MITIGATION OF THE CLIMATE CHANGE EFFECT ON YIELDS OF SMALLHOLDER FARMERS IN NKAYI, ZIMBABWE.

MSC THESIS REPORT

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AgMIP The Agricultural Model Intercomparison and Improvement Project

ABSTRACT

Climate change will probably decrease crop yields in Zimbabwe, putting the food security of smallholder farmers at stake. The impact of climate change on yield, yield variability and food self-sufficiency by mid-21st century in Nkayi, representative for agro-ecological zone IV, was analyzed by simulating maize and sorghum yields under the baseline climate scenario and five possible future climate scenarios. The future climate scenarios were all hotter, and either drier or wetter than the baseline climate scenario. Combinations of different cultivars, sowing windows and levels of nitrogen application were tested under all climate scenarios to find out whether climate change impact could be mitigated by management. Yields were mainly affected by rainfall and less by temperature. Maize and sorghum yields were not affected when both temperature and rainfall increased, but were decreased up to 23 and 18 percent respectively when temperature increased while rainfall decreased. Food self-sufficiency was affected similar to yield for both maize and sorghum. However, the food self-sufficiency was in all climate scenarios higher when sorghum was sown than when maize was sown. N application was the only adaptive management option that had good potential to mitigate the impact of climate change on yield. Integration of sorghum in the cropping system is needed to mitigate the impact of climate change on food self-sufficiency.

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1 INTRODUCTION

1.1 PROBLEM DESCRIPTION

1.1.1 CLIMATE CHANGE

In many places around the world, the effects of climate change have become apparent. The average global temperature has increased with 0,85 °C in the period 1880-2012 and precipitation patterns have altered (IPCC, 2013a). Although climate change is not experienced negatively all over the world, many places have experienced negative effects. This is also the case in the semi-arid tropics of southern Africa. Temperatures have increased and are expected to increase with another 1-4 °C by the end of the 21st century (Unganai, 1996; IPCC, 2013a). Precipitation projections are less certain, but rainfall variability is expected to increase, and rainfall at the start of the cropping season (October, November) is expected to decrease, thereby delaying the onset of consistent rain (IPCC, 2007; Tadross *et al*., 2009). Also the length and frequency of dry spells during the cropping season have already increased in some parts of southern Africa. (Tadross *et al*., 2009; Rurinda *et al*., 2013). Finally, the frequency and intensity of *El Niño* events have increased, bringing a decrease in rainfall to large parts of southern Africa (Phillips *et al*., 1998; WMO, 2014). Events occurred once in every 10-20 years before 1980; but already six events have occurred from 1980 to 2014 (WMO, 2014). One of the most severe *El Niño* of all time has taken place in the period 2015-2016 (WMO, 2015).

Climate change will have an negative impact on crop production in the semi-arid tropics of southern Africa (Zinyengere *et al*., 2013; Masikati *et al*., 2014). Yields are likely to decline due to a shorter cropping season caused by a delay in consistent rain, or due to water stress during critical development stages (Tadross *et al*., 2009; Rurinda *et al*., 2013; Rurinda *et al*., 2014). Higher temperatures increase the crop maturation rate and hence decrease the time available for biomass accumulation. The water demand is increased due to higher transpiration rates, causing faster depletion of the available water quantity (Springate & Kover, 2014). More severe heat waves are also expected to decrease crop yields, especially under drought conditions (Lobell *et al*., 2011).

1.1.2 SMALLHOLDER FARMERS

In Zimbabwe, like in many third world countries, agriculture is the largest source of employment. Sixty to seventy percent of the farmers in Zimbabwe are smallholder farmers, who are among the poorest people in the region and are very vulnerable to climate change (Masikati *et al*., 2014). Smallholder farmers often practice rain-fed agriculture on infertile soils. They lack external inputs like fertilizer due to unavailability or high costs. Selling products is difficult due to poorly developed infrastructure and markets. Furthermore, smallholder farmers often do not have access to sufficient labour, financial credit and improved technologies (Masikati *et al*., 2014).

Smallholder farmers face high risks with climate change. Investments in on-farm activities and external inputs will less often repay themselves if crop yields are failing more often due to drought or heat waves. In case of fertilizer application, this risk makes smallholder farmers hesitant to make the investment, particularly at the recommended rate (Mafongoya *et al*., 2006). Moreover, if crops are failing, smallholder farmers will have no food, and because of their dependency on agriculture for an income, smallholder farmers will sometimes not even have money to buy food on the market (Kandji *et al.* 2006).

1.1.3 CROPPING SYSTEM

Due to the colonial history of Zimbabwe, in which a lot of effort was put in maize breeding and maize (*Zea maize* L.) promotion by the government, a lot of maize is grown as staple crop, even in semi-arid areas (Eicher, 1995; Government of Zimbabwe, 2002). Before the introduction of maize, small grains like sorghum (*Sorghum bicolor* L. Moench) were grown extensively as staple crops in the semi-arid regions. Sorghum is known to be a drought resistant crop, because of its deep root system, high root length density and its high water use efficiency (Schittenhelm & Schroetter, 2014), and many studies have found that sorghum yields more than maize if exposed to drought stress (Singh and Singh, 1995; Staggenborg *et al*., 2008; Schittenhelm & Schroetter, 2014). However, in semi-arid Zimbabwe, re-adoption of sorghum is not likely to happen soon, probably due to the fact that maize is currently yielding more than sorghum (Twomlow *et al*., 2010; Rurinda *et al*., 2014). This might be related to the fact that hybrids are often used for maize cultivation while for sorghum only local varieties are available (Homann Kee-Tui *et al*., 2013). Moreover, farmers typically direct all available resources to optimize maize yield, while sorghum is neglected.

As crop failure is common during relatively dry rainy seasons, *e.g.* 2014/2015 and 2015/2016 (WFP, 2016), many people are occasionally not able to meet their minimum food needs. Introducing improved sorghum cultivars could play an important role in reducing crop failure in dry years, provided that sorghum management is improved.

1.2 AIM OF THE STUDY

To mitigate the negative impact of climate change on yields in southern Africa, adaptation measures are needed (Lobell *et al*., 2008). However, while a lot of studies made an effort to estimate the impact of climate change on yields in southern Africa (*e.g.* Fisher *et al*., 2005; Lobell *et al*., 2008; Zinyengere *et al*., 2013) only a few studies had a look into adaptive management strategies. The study of Howden *et al*. (2007) argues that even a small change farm management can significantly reduce the negative effect of moderate climate change on yields. Several studies in southern Africa show that fertilization intensity and time of sowing can have large effects on yield, which offers potential to mitigate the impact of climate change (*e.g.* Makadho, 1996; Phillips *et al*., 1998; Rurinda *et al*., 2013). Using adapted cultivars can possibly increase yield if those cultivars escape dry spells during their critical development stages (Rurinda *et al*., 2013). However, many of the studies on mitigation of climate change impact in southern Africa focused on maize yields only. While maize is obviously a major staple crop, other crops like sorghum have potential to become a more common food source. Another drawback of many existing studies is that they focus on average yields and average impacts of climate change and adaptation (e.g. Rurinda *et al*. 2015). However, for farmers, the variability in yield and food self-sufficiency is an important factor influencing decision making.

The aim of this study is to provide quantitative data on the effect of climate change on maize and sorghum yields and yield variability in the semi-arid tropics of Zimbabwe, and on how various management options will influence yields under current and future climate conditions. Yields of maize and sorghum were simulated under current and future climate and incorporated management options were choice of cultivar, time of sowing, fertilization intensity and rotation with groundnut (*Arachis hypogaea* L.). This quantitative data on yield averages and variability may help smallholder farmers in that region with decision making on which crop to grow and which management to apply.

2 RESEARCH QUESTIONS

2.1 MAIN QUESTION

- How do crop management options influence the impact of climate change on maize and sorghum yield and yield variability?

2.2 SUBQUESTIONS

- How did temperature and rainfall change over the past 30 years?
- How do different future climate scenarios compare to each other and to the baseline climate?
- How do the yield and yield variability of maize and sorghum compare between current and future climate?
- How do choice of cultivar, sowing window, amount of N application and rotation (yes/no) influence the yield and yield variability of maize and sorghum under current climate and future climate?
- How will the food self-sufficiency of farmers be affected by climate, crop and management strategy?

3 METHODOLOGY

Yields of maize and sorghum were simulated with the crop growth model APSIM. With input of crop, soil, climate and management data, the model simulates yields, among many other variables.

In the report the term yield is used, but to be specific, attainable yield should be used. Yields were not affected by pests, diseases or competition with weeds. Phosphorus was also not incorporated and was therefore not a limiting factor. Water and nitrogen were limiting factors.

A lot of farms in Zimbabwe are crop-livestock systems, with a lot of interactions between field, farm and livestock. This research focusses on the crop aspect of the farm. Outputs will therefore only be discussed at field level, not at farm level.

3.1 SITE DESCRIPTION AND CURRENT SITUATION

This study was implemented for the Nkayi district, a district with low and variable rainfall that is located east of central Zimbabwe (Figure 2). Most of Nkayi is in agro-ecological zone IV, receiving 450-650 mm annually. Some parts in the north of Nkayi are in agro-ecological zone III and receive a little more rain, 500-800 mm annually (Vincent and Thomas, 1961). Within a year there is a distinct wet and dry season (Figure 1). Soils vary from deep Kalahari sands (Arenosols), which are inherently infertile, to clay and clay loams that are somewhat more fertile but still depleted in nutrients due to crop cultivation without soil replenishment.

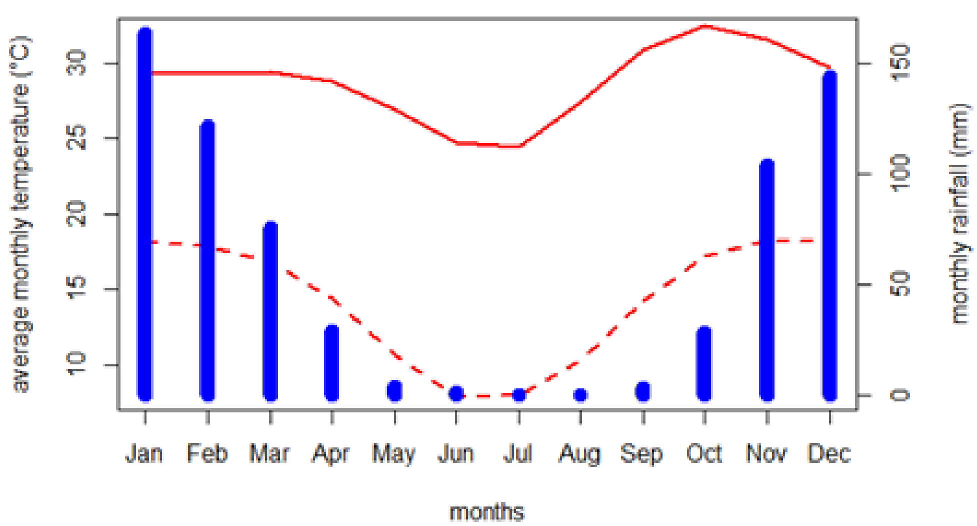

Figure 1: The monthly averages of maximum temperatures (upper line), minimum temperatures (lower line) and rainfall (bars) in the Nkayi district.

The most common farming system in the area, as in the whole of Zimbabwe, is the crop-livestock farming system, in which cattle provide manure, draft power, transport, cash and food (Masikati, 2015). Sixty percent of the farmers keep cattle but only one in three of all farming households applies manure. Inorganic fertilizer is only applied by one in five of the farmers. (Kee-Tui *et al*., 2013). It is therefore not surprising that average crop productivity in the district is very low, only about 650 kg ha^{-1} of maize (Masikati, 2011). Most cropping systems in Nkayi are based on a monoculture of maize. Next to maize, smaller areas are cultivated with crops like sorghum, finger millet (*Eleusine coracana* L.*)*, groundnut and cowpeas (*Vigna unguiculata* L. Walp). Maize and groundnut are planted before all other crops. If available, most fertilizer or manure is applied to maize, and maize is most intensively managed (*e.g.* weeding, conservation agriculture) (Kee-Tui *et al*., 2013).

The research was carried out with soil and climate data from the Nkayi region because its climate and soil, as well as the farmers practices, are representative for the whole agricultural region IV, which covers approximately one third of Zimbabwe.

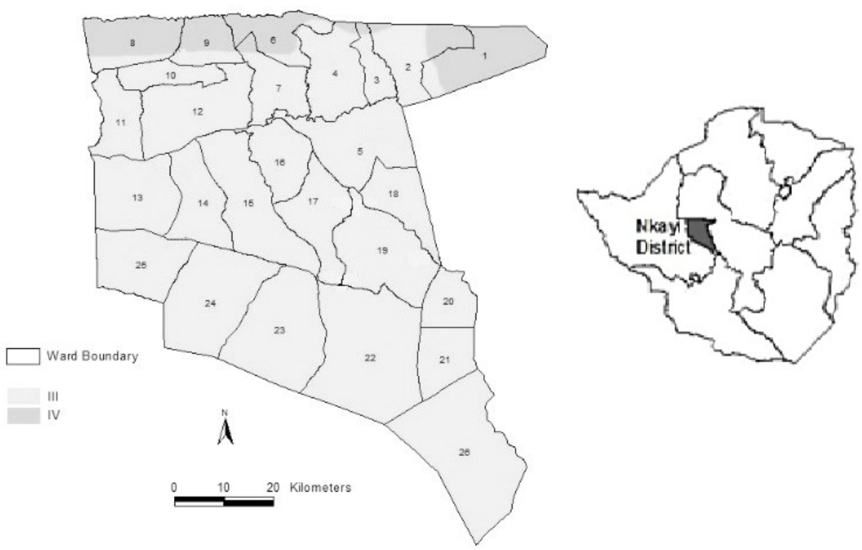

Figure 2: The Nkayi district with its location in Zimbabwe.

3.2 MODEL DESCRIPTION

The Agricultural Production Systems sIMulator (APSIM) was developed by the Agricultural Production Systems Research Unit in Australia. 'APSIM is comprised of a set of biophysical models that capture the science and management of the system being modelled' (Holzworth *et al*., 2014). The models are categorized into plant, soil, animal and climate models, each based on the mathematical representation of various biophysical processes. To give an example, the water balance in the soil is modelled based on a mathematical representation of processes like drainage and evaporation. All models in APSIM are linked to each other by a software framework, which makes it possible for states and rates in one model to be influenced by states and rates in the other model (Holzworth *et al*., 2014). Exchange of information between models and the calculation of all the variables is done on a daily basis.

Data on climate, soil characteristics, crop type and variety, and management are used as input to the model. Management rules can be changed to simulate the different management strategies tested in this research. The output of interest was attainable yield on a yearly base. Daily output of other variables like temperature, available soil water and NO_3^- were used for interpreting the results.

APSIM is used extensively by researchers to assess on-farm management practices and climate change adaptations strategies (Holzworth *et al*., 2014). Recently, the model was used successfully in climate impact studies for sorghum and maize in southern Africa (Turner and Roa, 2013; Rurinda *et al*., 2015). Therefore, APSIM is an appropriate tool for this research.

3.3 GENERAL APPROACH

Yields were compared for different management strategies and climate scenarios. The management strategies tested for sorghum and maize comprise four management options: choice of cultivar, sowing window, amount of N application and rotation (yes/no). Cultivar, sowing window and N application can each take three 'levels' (Figure 3), which are discussed further in methodology section 3.4.3, 3.4.4 and 3.4.5. Rotation can only have two levels, which are either rotation or no rotation. In this study, all combination of all levels of the four variables were made, adding up to 3 cultivars * 3 sowing windows * 3 different amounts of N application * 2 rotation strategies = 54 management strategies for each crop. The climate scenarios included a baseline climate dataset and five future climate scenarios created by GCM's (section 3.4.2). Both maize and sorghum yields were simulated for every combination of management options under six climate scenarios.

Before these main simulations were conducted, inputs to the simulations were explored. This involved firstly a comparison of the characteristics from the six climate scenarios. Secondly the characteristics of the management options were determined, which involved the choice of the cultivars used, the sowing windows, the levels of N application and the setup of the rotation system.

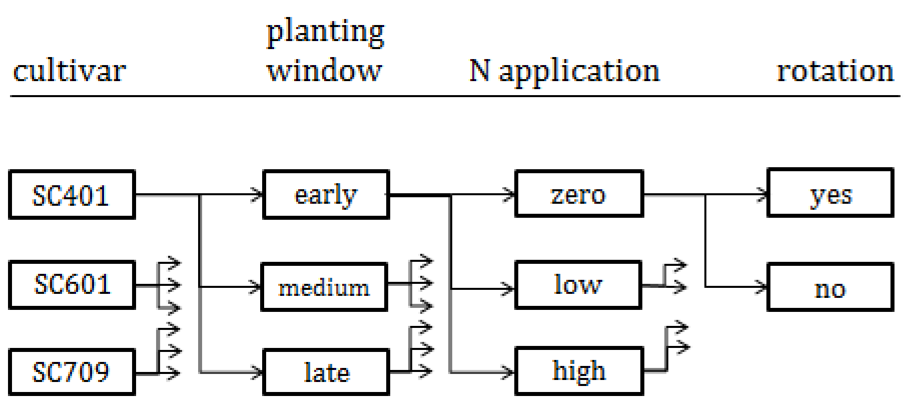

Figure 3: Schematic overview of the management options that determine the management strategies.

3.4 MODEL INPUTS

3.4.1 SOIL

Soil parameters were taken from a representative soil for the Nkayi district. The soil is a sandy loam with a maximal water availability of approximately 0.12 mm mm^{-1} in the top soil, and a decreasing maximal water availability with depth (Table 1). The inorganic N contents in the soil is low, with a value of approximately 5 kg ha^{-1} in the top layer. Also the organic carbon content is low, decreasing from a 0.5 percent in the topsoil to a 0.26 percent at 75 cm. The initial value of surface organic matter (surface OM) was set to 0 kg ha^{-1} and the initial fraction available soil water was set to 20 percent of the maximum available soil water, filled from the top.

Table 1: Soil properties used in APSIM. LL15 = lower limit volumetric water content, DUL = drained upper limit volumetric water content, SAT = saturated volumetric water content, OC = organic carbon content BD = bulk density.

Depth	**LL15**	**DUL**	**SAT**	**NO_3^-**	**NH_4^+**	**OC**	**BD**	**pH**
Cm	mm mm^{-1}	mm mm^{-1}	mm mm^{-1}	kg ha^{-1}	kg ha^{-1}	%	g cm^{-3}	
0-15	0.154	0.284	0.384	4.408	0.6	0.487	1.50	5.83
15-30	0.183	0.303	0.403	3.868	0.1	0.387	1.46	5.66
30-45	0.233	0.303	0.403	2.506	0.1	0.370	1.45	5.36
45-60	0.243	0.303	0.403	1.085	0.1	0.314	1.45	5.35
60-75	0.272	0.322	0.422	0.886	0.1	0.256	1.40	4.96

3.4.2 CLIMATE

Baseline climate

The baseline climate dataset used for Nkayi in this study is the same dataset as described and used in the study of Masikati *et al*. (2015). The dataset was constructed with historical daily records from the Nkayi weather station. The dataset contains 31 years (1980-2010) of eight meteorological variables. For climate analysis, minimum temperature, maximum temperature and rainfall were considered in this study.

