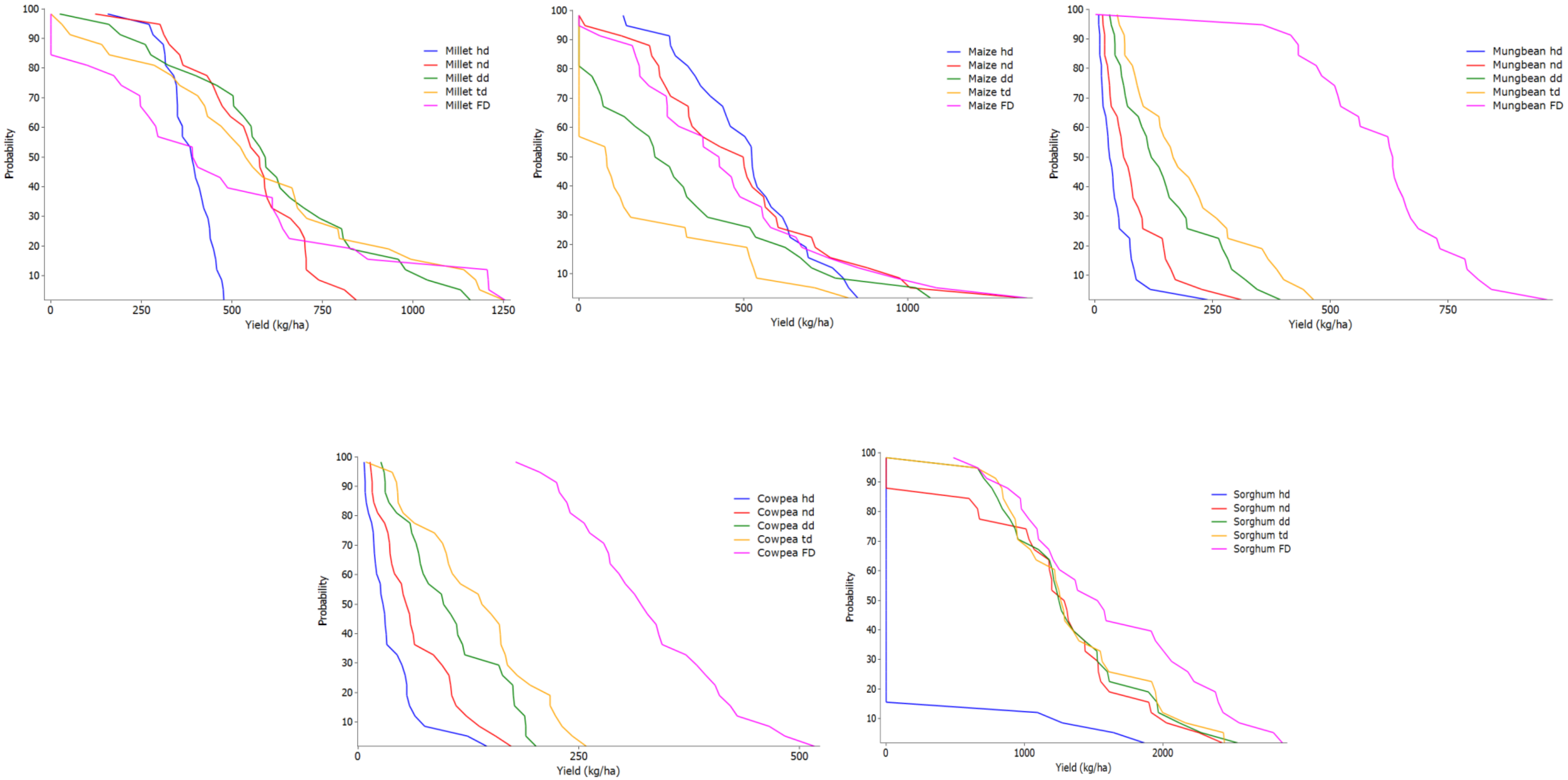


Figure 22 The probability of exceeding a given yield of millet, maize, mung bean, cowpea and sorghum based on 30 years of weather data for different sowing densities: normal density (nd) defined as “baseline”, half density (hd), , double density (dd), triple density (td) and the sowing density and row spacing of Farm D (FD).

3.8.2. Sowing Time

Comparison of the three main sowing times used by the surveyed farmers (October, December and January) showed that maize, mung bean; cowpea and sorghum are likely to achieve marginal yield gains when sown in December, while millet sown in January or December was preferable to October sowing (Figure 23). Of these crops it was mung bean and cowpea that had the largest proportional yield differences. Mung bean had a 50% probability of exceeding 80 kg/ha when sown in December, but 50 kg/ha when sown in October. Cowpea had a 50% probability of exceeding 30 kg/ha when shown in January, 60 kg/ha in October and 65 kg/ha in December. For maize and sorghum, yields at 50% probability were very similar. However, at the extremes of probability there were greater differences. Maize had a 90% chance of exceeding 225 kg/ha for December and October sowing, but the chance of this yield from January sowing was 75%. Additionally, sorghum experienced crop failures in 10% of years when sown in October, whereas December and January sowing experienced no crop failures.

Generally the main rainy season occurs from December to March (SuLaMa, 2011), however, rains may also occur before this (Figure 18). With the potential for rains in October/November, thus some farmers planted during this month, and also because their labour limitations would prevent them from waiting until the first heavy rains to sow. This is in keeping with the generated MarkSim weather, which gave a median rainfall of 36mm in November (Figure 18). As mentioned previously, Farm A sowed in October with a second sowing in January if the rains failed, Farm B planted in October only, Farm C in December, or January if the rains failed, and Farm D in January. It is notable that two of the farmers use a strategy of sowing twice during the season to help manage their risks given the highly variable rainfall. However, for those farmers that plant once it becomes essential to plant when they are most likely to achieve the best yield, year after year. For millet maize and sorghum there appears to be some differences in yield associated with the different sowing dates (Figure 23). However, for mung bean and cowpea the differences are slightly larger indicating these crops are more sensitive to their sowing time. Thus for farmers that only sow mung bean and cowpea in January, marginal yield gains may be achieved through sowing in December (Figure 23).

The results of the simulation suggest that some improvements to crop yields may be achieved through alteration of the sowing date. Following up with additional field research may be desirable to explore this effect under field conditions. Furthermore, a cost benefit analysis may also be beneficial. It appears that farmers could minimize yield risk by sowing in December, and could also reduce the additional labour and potentially the extra seed cost associated with a second sowing. This would allow farmers to utilise the saved labour hours for another activity. Alternatively, for farmers with periodic or spontaneous labour limitations this scenario may help them to decide which crops benefit most from being sown early in the season, and which ones can wait, until more labour is available.

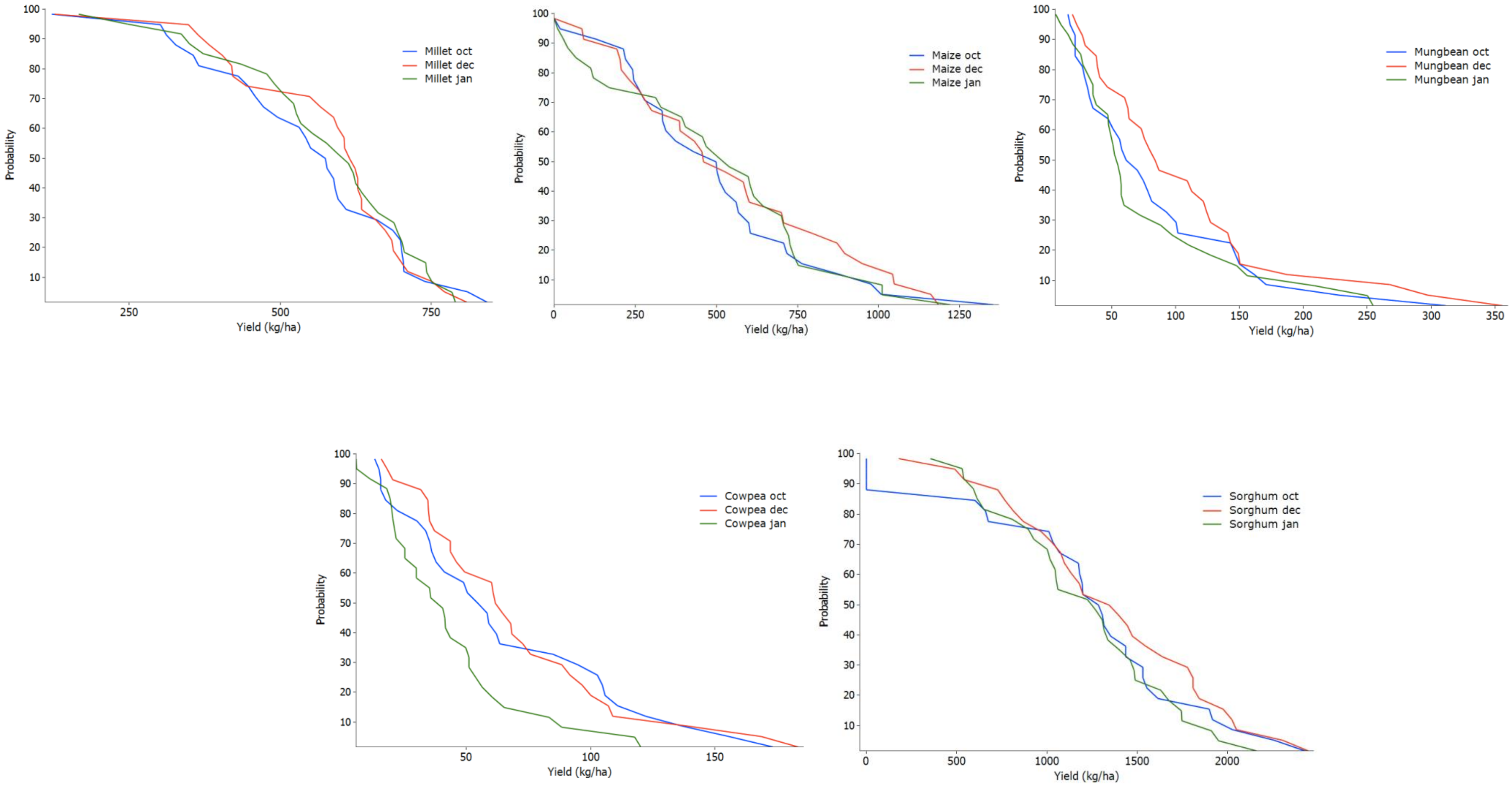


Figure 23 The probability of exceeding a given yield of millet, maize, mungbean, cowpea and sorghum over 30 years for October (oct) defined as "baseline", December (dec) and January (jan) sowing dates, based on the simulation parameters.

3.9. Model-based Exploration of Interventions

3.9.1. Cultivar

Millet

A comparison of three millet cultivars using APSIM revealed large differences in cultivar performance (Figure 24). Over the 30 years simulated there was a 50% chance of exceeding 575kg/ha for Wrajpop, 750 kg/ha for bj104 and 900 kg/ha for ZATIB. This constitutes a 63% greater yield from the cultivar bj104 compared to Wrajpop across the 30 year period. Interestingly the differences between the yields of the cultivars occurred at all levels of probability, even the very high probabilities. For instance there is a 75% probability of exceeding a yield of 446 kg/ha for Wrajpop, 576 kg/ha for ZATIB and 742 kg/ha for bj104. Thus indicating that bj104 outperforms the other cultivars with a high level of probability.