To find out whether climate change is apparent in historical long-term observations in Nkayi, the baseline climate dataset was analyzed. The following characteristics that are contained in the dataset were compared between the 30 rainy seasons (November - April): average minimum and maximum temperature, growing season rainfall, start and end of the rainy season (first and last day with an accumulated amount of at least 20 mm rainfall on this day and the past four days) , number of days with extreme temperature (maximal temperature above 35 ºC) in the rainy season, the number of days with extreme rainfall (above 20 mm/day) in the rainy season, and the number of drought days in the rainy season.

Future climate

Future climate projections (2040-2070) of temperature and rainfall in the Nkayi district were made by twenty different general circulation models (GCM's) under the RCP8.5 scenario. GCM's are numerical models that represent physical processes in the atmosphere, ocean, cryosphere and land surface with use of a three dimensional grid over the globe. They have the potential to provide geographically and physically consistent estimates of regional climate change which are required in impact analysis studies like this one (IPCC, 2013b). The Representative Concentration Pathway 8.5 predicts a radiative forcing of 8.5 W m^{-2} by the end of this century due to the increased amount of greenhouse gases in the atmosphere (Riahi *et al*., 2011). To compare, the current radiative forcing is about 2.3 W m^{-2}, but has already almost doubled since 1980 (IPCC, 2013a). RCP8.5 is the most upper bound of all RCP's and assumes the absence of any climate change mitigation policies while the world population is large and energy saving technologies develop slowly (Riahi *et al*., 2011). RCP8.5 is the worst case scenario and is likely to show stronger changes in temperature and rainfall and hence potentially more severe changes in maize and sorghum yield than other RCP's. Projections were made for the period 2040-2070 since in this period the impact of climate change is already quite distinct, but the uncertainty in predictions is still relatively small compared to the end-of-century period (Zinyengere *et al*., 2013).

Each climate projection contains 31 years of daily data, similar to the baseline dataset. In Figure 4 the twenty GCM projections for Nkayi are plotted based on their average temperature increase and change in rainfall compared to the baseline. The figure is divided into five parts with a different change in temperature and rainfall, and from each part one projection was selected to represent a possible future climate scenario. Projection A, D, F, R and Z were selected as the five possible future scenarios. All future climate datasets were then constructed following the delta approach (Masikati *et al*., 2015), which means that daily values of temperature and rainfall were shifted proportionally from the baseline. The temporal distribution of rain in future climate datasets is therefore equal to the distribution of rain in the baseline dataset.

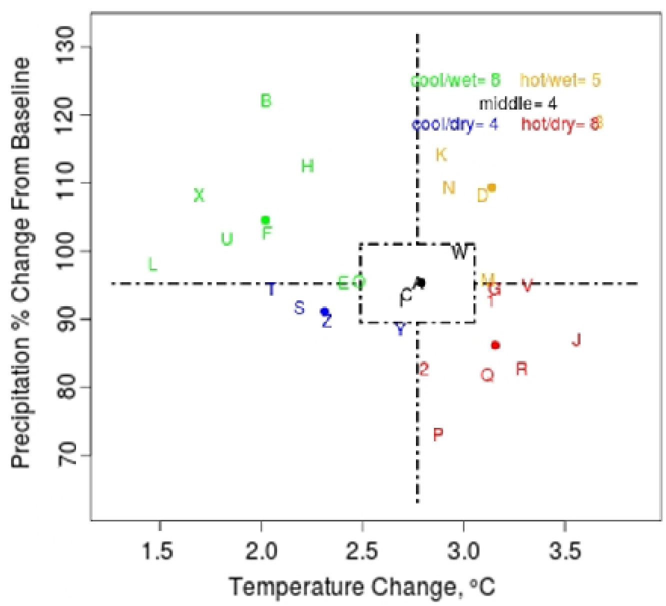

Figure 4: Average temperature and precipitation change (compared to the baseline) of projections made by the twenty GCM's. The figure is divided into five parts that contain projections from GCMs that are either (relatively) cool/wet, (relatively) cool/dry, hot/wet, hot/dry or average in temperature increase and change in rainfall. Source: O. Crespo, personal communication.

To get an idea about the differences between the current climate and future projections, the baseline climate dataset and the future climate datasets were compared based on the following characteristics of the rainy season: average minimum and maximum temperature, growing season rainfall, number of days with extreme temperature (maximal temperature above 35 °C), and the number of days with extreme rainfall (above 20 mm/day). Because the temporal distribution is the same in all six datasets, it was not useful to compare the start date of the rainy season and the number of drought days in the rainy season.

3.4.3 CULTIVARS

The crops taken into account in this study were maize (Zea mays L.) and sorghum (Sorghum bicolor L. Moench). From both maize and sorghum, three cultivars were selected: a short maturing, a medium maturing and a long maturing cultivar. For maize the selected cultivars were SC401, SC601 and SC709. The maize cultivars are all Zimbabwean hybrids and pre-defined in APSIM. The selection of sorghum cultivars to be modelled was less straightforward. Almost no hybrid sorghum is grown in Zimbabwe, except for the early/medium maturing cultivar 'Macia'. To still cover three maturing times, the APSIM pre-defined hypothetical sorghum cultivars, 'early', 'medium' and 'late' were selected. Those three hypothetical cultivars were also used in the paper of Turner and Rao (2013) to analyze factors that influence sorghum yield. In this study, the cultivars are called earlyS, mediumS and lateS.

The predicted grain yield by APSIM of the short maturing maize cultivar SC401 was evaluated based on experimental data from the rainy seasons 2009/2010 and 2010/2011 at Makoni and Hwedza in the study of Rurinda *et al*. (2015). Soil conditions and rainfall at both sites are similar to Nkayi, while annual rainfall is higher in Makoni and similar in Hwedza. Also the medium maturing maize cultivar SC625 was evaluated in that study. The parameters of 625 in APSIM are very similar to the maize cultivar SC601 used in this study. In the season 2009/2010 yield predictions compared reasonably well with yields at both sites, for both cultivars, sown early or during the medium window and with all three fertilizer rates ($R^2 > 0.8$, RMSE < 0.5).

Turner and Roa (2013) used the three hypothetical sorghum cultivars in their study to explore the effects of water and fertility stresses on sorghum productivity. The performance of APSIM in terms of simulating sorghum yields in semi-arid regions of Africa was proven to be sufficient in the study of MacCarthy *et al*. (2009). The observed and predicted values of the study were almost 1:1 correlated with an R^2 of 0.74 over two soils and a range of fertilization rates. Ncube *et al*., (2007) showed that the earlyS cultivar in APSIM was able to predict the yield of the early maturing sorghum cultivar SV4 in experiments at Lucydale, Zimbabwe.

Unfortunately, there were no studies found that did field trials over more than 2 or 3 years to validate predictions of APSIM. Therefor it is not clear whether APSIM is well able to predict yields over a wide range of climate conditions.

To determine the differences in time to maturity between cultivars, the average time to maturity was obtained for all cultivars by running simulations with baseline climate conditions, zero N application and sowing in all three sowing windows. Time to maturity was calculated as the days between sowing and harvest of the crop.

3.4.4 MANAGEMENT – SOWING WINDOW

The crops were sown in three sowing windows, including early, October 25th – November 20th; medium, November 21st – December 15th; and late, December 16th – January 10th. The sowing windows are based on long-term recall of farmers in Zimbabwe (Rurinda *et al*., 2013). A simulation rule was set up so that sowing takes place if within the past five days an accumulated amount of 20 mm of rain has fallen. If this is not the case, sowing will happen at the last day of the sowing window.

3.4.5 MANAGEMENT – N APPLICATION

The crops received three levels of N application. Zero application as a control was the first level. The other two levels of N application were dependent on crop type and on rotation with groundnut or not. N response curves were constructed to find the two levels of N application. The low N application level was determined by the average amount of N application that was needed to reach a yield increase (compared to the control yield) of half of the difference of water-limited potential yield and control yield. The high N application level was determined by the amount needed to reach a yield increase of 90% of the difference between water-limited potential and control yield. Half of the N was applied at sowing while the other half was applied 35 days after sowing.

The N response curves were constructed for two reasons. The first reason was to determine the levels of N application to sorghum and maize, in a system with and without rotation. The second reason was to get insight into how crops would respond to N application under different management strategies. To that end, nine different values of N application (0, 10, 20, 30, 40, 50, 75, 100, 150 kg ha^{-1}) were assigned to each combination of cultivar, sowing window and rotation (yes/no). With use of the baseline climate data, yield was simulated under each level of N application.

3.4.6 MANAGEMENT – ROTATION (YES/NO)

Maize and sorghum could be either grown continuously, every year the same crop, or in rotation with groundnut, alternating every year. Rotation was used as a strategy to improve soil fertility by using the ability of groundnut to fix N from the atmosphere. When groundnut residues are left on the field after harvest, they decompose together with the roots, and the fixed N becomes available to the cereal grown in the subsequent year.

The pre-defined cultivar 'Chico' was used as the groundnut cultivar. The crop was sown between October 25th and January 10th if the cumulative rainfall in the last five days was 30 mm or more. 50 percent of the groundnut residues was left on the field. The crop didn't receive fertilizer. Groundnut was used as a management strategy, and the effects of climate and management strategy on yields of groundnut were not considered in this study.

3.5 SIMULATION SETUP

The climate datasets of the six scenarios all contain 31 years of data. Since the rainy seasons extends over two calendar years, just 30 values for yield were obtained from each simulation of a continuous cropping system. In the case of a cereal-groundnut rotation, each simulation had to be run twice with the same climate data, because the cereal and groundnut are alternating each year, and one simulation therefore calculated fifteen values for each crop. In the first simulation maize is grown in the first season while the second simulation groundnut is grown in the first season. The cereal yields from the first year of a rotation simulation were omitted, because no groundnut had been grown the year before.

The primary interest of this study is the climatic effect on yields. Therefore other factors that could influence yields were eliminated as much as possible. Two of those factors are the amount of water and nutrients present at the start of the growing/rainy season. If simulations are run for thirty years, soil quality could build up or deteriorate over time, influencing nutrient and water availability. Also water availability could differ each year dependent on for instance the length of the previous dry season. Therefore, the total amount of soil nitrogen (soil N; the amount of NH_4^+ and NO_3^- present in the soil), surface OM and soil water were reset every year of the simulation in the dry season (August 1st). In that way the initial conditions of each year of simulation were equal, and differences in water or nutrient availability depended on climatic factors, not on the initial amount present.

For continuous cropping, the properties were reset every year of the simulation. However, an annual reset of soil N and surface OM would not make sense for a cereal-groundnut rotation. If soil N and the surface OM would be reset every year, the effect of rotation on yield would be removed. The solution is to reset the soil N and surface OM once every two years for rotation simulations. Unfortunately, APSIM doesn't give the option to reset soil N and surface OM on a fixed date once every two years, so it was decided to reset them at sowing of groundnut, which is once every two years. The hypothesis for this solution was that the inherent soil fertility is not affected much after one year of cultivation, which is important with respect to the discussion in the former paragraph.

3.6 PERFORMANCE EVALUATION

Unfortunately, insufficient maize yield data from the study sites was available to evaluate the model performance for the maize cultivars used in this study. Also for the hypothetical sorghum cultivars in the model no corresponding real-world data was available. Therefore, literature from semi-arid regions in Africa, in which maize and sorghum yields were predicted with APSIM and compared with observations, was used to discuss the model performance.

3.7 DATA ANALYSIS

This section explains how simulation outputs were analyzed. Explanation of the statistical test used can be found in appendix 12.1. If ANOVA detected a significant effect of an explanatory variable, Fisher's LSD was used to compare the values of the dependent variable over the different levels of the explanatory variable.

3.7.1 CLIMATE

Linear regression was used to assess trends in the baseline climate dataset. The climate characteristic was taken as the dependent variable, and time/season was used as explanatory variable. The values of climate characteristics between the baseline and future climate were compared with one-way ANOVA. In this case, the climate characteristic was the dependent variable and climate scenario was the explanatory variable with a factor level for each climate scenario.

3.7.2 YIELD

Yields were compared between management strategies or climate scenarios by using the thirty yields from a simulation as replicates. Yield was compared between climate scenarios with the use of one-way ANOVA, with yield as dependent variable and climate scenario as explanatory variable. Within each climate scenario two-way ANOVA was used to find out whether the yield was dependent on the different management options, or interactions between those management options. The management options were explanatory variable with two or three factor levels.

3.7.3 YIELD VARIABILITY

Yield variability associated with management strategies or climate scenarios was assessed by one value, the yield variability index, calculated by subtracting the 10th percentile yield from the 90th percentile yield of a simulation and then dividing by the maximum yield obtained across all management strategies and climate scenarios. This value gives an indication of the difference in yield between good and poor years for agriculture. The yield variability index can be compared between all management strategies and climate scenarios, and between maize and sorghum. Similar to the analysis of yield, the yield variability index was analyzed with the use of one-way ANOVA between climate scenarios and with the use of two-way ANOVA within climate scenarios. However, due to the fact that there is only one yield variability index per management strategy (compared to 30 values of yield) when the yield was compared within climate scenarios, the sample size per management strategy was reduced to one. This meant that the ANOVA model didn't have any degrees of freedom left when all three explanatory variable, including interactions, were used. Therefore, it was decided to remove interactions from the model and only analyze main effects. In this case 20 degrees of freedom were left. Starting from 27 degrees of freedom (27 management strategies), one degree was subtracted since it was used the create the base model (*e.g.* cultivar = SC401, sowing window = early, N application = zero), and the other six were used to differ the levels of each management option (cultivar: SC601, SC709; sowing window: medium, late; N application: low, high).

3.7.4 FOOD SELF-SUFFICIENCY

Farms were assumed to be food self-sufficient if maize yield was above 750 kg ha^{-1}. This value was derived from two different studies. Masikati *et al.* (2015) show that the average household in Nkayi consists of 6.6 heads. The average area under maize cultivation per farm is 1.3 ha, so that each hectare should provide food for 6.6/1.3 = 5 persons. The average maize consumption per capita is 153 kg (Hassan *et al.*, 1999), so the amount of maize that has to be produced per hectare to ensure subsistence for a smallholder farmer and his/her family is approximately 750 kg ha^{-1} (153*5). For simplicity it was assumed that the sorghum requirement would be equal if sorghum would the major staple crop. It should be taken in mind that the choice of food self-sufficiency threshold value has a large influence on the results and conclusions.

In the analysis, the number of years with yields above 750 kg/ha were determined for each 30 year run. Hence, as with yield variability, only one value was produced for each simulation/management strategy and the procedure of statistical analysis was the same.

4 RESULTS – INPUTS OF THE MAIN SIMULATIONS

4.1 CLIMATE

4.1.1 TRENDS IN BASELINE CLIMATE DATASET

For minimum and maximum temperature Masikati *et al*. (2015) found an increase of respectively 0.03 and 0.3 °C per decade , but these increases were not significant. Masikati *et al*. (2015) didn't find a trend in annual rainfall.

From additional analysis in this study, the number of days with extreme temperature showed an insignificant, decreasing trend over time in Nkayi (Figure 5). The trends in the number of days with extreme rainfall and the number of drought days were positive. The trend in drought days was far from significant but the trend in extreme rainfall days was almost significant (p = 0.09). The date of the start and the end of the rainy season both showed a slightly increasing trend, but neither was significant. The total length of the rainy season remained approximately 140 days.

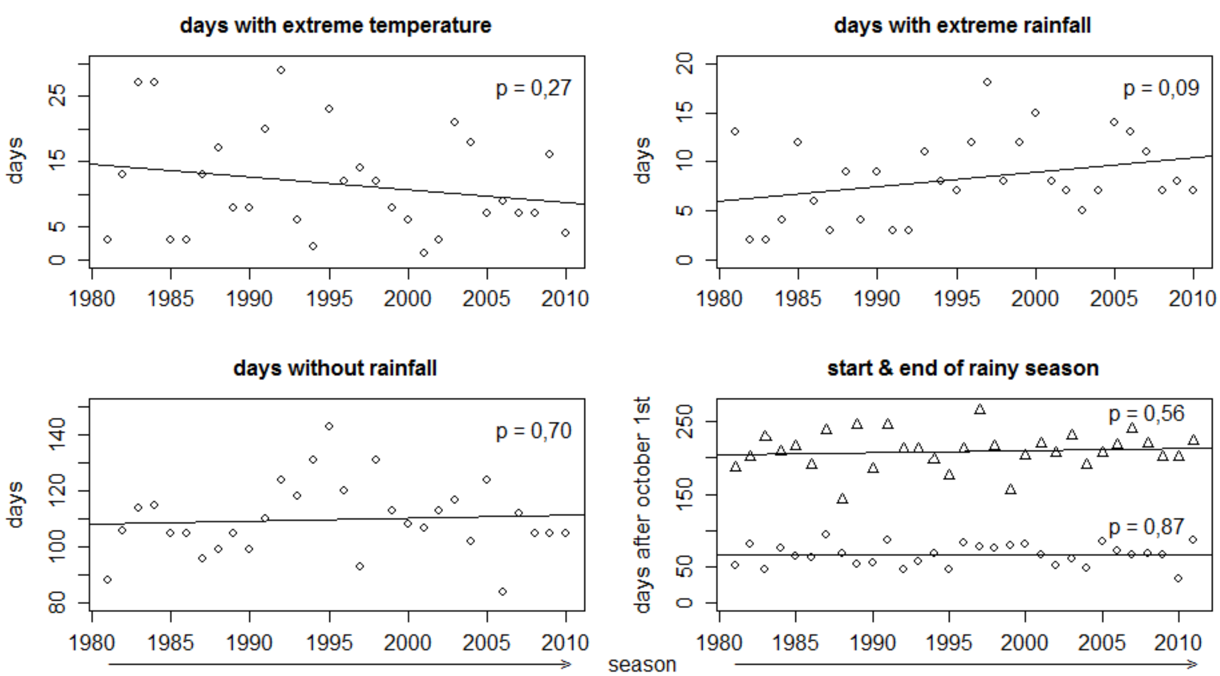

Figure 5: Number of days with extreme temperature and extreme rainfall in the rainy season, number of drought days in the rainy season, and the date of the start (circle) and end (triangle) of the rainy season plotted from 1980 until 2010. Linear regression was used to find whether relations between the climate characteristics and time were significant (p < 0.05).

4.1.2 DIFFERENCES BETWEEN BASELINE AND FUTURE CLIMATE SCENARIOS

The average rainfall in the rainy season was highest for the 'hot/wet' scenario with 678 mm, followed by the 'cool/wet' scenario and the baseline scenario with respectively 638 and 621 mm (Figure 6). The 'cool/dry' and 'hot/dry' scenarios receive the least rainfall in the rainy season, with averages of 560 and 531 mm respectively. None of the future climate scenarios received a significantly different amount of rainfall compared to the baseline, but the amounts of rainfall in the 'hot/dry' and 'hot/wet' scenario were significantly different to each other and to the cool/wet and 'cool/dry' scenario respectively.