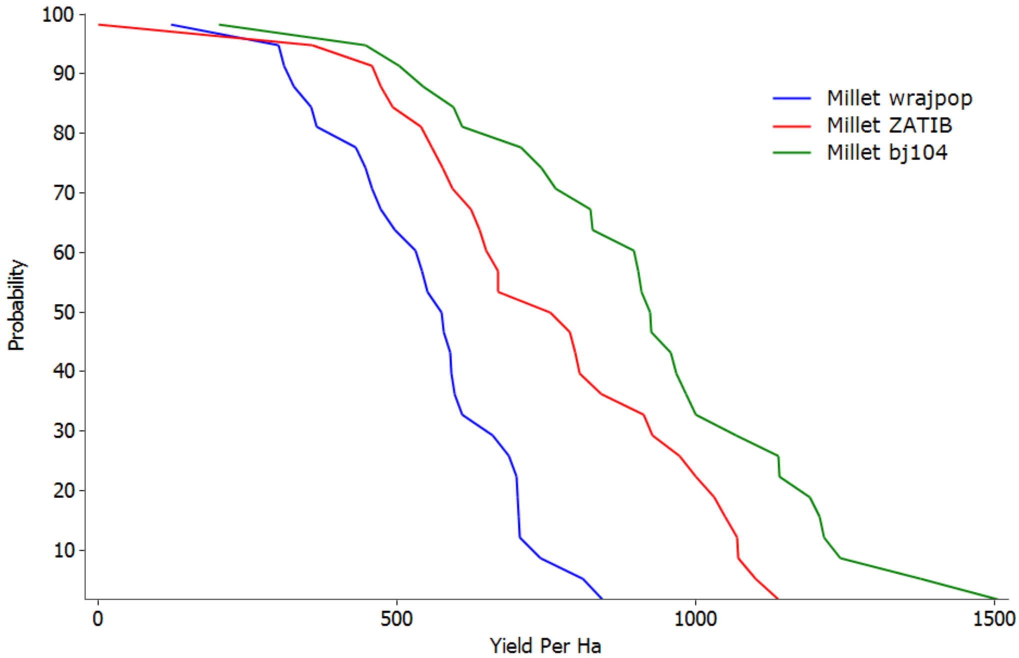


Figure 24 The probability of exceeding a given yield of millet over 30 years for different cultivars (Wrajpop defined as "baseline", ZATIB and bj104), based on the simulation parameters.

The results of the comparison show that cultivar bj104 gave the greatest yield at each level of probability and thus that it outperformed the other cultivars in all years of the simulation. The cause of these differences is related to the cultivar specific crop parameters in APSIM. Notable differences in the cultivar parameters include: Grains per head, grain growth rate, thermal time of development, and leaf size and number. The cultivars Wrajpop and ZATIB differ mainly in their rate of development (ZATIB develops faster). However, the cultivar bj104 in addition to developing faster, also has a different growth form, larger numbers of grain per head, and a greater grain growth rate.

Maize

The maize cultivars showed substantial differences in expected yields (Figure 25). There was a 50% probability of exceeding 500 kg/ha for Mwi Local, 1000 kg/ha for Timor Local and 1300 kg/ha for Pioneer 3237. This suggests that in 50% of years Pioneer 3237 would yield 800 kg/ha more than Mwi Local. Overall Pioneer 3237 outperformed the other varieties at all probability levels. The

Mwi local and Timor local cultivars had a varied performance. Mwi local outperformed Timor local, at the highest level of probability (between 75 and 100%), however, at every other level of probability Timor local produced more. The relative performance of the different cultivars is noticeable at the extremes of probability. At a 75% probability of exceedance, the yields were 262 kg/ha for Mwi Local, 263 kg/ha for Timor Local and 1000 kg/ha for Pioneer 3237. Indicating a transition point at which the local varieties performed very similarly. However, at a 25% probability of exceedance the yields were 604 kg/ha for Mwi Local, 1465 kg/ha for Timor Local, and 1738 kg/ha for Pioneer 3237 showing that the yield difference between the local varieties had changed substantially.

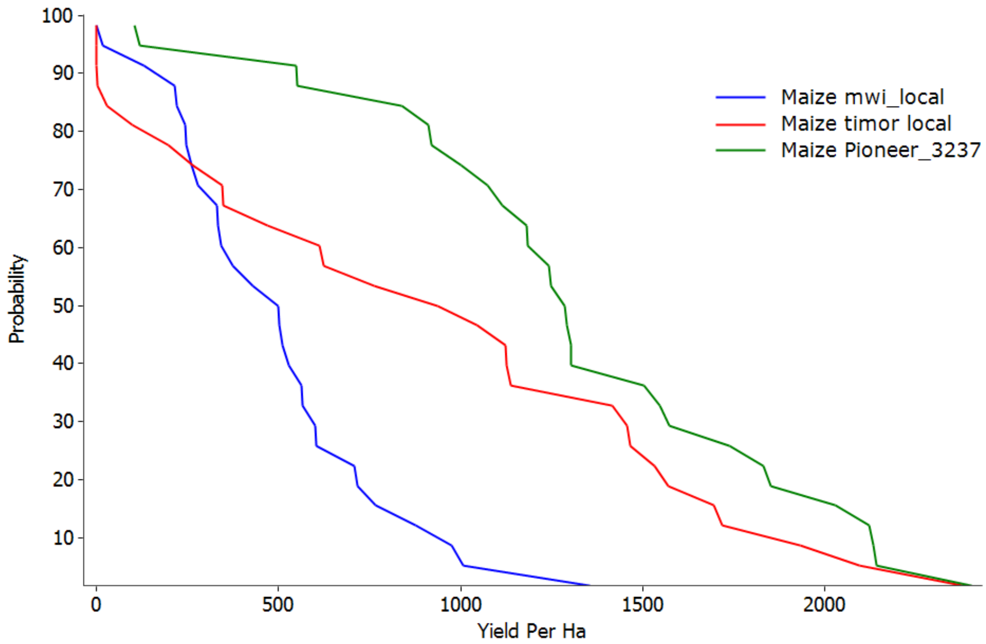


Figure 25 The probability of exceeding a given yield of maize over 30 years for different cultivars (mwi_local defined as "baseline", timor local and Pioneer_3237), based on the simulation parameters.

The results of the comparison showed that Pioneer 3237 attained greater yields in each year of the simulation. Differences in overall crop performance were related to grains per head, grain growth rate, time of flowering and growth duration. The local cultivars differed mainly in grain growth rate and phenological development. The Timor cultivar developed faster while the grain growth rate was also 48% higher than the Mwi cultivar. In contrast the Pioneer cultivar developed at a similar rate to the Mwi cultivar, but like the Timor cultivar had a much higher grain growth rate.

Mung bean

The simulation of three Mung bean cultivars, Satin, Green diamond and Celera, revealed some yield differences between the cultivars (Figure 26). At 50% probability of exceedance crop yields were 15 kg/ha for Satin, 40 kg/ha for Green Diamond and 60 kg/ha for Celera. Yields were greater for Celera at all levels of probability. Each of the the curves has a relatively similar shape indicating that the cultivars responded quite similarly to the different weather conditions. The curves are relatively steep between 100% and 30% probability of exceedance, particularly for the satin cultivar indicating only a gradual change in yield as the probability decreased. However, after 30% probability of exceedance the slope becomes more horizontal, indicating considerably higher yields may be expected in 1 out of 3 years, this is particularly apparent at the 10% exceedance rate. Overall the most productive cultivar was Celera which had the highest yield at each level of probability, in addition to having the highest maximal yield of 311 kg/ha .

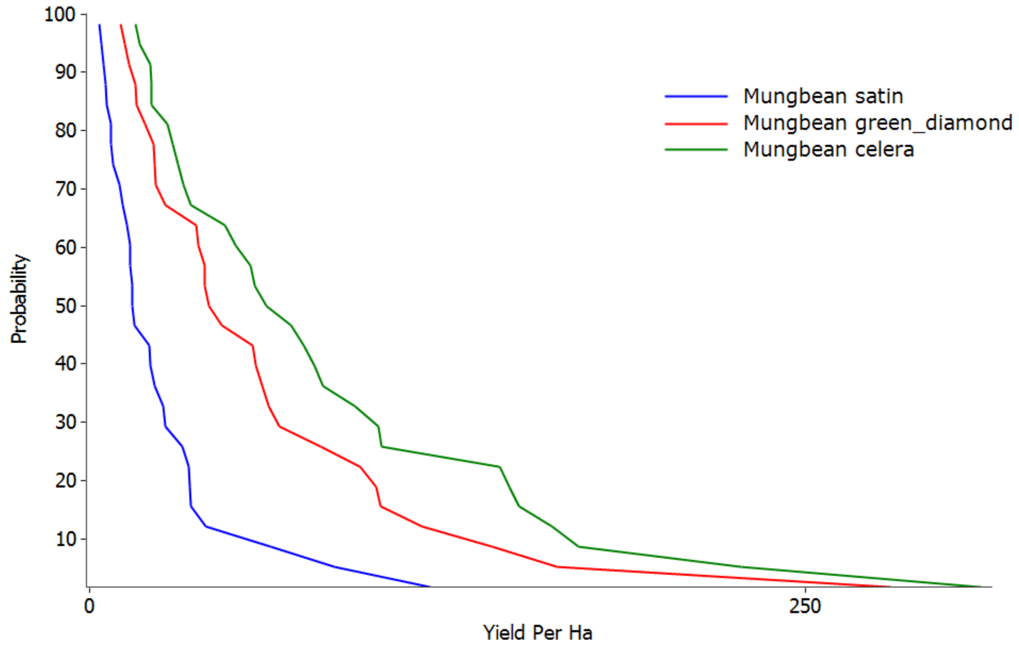


Figure 26 The probability of exceeding a given yield of mung bean over 30 years for different cultivars (Satin, Green diamond and Celera which was defined as "baseline"), based on the simulation parameters.

The comparison of these cultivars shows that Celera outperformed the other cultivars across all years under the differing weather conditions simulated. The attributes which allow this cultivar to perform better where related to phenology and harvest index potential, with the main difference being that the cultivars Green diamond and Celera had a slower rate of development than the Satin cultivar.

Cultivar selection was the most highly ranked intervention by development organisations while it is also easiest to implement by farmers. For each of the crop species, simulated changes to the cultivar resulted in substantial changes in production. It should be stressed that these scenarios provide an indication of potential production, and do not account for pest, disease or weed pressure which will play a major role in the relative success of a crop. Nevertheless, given the simulation parameters, it provides an indication that crop yields are sensitive to the cultivars used and consequently this may be a viable avenue for further research. Previous research has shown that the use of hybrid maize seeds resulted in yield gains of up to 30% even under unfavourable conditions compared to 14-25% for open pollinated varieties in Africa (Byerlee et al., 1996). However, other researchers suggest little benefit from using improved cultivars alone, with the main benefits occurring when fertility and water stress is being minimized (Ahmed et al., 2000).

In the context of Efoetsy, there is very limited access to improved cultivars; the seeds that are grown are either saved from the previous harvest, bought from a friend, or from the local market. Though there is also the potential of seed distribution by development organisations. The systematic breeding or introduction of new cultivars was not considered by local farmers. Thus, local crop development was highly limited. The general opinion of farmers was that a tall crop was a strong one and therefore better. In this regard, though improved cultivars are likely to offer a great deal of opportunities to the local farmers, to realise these opportunities will require a greater understanding of seeds, and seed saving. A plausible method to achieve this would be to begin evolutionary plant breeding in Efoetsy. Multiple populations of diverse origins are sown together, resulting in high genetic diversity in the offspring, each season natural selection based on prevailing conditions, and through farmer preferences, tailors the gene pool towards a population which matches the requirements of the local environment and people (Phillips et al., 2005). Such a method is recommended as a method of improving crops in low input systems with unpredictable stress conditions. Other issues include the appearance, taste and cooking properties of improved varieties which may not always match local preferences.

3.9.2. Time and Frequency of Weeding

Millet

Several simulations were run to explore the impact of weeds and weeding on the grain yield of millet (Figure 27). In all cases the crop with no weeds present performed substantially better than when weeds were in competition with the crop. Furthermore, in the absence of weeds, crops produced grains in all years. Conversely, if weed competition was severe yields were zero for all years. Even with partial weed control, the presence of weeds as part of model-based exploration resulted in crop failure in 15-20% of years. Of the different weeding regimes examined the scenario using two weedings at a given weed biomass gave the highest yields. Note that when a 500 kg/ha weed biomass threshold was used to initiate weeding, a third weeding did not occur in most years due to the weed biomass not reaching 500 kg/ha after the second weeding and before the crop was harvested. The reason for two weedings performing better than three at the 125 kg/ha and 250 kg/ha thresholds is not immediately clear and would be interesting to investigate further. Overall two weeding’s at a biomass threshold of 250 kg/ha gave the greatest yield in these scenarios

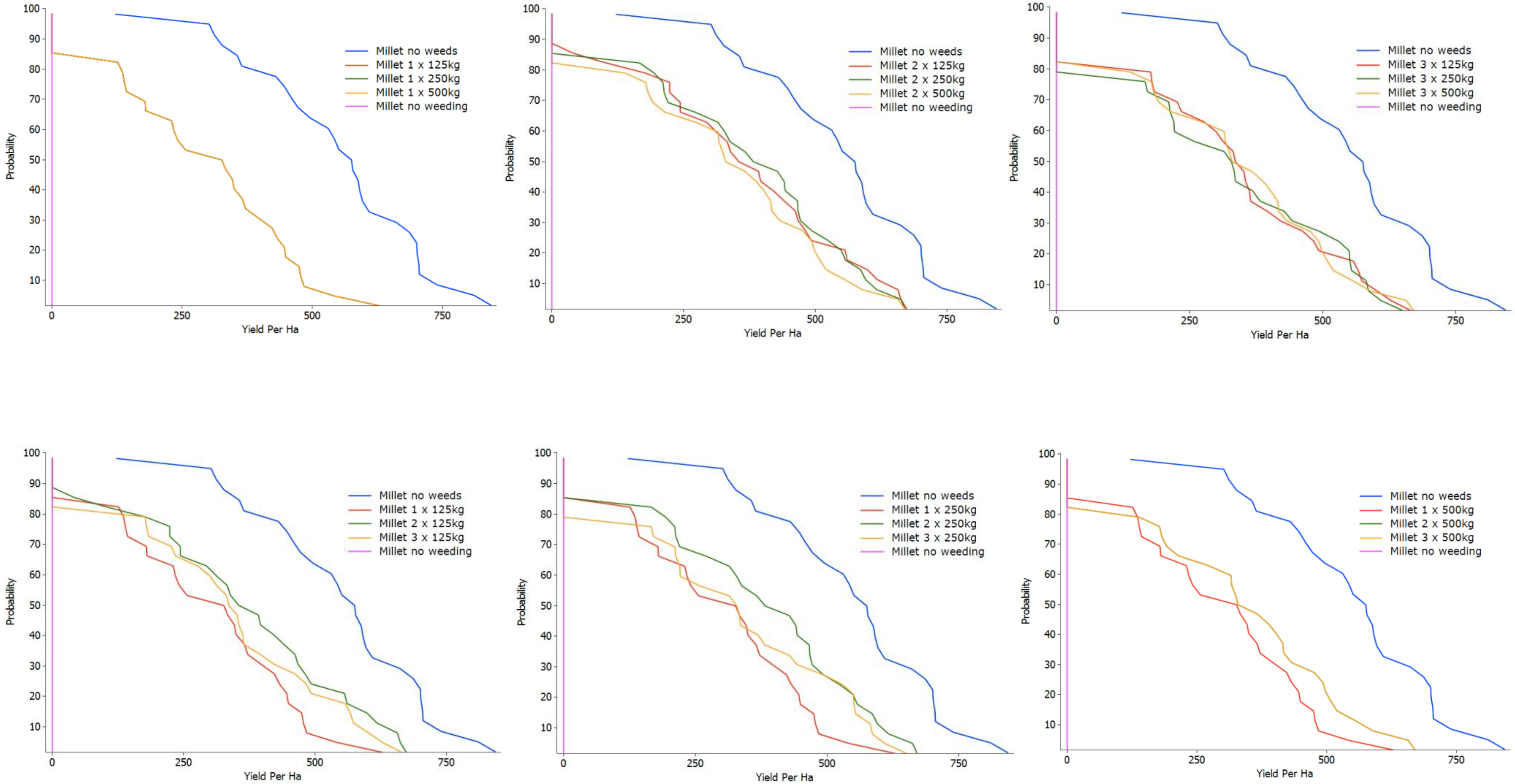


Figure 27 The impact of weeds on Millet yields under different weed management conditions. Millet 1 x 125 kg corresponds to one complete weeding at a weed biomass threshold of 125 kg/ha, Millet 2 x 250 kg corresponds to two complete weedings when weed biomass threshold reaches 250 kg/ha and so forth.

Maize

The highest crop yields occurred when weeds were present, but were removed more frequently (Figure 28). This occurred with three weedings at the weed biomass threshold of 125 kg/ha. It is speculated this was caused by beneficial changes to OC% and N over the 30 years when weeds were present. In this instance, OC increased from 0.4% to 0.52% where as in the weed free condition OC decreased to 0.37%. Furthermore, total nitrogen in the top 10 cm of soil increased from 540 kg/ha to 702 kg/ha when weeds were present vs a decrease to 498 kg/ha when weeds were not present (results not shown).

The worst scenario occurred when weeds were present but with no weed control applied; this resulted in complete crop failure in all cases. However, even with no weeds present crop failures occurred in 15% of years. If weeds were present and only removed once, crop failures occurred in up to 45% of years. Weeding twice per season reduced the risk of crop failure to 20%. Weeding an additional time per season further reduced this risk to about 15%. The optimal weed biomass (the biomass to achieve the highest crop yield) to initiate weeding depended on weed frequency. When one or three weedings took place a threshold of 125 kg/ha proved optimal. However, when two weedings were employed a weed biomass threshold of 250 kg/ha performed better.

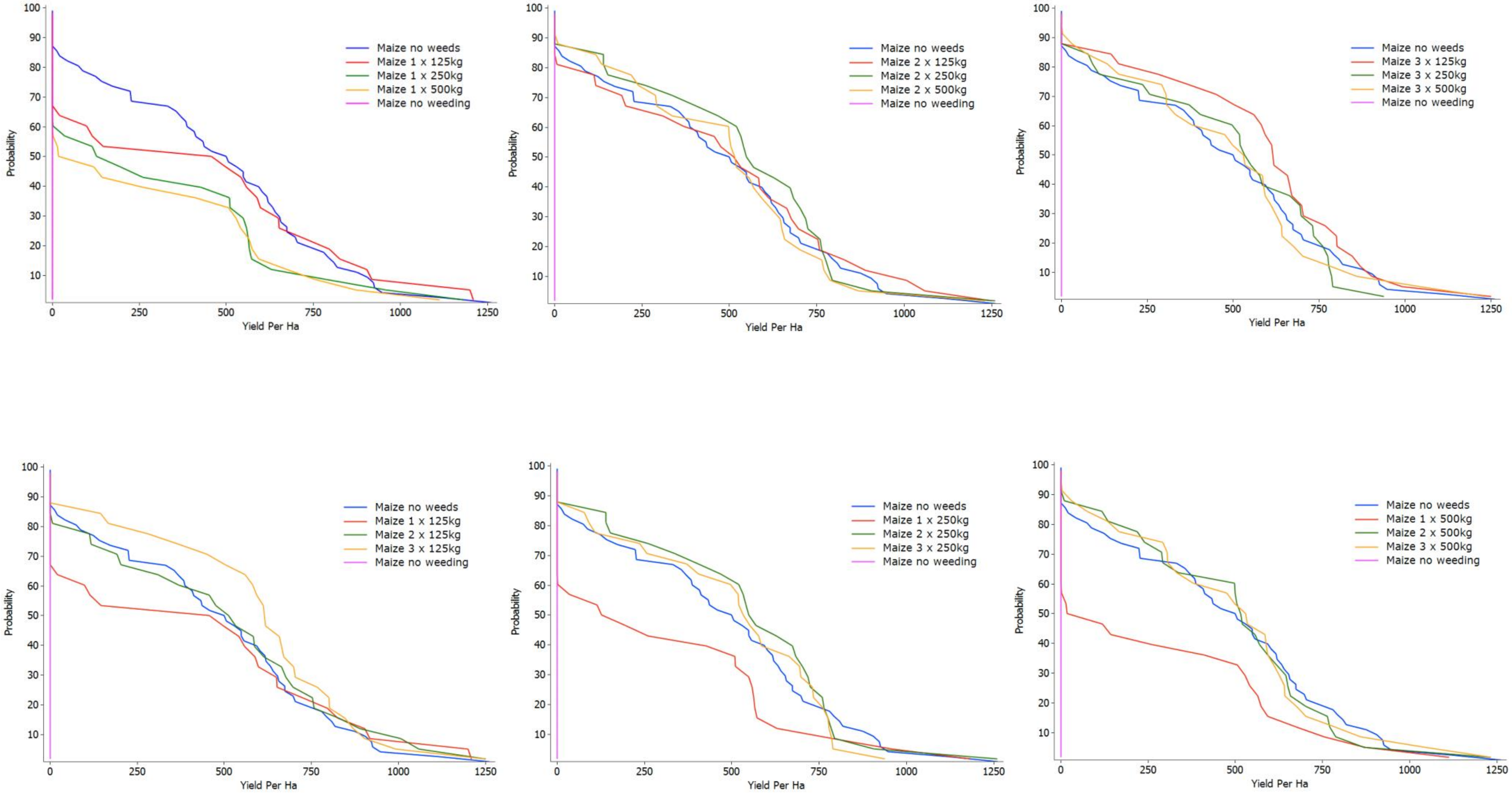


Figure 28 The impact of weeds on maize yields under different management conditions. Maize 1 x 125 kg corresponds to one complete weeding at a weed biomass threshold of 125 kg/ha, Maize 2 x 250 kg corresponds to two complete weedings when weed biomass threshold reaches 250 kg/ha and so forth.

Mung bean

The weeding simulations for mung bean have shown that the yields for mung bean were highest when no weeds were present (Figure 29). Furthermore, in the absence of weeds the crop produced some yield during each year. Conversely, if no weeding was performed the crop never produced any seeds. A weeding frequency of once per season did not seem to be adequate to effectively minimize yield losses as the maximal predicted crop yield was only 34 kg/ha while there was only a 15% chance of yields greater than 15 kg/ha. Weeding twice rather than once resulted in yield gains across all weed biomass threshold scenarios. A third weeding further improved yields at the 125 kg/ha and 250 kg/ha weeding thresholds, with expected yields at a given probability often more than double those achieved when one weeding was performed. As was the case for millet and maize, APSIM did not perform the third weeding at the 500 kg/ha weed threshold, as this threshold was not attained. Overall, the simulations show that frequent weeding, before the weed biomass becomes too high is preferable for mung bean and that failure to do so will result in substantial, if not complete yield losses.