The average minimum and maximum temperature under the baseline were approximately 17 °C and 30 °C respectively (Figure 6). The average maximum temperature increase was smallest in the 'cool' scenarios with an increase of approximately 1 °C, but there was no significant difference in maximum temperature increase between the 'middle' and the two 'hot' scenarios in which the increase was approximately 2 °C. The minimum temperature increase was similar to the maximum temperature increase, with the only difference that the minimum temperature increase was significantly higher for the 'hot' scenarios compared to the 'middle' scenario, while the maximum temperature increase for the 'hot' scenarios and the 'middle' scenario was similar.

The number of extreme rainfall days was approximately 8 in the scenarios 'baseline', 'cool/wet' and 'middle' (Figure 6). The number of extreme rainfall days was similar between the former three scenarios and the other scenarios, but the amount of extreme rainfall days was higher in the 'hot/wet' scenario than in the 'hot/dry' and 'cool/dry' scenario. The number of extreme temperature days was 10 under the baseline scenario, approximately 25 in the 'cool' scenarios and over 40 in the 'hot' and the 'middle' scenarios (Figure 6).

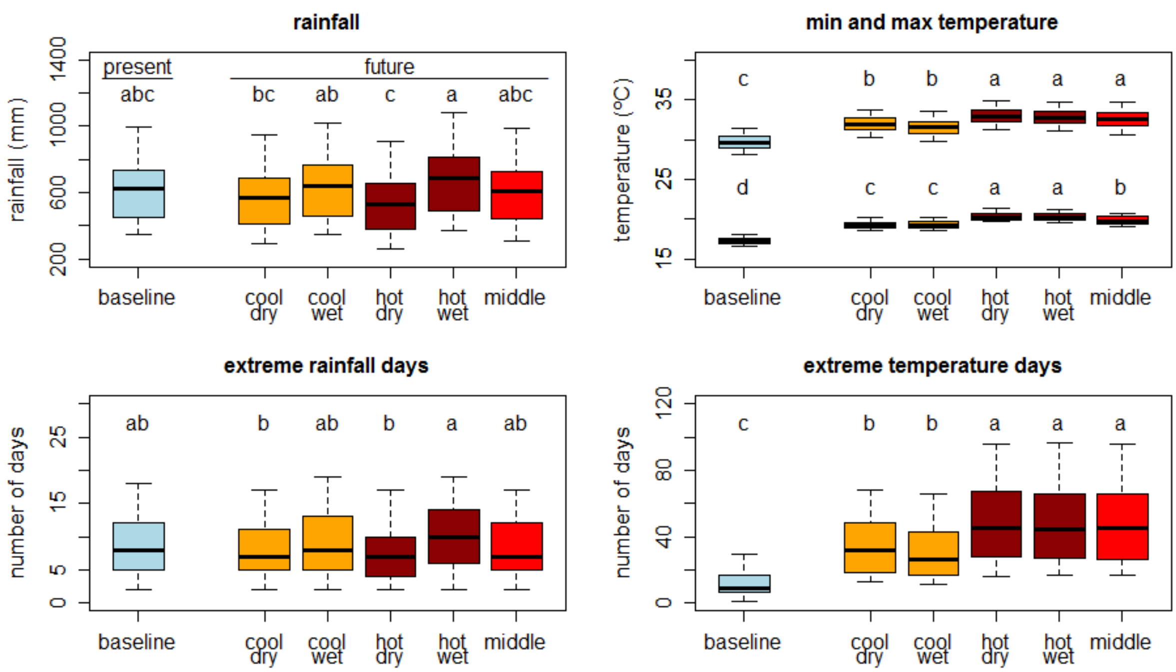

Figure 6: Rainfall, minimum and maximum temperatures, and days with extreme rainfall and extreme temperature within the rainy season are plotted for the baseline climate scenario, and the five future climate scenarios. The letters above the boxplots are results from the Fisher's LSD test: scenarios with no letter in common are significantly different from each other.

4.2 CULTIVARS

Time to maturity of maize cultivar SC401 was 122 days. The time to maturity of cultivar SC601 was 11 days longer than of that of cultivar SC401, and the time to maturity of cultivar SC709 was 17 days longer than that of cultivar SC401 (Table 2). Time to maturity of sorghum cultivar earlyS was 111 days. The time to maturity of cultivar mediumS was 6 days longer than that of cultivar earlyS and the time to maturity of cultivar lateS was 7 days shorter than that of cultivar earlyS.

A striking observation was the short time to maturity for the late maturing sorghum cultivar (104 days), which was lower than the time to maturity for the early and medium maturing sorghum cultivars. It was found that the harvest dates of cultivar lateS were very early in the season and that the cultivar was not producing yield. In the parameter sets, the only difference in phenology between lateS and the other two cultivars was the thermal time from end juvenile to flower initiation (tt_endjuv_init). The values of this parameter for cultivars earlyS, mediumS and lateS were 114, 157 and 201 °Cd respectively. By decreasing tt_endjuv_init for cultivar late S, the problem of crop failure eventually disappeared, at a value of 168 °Cd. With this new value of tt_endjuv_init the average time to maturity of the late maturing cultivar increased to 122 days.

Table 2: The average simulated time to maturity in days for the maize and sorghum cultivars. The time to maturity of the sorghum cultivar lateS was in first instance 104 days, but was changed to 122 days by adjusting a phenology parameter.

Crop	**Cultivar**	**time to maturity**
		days
Maize	**SC401**	122
	SC601	133
	SC709	139
sorghum	**earlyS**	111
	mediumS	119
	lateS	104 → 122

4.3 MANAGEMENT

4.3.1 N APPLICATION

From Figure 7 was decided that the three levels of N application, 'zero', 'low' and 'high', should be respectively 0, 20 and 60 kg ha^{-1} for continuous maize and 0, 20 and 80 kg ha^{-1} for continuous sorghum. The levels of the three N application for maize and sorghum under rotation were not calculated because rotation was eventually omitted as a management strategy (see end of this section).

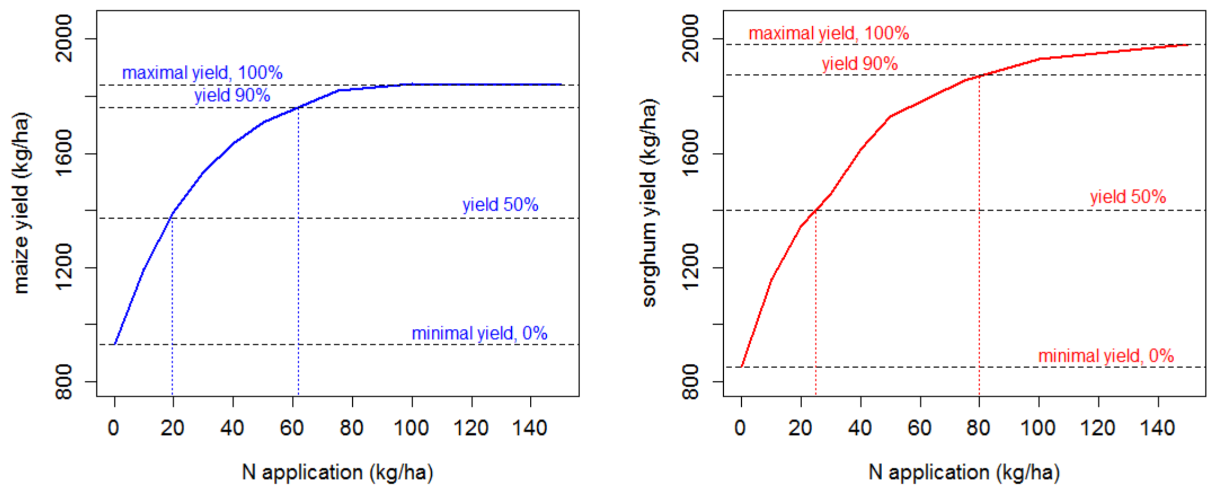

Figure 7: The nitrogen response curves of maize and sorghum across all cultivars and sowing windows.

4.3.2 ROTATION (YES/NO)

The effect of rotation on maize yield was small (Figure 8a,b), even without the application of inorganic N fertilizer to maize. The effect at zero N application was between 50 and 200 kg ha^{-1} in the case of the maize cultivar SC401. For the other maize and sorghum cultivars the yield effect of rotation was similarly small. To find out why this effect was so small, daily values of NO_3^- in the soil and total N in crop residues were obtained from a rotation simulation of maize and a continuous maize simulation without fertilizer application. NO_3^- was chosen because it is directly available for uptake by crops. As described in the simulation setup, the soil N was reset once every two years in the rotation simulation.

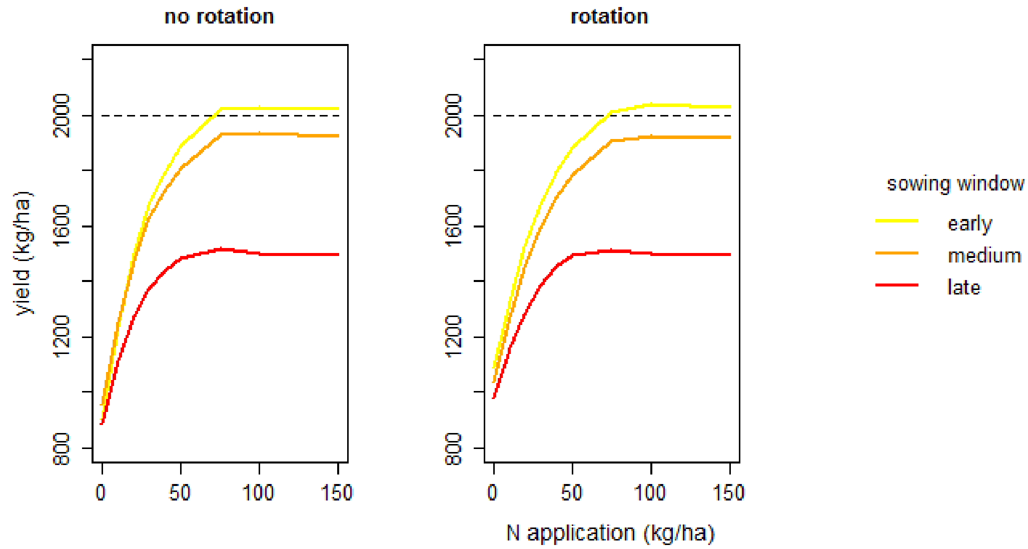

Figure 8: The nitrogen response curves of maize cultivar SC401 sown in different sowing windows, in **a)** a system without rotation, **b)** a system with rotation.

In Figure 9a, the NO_3^- content in a rotation system was plotted over a time span of four years. In the first and third rainy season, groundnut was grown, and in the second and fourth rainy season maize was grown. It can be seen that at sowing of groundnut, the NO_3^- content was reset to its initial values of ±13 kg ha^{-1}. During the growth of maize and groundnut, the NO_3^- content decreases due to uptake by the crop. In Figure 9b, the NO_3^- content in a continuous maize system was plotted. The NO_3^- content was reset to its initial value every year on August 1st. In Figure 9c, N in surface OM (from residues) in a rotation system was plotted over the four year time span. At sowing of groundnut the surface OM was reset, but this is not visible in the figure since no above ground residues were left on the field after maize harvesting. The steep increase of surface OM at groundnut harvesting is due to the fact that half of the groundnut residues were left on the field. With decomposition of the residues the amount of N in surface OM decreases.

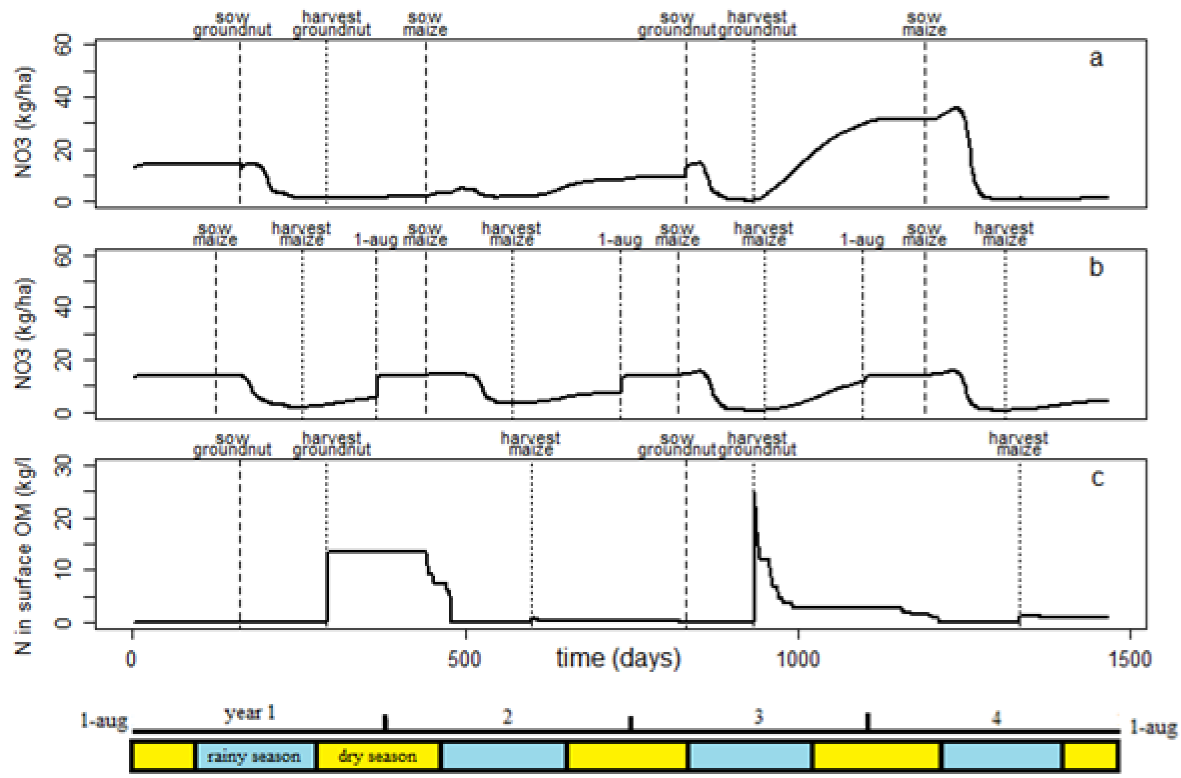

Figure 9: Four year time lapse (August 1st 1990 – July 30th 1994) of **a)** NO_3^- in soil during a rotation simulation. **b)** NO_3^- in soil during an simulation with continuous maize. **c)** total N in surface OM during a rotation simulation.

After maize was harvested in the continuous simulation, the NO_3^- content did not always rise again to its initial value (Figure 9b; reset to initial value is clearly visible). Hence, the hypothesis that a time period of two years is too short to affect the inherent soil fertility was wrong. With this in mind, the small effect of rotation on yield can be explained from Figure 9a, b and c. It can be seen that the effect of decomposition of groundnut residues on the NO_3^- content was very small after the harvest of groundnut in the first rainy season. At the time that maize was sown at the start of the second rainy season, the total NO_3^- content at was lower in the rotation system than in the system with continuous maize (Figure 9 a and b). After groundnut harvesting in the third rainy season, the effect of groundnut residue decomposition on the NO_3^- content was much larger and therefore the total NO_3^- content at maize sowing in the fourth rainy season was higher in the rotation system than in the system without rotation.

The difference in magnitude of the effect of groundnut residues on the NO_3^- content could be partly attributed to the amount of groundnut residues present and the N content in those residues (Figure 9c). However, a larger share was attributed to the fact that in the model, nitrification is positively related to available soil water if the soil water content is below halfway LL15 and DUL. Nitrification even stops if the soil water becomes lower than the LL15 of the soil. The period after groundnut harvest in the first rainy season was drier than the period after groundnut harvest in the third rainy season (not shown in figure), with less available soil water and hence less nitrification as a result.

Nitrification was thus very dependent on weather conditions, and rotation with groundnut only had a distinct positive effect on the NO_3^- content in relatively wet years. Thereby, in dry years, the NO_3^- content at maize sowing in a rotation simulation was lower than the NO_3^- content at maize sowing in the continuous maize simulation, because the NO_3^- content in a rotation simulation was not able to rise again to its initial value in the year after the reset of soil N. In approximately 60 percent of 30 growing seasons, the NO_3^- content at maize sowing was higher in the continuous maize simulation than in the rotation simulation (Table 3). The average NO_3^- content at maize sowing was similar in both simulation setups.

Table 3: Comparison between the soil NO_3^- content at sowing of maize in a system with rotation and a system without rotation. Values obtained from NO_3^- content values in 29 years.

	highest NO_3^- content at sowing	**average NO_3^- content at sowing**
	%	kg ha^{-1}
rotation *(reset N 1x / 2 years)*	41	14.4
no rotation	59	14.3

5 DISCUSSION OF THE MAIN SIMULATION INPUTS

5.1 CLIMATE

5.1.1 TRENDS IN BASELINE CLIMATE DATASET

As already mentioned in the introduction, the temperature is expected to rise in the future over large parts of southern Africa, and predictions on annual rainfall are yet uncertain. Masikati *et al.* (2015) also found an increasing trend in temperature when they analyzed the climate dataset for Nkayi, the dataset that is also used in our study. Annual rainfall in Nkayi will not be changing according to Masikati *et al.* (2015).

The decreasing trend in number of days with extreme temperature is in contrast with the prediction of IPCC (2013a) that in most places more high temperature extremes will occur as the global temperature increases due to climate change. The predicted increases in the number of days with extreme rainfall and the number of drought days are in line with literature. The number of heavy precipitation events has increased in more regions than it has decreased since 1950 (IPCC, 2013a; Westra *et al*., 2013) and the amount of drought days has increased over large parts of southern Africa (Tadross *et al*., 2009). The absence of a trend in total rainfall as found in Masikati *et al*. (2015) could be explained by the fact that the days without rainfall are counteracted by the increase in extreme rainfall events (Tadross *et al*., 2009). An increase in extreme rainfall events might be caused by the increase in temperature (Westra *et al*., 2013). Extreme rainfall events can cause problems because more surface runoff will occur which can cause floods and erosion. Floods with a one in hundred year occurrence nowadays would be likely to occur two to four times more often by the end of the 21st century in southern Africa (Hirabayashi *et al*., 2013). Finally, our study found a delay in the start and the end of the rainy season. The study of Tadross *et al*. (2009) analyzed a larger area in southern Africa on climate trends and found that the start of the rainy season has delayed over large parts of southern Africa. Tadross *et al*. (2005) and Rurinda *et al.* (2013) found evidence that the rainy season is also delaying in Zimbabwe. The length of the rainy season has decreased in some areas, because the end of the rainy season is not delayed (Tadross *et al*., 2009; Rurinda *et al*., 2013). A shortening of the rainy season due to a later onset of consistent rain possibly decreases yields. The study of Shumba (1989) reports a maize yield reduction of 2.3 % per day of delay in planting, while Rurinda *et al*. (2013) find that the planting of maize can be delayed with up to four weeks before the yield is reduced profoundly.