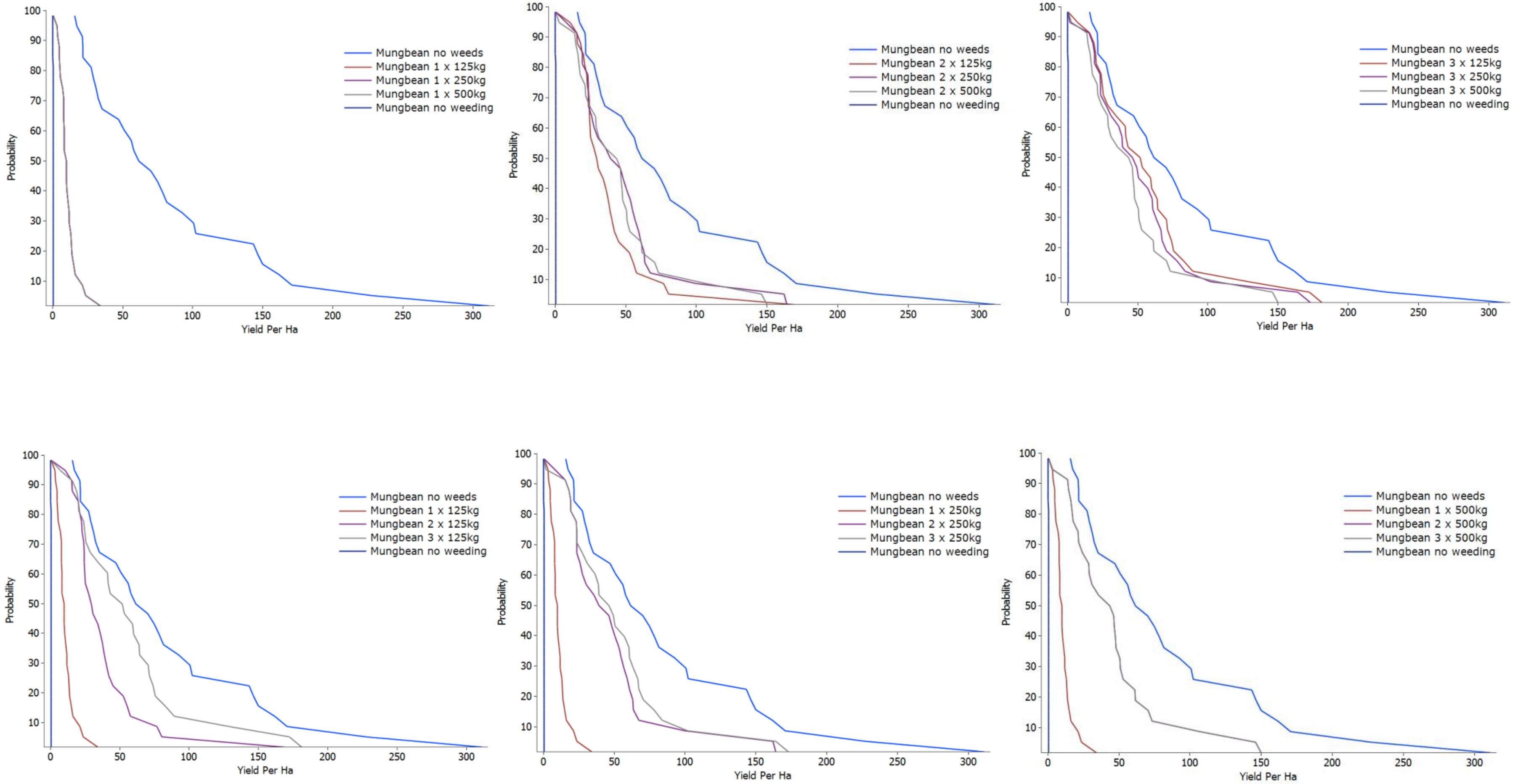


Figure 29 the impact of weeds on mung bean yields under different management conditions. Mungbean 1 x 125 kg corresponds to one complete weeding at a weed biomass threshold of 125 kg/ha, Mungbean 2 x 250 kg corresponds to two complete weedings when weed biomass threshold reaches 250 kg/ha and so forth.

Based on model-based explorations it appears that the presence of weeds resulted in substantial decreases in crop yields in most cases. Generally the risk of yield failures was greatly reduced, for farmers in Efoetsy, by timely and frequent weeding, whereas, in the absence of weeding predicted yields tend to be zero which is consistent with research by Klaij et al. (1996). With one weeding per season all crops would produce some yield although not consistently. For example, maize still experienced complete yield failure 50% of the time. The implementation of a second weeding provided substantial yield improvements for all crops totalling 25% for millet, 50% for maize and 300% for mung bean compared to a single weeding over the 30 year period. A third weeding produced mixed results, depending on the crop and time (biomass threshold) at which weeding occurred. In the case of maize and millet three weeding's at a threshold of 125 kg/ha appeared to be best while for millet two weeding's at a 250 kg/ha threshold may be preferable. What was rather intriguing when examining the model-based explorations was that when weeds were managed intensively the yield of maize was higher than when no weeds were present at all. Further simulations with APSIM, showed that the presence of weeds had beneficial effects on soil organic carbon (OC) and N over the 30 year period, which seems to offset the negative impact weeds have with regards to competition for nutrients and water (results not shown).

It is important to recognise from these scenarios that different crops benefit from different management regimes. Some crops show much greater vulnerability to yield failure under weed pressure and thus benefit more from frequent weed control. It is also insightful that a second weeding provides substantial benefits to all crops. So although this requires additional labour investments the improved yields are likely to compensate for this. In terms of actual farm practices, the interviewed farmers weeded between one and three times. Those who weed only once are likely to benefit from a second weeding. However, labour constrains remain an issue. It takes two people seven days, working five hours per day (total 134 hours), to weed 1 ha of cropped land in Efoetsy. Thus the farmers may not reach their desired level of weeding and face a trade-off between yields obtained and the time spent weeding. For maize a second weeding reduced the risk of crop failure by between 15 and 30% depending on the weed biomass threshold. When weeded only once the chance of exceeding 250 kg/ha of maize was around 45% but when weeded twice there was a 70% chance of exceeding 250 kg/ha. For millet a second weeding improved yields at a given probability by around 80 kg/ha and for mung bean around 50 kg/ha. This gave a return on investment of between 0.4 kg and 0.6 kg of grain per hour spent weeding (after the 1st weeding). However, the indicated weeding time is for weeding with a hoe and opportunities exist for reducing this investment. For instance sowing in rows and investing in a basic form of partial mechanization (wheel-based man operated weeder) may allow for more effective weeding which could reduce the time investments considerably thus allowing for a greater return on labour hours.

3.9.3. Application of Crop Residues and Manure

Millet

The impact of manure application and crop residue use on millet crop yields is shown in Figure 30. Very little differences occurred among the first four treatments. Indeed the retention of crop residues and application of low levels of manure (5 ton/ha) did not result in major yield improvements over the baseline condition, in which all residues are removed and no manure was applied. With a higher manure application of 20 ton/ha some yield benefits were apparent, but the impact remained small. When residues were retained and 20 ton/ha manure was applied the probability of exceeding 500 kg/ha of millet was 78% compared to 62% when no manure or residues were applied. This makes it 16% more likely to achieve a yield over 500 kg/ha when 20 ton/ha of manure is applied and residue retained compared to when residues are removed and no manure is applied.

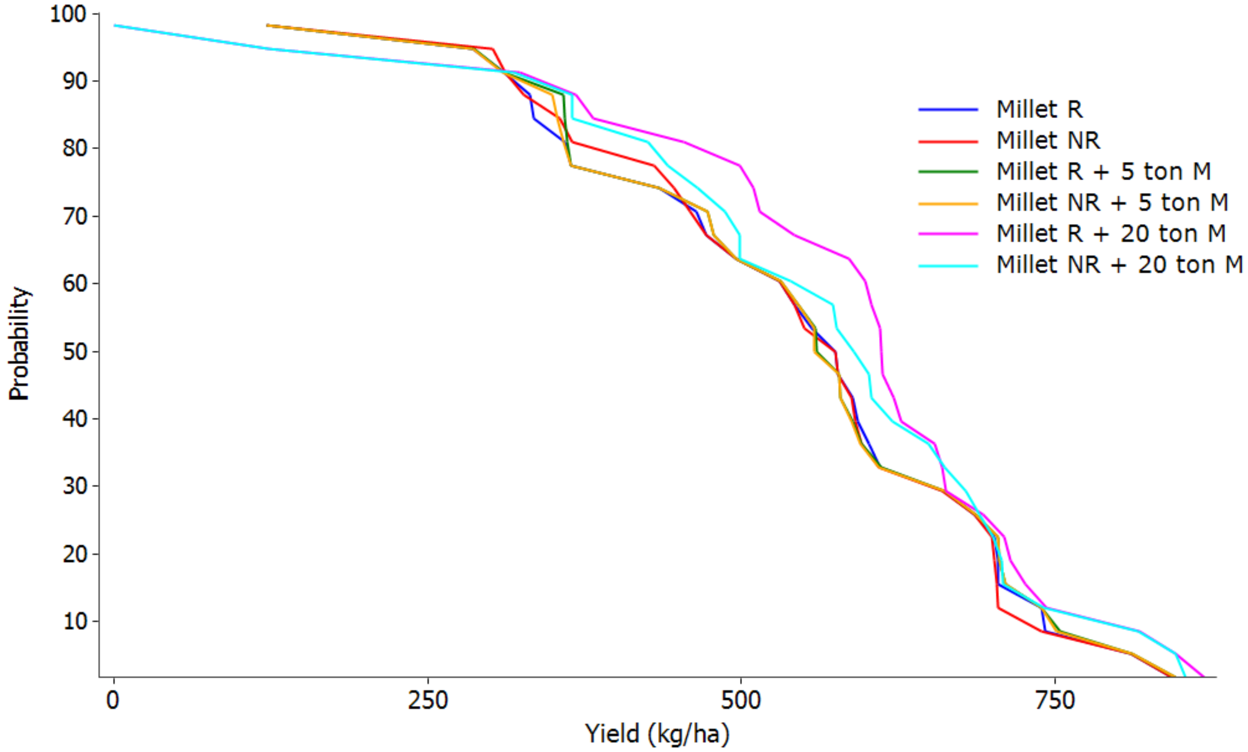


Figure 30 The probability of exceeding a given yield of millet over 30 years for different residue and manure scenarios: with residues (R) no residues (NR) with differing levels of manure (M) amendment. Millet NR was defined as "baseline".

Maize

The impact of manure application and crop residue use on maize crop yields is shown in Figure 31. The baseline scenario (maize NR) in which no residue is applied had the lowest yield of all scenarios and had a 40% chance of a crop yield over 500 kg/ha. The treatment Maize R, in which crop residues were retained, resulted in tangible benefits to yield. Increasing the probability of a crop yield over 500 kg/ha from 40%, in the baseline scenario, to 55%, an increase of 15%. The highest yielding scenario was achieved with residues and 20 ton/ha manure. This gave a 73% chance of yields over 500 kg/ha. Furthermore, the probability of obtaining a yield over 700 kg/ha was increased from 20%, in the baseline scenario, to 60% in the scenario with residue and 20 ton/ha manure.

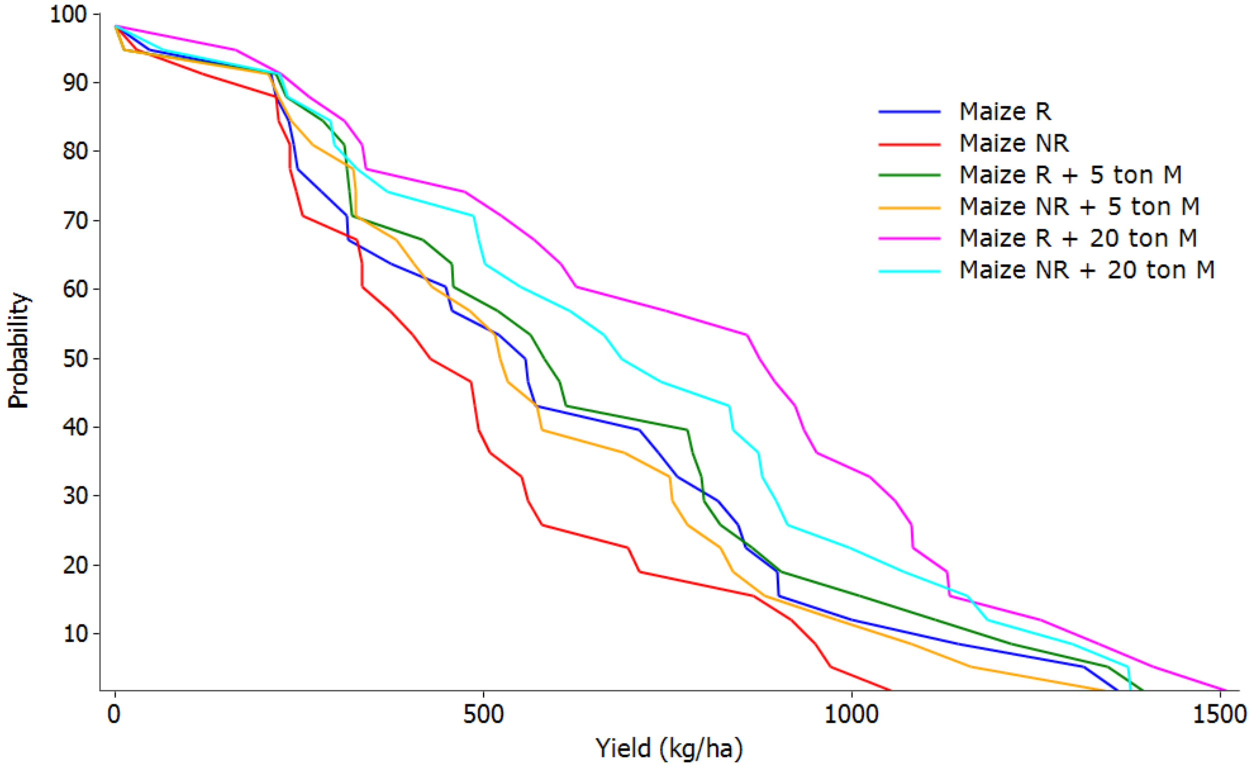


Figure 31 The probability of exceeding a given yield of maize over 30 years for different residue and manure scenarios: with residues (R) no residues (NR) with differing levels of manure (M) amendment. Maize NR was defined as "baseline".

Mung bean

The effect of manure application and crop residue use on mung bean crop yields is shown in Figure 32. No differences were found between any of the modelled treatment scenarios, indeed all the curves overlap. Further APSIM explorations revealed that in the baseline condition (no residue, no manure) OC reduced from 0.4% to 0.24% and the total nitrogen (in the top 10 cm soil profile) reduced from 540 kg/ha to 324 kg/ha after 30 years. The retention of crop residues and addition of 20 ton/ha manure mitigated this loss, and achieved marginal gains at the end of 30 years (OC 0.45% and N 616 kg/ha, result not shown). However, this did not result in greater yields. Based on the previous experiments investigating the effects of sowing density and row spacing on mung bean yields a further simulation was developed (not shown) in which plant density per ha was maintained, but row spacing halved to 50 cm. In this situation mung bean did show a yield response, with cumulative yields 13% greater when residues were retained and 20 ton/ha manure were applied, thus implying that row spacing defined the yield response to manure and crop residues.

It is also relevant that although the model can simulate the impact of residues on surface runoff, deep drainage, and soil evaporation, it uses a relatively simple approach of soil water balance. This creates limits as to how the model can represent the partitioning of water between groundwater drainage and soil evaporation, in addition to the suppression of soil evaporation (Mupangwa et al., 2011). Furthermore, the significant effects that organic matter (OM) can have on LL15 and DUL are not represented in the APSIM model (Hudson, 1994).

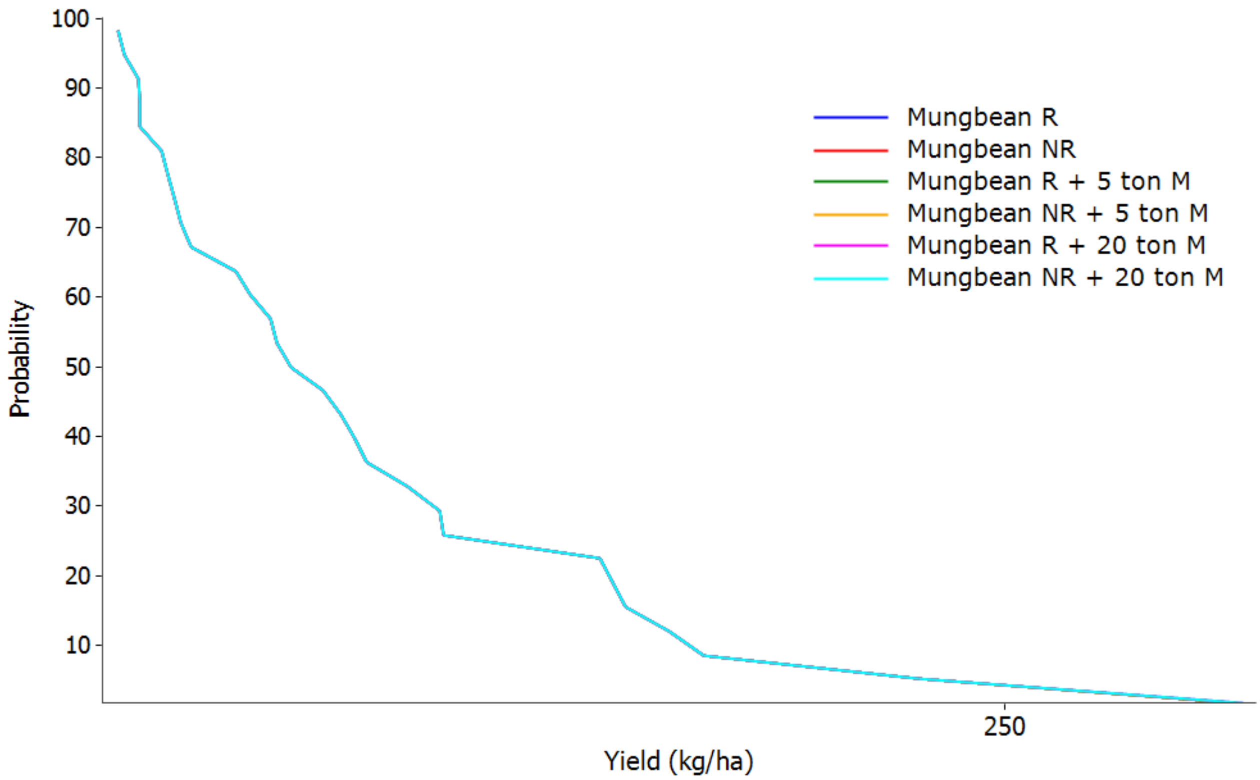


Figure 32 The probability of exceeding a given yield of mung bean over 30 years for different residue and manure scenarios: with residues (R) no residues (NR) with differing levels of manure (M) amendment. Mungbean NR was defined as "baseline"

The results of the APSIM simulations for millet, maize and mung bean with varied application rates of manure combined with residue retention versus removal treatment combinations show substantial crop differences. Maize yields increased substantially when organic amendments were applied, whilst millet only benefited marginally and the baseline mung bean scenario showed no response. These differences may be accounted for by different yield limiting and yield defining factors governing the final yields most greatly. In this context, both intrinsic crop differences and also differences in the management practices differ across these crops. As previously shown, maize and millet are sown at densities close to their optimal for the site conditions as related to the overall availability of water and nutrients. Any increases in sowing density, resulted in a trade-off in which increased interplant competition would reduce yields during years with unfavourable weather conditions but increase yields when weather conditions were favourable (quantity and distribution of rainfall). This did not occur for mung bean which benefited substantially from a reduced row spacing and increased sowing density suggesting that these factors were most limiting. Additional APSIM simulations explored if mung bean sown at a higher density would respond to manure; mung bean yields did respond to manure when the sowing density was increased from 30,000 plants/ha to 120,000 plants/ha (results not shown). Additionally, when the density per ha was maintained, but row spacing halved to 50cm mung bean also showed a yield response. These results suggest that the crop could not benefit from the improved fertility at its current row spacing or sowing density, but that once these factors were more optimal then yield gains from fertility enhancement were likely. Consequently, it is suggested that the current factors limiting and defining yields appears to vary with the crop as related to crop traits, crop adaptation, and prevailing management practices. For some crops, available water and/or nutrients may be most limiting (e.g. maize) while for others (mung bean) the farmer management (row spacing and sowing density) appeared to be the main defining factors. A better understanding of these differences and underlying processes may be essential when designing systems and structuring future management practices. In this manner farmers and extension officers may capitalize on a better understanding of which factors are likely to be the most limiting when making both strategic and tactical decisions. These insights may also be useful for *a priori* trade-off assessment thereby basing intervention schemes on a more target-oriented approach. In this, the decision making process may be enhanced by concentrating farm investments, in terms of labour or other inputs, on interventions that are less risky and most likely to be effective in terms of yield benefits. The limited response to manure inputs is in keeping with accounts of two of the interviewed farmers who were adamant that manure had no impact on crop yields. Model-based exploration confirmed that, unless large quantities of manure were added, the response of millet and mung bean to manure amendments would probably be too small for farmers to notice. This is consistent with local applied field research which showed that manure applications between 5 and 10 tons/ha only had an effect on cassava yields in the most nutrient-depleted fields (Hanisch, 2015a). It was reasoned that this was due to the low quality of the manure (associated with the poor diet of the animals and storage practices for the manure), nitrogen immobilisation and water limitations, which hampered the crop yield response to the nutrient inputs. This is consistent with other research which has shown that the use of organic amendments with a low C:N are susceptible to nitrogen immobilisation, which may even cause yield reductions (Giller et al., 2009). Furthermore, under farm conditions the impact of pests, diseases and weeds may off-set any potential yield increases associated with enhanced soil fertility. An additional APSIM simulation was run to explore this possibility for weeds; this showed that there was no overall beneficial impact of manure on maize yields (results not shown). It is known that fertiliser has a varied impact on weed population dynamics based on the local context, management and weed characteristics (Sweeney et al., 2008), but may increase weed growth and hence its competitiveness with the crop (Bajwa et al., 2014). Furthermore, manure is known to contain weed seeds (Schlather, 1994) which may increase the weed seed bank and may introduce more competitive weeds. With regards to pests and pathogens higher fertility can have both positive and negative effects. Plants with nutrient deficiencies are known to be more susceptible to pests and pathogens (Huber, 1989). Thus, improved fertility may improve pest and pathogenic resistance in the crop. Though it must also be considered that with high applications of nitrogen pest populations increase (Sohall et al., 2007). Field studies would be required to ascertain these impacts.