5.1.2 DIFFERENCES BETWEEN BASELINE AND FUTURE CLIMATE SCENARIOS

The projected increase of minimum temperature, between 2.0 °C (cool/dry) and 3.1 °C (hot/dry), and of maximum temperature, between 1.9 °C (cool/wet) and 3.3 °C (hot/dry), by the period 2040-2070, are higher than the projected global average temperature increase of approximately 2 °C under RCP8.5 (IPCC, 2013a).

Due to the delta approach used in the construction of the future climate scenarios (Masikati *et al*., 2015), the differences in number of extreme rainfall days and the number of extreme temperature days between the baseline scenario and the future climate scenarios were similar to the differences in rainy season rainfall, and maximal temperature. This could be realistic in the case of temperature, however the relation between the number of extreme rainfall days and rainy season rainfall would probably not be this tight, as the amount of extreme rainfall days increased in the past 30 years (Figure 5) while rainy season rainfall didn't show a trend (Masikati *et al*., 2015).

5.2 CULTIVARS

The simulated time to maturity for cultivar SC401 in this study was 122 days, while the study of Rurinda *et al*. (2015) found a time to maturity of 131 days. Also the time to maturity for cultivar SC625 used in the same study was larger than the simulated time to maturity for cultivar SC601 used in this study, while the parameterization of the two cultivars was similar. The values for time to maturity in the study of Rurinda *et al*. (2015) were obtained in field trials in Makoni and Hwedza, areas that receive more rainfall Nkayi. The crop maturation rate (phenology) is delayed by water stress in APSIM, and this could explain the longer time to maturity found in our study than in the study of Rurinda *et al*. (2015).

The sorghum cultivars had a shorter time to maturity than maize cultivars, which was as expected. The early/medium maturing sorghum cultivar 'Macia' has, according to Rurinda *et al*. (2014), a time to maturity of 114 days, which is in line with the results on mediumS in our study.

The time to maturity for the sorghum cultivar lateS was only 3 days longer than the time to maturity for the sorghum cultivar mediumS. Therefore, it was decided to drop the late maturing cultivar from the study.

5.3 MANAGEMENT

5.3.1 ROTATION (YES/NO)

When the soil N in the rotation simulation was reset once in two years, the NO_3^- content at maize sowing was 60 percent of the time lower in the rotation simulation than in the continuous maize simulation. Because the observed positive effect of rotation with groundnut (Ncube et al., 2007) could not be mimicked by the model, rotation (yes/no) was dropped as a management option.

6 PERFORMANCE EVALUATION

Insufficient maize and sorghum yield data was available to execute a formal model evaluation. Therefore, simulated maize and sorghum yields were compared with yield data from field trials in other studies from Zimbabwe or semi-arid Africa.

The lowest simulated maize yield was 0 kg ha^{-1}, obtained in the poorest agricultural seasons but independent of the level of N application. The highest simulated maize yield was approximately 3300 kg ha^{-1}, obtained in the best agricultural season with a high application of N (60 kg N ha^{-1}). The lowest simulated sorghum yield was approximately 400, independent of the level of N application. The highest simulated sorghum yield was approximately 3600 kg ha^{-1}, obtained in the best agricultural season with a high application of N (80 kg N ha^{-1}).

Observed maize yields that were obtained without application of N reported in other studies were in-between 100 and 800 kg ha^{-1} (Table 4). With application of N, yields could be as high as 2500-3000 kg ha^{-1}, and in one case even more than 5000 kg ha^{-1}. Sorghum yields found in literature were in-between 300 and 3300 kg ha^{-1}. All maize and sorghum cultivars used in the studies that are listed in Table 4 were improved cultivars.

Simulated maize and sorghum yields were reasonable similar to the actual yields found in field trials. However, while average simulated sorghum yields were higher than the average simulated maize yields, the sorghum yields from field trials were lower than maize yields from field trials in two studies in semi-arid Africa (Rurinda *et al*., 2014; Traore *et al*., 2014). A reason that the simulated sorghum yields in our study were higher than the simulated maize yields, contrary to findings of Rurinda *et al*., (2014) and Traore *et al*., (2014), could be that rainfall in those two studies was higher than the average rainfall in Nkayi. Therefore, the better drought resistance of sorghum was helpful in Nkayi (simulations) but not in the areas of the two studies. This suggestion was supported by the fact that the actual sorghum yield was higher than the actual maize yield in the study with less rainfall than average Nkayi rainfall (Murungweni *et al*., 2015). Nevertheless, the highest obtained simulated sorghum yield was also higher than the highest obtained simulated maize yield. This is strange since the potential yield of most improved sorghum crops is (currently) lower than that of improved maize crops (Rurinda *et al*, 2014; Traore *et al*., 2014). The current improved cultivars/hybrids of sorghum in Zimbabwe have not been bred as extensively as maize cultivars (personal communication P. Masikati). APSIM probably assigned properties to the sorghum cultivars that are not (yet) present in the improved cultivars of sorghum. An important property that is different between simulated and observed sorghum is the harvest index. The observed harvest index of sorghum was in most cases below 15 percent (Traore *et al*., 2014), while the average simulated harvest index in the baseline climate scenarios was approximately 40 percent. The observed harvest index of maize was 25-40 percent (Traore *et al*., 2014), while the average simulated harvest index of maize was 28 percent.

It was decided that the absolute sorghum yields simulated in this study could not be interpreted as current actual yields. Absolute yields of maize and sorghum could therefore not be compared. Relative differences between yields of the same crop under different management strategies or climate scenario, or relative differences between yields in different years (yield variability), were compared in this study. These relative differences were also compared between maize and sorghum. Food self-sufficiency is linked to both potential yield and yield variability, and therefor also compared between maize and sorghum. However, more care was taken in interpreting these results.

Table 4: Maize and sorghum yields from field trials executed for studies in Zimbabwe or in semi-arid Africa. Only improved cultivars of sorghum and maize were used in these studies. *These yields were obtained across either five different maize cultivars or three different sorghum cultivars and across treatments with and without manure application.

Study	**country & site**	**Season**	**Rainfall**	**N application to maize**	**maize yield**	**N application to sorghum**	**sorghum yield**
			mm		kg ha^{-1}		kg ha^{-1}
Murungweni	Zimbabwe	2008/2009	376 - 646	manure	900*	Manure	1800*
et al., 2015	*Gonarezhou*	2009/2010	410 - 602	manure	200*	Manure	400*
Ncube	Zimbabwe	2002/2003	300	-	-	0	2000
et al., 2007	*Lucydale*	2004/2005	300	-	-	0	500
		2003/2004	300	-	-	legume residues	800-1600
		2004/2005	650	-	-	legume residues	700-1300
Rurinda	Zimbabwe	2009/2010	750	0	800	0	300
et al., 2014	*Makoni*			35	2300	35	2200
				90	5400	90	3300
		2010/2011	820	0	400	-	-
				35	1000	-	-
				90	2400	-	-
	Zimbabwe	2009/2010	650	0	200	0	500
	Hwedza			35	1900	35	1700
				90	3000	90	2800
		2010/2011	780	0	100	-	-
				35	1500	-	-
				90	1900	-	-
Traore	Mali	2009	842	85	2100	39	1100
et al., 2014	*N'Tarla*	2010	1248	85	1600	39	600
		2011	685	85	1500	39	1200

7 RESULTS – MAIN SIMULATIONS

7.1 YIELD

7.1.1 MAIZE

The average maize yield across all management options was 1363 kg ha^{-1} in the baseline climate scenario (Figure 10a). The yields in the future climate scenarios 'cool/wet' and 'hot/wet' were similar to the maize yield in the baseline climate. In the future climate scenarios 'middle' and 'cool/dry', the average maize yield was significantly lower with a value of approximately 1200 kg ha^{-1}. The average maize yield was 1054 kg ha^{-1} in the future scenario 'hot/dry', which is a decrease of 23 percent compared to the baseline.

Interactions between management options were not significantly influencing the maize yields in any climate scenario (although p-values of the interaction between sowing window and N application were low) (Table 7 in appendix 12.2.1), so the effect of each management option on the maize yield can be assessed individually. In this, the average yield for a particular the level of a management option was calculated across all levels of the other management options.

The maize yield was not affected by the choice of cultivar in all climate scenarios. The yield of the short maturing cultivar SC401 was similar to the yields of the medium and late maturing cultivars SC601 and SC709 (Figure 10b; Table 7 in appendix 12.2.1).

Time of sowing affected the maize yield in the baseline scenario and in the three future climate scenarios 'cool/dry', 'hot/wet' and 'middle' (Figure 10c; Table 7 in appendix 12.2.1). In these climate scenarios the yield was between 200 and 300 kg ha^{-1} lower when maize was sown in the late sowing window than when maize was sown in the early or medium sowing window. The yield was similar when maize was sown in the early or medium window. In the climate scenarios 'cool/wet' ($p = 0.06$) and 'hot/dry' the same trend was visible as in the other scenarios, however the differences in yield were insignificant between all sowing windows.

The amount of N application had a large effect on the maize yield in all climate scenarios (Figure 10d; Table 7 in appendix 12.2.1). The maize yield was significantly higher when a high amount of N was applied than when a low amount of N was applied to the crop. Also, the maize yield was significantly higher when a low amount of N was applied than when no N was applied to the crop. In the baseline and the future climate scenarios 'cool/wet' and 'hot/wet', low N application increased the maize yield with approximately 50 percent compared to zero N application and high N application increased the maize yield with approximately 90 percent compared to zero N application (as determined in the methodology). For the future climate scenarios 'cool/dry' and 'middle' these values were approximately 40 and 70 percent respectively, and for the future climate scenario 'hot/dry' these values were 40 and 60 percent.

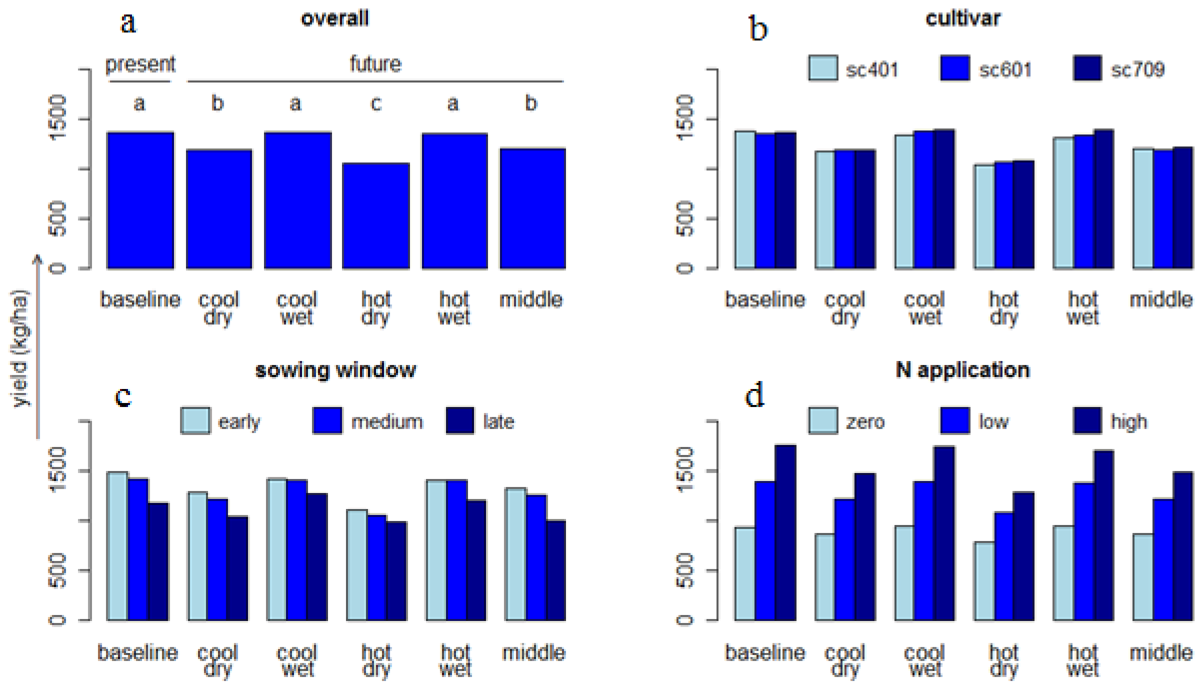

Figure 10: Average maize yield plotted for the baseline and the five future climate scenarios. **a)** The average yield of all management strategies together. Scenarios with no letter in common were significantly different according to the Fisher's LSD test. **b)** The average yield for each cultivar, across all sowing windows and levels of N application. **c)** The average yield for each sowing window, across all cultivars and levels of N application. **d)** The average yield for each level of N application, across all cultivars and sowing windows.

7.1.2 SORGHUM

The average sorghum yield in the baseline climate scenario was 1842 kg ha^{-1} (Figure 11a). The effect of climate on sorghum yield was similar to the effect of climate on maize yield. The yield in future climate scenarios 'cool/wet' and 'hot/wet' was similar to the yield under the baseline scenario, the yield was significantly lower in climate scenarios 'cool/dry' and 'middle' (1650 kg ha^{-1}), and the yield was significantly lowest in the future climate scenario 'hot/dry' (1509 kg ha^{-1}). The yield in the 'hot/dry' scenario is 17 percent less than in the baseline climate scenario.

Interactions between management options were not significantly influencing the sorghum yields under any climate scenario (Table 10 in appendix 12.2.2), so the effect of each management option on the sorghum yield was assessed individually.

As for maize, the sorghum yield was not affected by the choice of cultivar under all climate scenarios. The yield of the early maturing cultivar earlyS is similar to the yield of the medium maturing cultivar mediumS (Table 10 in appendix 12.2.2).

Time of sowing affected the sorghum yield in the baseline climate scenario and in the future climate scenario 'middle' (Table 10 in appendix 12.2.2). In these climate scenarios the yield was approximately 200 kg ha^{-1} lower when sorghum was sown in the late sowing window, than when sown in the early and medium sowing window. The yield was similar when sorghum was sown in the early or medium window. In the remaining climate scenarios the differences in yield were insignificant between all sowing windows.

The amount of N application had a large effect on the sorghum yield in all climate scenarios (Table 10 in appendix 12.2.2). The sorghum yield was significantly higher when a high amount of N was applied than when a low amount of N was applied to the crop. Also, the sorghum yield was significantly higher when a low amount of N was applied than when no N was applied to the crop. In the baseline and the future climate scenarios 'cool/wet' and 'hot/wet', low N application increased the sorghum yield with approximately 50 percent compared to zero N application and high N application increased the sorghum yield with approximately 90 percent compared to zero N application. For the future climate scenarios 'cool/dry' and 'hot/dry' and 'middle' these values were approximately 40 and 75 percent respectively.

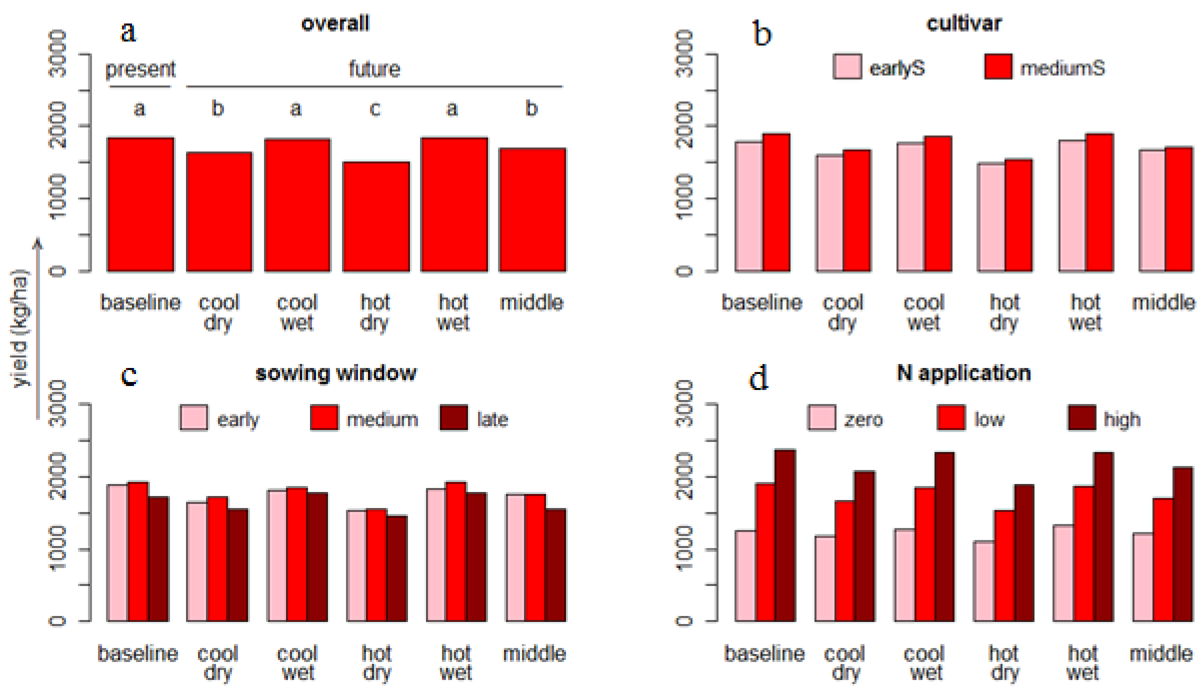

Figure 11: Average sorghum yield plotted for the baseline and the five future climate scenarios. **a)** The average yield of all management strategies together. Scenarios with no letter in common were significantly different according to the Fisher's LSD test. **b)** The average yield for each cultivar, across all sowing windows and levels of N application. **c)** The average yield for each sowing window, across all cultivars and levels of N application. **d)** The average yield for each level of N application, across all cultivars and sowing windows.

7.2 YIELD VARIABILITY

7.2.1 MAIZE

The maize yield variability index across all management options was 0.55 in the baseline climate scenario (Table 5). The maize yield variability indexes in the other climate scenarios were not significantly different from the yield variability index in the baseline climate scenario.

The choice of cultivar affected the maize yield variability index in the future climate scenarios 'cool/wet', 'hot/dry', 'hot/wet' and 'middle' (Table 5; Table 8 in appendix 12.2.1). A significant relation between yield variability index and cultivar choice was not found in the baseline climate scenario and the future 'cool/dry' scenario. When yield variability was affected by choice of cultivar, it was higher for the late maturing cultivar SC709, than for the early maturing cultivars SC401. The yield variability index of SC601 was similar to SC401 and SC709, or to both.

Sowing window affected the maize yield variability index in the baseline climate scenario and the future climate scenarios 'cool/wet' and 'hot/wet' (Table 5; Table 8 in appendix 12.2.1). A significant relation between sowing window and maize yield variability index was not found in the other climate scenarios. When maize yield variability was affected by sowing window, the yield variability index was similar for the early and medium sowing window, while it was higher for the late sowing window.

In all climate scenarios maize yield variability index was affected by the amount of N application (Table 5; Table 8 in appendix 12.2.1). The yield variability index was highest with the high amount of N application, lower with the low amount of N application and lowest without application of N.