Development organisations should undertake more in-depth research into the short- and long-term consequences of manure use (quantity and quality) and crop management (row spacing and plant density) on crop responses to manure in this region. The results of the current study showed that the possible gains from utilising manure are quite limited for certain crops. It may be that a combination of different interventions (technology package) may be required to achieve more impactful yield gains in manure-based systems. Furthermore, improving the manure quality, and experimenting with the time of application may also be beneficial. However, given that few individuals have reliable access to manure, the high labour investment required to use it and the taboo on using manure, it is unlikely that farmers will use manure unless substantial yield gains are realised. One possible opportunity is for households with animals to practice corralling. From field experience a few households already do so, but do not currently utilise the manure, or the corals, for cropping. Farm D had a coral of 0.1 ha (the largest one in the village). If their 8 zebu spend 50% of their time in the coral and produce between 0.4 and 1.8 tons DM manure per cow annually (Paul et al., 2009). This would result in between 3.2 – 14.4 tons DM manure annually, the equivalent of 32-144 tons/ha. If two corals were utilised one could be cropped whilst the other is used for cattle, thus avoiding the labour cost of collecting and redistributing manure.

3.9.4. Assessing Relevant Yield-limiting and Yield-defining Factors

Explorations of the factors most limiting or defining to millet production are shown in (Figure 33 and Figure 34). Millet was assessed as it was the most popular crop grown by farmers that we could simulate. The first graph shows the impact of crop density, irrigation and urea in the absence of weeds (Figure 33). The second includes weed effects under a management regime of weeding on three occasions when the weed biomass reached a threshold of 125 kg/ha (Figure 34).

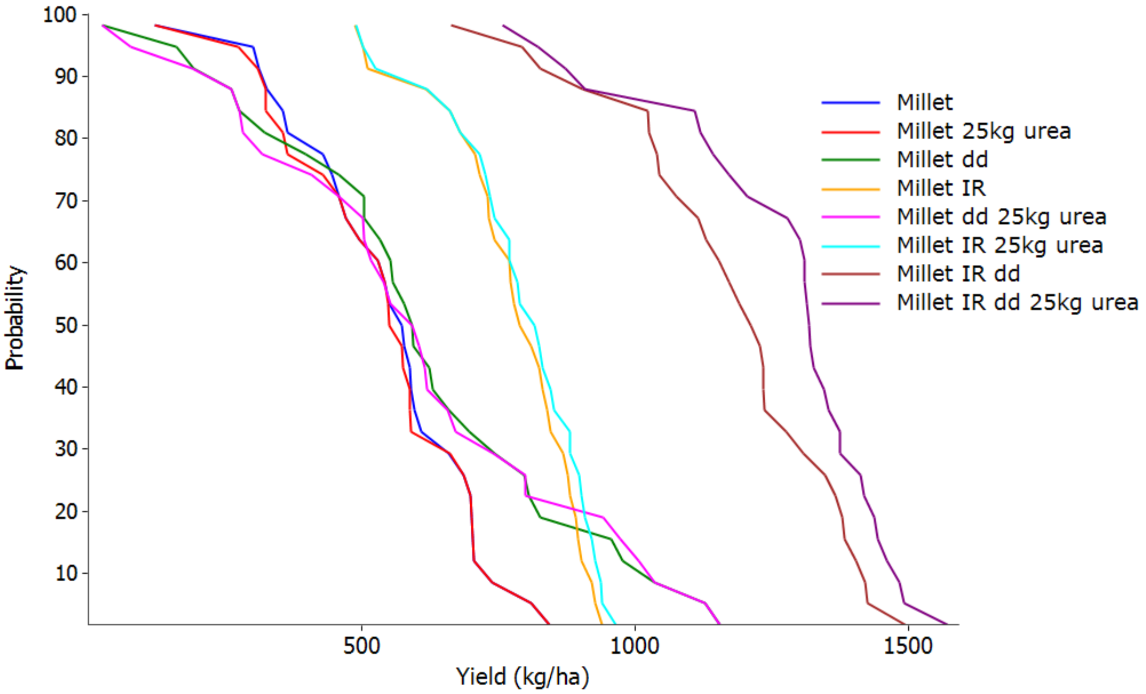


Figure 33: Exploration of the limiting factors to millet yields through the use of irrigation (IR), fertiliser (urea), and double density sowing rates (dd). Millet was defined as "baseline".

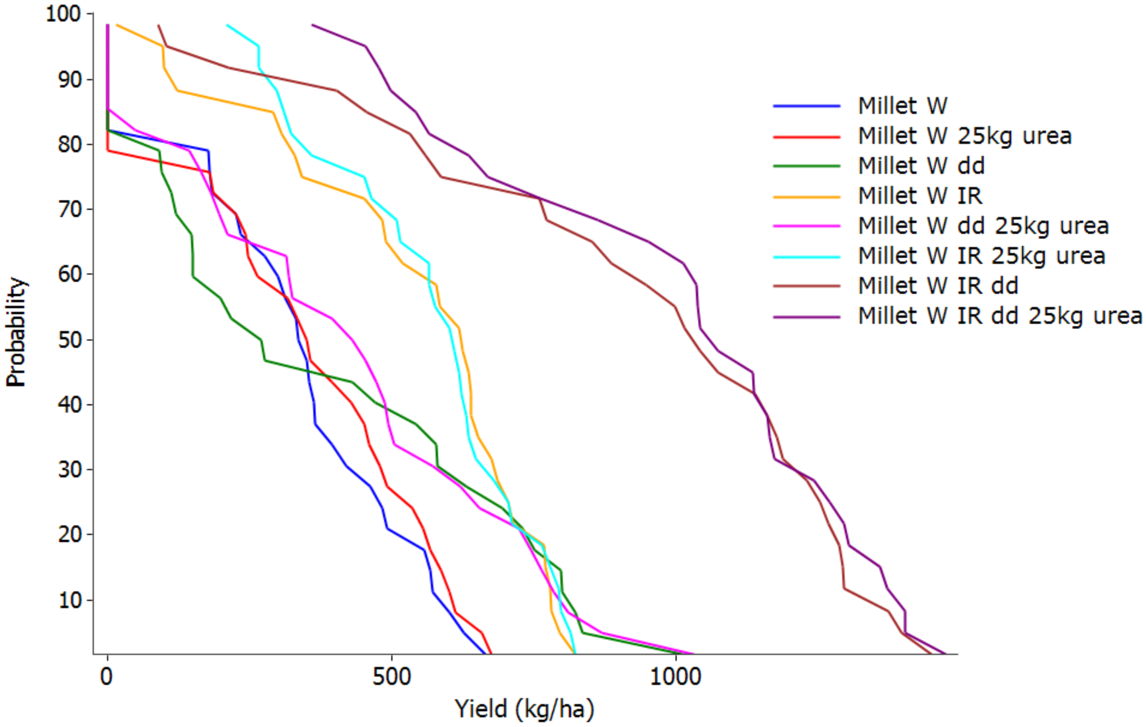


Figure 34: Exploration of the limiting factors to millet yields with weeds with different treatments of irrigation (IR), fertiliser (urea), and double density sowing rates (dd). Millet W was defined as "baseline".

The scenarios outline the major interactive effects of plant density and yield limiting factors on crop yields in Efoetsy. In the first exploration (Figure 33) there was a 50% probability of millet yields exceeding; 570 kg/ha in the baseline, 550 kg/ha when urea was applied, 590 kg/ha at double the baseline sowing density, 770 kg/ha when irrigation was applied, 590 kg/ha when the density was doubled and urea was applied, 800 kg/ha when irrigated with urea applied, 1200 kg/ha with irrigation and double density, and 1310 kg/ha with irrigation, double density and urea application. Irrigation had the greatest impact indicating water was most limiting to yield. Once this limitation was removed the density became the most defining factor, once the density was increased the impact of fertiliser application then became more pronounced.

In the second exploration (Figure 34) where weeds were included there was a 50% probability of millet yields exceeding; 350 kg/ha in the baseline, 360 kg/ha when urea was applied, 260 kg/ha at double the baseline sowing density, 620 kg/ha when irrigation was applied, 440 kg/ha when the density was doubled and urea was applied, 600 kg/ha when irrigated with urea, 1030 kg/ha with irrigation and double density, and 1060 kg/ha with irrigation, double density and urea application. Weeds had a substantial impact, reducing the expected yield to be achieved at a given probability and resulted in a 20% probability of crop failure when no irrigation was used. Nevertheless, the factors most limiting, or defining, of crop yields remained the same. First water, then density, then nutrients.

Overall these simulations help to show the factors limiting or defining crop yields in Efoetsy, and how once one factor is addressed, a new limiting factor emerges. The model shows that water is the overarching limiting factor to millet crop yields in Efoetsy. Given that water availability is predicted to decline in the area due to climate change, water may become even more limiting to millet production in the future (Tadross et al., 2008). If efforts are not made to overcome this, the area will have a high vulnerability to desertification (USDA, 1998). Nevertheless, no organisation saw any feasibility for widespread irrigation in this area except for small-scale intensive vegetable production in corralled areas near the homesteads. Thus, strategies will have to be used which make the most of the water limitations of this region.

4. Conclusion

The development, and use of an expert based typology was able to distinguish small holder farmers based on structural farm characteristics, particularly wealth (number of zebu and charrette ownership), education, and off farm employment. The typology resulted in four farm types: "poor", "average", "rich" and "alternative income". However, the farm survey showed that these differences were not associated with substantial changes to crop management based on the resources of the farm. Rather, differences were subtle: time of planting, sowing density, row spacing and weeding, based on personal preferences and labour constraints of farmers.

Given the similar farm management practices and challenges faced by the farmers, the potential interventions to improve crop productivity were generally applicable to each of the farmers interviewed. The most frequently advocated best bet solutions by local development organisations were: the provision of new crop varieties, manure/composting, crop rotation, weeding, clay pot / small scale irrigation, agroforestry and intercropping. Whilst the most common smallholder practices to improve production were weeding and increasing the area of cultivated land. Additionally all the farmers expressed their openness to: use different crop varieties, plant more than once per year, use intercropping and grow trees. Thus, there was a suite of context-appropriate "best bet" solutions advocated by development organisations that met the social, political and resource context of the farmers.

APSIM was parametrized to assess the impact of different smallholder practices on baseline crop productivity. This highlighted the impact of sowing time and sowing density on crop yields. Sowing time did affect crop yields, though only marginally for millet, maize and sorghum. For mung bean and cowpea the effect was proportionally greater with both achieving moderate improvements from sowing in December. Thus, the different planting times used by the farmers may be expected to have some impact on final crop yields. Additionally, it was shown that, given the modelled farming practices, some crops (cowpea and mung bean) may be more sensitive to changes in their planting dates than others. The other principal difference between farmer practices was differences in sowing density and row spacing. Though three of the farmers had similar practices, one had a much higher sowing density. These differences did affect crop performance, with Farm D yielding slightly more for sorghum, and considerably more for cowpea and mung bean. Whilst Farm A had marginally higher yields for maize and millet. Thus, differences in smallholder practices may be expected to cause differences in crop performance. Consequently, consideration should be made for farmer differences when exploring the efficacy of interventions. As differences in farmer practices may result in differences in crop performance which may be a determining factor in the success of an intervention.