Table 5: The average maize yield variability index (90^{th} – 10^{th} percentile of yields in 30 years divided by the potential maize yield) for different cultivars, sowing windows and N applications under the baseline and the five future climate scenarios. The yield variability index of a certain level of a certain management option was averaged across all levels of the other management options. The average yield variability index across all management options is also shown (overall). Values of overall yield variability index with no letter in common were significantly different according to the Fisher's LSD test.

management option	*Level*	*climate scenario*					
		Baseline	**future cool/dry**	**future cool/wet**	**future hot/dry**	**future hot/wet**	**future middle**
cultivar	**SC401**	0.52	0.56	0.49	0.55	0.49	0.51
	SC601	0.56	0.56	0.54	0.58	0.53	0.54
	SC709	0.57	0.57	0.57	0.60	0.57	0.58
sowing window	**Early**	0.50	0.55	0.51	0.57	0.51	0.54
	medium	0.54	0.59	0.52	0.58	0.51	0.55
	Late	0.60	0.57	0.58	0.58	0.57	0.55
N application	**Zero**	0.26	0.33	0.27	0.35	0.28	0.31
	Low	0.53	0.56	0.52	0.57	0.52	0.54
	High	0.85	0.81	0.82	0.81	0.79	0.78
Overall		0.55[a]	0.57[a]	0.54[a]	0.58[a]	0.53[a]	0.55[a]

7.2.2 SORGHUM

The sorghum yield variability index in the baseline climate scenario was 0.43 (Table 6). The values of sorghum yield variability index in the other climate scenarios were not significantly different from the yield variability index in the baseline scenario.

The choice of cultivar affected the sorghum yield variability index in all six climate scenarios. The sorghum yield variability index was higher when the medium maturing cultivar was grown than when the early maturing cultivar was grown (Table 6; Table 11 in appendix 12.2.2).

Sowing window affected the sorghum yield variability index in all six climate scenarios. As for maize, the yield variability index in those scenarios was higher for the late sowing window than for the early sowing window. The yield variability index for the medium sowing window was equal to the late or early sowing window, or was in-between those values (Table 6; Table 11 in appendix 12.2.2).

Sorghum yield variability index was affected by the amount of N application in all climate scenarios. The yield variability index was highest with the high amount of N application, lower with the low amount of N application and lowest without application of N (Table 6; Table 11 in appendix 12.2.2).

Table 6: The average sorghum yield variability index (90th – 10th percentile of yields in 30 different years divided by the potential sorghum yield) for different cultivars, sowing windows and N applications under the baseline and the five future climate scenarios. The yield variability index of a certain level of a certain management options was averaged across all levels of the other management options. The average yield variability index across all management options is also shown (overall). Values of overall yield variability index with no letter in common were significantly different according to the Fisher's LSD test.

management option	*level*	*climate scenario*					
		baseline	**future cool/dry**	**future cool/wet**	**future hot/dry**	**future hot/wet**	**future middle**
Cultivar	**earlyS**	0.38	0.45	0.38	0.47	0.37	0.42
	mediumS	0.48	0.52	0.48	0.56	0.46	0.53
sowing window	**early**	0.37	0.43	0.38	0.48	0.40	0.41
	medium	0.42	0.49	0.42	0.51	0.38	0.47
	late	0.49	0.54	0.49	0.56	0.48	0.54
N application	**zero**	0.23	0.30	0.24	0.32	0.24	0.29
	Low	0.43	0.48	0.41	0.51	0.41	0.47
	high	0.62	0.68	0.63	0.71	0.60	0.66
Overall		0.43[a]	0.49[a]	0.43[a]	0.52[a]	0.42[a]	0.47[a]

7.3 FOOD SELF-SUFFICIENCY

7.3.1 MAIZE

Food self-sufficiency from maize and maize yield were similarly affected by climate. The food self-sufficiency was similar in the baseline, future 'cool/wet' and future 'hot/wet' scenarios. With maize as staple crop, a smallholder farmer would be food self-sufficient in 22 of the 30 years (Figure 12a). In other words, a farmer would on average not be food self-sufficient once every four years. In the future 'cool/dry' and 'middle' scenarios, food self-sufficiency was obtained in 63-67 percent of the years, and under the future 'hot/dry' scenario, food self-sufficiency was obtained less than 60 percent of the time.

In the future climate scenarios 'cool/wet', 'hot/dry' and 'hot/wet' the choice of cultivar affected the food self-sufficiency (Figure 12b; Table 9 in appendix 12.2.1). In these climate scenarios, the food self-sufficiency is higher when cultivar SC709 is sown than when cultivar SC401 is sown. Similar to yield, the food self-sufficiency was not significantly affected by cultivar choice in the other three climate scenarios.

The effect of sowing window on food self-sufficiency was similar to its effect on yield. The effect of sowing window was significant in all climate scenarios. In all climate scenarios but the future climate scenario 'hot/wet', the food self-sufficiency was highest when maize was sown in the early sowing window, and lowest when maize was sown in the late sowing window (Figure 12c; Table 9 in appendix 12.2.1).

Contradicting to its effect on yield, N application did not significantly affect the food self-sufficiency under any future climate scenarios. Under the baseline climate the food self-sufficiency was highest when no fertilizer is applied (Figure 12c; Table 9 in appendix 12.2.1).

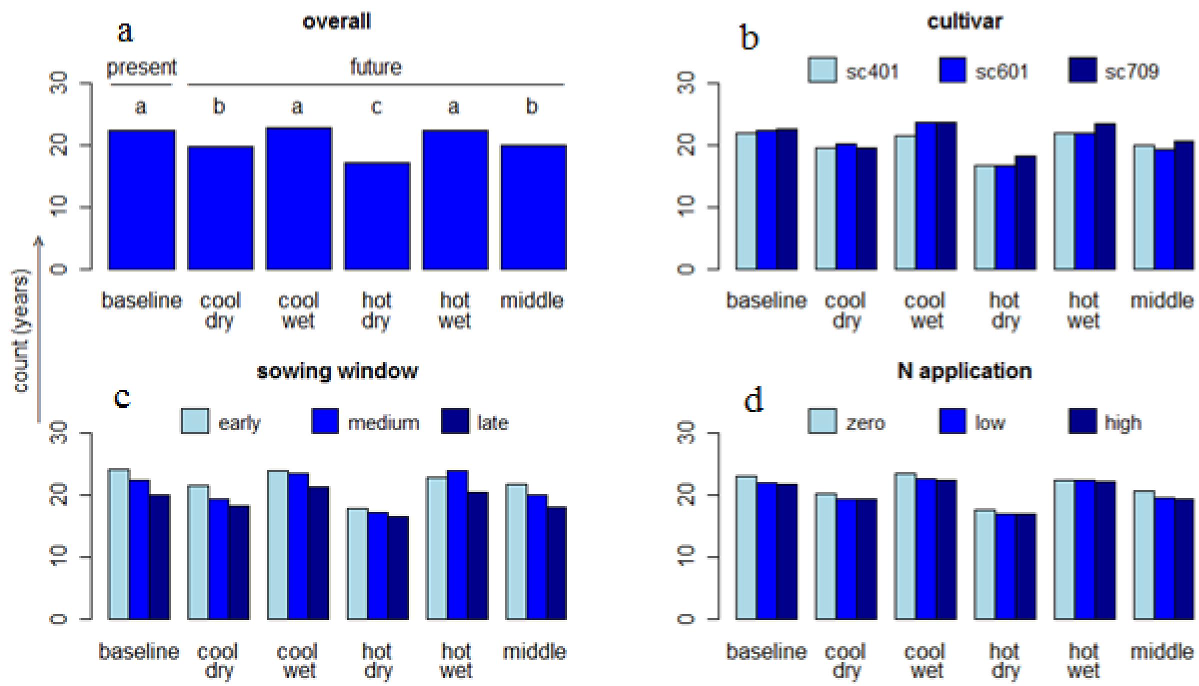

Figure 12: Number of years out of thirty in which food self-sufficiency was achieved when maize was grown for the baseline and the five future climate scenarios**.** Scenarios with no letter in common were significantly different according to the Fisher's LSD test. **a)** The average count of all management strategies together. **b)** The average count for each cultivar, across all sowing windows and levels of N application. **c)** The average count for each sowing window, across all cultivars and levels of N application. **d)** The average count for each level of N application, across all cultivars and sowing windows.

7.3.2 SORGHUM

Food self-sufficiency from sorghum and sorghum yield were affected by climate in the same way. The food self-sufficiency was similar in the baseline, future 'cool/wet' and future 'hot/wet' scenarios. With sorghum as staple crop, a smallholder farmer would be food self-sufficient in 26-27 of the 30 years (Figure 13a). In these scenarios, a smallholder farmer would not be self-sufficient once every 9 years. In the future 'cool/dry' and 'middle' scenarios, food self-sufficiency was obtained in 80-83 percent of the years, and under the future 'hot/dry' scenario, food self-sufficiency was obtained approximately 75 percent of the time.

In the future climate scenarios 'cool/wet' and 'middle', the choice of sorghum cultivar affected the food self-sufficiency (Figure 13b; Table 12 in appendix 12.2.2). This was not shown in the other four climate scenarios. When the food self-sufficiency was affected by the choice of cultivar, the food self-sufficiency was higher when the early maturing cultivar earlyS was grown, than when the medium maturing cultivar mediumS was grown. This was opposite to the effect of cultivar choice on sorghum yield, however, both the effect of cultivar choice on sorghum yield and food self-sufficiency were very small.

Sowing window affected food self-sufficiency in all six climate scenarios. In all climate scenarios the food self-sufficiency was highest when sorghum was sown in the early sowing window, and lowest when sorghum was sown in the late sowing window. The food self-sufficiency when sorghum was sown in the medium window was either similar to the food sufficiency when sorghum was sown in the early or late window, or had a value in-between (Figure 13b; Table 12 in appendix 12.2.2).

In contrast to yield, food self-sufficiency was only affected by N application in the future 'hot/dry' scenario. In this climate scenario, the food self-sufficiency was higher when N was applied in a low or a high amount, than when no N was applied to sorghum (Figure 13b; Table 12 in appendix 12.2.2).

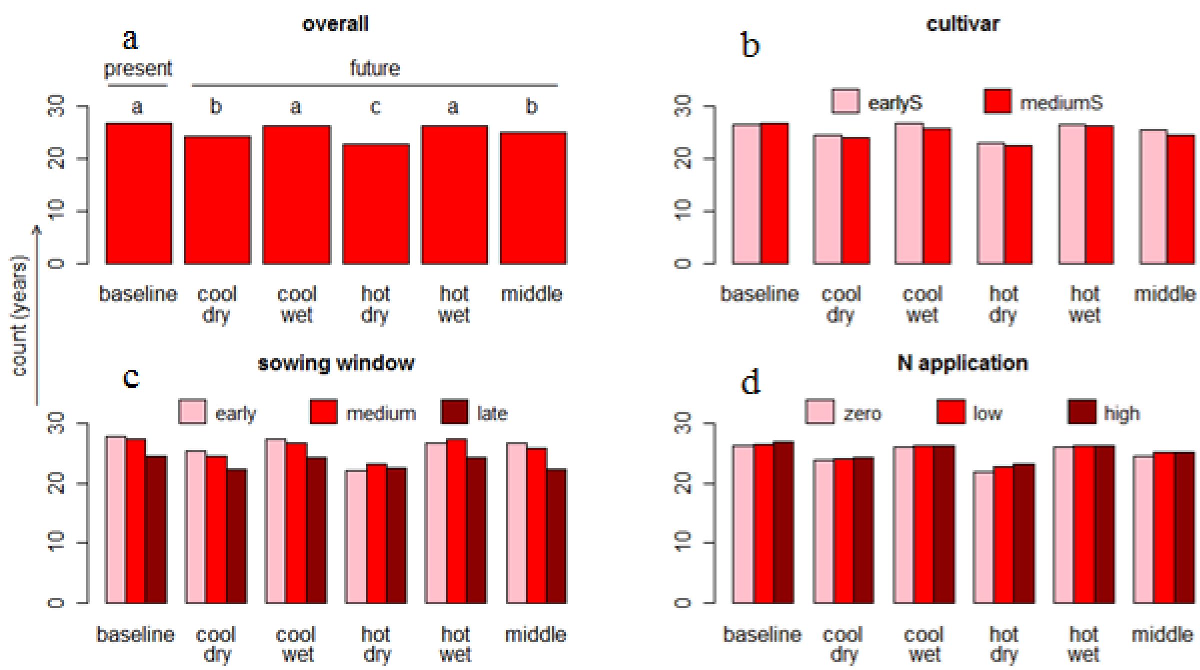

Figure 13: Number of years out of thirty in which food self-sufficient was achieved when sorghum was grown for the baseline and the five future climate scenarios. Scenarios with no letter in common were significantly different according to the Fisher's LSD test. **a)** The average count of all management strategies together. **b)** The average count for each cultivar, across all sowing windows and levels of N application. **c)** The average count for each sowing window, across all cultivars and levels of N application. **d)** The average count for each level of N application, across all cultivars and sowing windows.

7.4 COMPARISON WITHIN AND BETWEEN RESULTS OF MAIZE AND SORGHUM

7.4.1 CLIMATE

The effect of climate scenarios on maize and sorghum yield was similar, with a slightly smaller effect in the case of sorghum. In the future climate scenarios, yields were either lower than or similar to yields in the current climate scenario. The yields of sorghum and maize seemed to be positively related with rainfall because the overall yields were lower in the future scenarios 'cool/dry' and 'hot/dry' than in the baseline scenario and the future 'cool/wet' and 'hot/wet' scenario. Relative differences in maize and sorghum yields between climate scenarios (Figure 10a, Figure 11a) were almost similar to the relative changes in rainfall (Figure 6) between climate scenarios. Maize and sorghum yields also seemed to be negatively influenced by an increase in temperature. The overall yields were lower in the future 'middle' scenario than in the baseline scenario and the overall yields were lower in the future 'hot/dry' scenario than in the future 'cool/dry' scenario.

The overall maize yield variability index was higher than the overall sorghum yield variability index. The overall maize and sorghum yield variability indexes were similar between all climate scenarios. However, the range in values for the yield variability index is high per climate scenario due to the large differences in yield variability index for different N applications, and therefore, differences between scenarios could be hardly detected. Not taking into account the ANOVA results, the yield variability index seemed to be negatively related with rainfall since it was highest in the future 'dry' scenario and lowest in the future 'wet' scenarios and the baseline scenario. The differences in yield variability index between future 'dry' and 'wet' scenarios were more pronounced for sorghum than for maize.

The overall food self-sufficiency of farmers was approximately 20 percent higher when sorghum is grown than when maize is grown, in all climate scenarios. The effect of the climate scenarios on food self-sufficiency was smaller than on yield for both maize and sorghum.

Elaboration

In Figure 14, maize and sorghum yields were plotted against the amount of rainy season rainfall and against the mean maximum temperature in the rainy season (maximum temperature was analyzed since it is the most important temperature variable related to heat stress). Due to correlation between rainfall and mean maximum temperature (Figure 27 in appendix 12.4), the relation between yield and rainfall could be partly explained by mean maximum temperature and *vice versa*. Therefore, only the yields that were found in a rainy season with an average max temperature between 31 and 33 degrees Celsius were used to plot against annual rainfall, and only yields that were found in a rainy season with a cumulative rainfall between 500 and 700 mm were used to plot against temperature. Figure 14a and Figure 14c confirm the positive correlation between yield and rainfall. However, extra rainfall above approximately 900 mm did not affect the yields of both maize and sorghum anymore. In Figure 14b and Figure 14d there is not a clear correlation visible between maximum temperature in the rainy season and maize and sorghum yields.

In-between 300 mm and 900 mm rainfall, there was a large variability in maize and sorghum yields in seasons that had a similar amount of rainfall (Figure 14a, Figure 14c). It could not be explained by differences in N application, since these yield values were obtained by averaging across all management strategies (so also across all levels of N application). The variability was probably caused by the distribution of rain within the rainy season. The distribution of rain seems to be less important in years with relatively much rain compared to years with relatively less rain, since the yield variability decreased with increasing rainfall (Figure 14a, Figure 14c).

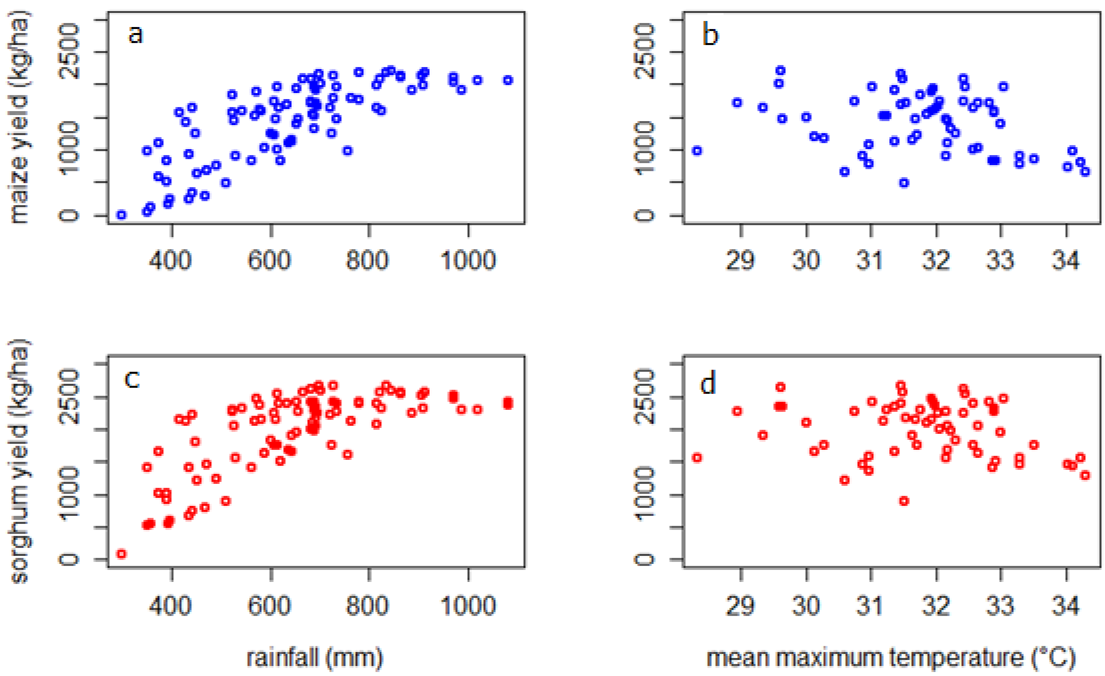

Figure 14: Maize and sorghum yields (average across all management strategies) plotted against rainfall and mean maximum temperature in the rainy season. Yields simulated under all six scenarios were used to create the figures. Yields that were found in a rainy season with an mean maximum temperature between 31 and 33 degrees Celsius were used to plot against annual rainfall. Yields that were found in a rainy season with a cumulative rainfall between 500 and 700 mm were used to plot against temperature.

7.4.2 CULTIVAR CHOICE

Both maize and sorghum yields were not affected by cultivar choice in all climate scenarios. However, probability plots (Figure 15) show that in the baseline climate scenario, the medium maturing sorghum cultivar was yielding more than the early maturing cultivar in good agricultural seasons. On the other hand, the yield of the early maturing sorghum cultivar was slightly higher than the yield of the medium maturing cultivar in poor agricultural seasons. In the future climate scenarios this was also the case, but the advantage of mediumS over earlyS in good agricultural seasons was smaller (Figure 25 in appendix 12.3). In all climate scenarios, and especially in the future 'dry' scenarios, there was no effect of cultivar choice on maize yields, whether it was a bad or good agricultural season (Figure 15;Figure 24 in appendix 12.3).

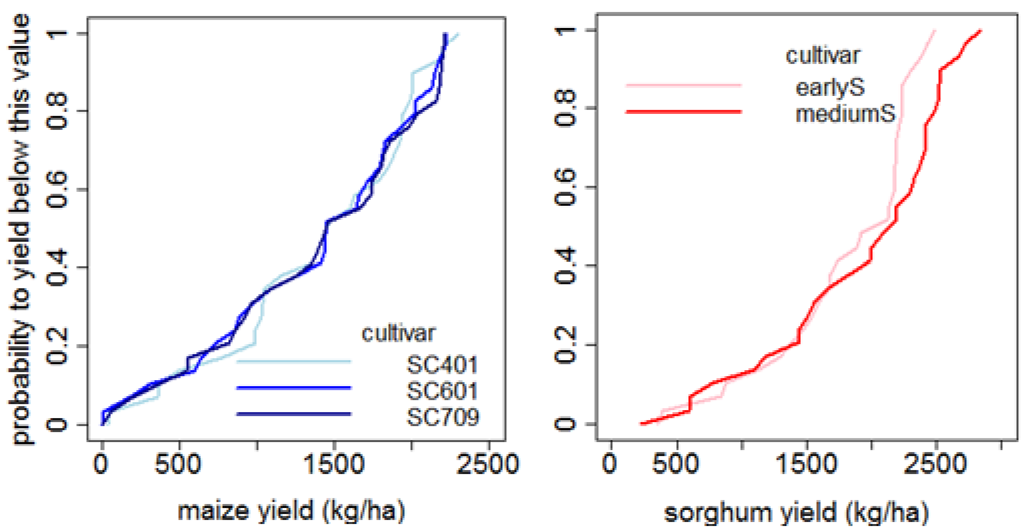

Figure 15: Probability plots of maize and sorghum yields in the baseline climate scenario, for different cultivars, averaged across all levels of the other management options. SC401 is the early maturing maize cultivar, SC601 is the medium maturing maize cultivar and SC709 is the late maturing maize cultivar. EarlyS is the early maturing sorghum cultivar and mediums S is the medium maturing sorghum cultivar.

The yield variability index of the medium maturing sorghum cultivar was in all climate scenarios different from the early maturing cultivar, while the yield variabilities of the three maize cultivars were in none of the climate scenarios all different. Also, the differences in yield variability index between cultivars were larger for sorghum than for maize. In the baseline climate, maize yields differed slightly between cultivars across the years, but the cultivar that yielded highest was often different (Figure 16), not depending on whether it was a good or poor agricultural season. For sorghum, differences in yields between the two cultivars across years were more pronounced. The early maturing sorghum cultivar yielded less than the medium maturing sorghum cultivar in good agricultural seasons and often slightly more than the medium cultivar in poor agricultural seasons.

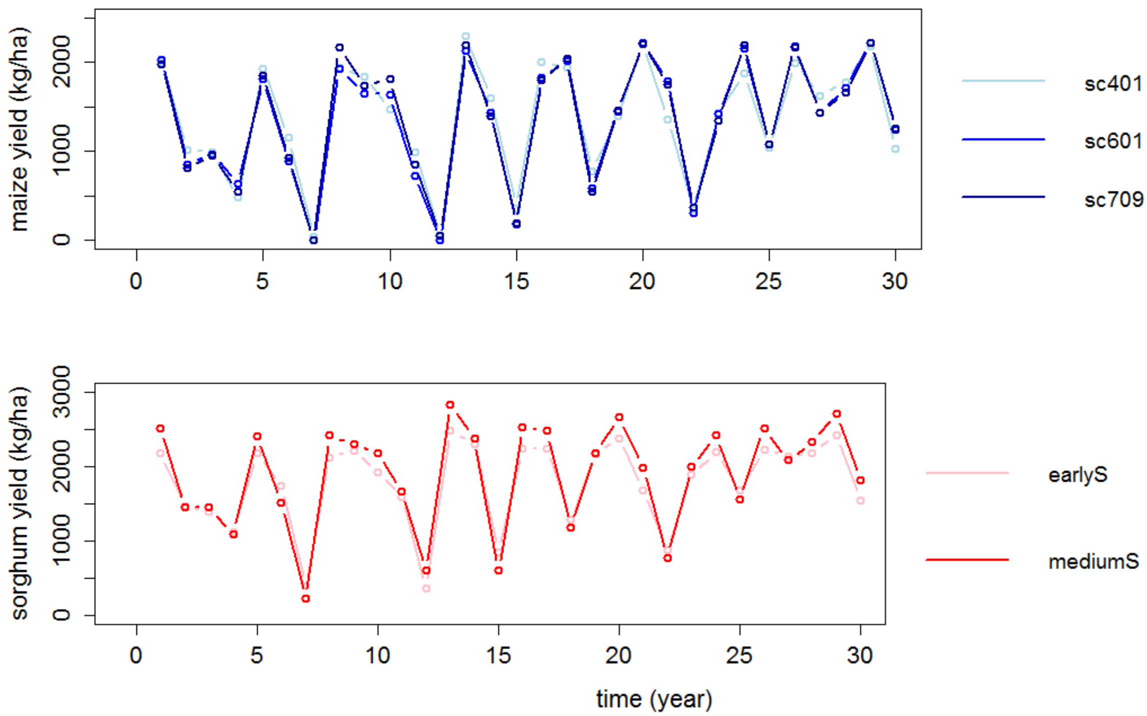

Figure 16: Average annual maize and sorghum yields for different cultivars, across all sowing windows and levels of N application. The yields in this figure were simulated with use of baseline climate data.

In the baseline climate scenario, food self-sufficiency from maize and sorghum was not affected by the cultivar choice. In future climate scenarios, the food self-sufficiency from the late maturing maize cultivar was higher or similar (dependent on the climate scenario) to the food self-sufficiency from the early maturing cultivar. In future climate scenarios, the food self-sufficiency from the medium maturing sorghum cultivar was either slightly lower or similar to the food self-sufficiency from the early maturing sorghum cultivar. The probability to yield above 750 kg ha^{-1} for sorghum was often slightly higher for cultivar earlyS than for cultivar mediumS (Figure 15, and Figure 25 in appendix 12.3). However, the effect of cultivar choice on maize food self-sufficiency was not always well translated in the probability plots of all climate scenarios in Figure 24.

7.4.3 SOWING WINDOW

Sowing window affected the maize yield in all scenarios except for the future 'hot/dry' scenario, while sowing window affected sorghum yield only in the baseline scenario and the 'middle' scenario. When the yield was affected by sowing window, the late sown crop was always yielding less than the early and medium sown crops for both maize and sorghum. However, the relative yield difference between the late sown crop and the early and medium sown crop was larger for maize than for sorghum. The positive effect of early sowing on maize yield was noticeable across bad, medium and good agricultural seasons, while the positive effect of early sowing on sorghum yield was most expressed in poor agricultural seasons (Figure 17; Figure 24 and Figure 25 in appendix 12.3).

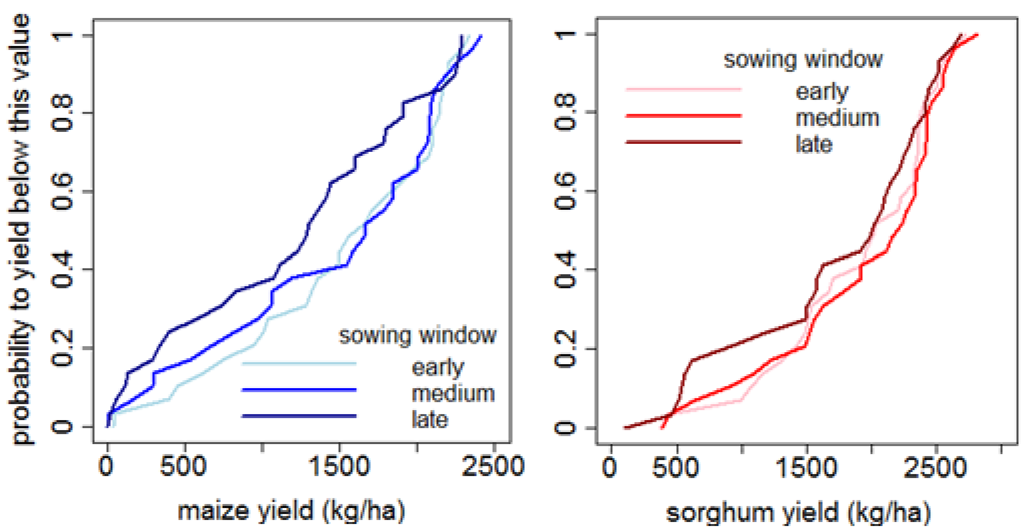

Figure 17: Probability plots of maize and sorghum yields in the baseline climate scenario, for different sowing windows, averaged across all levels of the other management options.

The maize yield variability index was affected by sowing window in the future 'wet' scenarios and the baseline scenario, while sorghum yield variability index was affected by sowing window in all climate scenarios. The differences in yield variability index between sowing windows were slightly larger for sorghum than for maize. When affected, maize yield variability index was higher when sown late than when sown early, and this was also true for sorghum. In the baseline climate scenario, late sown maize was often yielding less than early and medium sown maize in good agricultural seasons, sometimes with differences over 1000 kg ha^{-1} (Figure 18).

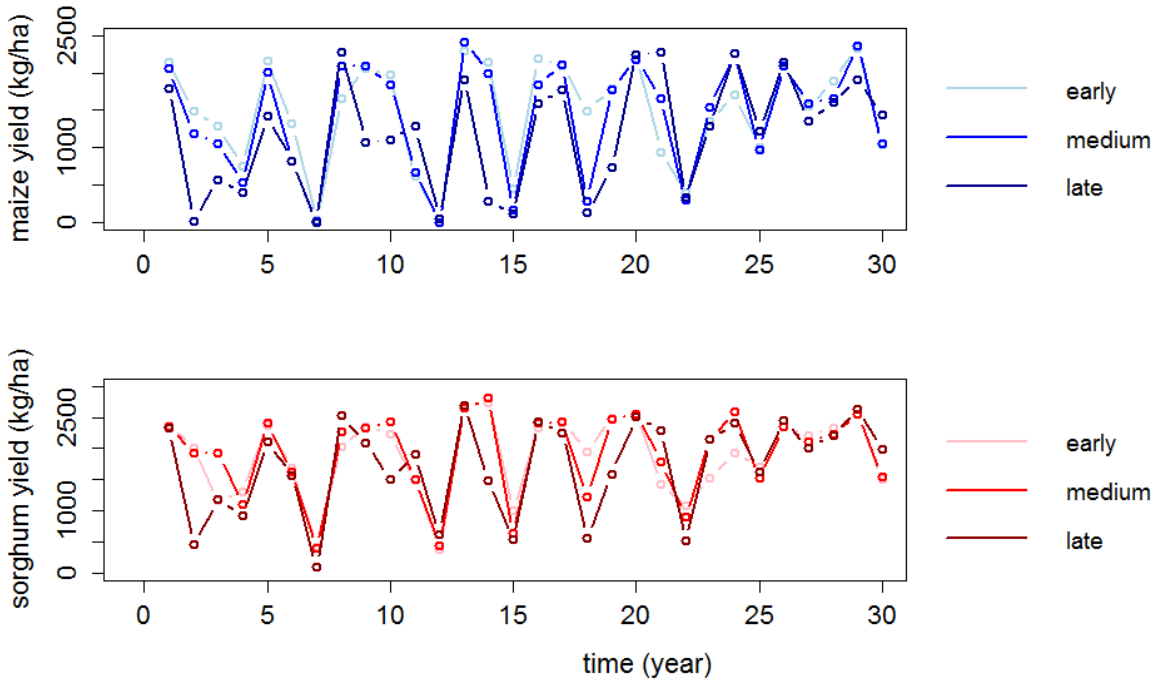

Figure 18: Average annual maize and sorghum yields for different sowing windows, across all cultivars and levels of N application. The yields in this figure were simulated with use of baseline climate data.

For maize, food self-sufficiency was affected by sowing window in a similar way as yield. The food self-sufficiency was lower in all climate scenarios when maize was sown in the late window than when maize was sown in the early window. For sorghum, the food self-sufficiency was lower in all climate scenarios with late sowing as compared to early sowing, while for average yield, this was the case in two climate scenarios only. The reduction in food self-sufficiency due to a late sown crop compared to an early sown crop was relatively larger for maize than for sorghum.

Elaboration

Possible explanations for the reduced yield of late sown maize and sorghum could be reduced available water content or reduced radiation for photosynthesis during the growing period. A medium maturing maize and sorghum cultivar were taken to calculate the average daily radiation intensity during their growing periods. The average daily radiation intensities for sown medium or late were relatively 3 and 6 percent lower respectively than the average daily radiation intensity for maize sown early (Figure 19a). The relative differences were the same for sorghum (Figure 19c).

The average available soil water content for medium sown maize was relatively 7 percent higher than for early sown maize. The average available soil water content for late sown maize was equal to the available soil water content for early sown maize (Figure 19b). The average available soil water content for sorghum sown in the medium and late sowing period were relatively 13 and 8 percent higher respectively than for sorghum sown early (Figure 19d). However, when the average available soil water contents during the second halve of the growing period were compared between sowing windows, it was found that this value was relatively 37 and 16 percent lower respectively for maize sown in the late and medium window, compared to the maize sown in the early window(Figure 19b). The average available soil water content during the second halve of the growing period was relatively 26 and 10 percent lower respectively for late and medium sown sorghum, compared to the early sown sorghum (Figure 19d).

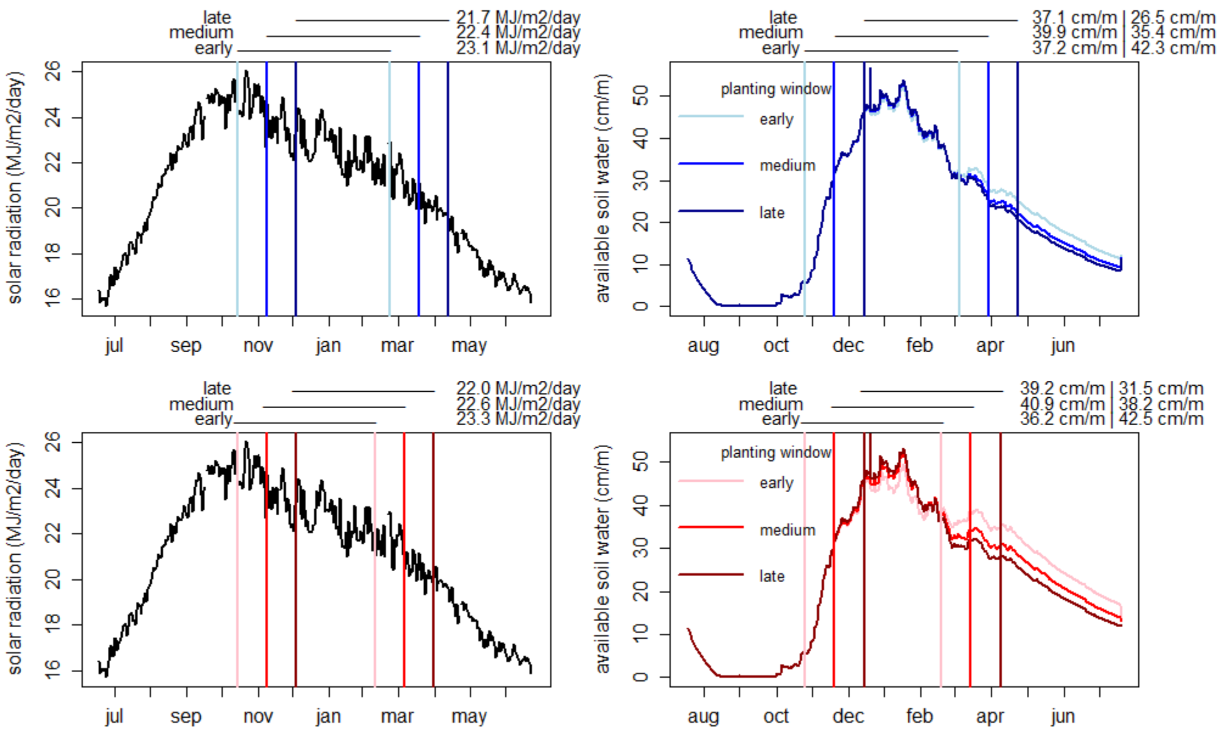

Figure 19: The annual radiation cycle (averaged over 30 years daily radiation data) plotted with an indication of the growing periods of early, medium and late sown medium maturing **a)** maize, and **c)** sorghum (sowing to harvest). The numbers above the graphs are the average values of radiation intensity in each growing period. Further, the annual available soil water cycles is plotted for **b)** maize, and **d)** sorghum, sown in the early, medium and late window with indications of their growing periods. The numbers above the graphs are the average available soil water in each whole growing period and in the second half of each growing period respectively.

As was mentioned before, the p-values for interaction between N application and sowing window were low (but not significant) for all climate scenarios in the case of maize (Table 7 in appendix 12.2.1), but not for sorghum. In the baseline climate scenario, the yield of maize under a high application of N was 5 and 37 percent lower when sown in the medium and late sowing window respectively, compared to sown in the early sowing window (Figure 20). Under a low N application the maize yield was respectively 5 and 18 percent lower for the medium and late sowing periods, compared to the early sowing period. When no N was applied to maize, the yield for the early, medium and late sowing periods were similar. Sorghum yields were not different when sown in the medium period compared to the early period under all levels of N application. The differences in sorghum yield between the late and early growing period were respectively 10 and 13 percent under low and high application of N. Without N application no differences in yield were found between the three sowing windows.

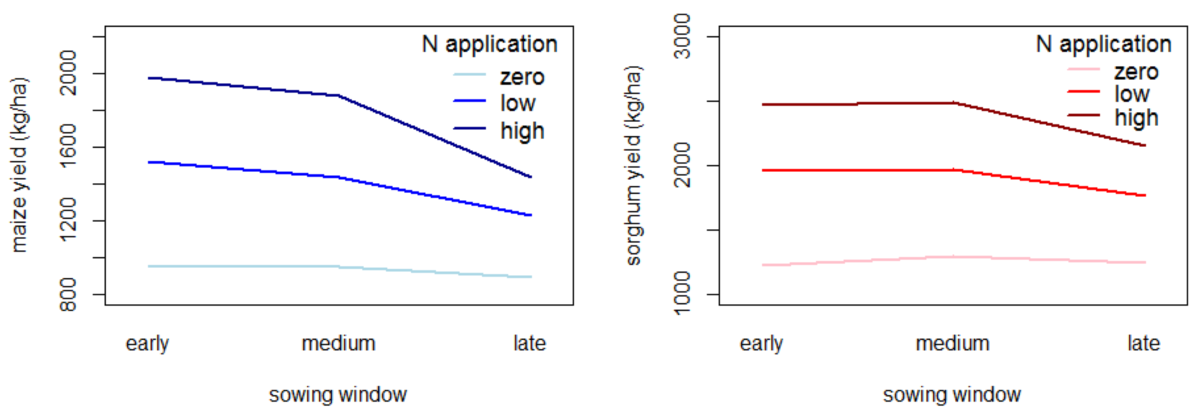

Figure 20: Maize and sorghum yields against the sowing window, for different levels of N application. The yields in this figures were simulated with use of the baseline climate data.