Cultivar choice, weeding and the use of manure and/or residues were development interventions chosen for further model based exploration. The model predicted substantial cultivar yield differences for millet, maize and mung bean, thus showing high crop sensitivity to cultivar and supporting the use of different cultivars as a viable intervention strategy. With regard to weed management, the timing and frequency of weeding was found to have a large impact on crop yields. At least one weeding was necessary to obtain a yield and a second weeding provided improvements totalling 25% for millet, 50% for maize and 300% for mung bean compared to a single weeding over the 30 year period. A third weeding produced mixed results, depending on the crop and time (weed biomass threshold) at which weeding occurred. In the case of maize and millet, weeding three times when the weed biomass reached 125 kg/ha weeds appeared to give the highest yield, while for millet weeding twice at a weed biomass of 250 kg/ha was more beneficial. The final intervention modelled the use of manure and residues. This predicted that for the highest application rate, when residue was retained and 20 ton/ha of manure was applied, the probability of crop yields over 500 kg/ha increased from 40% to 73% for maize and from 62% to 78% for millet. Interestingly, mung bean did not show any response. The lack of response may be due to the yield currently being defined by the sowing density (and row spacing).

Overall the yield response to the different interventions varied substantially with the crop. These differences may be accounted for by different yield limiting factors governing final yields most greatly. In this context, both intrinsic crop differences and also differences in the management practices are likely to affect the success of development interventions in Efoetsy. Nevertheless, in the context of a variable climate, it was seen that the development approaches of, cultivar, weeding and manure use may offer opportunities to improve the crop yields for farmers in Efoetsy. But that these improvements are likely to be crop specific and influenced by other farm practices such as planting time and sowing density. Thus focusing on crop specific approaches and providing recommended farm management practices would be most likely to achieve yield benefits from the desired intervention. Despite these opportunities, the system will remain water limited and crop damage from pests, disease and cyclones will further reduce the crop yields predicted in the simulations. Furthermore, the changing climate is expected to further reduce crop yields as the climate continues to change. In this regard more radical changes to farming practices may be necessary, if the farmers are to continue to subsist in Efoetsy. One such option mentioned by development agencies and farmers is tree crops, or agroforestry and this warrants further investigation.

Based on field experiences, it was apparent that several local resources may be investigated for further development. Particularly; prickly pear, mango and papaya. The prickly pear appears as one of the most reliable and easily maintained plants grown locally. It grows abundantly, and is an important food source during the lean period. The downside of this fruit is that the seeds are known to cause constipation and bezoars (Eitan et al., 2006). As little as six fruits are needed to cause constipation, thus when it becomes a major food source this effect is exaggerated and can cause severe health problems. Locally this is known to cause the deaths of children and elderly who eat too much during the lean season. A solution to this would be to introduce a hybrid variety with no seeds that could be propagated by leaf cuttings. Future research would need to investigate the practical and ecological significance of this, but offers a promising area of development. An additional fruit, which has proven success in Efoetsy, is the papaya. The main limitation to its cultivation appeared to be the smallholders ability to propagate it. Thus it would be beneficial for development organisations to help establish these plants to help further assess the production potential in Efoetsy. Further fruit for investigation is the mango. They are known to grow within 100 km of the village, but villagers' attempts to cultivate them have failed thus far. A local farmer said they will germinate and grow for one or two years, then die. Given the high evapotranspiration potential of the soil and the salinity of the local well water used to irrigate the seedlings, it is likely they succumbed to salt stress, to which mangos are vulnerable. However, if the soil is periodically flushed clean of salts this may be overcome. Alternatively salt tolerant varieties and root stocks are available (Gutam et al., 2011) and their introduction may provide an important additional food source. Ultimately, the best chance of improving the productivity in this smallholder systems will come through a multicomponent approach including different cropping interventions, agroforestry and other development options.

References

Ahmed, M., Sanders, J., & Nell, W. (2000). New sorghum and millet cultivar introduction in Sub-Saharan Africa: impacts and research agenda. *Agricultural Systems, 64*(1), 55-65.

Alvarez, S., Paas, W., Descheemaeker, K., Tittonell, P., & Groot, J. (2014). Typology construction, a way of dealing with farm diversity.

Anderson, J. R. (2008). Agricultural advisory services.

Bajwa, A. A., Anjum, S. A., Nafees, W., Tanveer, M., & Saeed, H. S. (2014). Impact of fertilizer use on weed management in conservation agriculture-a review. *Pakistan Journal of Agricultural Research, 27*(1), 69-78.

Bates, B., Kundzewicz, Z., Wu, S., & Palutikof, J. (2008). Climate change and water. Intergovernmental Panel on Climate Change (IPCC): Cambridge University Press.

Bationo, A., Christianson, C., & Baethgen, W. (1990). Plant density and nitrogen fertilizer effects on pearl millet production in Niger. *Agronomy Journal, 82*(2), 290-295.

Battistini, R. (1964). *Géographie humaine de la plaine côtière Mahafaly* (Vol. 12): [Toulouse]: Editions Cujas.

Birner, R., Davis, K., Pender, J., Nkonya, E., Anandajayasekeram, P., Ekboir, J., . . . Benin, S. (2009). From best practice to best fit: a framework for designing and analyzing pluralistic agricultural advisory services worldwide. *Journal of agricultural education and extension, 15*(4), 341-355.

Birner, R., Davis, K., Pender, J., Nkonya, E., Anandajayasekeram, P., Ekboir, J. M., . . . Benin, S. (2006). From" best practice" to" best fit": a framework for designing and analyzing pluralistic agricultural advisory services: International Food Policy Research Institute (IFPRI).

Blanc-Pamard, C., & Fauroux, E. (2004). L'illusion participative (Vol. 31): Presses de Sciences Po.

Brinkmann, K., Noromiarilanto, F., Ratovonamana, R. Y., & Buerkert, A. (2014). Deforestation processes in south-western Madagascar over the past 40 years: what can we learn from settlement characteristics? *Agriculture, Ecosystems & Environment, 195*, 231-243.

Byerlee, D., & Heisey, P. W. (1996). Past and potential impacts of maize research in sub-Saharan Africa: a critical assessment. *Food Policy, 21*(3), 255-277.

CCD. (2015). *Appui des populations sinistrées et vulnérables de la commune de Beheloka, Maroarivio, Ankazomanga dans le District de Tolaria et Betioky Sud*. Proposition de projet de VCT au PAM.

CGIAR. (2015). MarkSim. from http://gisweb.ciat.cgiar.org/MarkSimGCM/

Cline, W. R. (2007). Global warming and agriculture: Impact estimates by country. Peterson Institute.

Coudouel, A., Hentschel, J. S., & Wodon, Q. T. (2002). Poverty measurement and analysis. *A Sourcebook for poverty reduction strategies, 1*, 27-74.

Cox, H., Hammer, G., & Robertson, M. (2001). Opportunities for crop modelling in barley.

d-maps.com. (2014). Madagascar. from http://d-maps.com/carte.php?num_car=35065&lang=en

Daskalopoulou, I., & Petrou, A. (2002). Utilising a farm typology to identify potential adopters of alternative farming activities in Greek agriculture. *Journal of Rural Studies, 18*(1), 95-103.

Dostie, B., Haggblade, S., & Randriamamonjy, J. (2002). Seasonal poverty in Madagascar: magnitude and solutions. *Food Policy, 27*(5), 493-518.

Eitan, A., Bickel, A., & Katz, I. M. (2006). Fecal impaction in adults: report of 30 cases of seed bezoars in the rectum. *Diseases of the colon & rectum, 49*(11), 1768-1771.

El Naim, A. M., Jabereldar, A. A., Ahmed, S. E., Ismaeil, F. M., & Ibrahim, E. A. (2012). Determination of suitable variety and plants per stand of cowpea (Vigna unguiculata L. Walp) in the sandy soil, Sudan. *Advances in life Sciences, 2*(1), 1-5.

Escobar, G., & Berdegue, J. (1990). Conceptos y metodología para la tipificación de sistemas de finca: la experiencia de RIMISP. *Tipificación de sistemas de producción agrícola. RIMISP (Ed) Santiago de Chile*, 13-43.

FAO. (1996). Declaration on world food security. World Food Summit, Rome.

FAO. (2014a). Madagascar and FAO, Building resilience and sustainable food and nutrition security.

FAO. (2014b). Supporting smallholder farmers in southern Africa to better manage climate-related risks to crop production and post-harvest handling *Madagascar Community Profiling Report*.

Feder, G., Just, R. E., & Zilberman, D. (1985). Adoption of agricultural innovations in developing countries: A survey. *Economic development and cultural change*, 255-298.

Gbetibouo, G., & Hassan, R. (2005). Measuring the economic impact of climate change on major South African field crops: a Ricardian approach. *Global and Planetary Change, 47*(2), 143-152.

Giller, K. E., Leeuwis, C., Andersson, J. A., Andriesse, W., Brouwer, A., Frost, P., . . . Koning, N. (2008). Competing claims on natural resources: what role for science?

Giller, K. E., Tittonell, P., Rufino, M. C., Van Wijk, M., Zingore, S., Mapfumo, P., . . . Corbeels, M. (2011). Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. *Agricultural Systems, 104*(2), 191-203.

Giller, K. E., Witter, E., Corbeels, M., & Tittonell, P. (2009). Conservation agriculture and smallholder farming in Africa: the heretics' view. *Field crops research, 114*(1), 23-34.

GoogleEarthPro. (2015). Efoetsy. Mountain View California: Google, Inc.

Guerra, C., & Stephanie, C. (2014). Integration of smallholder farmers into agribusiness value chains under restrictive markets: the case of the littoral-Mahafaly plateau transect in south-western Madagascar.

Günther, I., & Harttgen, K. (2009). Estimating Households Vulnerability to Idiosyncratic and Covariate Shocks: A Novel Method Applied in Madagascar. *World Development, 37*(7), 1222-1234. doi: http://dx.doi.org/10.1016/j.worlddev.2008.11.006

Gutam, S., & Singh, V. (2011). Salt tolerant rootstocks for increasing quality production of mango (Mangifera indica L.).

Guyot, L. (2002). Reconnaissance hydrogéologique pour l'alimentation en eau d'une plaine littorale en milieu semi-aride: Sud Ouest de Madagascar (Doctoral dissertation, Université de Nantes).

Hanisch, S. (2015a). *Improving cropping systems of semi-arid south-western Madagascar under multiple ecological and socio-economic constraints.* Kassel.

Hanisch, S. (2015b). *Unpublished soil data*.

Hänke, H. (2015). Household Survey Data.

HarvestChoice. (2010). HC27: Generic/Prototypical Soil Profiles. Washington, DC., and University of Minnesota: International Food Policy Research Institute.

Haut de sigy, G. (1970). Contribution to the study of fertility investments on the lateritic hills of the highlands in Madagascar. *Agron. trop., Paris, 25*(5), 441-471.

Hillegeist, A. (2015). Digital Soil Map of the World. Retrieved 15/05/2015, 2015, from http://worldmap.harvard.edu/data/geonode:DSM

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., Linden, P. J. v. d., Dai, X., . . . Johnson, C. A. (2001). Climate Change 2001: The Scientific Basis. University of Cambridge: Intergovernmental Panel on Climate Change.

Huber, D. (1989). The role of nutrition in the take-all disease of wheat and other small grains. *Soil borne Plant Pathogens: Management of Diseases with Macro and microelements*(The American Phytopathological Society), 46-75.

Hudson, B. D. (1994). Soil organic matter and available water capacity. *Journal of Soil and Water Conservation, 49*(2), 189-194.

ICRA. (2015). Typology Key Concepts.

INSTAT. (2006). Enquête auprès des ménages 2005 (f. e. d. budget, Trans.). Antananarivo: Ministère de l’économie.