7.4.4 N APPLICATION

The yield of both maize and sorghum, and in all climate scenarios was highest when a high level of N was applied, lower when a low level of N was applied, and lowest when no N was applied. The difference between scenarios was the magnitude of the effect of fertilizer on maize and sorghum yields. For both maize and sorghum, the effect of fertilizer was weakest in the 'dry' future climate scenario.

In the baseline climate scenario, maize completely failed to yield in approximately 8 percent of the years, regardless whether N was applied to the crop (Figure 21). In the subsequent 30 percent of the poorest agricultural seasons, maize yields were small, and similar between all levels of N application. The yield of maize that received the high fertilizer level was only higher to the yield of maize that received the low fertilizer level in the best 50 percent of agricultural seasons. Sorghum yielded at least above 200 kg ha^{-1}, even in the poorest agricultural seasons. In approximately the poorest 15 percent of agricultural seasons, N application did not influence sorghum yield. In approximately 20 percent of the poorest agricultural seasons, sorghum under high N application did not yield higher than sorghum under low N application. In future climate scenarios the same trend was visible as shown in Figure 21. However, in the future 'dry' scenarios, the probability that N application affected yield was decreased (shifted up), especially in the case of maize (Figure 24 and Figure 25 in appendix 12.3). In the 'hot/dry' scenario, the most extreme scenario, maize with N application yielded higher than maize without N application in the best 50 percent of agricultural seasons only. Maize with a high N application yielded higher than maize with a low N application in approximately the best 30 percent of agricultural seasons only. For sorghum, these probability values were approximately 70 and 50 percent respectively in the 'hot/dry' climate scenario.

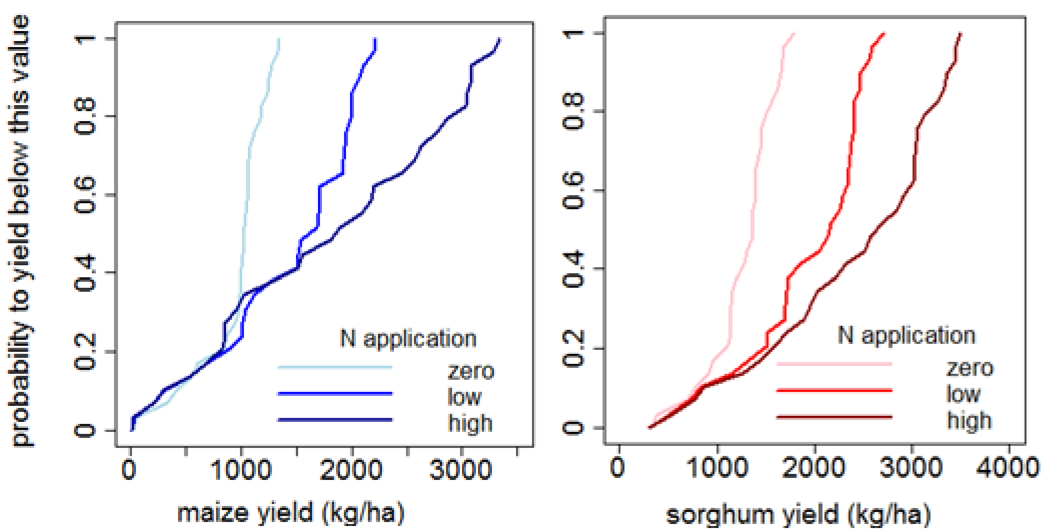

Figure 21: Probability plots of maize and sorghum yields in the baseline climate scenario, for different levels of N application, averaged across all levels of the other management options.

The yield variability indexes of both maize and sorghum were affected by N application in all climate scenarios. The difference in yield variability index between levels of N application was larger for maize than for sorghum. In good agricultural seasons, the maize yield was highest with a high N application, in-between with a low N application, and lowest without N application (Figure 22). In poor agricultural seasons yields were more or less similar. The effect of N application in good agricultural seasons on sorghum was similar to the effect on maize. However, also in poor agricultural seasons, sorghum with N application often yielded higher than sorghum without N application.

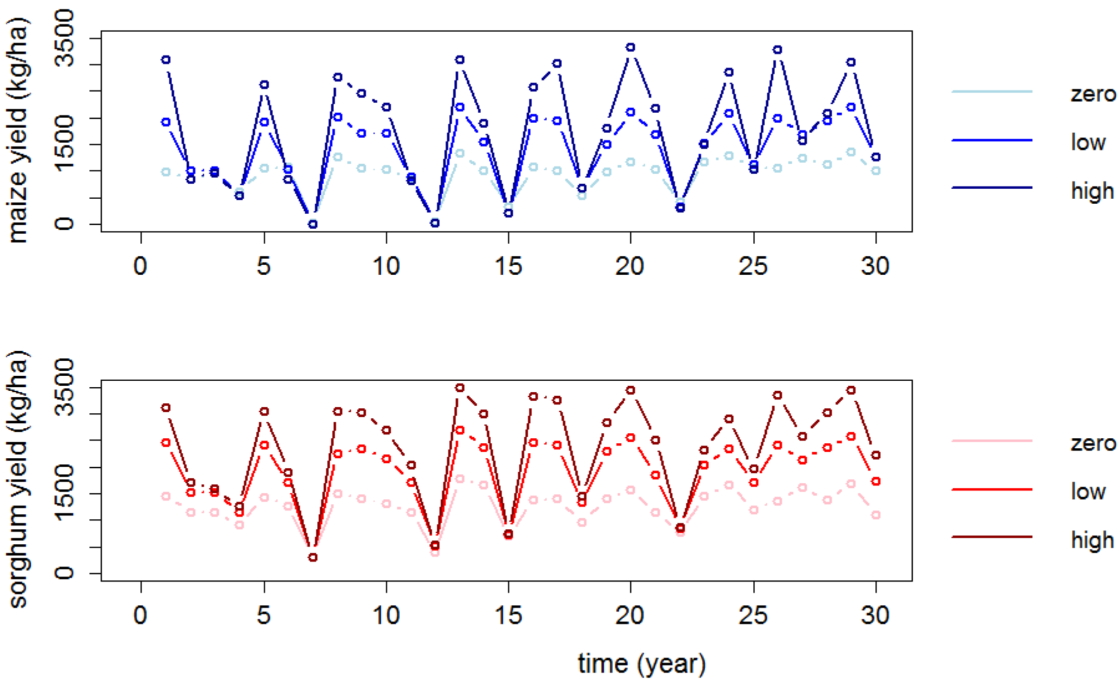

Figure 22 Average annual maize and sorghum yields for different levels of N application, across all cultivars and sowing windows. The yields in this figure were simulated with use of baseline climate data.

Food self-sufficiency from maize showed a decreasing trend with an increasing amount of fertilizer applied in all climate scenarios. This trend was only significant in the baseline climate scenario. The food self-sufficiency from sorghum showed an increasing trend with the amount of fertilizer applied in all climate scenarios. This trend was only significant in the future 'hot/dry' scenario. From the probability plot in Figure 21 cannot be seen that the probability to yield above 750 kg ha^{-1} was higher when no N was applied to maize than when N was applied to maize. However, when the probability plots were constructed for each sowing window separately, it was visible that the probability to yield above 750 kg ha^{-1} without N application was higher when maize was sown in the medium window or in the late window (Figure 26 in appendix 12.3).

Elaboration

The available soil water patterns with different levels of N application were diverging from January onwards for both maize and sorghum(however, dependent on the growing period of the crop) (Figure 23). When a medium maturing cultivar of maize was sown in the medium sowing window, the average soil water availability during the second part of its growing period was 40 percent if no N was applied, 35 percent if a low level of N was applied and 31 percent if a high level of N was applied. For sorghum, the soil water availability in the second part of its growing season was 41 percent if no N was applied, 38 percent if a low level of N was applied, and 35 percent if a high level of N was applied.

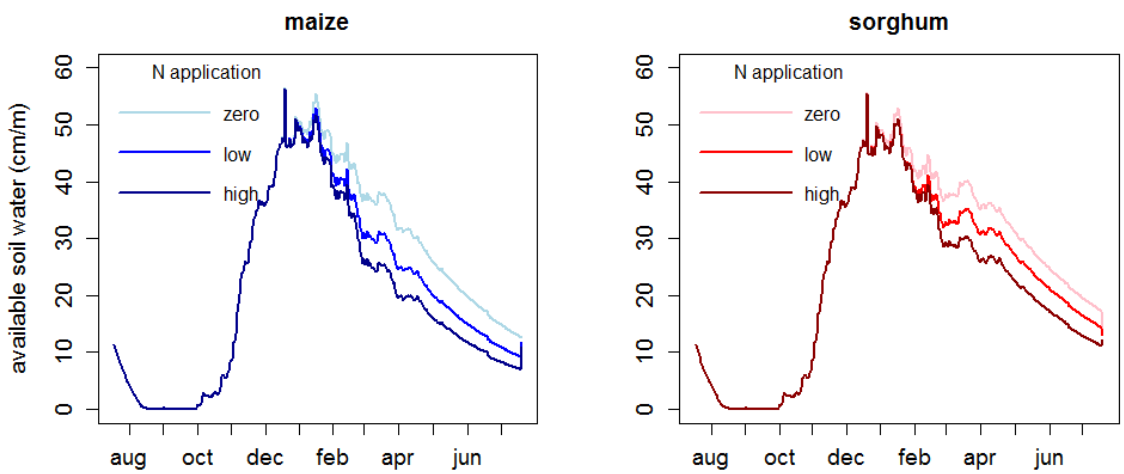

Figure 23: The annual available soil water cycle maize and sorghum, receiving zero N, a low application of N, or a high application of N. The figure was constructed with use of baseline climate data.

8 DISSCUSSION – MAIN SIMULATIONS

8.1 CLIMATE CHANGE IMPACT ON YIELD

Maize and sorghum yields were mostly affected by a decrease in rainfall and less by an increase in temperature. These findings confirm the conclusion by Hussein (1987) that crop production in Zimbabwe is mainly determined by the availability of soil water, while temperature is of less importance. Also Turner & Roa (2013) did not find lower yields when they evaluate the impact of increased temperatures on sorghum. Contrary, Rurinda *et al*. (2015) mentioned that a decline in future maize yields was driven by an increase in temperature. A higher temperature would increase the crop maturation rate, thereby shortening the growing period (Springate & Kover, 2014). However, in our study there was not an obvious relation found between temperature and crop maturation rate (Table 13 in appendix 12.4). This can be explained by the fact that in APSIM, crop maturation rate was, besides temperature, also affected by the soil water availability. Below a certain available soil water threshold, the crop maturation rate was decreased, meaning that there was a possibility that long maturing crops were yielding less than short maturing crops because the long maturity could be caused by water stress.

The predicted yield decrease by mid-21st century in the worst case future climate scenario (hot/dry for both) was slightly higher for maize than for sorghum with 23 and 18 percent respectively. Yield was not affected in the best case future scenarios 'hot/wet' and 'cool/wet'. The worst case scenario yield changes were in the range of predicted crop yield changes in southern Africa by mid-21st century from the review study of Zinyengere *et al*. (2013), which comprised results from many studies about climate change impact on yields in southern Africa. The best case scenario changes were more positive than the predicted crop yield changes in Zinyengere *et al*. (2013), but this could be due to the fact that not many studies take into account the possibility of higher rainfall in the future. A smaller impact of climate change in southern Africa on sorghum yield than on maize yield was also predicted by studies using statistical methods. Schlenker & Lobell (2011) predicted a decrease of 22 and 17 percent for maize and sorghum respectively by the mid-21st century. Lobell *et al*., (2008) predicted a decrease of 28 and 2 percent respectively by 2030. The study of Rurinda *et al.* (2015) predicted an decrease of approximately 30 percent in maize yield by mid-21st century under high radiative forcing with the use of APSIM. Studies that used process-based models to predict future sorghum yields in southern Africa, based on more than just temperature, were not found.

The climate change impact on food self-sufficiency was less severe than on yield, with a decrease of respectively 18 and 15 percent of food self-sufficient years in the worst case scenario. Food self-sufficiency did not change for both maize and sorghum in the best case future scenarios. The food self-sufficiency from sorghum in both the baseline climate scenario and future climate scenarios was approximately 20 percent higher than the food self-sufficiency from maize. This value might be lower in reality, since the potential yield of sorghum is overestimated by APSIM, but also shows the advantage of the higher drought resistance of sorghum over maize.

8.2 MANAGEMENT EFFECT ON YIELD

From the three management options tested, the choice of cultivar was least important for optimizing the maize and sorghum yields under the baseline and future climate scenarios. There was no effect of cultivar choice on maize yield while the medium maturing sorghum cultivar yielded up to 15 percent (baseline climate) more than the early maturing sorghum cultivar in good agricultural seasons, but slightly less in poor agricultural seasons. In good agricultural seasons, the benefit of a longer assimilation period was clearly visible for sorghum, while in poor agricultural seasons this benefit was probably counteracted by an elongated exposure to water stress. The benefit of a later maturing sorghum cultivar in a good agricultural season decreased in the future climate scenarios. If the length of the rainy season (Tadross *et al*., 2009; Rurinda *et al*., 2013) would decreased in the future climate scenarios, it could be possible that a longer maturing cultivar would be more often disadvantageous, especially when the crop is sown late in the season, since water stress would become more of an issue. The fact that maize yield was not affected by cultivar choice, even in good agricultural seasons, was strange, since the potential yields of the cultivars are very different (Rurinda *et al*., 2015). It would be expected that in good agricultural seasons, maize yield would increase due to a longer assimilation period, just like sorghum did. No good reason was found why this was the case. There is a possibility that the differences between maize cultivars were not well captured by APSIM, although the simulated time to maturity between the maize cultivars were indeed different (Table 2). More research will be needed to say more about this.

Sowing window was more important than choice of cultivar to optimize maize and sorghum yields. In the baseline climate scenario, yields were 20-25 percent higher when maize was sown in the early or medium window, than when sown in the late window. For sorghum the positive effect of sowing in the early or medium window was just above 10 percent, which can be partly explained by the fact that late sowing of sorghum mostly decreased yield in poor agricultural seasons, while late sowing decreased maize yield similarly across all seasons.

Observed maize and sorghum yields from field trials in recent studies were similar when sown in the early and medium window (Rurinda *et al*., 2014; Troare *et al*., 2014) suggesting that farmers will have a broad window to sow their cereals. However, the trial yields were more than halved when maize and sorghum were sown in the latest sowing window (Rurinda *et al*., 2014; Troare *et al*., 2014), a yield decline much more severe than found in the simulations of our study. The modelling study of Rurinda *et al*. (2015) found a steep decline in maize yield from half December onwards. The maize yield was approximately halved when sown at the end of December. Waddington and Hlatshwayo (1991) suggest that the decline in yield with late planting was caused by shortening day length and a delayed application of fertilizer. Our analysis indicated however that average day length was not very different between crops grown in the early or late growing period. Differences in average soil water content in the second halve of the growing period, in which the crop demands most water, were much stronger between sowing windows. The soil water content in in the second halve of the growing period was highest for maize and sorghum sown early, lower for medium sowing window and lowest for late sowing window, with larger difference between the late and medium sowing window than between the medium and the early sowing window. As a consequence, the application of N was less effective when a crop was sown late than when a crop was sown early, and this effect was stronger for maize than for sorghum. This was the main cause of the differences in yield between sowing windows. Nevertheless, sowing in the late window also has an advantage. The chance is higher that the grain filling phase occurs during a dry period when sown later, hence the pressure of pests and diseases is lower (Tadross *et al*., 2009). However, this cannot be modeled by APSIM.

In future climate scenarios the difference in yield between early, medium and late sown maize and sorghum became smaller, even insignificant for sorghum in most climate scenarios. Currently the average (maximum) temperature is lower during the growth of an early sown crop than during the growth of a late sown crop (Table 14 in appendix 12.4)(Waddington and Hlatshwayo, 1991), especially in the first 20 days after sowing (Table 14 in appendix 12.4). In APSIM, a fraction of the plants will be killed due high temperature immediately following emergence. When the average temperature rises, high temperature immediately following emergence will occur more often, and especially when a crop is sown early. Therefore, the positive effect of early sowing with regards to water availability could be counteracted by a higher temperature stress. More research is needed to confirm this hypothesis.

The yield variability index in the baseline scenario was lower when maize and sorghum were sown early than when they were sown late. This decrease in yield variability index was mainly caused by the fact that yields of maize and sorghum sown in the late window were more often extremely poor than when sown in the early or medium window. The sowing window of the crop that yielded highest alternated quite a lot between seasons, which could mean that yield was dependent on rainfall distribution in the growing period.

For maize, food self-sufficiency was similarly affected by sowing window as yield. In the case of sorghum however, food self-sufficiency was affected by sowing window in all climate scenarios, while yield was affected by sowing window in the baseline scenario and future 'middle' scenario only. This can be explained by the fact that the decreased effect of sowing window on sorghum yield in future climate scenarios was mainly visible in good agricultural seasons, and less in poor agricultural seasons, seasons in which food self-sufficiency is at stake.

Finally, of all management options considered, N application influenced the average yield the most strongly. In the baseline climate scenario, an application of 20 kg N ha^{-1}, increased both average maize and sorghum yield with 50 percent. A 90 percent yield increase was achieved with N applications 60 and 80 kg N ha^{-1} for maize and sorghum respectively. Application of N to maize was only effective in a bit more than 60 percent of the years, but application of N to sorghum was effective is almost 90 percent of the years. The relative yield differences between maize and sorghum yields with and without N application in field trials by Rurinda *et al*. (2014) were much larger than the differences found in our study. However, the control yields (without N application) were a lot smaller their study. Control yields in the study of Twomlow *et al*. (2010) were similar to control yield in our study but they also found a larger relative yield increase for maize, with an increase of approximately 60 percent at an N application rate of 17 kg N ha^{-1} and 100 percent at 42 kg N ha^{-1}. The effect of N application on yield might be underestimated in our study.

In all future climate scenarios, except the future 'wet', the effect of N application on yield was reduced compared to the baseline climate scenario. This was also found by Rurinda *et al*. (2015). The reduction was mainly caused by an increase in the relative amount of years in which water, instead of nutrients, is the limiting factor for crop growth. The effect of N application in good agricultural years was similar in all climate scenarios.