IPCC. (2013). Summary for Policymakers. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–30, doi:10.1017/CBO9781107415324.004.*

Jakusko, B., Anasunda, U., & Maustapha, A. (2013). Effect of inter-row spacing of some selected Cowpea (Vigna Unguiculata (L) Walp) varieties in Yola, Adamawa State, Nigeria. *Journal of Agriculture and Veterinary Science, 2*(3), 30-35.

Jan, A., Kaleem, S. A., Taj, F. H., & Khan, H. (2000). Response of mungbean cultivars to differentseeding densities at dry land conditions. *Pak. J. Biol. Sci, 3*(12), 2030-2032.

Keating, B. A., Carberry, P. S., Hammer, G. L., Probert, M. E., Robertson, M. J., Holzworth, D., . . . Hochman, Z. (2003). An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy, 18*(3), 267-288.

Klaij, M., & Hoogmoed, W. (1996). Weeding method and pre-sowing tillage effects on weed growth and pearl millet yield in a sandy soil of the West African Sahelian zone. *Soil and Tillage Research, 39*(1), 31-43.

Kostrowicki, J. (1977). Agricultural typology concept and method. *Agricultural Systems, 2*(1), 33-45.

Landais, E. (1998). Modelling farm diversity: new approaches to typology building in France. *Agricultural Systems, 58*(4), 505-527.

Lobell, D. B., & Field, C. B. (2007). Global scale climate–crop yield relationships and the impacts of recent warming. *Environmental research letters, 2*(1), 014002.

Mashiqa, P., Lekgari, L., & nNgwako, S. (ND). Effect of plant density on yield and yield components of maize in Botswana. *World of Sciences Journal, 1*(7), 173-179.

McCarthy, J. J. (2001). *Climate change 2001: impacts, adaptation, and vulnerability: contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change*: Cambridge University Press.

Meinke, H., Baethgen, W., Carberry, P., Donatelli, M., Hammer, G., Selvaraju, R., & Stöckle, C. (2001). Increasing profits and reducing risks in crop production using participatory systems simulation approaches. *Agricultural Systems, 70*(2), 493-513.

Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M., Lamarque, J., . . . Riahi, K. (2011). The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic change, 109*(1-2), 213-241.

Minten, B., & Barrett, C. B. (2008). Agricultural technology, productivity, and poverty in Madagascar. *World Development, 36*(5), 797-822.

Mupangwa, W., & Jewitt, G. (2011). Simulating the impact of no-till systems on field water fluxes and maize productivity under semi-arid conditions. *Physics and Chemistry of the Earth, Parts A/B/C, 36*(14), 1004-1011.

Neudert, R., Götter, J., Andriamparany, J., & Rakotoarisoa, M. (2014). *Income diversification, wealth, education and well-being in rural south-western Madagascar: Results from the Mahafaly Region*. Development Southern Africa.

Neudert , R., Götter, J., Andriamparany, J., & Rakotoarisoa, M. (in press). Income diversification, wealth, education and well-being in rural south-western Madagascar: Results from the Mahafaly Region. *Development Southern Africa*.

New, M., Hewitson, B., Stephenson, D. B., Tsiga, A., Kruger, A., Manhique, A., . . . Kululanga, E. (2006). Evidence of trends in daily climate extremes over southern and west Africa. Journal of Geophysical Research: Atmospheres (1984–2012), 111(D14).

Paul, S., Onduru, D., Wouters, B., Gachimbi, L., Zake, J., & Ebanyat, P. (2009). Cattle manure management in East Africa. *assessment, 94*, 289-298.

Phillips, S., & Wolfe, M. (2005). Evolutionary plant breeding for low input systems. *The Journal of Agricultural Science, 143*(04), 245-254.

Rakotonirainy, M., Nirina, I., Brunelli, C., Rakotoarinoro, R., Brown, A. T., & Valenti, P. (2011). Comprehensive Food and Nutrition Security and Vulnerability Analysis Rural Madagascar.

Ramalingam, B., Laric, M., & Primrose, J. (2014). From Best Practice to Best Fit: Understanding and Navigating Wicked Problems in International Development. *ODI draft paper*.

Rees, D. (1986). Crop growth, development and yield in semi-arid conditions in Botswana. I. The effects of population density and row spacing on Sorghum bicolor. *Experimental agriculture, 22*(02), 153-167.

Rosenzweig, C., & Parry, M. L. (1994). Potential impact of climate change on world food supply. Nature, 367(6459), 133-138.

Schlather, K. J. (1994). Incidence of weed seed in cow (Bos sp.) manure and its importance as a weed source for cropland. *Weed technology*, 304-310.

Sohall, A., Habibuil'ah, S. S., & Al, C. M. (2007). Effect of different doses of nitrogen fertilizer on sucking insect pests of cotton, gossypium *J. Agric. Res, 45*(1).

SuLaMa. (2011). Recherche participative pour appuyer la gestion durable des terres du Plateau Mahafaly dans le soud-ouest de Madagascar.

SuLaMa. (2014). Report on Household Baseline Survey Data.

Sweeney, A. E., Renner, K. A., Laboski, C., & Davis, A. (2008). Effect of fertilizer nitrogen on weed emergence and growth. *Weed science, 56*(5), 714-721.

Tadross, M., Randriamarolaza, L., Rabefitia, Z., & Zheng, K. (2008). Climate change in Madagascar; recent past and future. *Washington DC (World Bank)*.

Taj, F. H., Akbar, H., Basir, A., & Ullah, N. (2002). Effect of Row Spacing on Agronomic Traits and Yield of Mungbean (Vigna radiata L. Wilczek). *Asian Journal of Plant Sciences*.

Twomlow, S., Rohrbach, D., Dimes, J., Rusike, J., Mupangwa, W., Ncube, B., . . . Mahposa, P. (2010). Micro-dosing as a pathway to Africa's Green Revolution: evidence from broad-scale on-farm trials. *Nutrient Cycling in Agroecosystems, 88*(1), 3-15.

UNICEF. (2011). LE SUD CIMETIERE DE PROJETS

USDA. (1998). Global Desertification Vulnerability, Soil Science Division, World Soil Resources, Washington D.C.

Vololona, M., Kyotalime, M., Thomas, T., & Waithaka, M. (2013). Madagascar East african agriculture and climate change a comprehensive analysis: Intl Food Policy Res Inst.

von Heland, J., & Folke, C. (2014). A social contract with the ancestors—culture and ecosystem services in southern Madagascar. *Global Environmental Change, 24*, 251-264.

Watanabe, S., Hajima, T., Sudo, K., Nagashima, T., Takcmura, T., Okajima, H., . . . Yokohata, T. (2011). MIROC-ESM 2010: model description and basic results of CMIP 5-20 c 3 m experiments. *Geoscientific Model Development, 4*(4), 845-872.

WFP. (ND). Shocks: Natural disaster in Madagascar. In G. T. WFP Food Security Analysis Unit (HQ) (Ed.).

World Bank. (1996). Madagascar Poverty Report (Vol. 2). Washington, D.C.

World Bank. (2010). Madagascar. Retrieved 21/4/2015, 2014, from http://data.worldbank.org/country/madagascar

Appendix I

Semi Structured Discussion: Interventions southwest Madagascar

Introduction

Thank you for being here. The purpose of our discussion is to develop agricultural improvements suitable for a particular household in the Efoetsy village of the Beheloka region of southwest Madagascar.

Scenario

There is a household (6 people) in Efoetsy that has a few zebu. They grow cassava, maize, cowpea, mung bean, and sweet potato. They also grow a little bit of millet. Often their crops dont produce enough food to eat, but in good years they can sell surplus at the market. Their soil is sandy, and they dont add anything to it, or irrigate. They sow maize and beans after rain in december then cassava and sweet potato in january. They also sow some maize after any rain throughout the year. They use a hoe to sow their crops at a spacing of 1m x 1m. They also use the hoe for weeding (part of the field each week, it takes 3-4 weeks to do the whole field). They have little formal education and feel their main constraints are lack of rain (december-may) and money.

Questions

1. What do you think are the main limiting factors to crop production in this region? (eg. water, nutrients, sunlight, temperature, CO2, genetics (crop type or variety), pests, disease, weeds)
2. Why?
3. What intervention/s would you recommend to overcome these limiting factors? (eg water harvesting, nutrient amendment, lights, shading, CO2, change/add crop or variety, plant more of one crop, pest control, disease control, weed control, management: plant spacing, seeding area, time of seeding, seeds or seedlings, tillage, mulching)
4. How would you implement this/these intervention/s? (try to be specific with names, times, numbers or quantities)
5. Why would you use this/these intervention/s? what do you think will happen to crop production?
6. What makes one intervention better than other interventions?
7. Will the households use this intervention? why, why not? (consider local social, cultural, economic, knowledge, governance, resources and understanding of crop production)
8. How would you rank the interventions we have discussed based on improvement to production?
9. How would you rank the interventions we have discussed based on the likelihood the farmer will do it?
10. What do you think is necessary to do this in Efoetsy? (eg. teaching, field trials, IST support, government intervention, NGO support, provision of resources)

Appendix II

Semi structured interview

Thank you for meeting me. The purpose of this interview is to map farming system diversity in the ……….. region of southwest Madagascar. The intention is to categorise the population of farms into a few groups (or types) of farm that have similar characteristics. Such as: resources, social structures, knowledge and farm practices. This will be used to develop agricultural interventions which are relevant to the specific context of that group of farmers.

No	Question	Answer
1	How would you describe a typical household farm in the …………. region?	
2	Do you find household farms to be very similar, or very different in this region?	
3	Based on your experience, how many distinct household farms types exist in this region?	
4	Which characteristics do household farms differ in, in this region?	
5	How would you rank the importance of each characteristic in defining different farms?	
6	What are suitable units to differentiate farms based on these characteristics?	
7	How would you define the ….. farm types based on these characteristics?	

Characteristics that may be prompted for during the discussion:

Household size, education level, house hold land area, crops grown, crop harvest, possession of livestock, number of livestock, use of fertiliser, use of plough, Zebu cart, labour source, off farm income, main constraints.

Appendix III

Farm Data Collection Spreadsheet

Category	Description								
Site		Residence							
		Latitude							
		longitude							
		average slope							
		Size							
Surface residues	Crop Residue	Crop							
		% ground cover							
		C							
		N							
		P							
		Removed (Y/N)							
		Date of removal							
	Manure	% ground cover							
		C							
		N							
		P							
Management	Dates of Operations	Crop							
		Sowing time/s							
		If after rain how much							
		Intercropped with							
		Sowing density							
		Sowing density intercrop							
		Sowing depth (cm)							
		Row spacing							

		Harvesting							
		Duration							
		Weeding frequency							
		Weed cover							
		Irrigation							
Crop information		Seed source							
		Cultivar							
		Sowing date							
		Emergence							
		Panicle initiation							
		Flowering							
		Grain maturity							
		Yield good year							
		Yield average year							
		Yield bad year							
		Above ground Biomass							
		Below ground biomass							
		Biomass partitioning							
Fertilisation		For which crops							
		Type of fertiliser							
		Quantity							
		Time of application							
Seedbed preparation	Tillage	Time							
		Depth							
		% weeds killed							

What do you do to improve your productivity?		
What are your most important crops? why?		
Would you:	Yes/no	Why/why not
Change your sowing dates		
Plant more than once per year		
Change your crop species		
Change your crop varieties		
Use compost/mulch/manure		
Use fertilisers		
Use intercropping, eg maize cowpea		
Weed more frequently		
Use herbicides		
Grow trees		
Crop livestock integration (corralling)		