Although N application was most important to optimize the average yield, it did not affect food self-sufficiency much. In good agricultural seasons, the yield increased with application of N, but in poor agricultural seasons, yields with and without N application were similar. This also explains the higher yield variability index for the high level of N application and the lowest yield variability index when no N was applied. In the baseline climate scenario, when maize was sown medium or late, the food self-sufficiency was even negatively affected by N application. The maize crops grown with N application accumulated on average more biomass than the maize crops that did not receive N (Table 15 in appendix 12.4), which meant that they used more water because their average demand was larger. At the time of seed filling, the average soil water availability was lower for maize crops with N application than for crops that did not receive N. Hence, on average the former was more affected by water stress during grain filling than the latter. In the case of N application to sorghum, or to maize sown in the early window, the average soil water availability at seed filling was higher than for late sown maize, and in these cases water stress at seed filling was similar for crops with and without N application.

8.3 IMPLEMENTATION

Smallholder farmers in Nkayi are currently mainly focused on maize cultivation (Kee-Tui *et al*., 2013). When sorghum is included in the system as a staple crop, the resistance against crop failure in dry years could be increased. This could lead to a better food security, provided that hybrid cultivars are used (Rurinda *et al*., 2014) and effort and inputs will be more or less equally divided between maize and sorghum. To achieve the highest actual yields during medium to good agricultural seasons, maize is currently most suitable (Twomlow *et al*., 2010, Rurinda *et al*., 2014; Traore *et al*., 2014). Breeding is needed to create higher yielding sorghum cultivars, like the ones used in this simulation study.

Having a rough prediction of the 'quality' of the rainy season can be very important, since the effect of a management option on the yield can be very dependent on this quality. These predictions should be available to farmers and also taken seriously by farmers. For instance, a dry rainy season caused by *El Niño* can be predicted well. In an *El Niño* year farmer could be advised to sow relatively more sorghum and invest less money in fertilizer. When no predictions are available, some 'rules for prediction' could be established. For instance, pre-onset rainfall is often indicating that the rainy season will have an early onset over parts of Zimbabwe (Tadross *et al*., 2005).

A few recommendations to farmers:

- Farmers in Nkayi that grow sorghum sow it after maize. This is good since sorghum has a higher drought resistance than maize.
- The application of N to maize should be lower than 55–79 kg ha^{-1}, the recommended rate for Zimbabwe (Twomlow and Ncube, 2001), unless the probability of having a good agricultural season is very high. This is because the chance to yield more with a high application of N (60 kg ha^{-1}) than with a low application of N (20 kg ha^{-1}) is currently only 50 percent, and will become even less in the future. The risk of losing an investment in fertilizer is thus very high.
- Currently maize often receives fertilizer while sorghum does not. It would be sensible to apply some of the fertilizer to sorghum, because the probability that application of N would be effective is higher for sorghum than for maize.
- It would be good to sow all crops before the end of the medium window. However, since farm-level labour availability is a major constraint for many smallholder farmers in Zimbabwe (Dorward, 2013), crops will often also be sown in the late window. If maize is sown in the late window, application of N to this crop should be avoided.
- The medium maturing sorghum cultivar should be used over the short maturing sorghum cultivar because the gain is larger than the risk, however this probably changes if the future will become drier.

If the rainfall decreases, maize yields could reduce up to approximately three quarter of the current yield by mid-21st century (Figure 10). Optimizing management becomes less attractive since the differences in yield between the optimal management options and less optimal management options become smaller. The only management option that has a good potential to mitigate the impact of climate change on average yield is the application of N. However, the yield advantage will only be achieved in good agricultural seasons, and farmers will need to sell or store their grains to mitigate the impact of climate change. Maize can only be stored up to 9 months (Rurinda *et al*., 2014) and trade is difficult due to poorly developed markets and bad infrastructure (Masikati *et al*., 2015). Mitigation of climate change in terms of food-security can be achieved by adaptation of sorghum cultivation, and improved forecasting of the 'quality' of the rainy season.

Currently it will be hard to integrate sorghum in the cropping system because sorghum isn't very popular among smallholder farmers. People prefer the taste and color of maize over sorghum, sorghum is more susceptible to bird damage, weeding is more labour intensive, post-harvest processing of sorghum is difficult and labour intensive, and sorghum is less marketable than maize (Rurinda *et al*., 2014; Murungweni *et al*., 2015). However, breeding can reduce the susceptibility to bird damage (hanging grains, larger grains) and improve the taste and color of sorghum. The marketability of sorghum is probably related to the taste and color of sorghum. Also, the nutritious value of sorghum is higher than that of maize (Rurinda *et al*., 2014) which is an additional advantage of sorghum for the Zimbabwean diet.

9 CONCLUSION

The main question and the subsequent sub questions were:

- How did temperature and rainfall change over the past 30 years?
- How do different future climate scenarios compare to each other and to the baseline climate?
- How do the yield and yield variability of maize and sorghum compare between current and future climate?
- How do choice of cultivar, sowing window, amount of N application and rotation (yes/no) influence the yield and yield variability of maize and sorghum under current climate and future climate?
- How will the food self-sufficiency of farmers be affected by climate, crop and management strategy?

Over the past 30 years, the maximum temperature in Nkayi increased (approximately 1 °C) while the minimum temperature remained similar. There was no trend found in the annual rainfall, but the amount of extreme rainfall events increased.

Both the maximum and minimum temperature in the five future climate scenarios were in-between 1°C (cool/dry, cool/wet) and 2 °C (hot/dry, hot/wet) higher than in the baseline climate scenario. The amount of rainfall in the rainy season was highest in the future 'wet' scenario with approximately 650 mm, lower for the baseline scenario and the future 'middle' scenario with approximately 600 mm and lowest for the future 'dry' scenarios with approximately 550 mm. Distribution of rainfall within the baseline climate scenario and the future climate scenarios was equal.

In the baseline climate scenario, the average maize yield across all levels of the three management options was 1842 kg ha^{-1}. Absolute simulated sorghum yields were not trustworthy and will not be compared to maize. According to literature, average current sorghum yields in Zimbabwe are lower than average maize yields. Yield variability in the baseline climate scenario was higher for maize than for sorghum, due to the fact that sorghum yielded even in the poorest agricultural seasons, while maize failed. 80 percent of the maize yields covered 55 percent of the difference between zero and potential yield, while for sorghum this was 43 percent.

Average maize and sorghum yield decreased with 0-23 percent and 0-18 percent respectively in future climate scenarios compared to the baseline climate scenario. The yield decrease was largest for the 'hot/dry' scenario. There was no significant change in maize and sorghum yield between the future 'wet' scenarios and the baseline climate scenario. Differences in yield variability index between future climate scenarios and the baseline climate scenario were larger for sorghum than for maize. In all future climate scenarios, the yield variability index of sorghum was still lower than that of maize.

Choice of cultivar did not affect the maize and sorghum yield in the baseline climate scenario, although for maize this conclusion is open to discussion. Sowing window affected yields in the baseline scenario. The average maize yield and sorghum yield were respectively 25 and 10 percent lower when sown in the late window than when sown in the early or medium window. The yield decrease was mainly caused by a delayed application of fertilizer. Yield variability index was lowest when maize and sorghum were sown early since the yield in some poor agricultural years was improved compared to maize and sorghum sown later. In terms of improving average yield, N application was most effective. Maize and sorghum yields were on average 50 percent higher with application of 20 kg ha^{-1} N than without N application. Maize yield increased 90 percent compared to control when 60 kg ha^{-1} was applied. Sorghum increased 90 percent compared to control when 80 kg ha^{-1} was applied. The yield variability index increased with higher levels of N application because N application did not improve yields in poor agricultural years. Application of N to maize was only effective in a bit more than 60 percent of the years while application of N to sorghum was effective is almost 90 percent of the years.

The effect of sowing window and N application on sorghum yield decreased in 'dry' future climate scenarios. In the future 'hot/dry' scenario, the effect of sowing window on maize and sorghum yield was even insignificant. In this scenario, a low application of N increased both the average maize and sorghum yield with only 40 percent and an high application increase the average maize and sorghum yield with respectively 60 and 70 percent. The decreased effectiveness of N application was caused by the fact that the numbers years in which yield was limited by water availability instead of nutrients increased in the 'dry' future climate scenarios compared to the baseline scenario.

In the baseline climate scenario, food self-sufficiency was significantly higher when sorghum was grown than when maize was grown. For both maize and sorghum, food self-sufficiency was slightly less decreased than average yield due to climate change. The food self-sufficiency from maize and sorghum were decreased with respectively 18 and 15 percent in the worst case scenario ('hot/dry'). No large differences were found between the effect of cultivar on average yield and food self-sufficiency. However, while N application was most the most important management option to improve the average yields, N application did not improve the food self-sufficiency of farmers.

Concluding, the impact of climate change on maize and sorghum yields will mostly dependent on rainfall. The only management option that has a good potential to mitigate the impact of climate change on average yield is the application of N. Integration of sorghum in the cropping system is needed to mitigate the impact of climate change on food self-sufficiency.

10 RECOMMENDATIONS FOR FURTHER RESEARCH

- When repeating a similar kind of research, make sure to have a proper model validation with use of data from field trials, preferably under a large range of treatments. This will add reliability to the conclusions drawn from the analysis.
- When nutrient availability is an important limiting factor for crop growth, like in this study, a research would be improved if crop growth would be dependent on more than just N availability. Phosphorus limitation could be just as important as N limitation, especially on acid sandy soils as in Nkayi.
- Predictions of future climate could probably be improved by altering the temporal rainfall distribution compared to the baseline climate scenario. Predictions are that the rainy season will be delayed and shortened, and that prolonged dry spells will occur more often in the rainy season, and this cannot be captured using the delta approach to create future climate scenarios. It would be interesting to see how yields would be impacted by a different distribution in rainfall. Also the effect of management options on yield could be different.
- Results from this study could be used in a study about the mitigation of climate change impact on farm level instead of field level. However, livestock data should be also available than.

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12 APPENDIX

12.1 STATISTICAL TESTS

Linear regression
Equation 1 shows a linear models with dependent variable y and explanatory variable x. Linear regression is able to calculate the intercept α, the regression variable β, and the error ε. Thereby, it can show if the linear model has sufficient explanatory power and hence, if y is significantly dependent on *x.* In linear regression the *x* is a continuous/numeric variable.

1. $y = \alpha + \beta x + \varepsilon$

One-way ANOVA
One-way ANOVA (analysis of variance) is very similar to linear regression. The only difference with linear regression is that x isn't a numeric variable but a factor. This means that x never has a numeric value and is removed from the equation (see equation 2). While in linear regression β has only one value, the value of β depends on the factor level in one-way ANOVA.

2. $y = \alpha + \beta + \varepsilon$

Two-way ANOVA
In two-way ANOVA the dependent variable y is dependent on more than one explanatory variables.
In equation 3, y can be dependent on two variables independently, β and γ, but also one the interaction between the two variables. If more than two explanatory variables are included, the interaction of all variables should be incorporated in the model. Two-way ANOVA shows if y is explained by the model, and if so, which variables, or interactions do significantly influence the value of *y.*

3. $y = \alpha + \beta + \gamma + \beta\gamma + \varepsilon$

12.2 RESULTS OF ANOVA TESTS

12.2.1 MAIZE

Table 7: p-values for the ANOVA model testing effects of management options and their interactions on maize yield. The letters behind significant p-values are results from the Fisher's LSD test. The first letter belongs to the first level of a management option, either 'earlyS', 'early' or 'zero'. The middle and the last letter are the second and last level of a management option. Levels with no letter in common were significantly different according to the Fisher's LSD test.

Effects	*climate scenario*					
	baseline	**future cool/dry**	**future cool/wet**	**future hot/dry**	**future hot/wet**	**future middle**
Cultivar	0.96	0.96	0.76	0.84	0.61	0.96
sowing window	**0.00** a-a-b	**0.01** a-a-b	0.06	0.23	**0.00** a-a-b	**0.00** a-a-b
N application	**0.00** c-b-a	**0.00** c-b-a	**0.00** c-b-a	**0.00** c-b-a	**0.00** c-b-a	**0.00** c-b-a
cult : sow	0.97	0.81	0.93	0.99	0.99	0.96
cult : N	0.99	1.00	0.99	0.99	0.98	0.99
sow : N	0.09	0.19	0.34	0.4	0.21	0.07
cult : sow : N	1.00	1.00	1.00	1.00	1.00	1.00

Table 8: p-values for the ANOVA model testing effects of management options on maize yield variability. The letters behind significant p-values are results from the Fisher's LSD test. The first letter belongs to the first level of a management option, either 'earlyS', 'early' or 'zero'. The middle and the last letter are the second and last level of a management option. Levels with no letter in common were significantly different according to the Fisher's LSD test.

Effects	*climate scenario*					
	Baseline	**future cool/dry**	**future cool/wet**	**future hot/dry**	**future hot/wet**	**future middle**
cultivar	0.12	0.62	**0.01** b-a-a	**0.01** b-ab-a	**0.00** b-b-a	**0.03** b-ab-a
sowing window	**0.00** b-b-a	0.25	**0.00** b-b-a	0.87	**0.01** b-b-a	0.75
N application	**0.00** c-b-a	**0.00** c-b-a	**0.00** c-b-a	**0.00** c-b-a	**0.00** c-b-a	**0.00** c-b-a

Table 9: p-values for the ANOVA model testing effects of management options on food self-sufficiency when maize is grown. The letters behind significant p-values are results from the Fisher's LSD test. The first letter belongs to the first level of a management option, either 'earlyS', 'early' or 'zero'. The middle and the last letter are the second and last level of a management option. Levels with no letter in common were significantly different according to the Fisher's LSD test.

Effects	*climate scenario*					
	Baseline	**future cool/dry**	**future cool/wet**	**future hot/dry**	**future hot/wet**	**future middle**
cultivar	0.10	0.44	**0.00** b-a-a	**0.00** b-b-a	**0.01** b-b-a	0.08
sowing window	**0.00** a-b-c	**0.00** a-b-b	**0.00** a-a-b	**0.01** a-a-b	**0.00** b-a-c	**0.00** a-b-c
N application	**0.01** a-b-b	0.44	0.35	0.28	0.89	0.06

12.2.2 SORGHUM

Table 10: p-values for the ANOVA model testing effects of management options and their interactions on sorghum yield. The letters behind significant p-values are results from the Fisher's LSD test. The first letter belongs to the first level of a management option, either 'earlyS', 'early' or 'zero'. The middle and the last letter are the second and last level of a management option. Levels with no letter in common were significantly different according to the Fisher's LSD test.

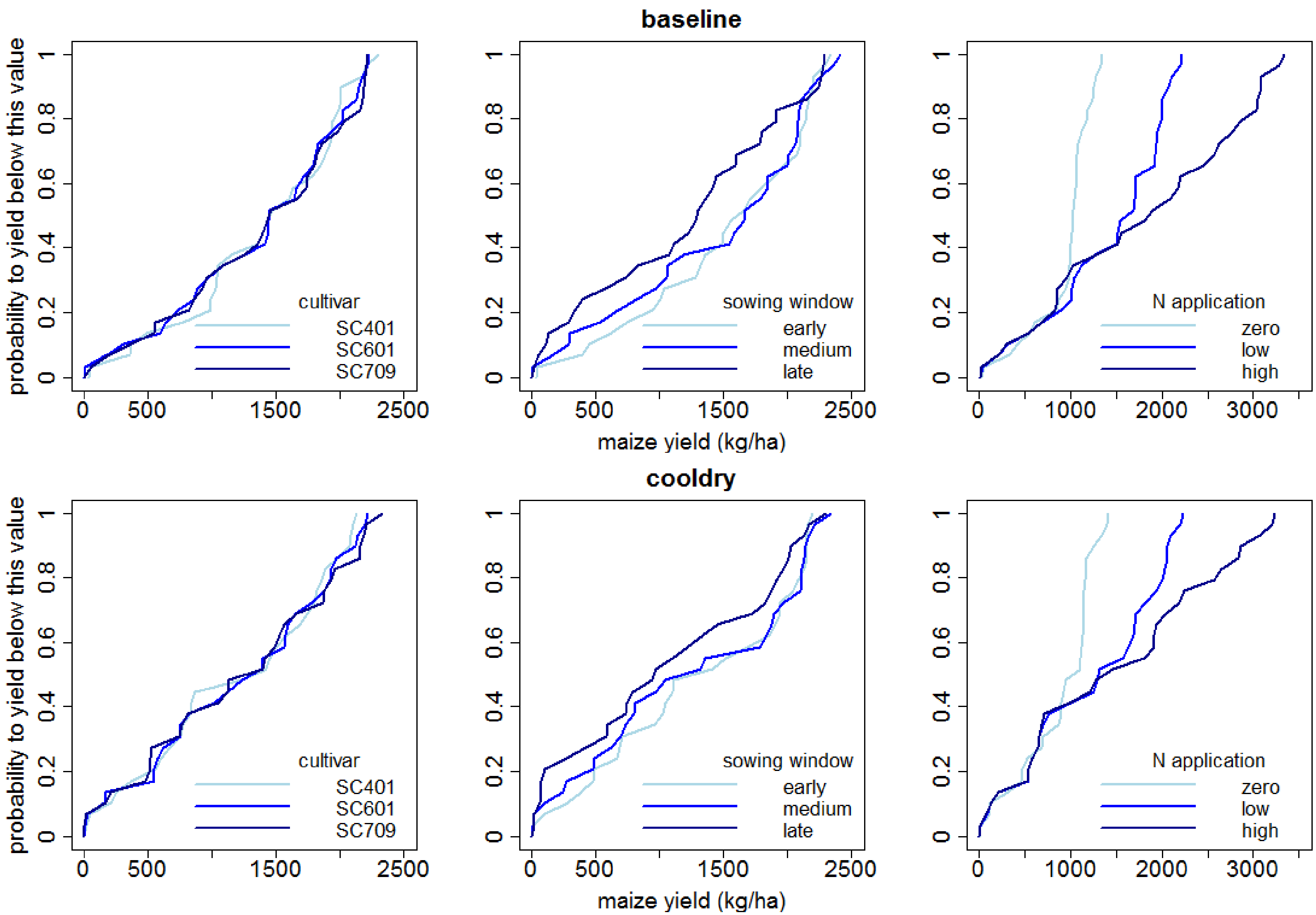
Effects	*climate scenario*					
	Baseline	**future cool/dry**	**future cool/wet**	**future hot/dry**	**future hot/wet**	**future middle**
Cultivar	0.09	0.33	0.18	0.46	0.12	0.55
sowing window	**0.03** a-a-b	0.21	0.67	0.57	0.10	**0.02** a-a-b
N application	**0.00** c-b-a	**0.00** c-b-a	**0.00** c-b-a	**0.00** c-b-a	**0.00** c-b-a	**0.00** c-b-a
cult : sow	0.78	0.71	0.74	0.89	0.83	0.68
cult : N	0.11	0.46	0.23	0.64	0.31	0.48
sow : N	0.50	0.71	0.58	0.77	0.47	0.49
cult : sow : N	1.00	1.00	1.00	1.00	1.00	1.00

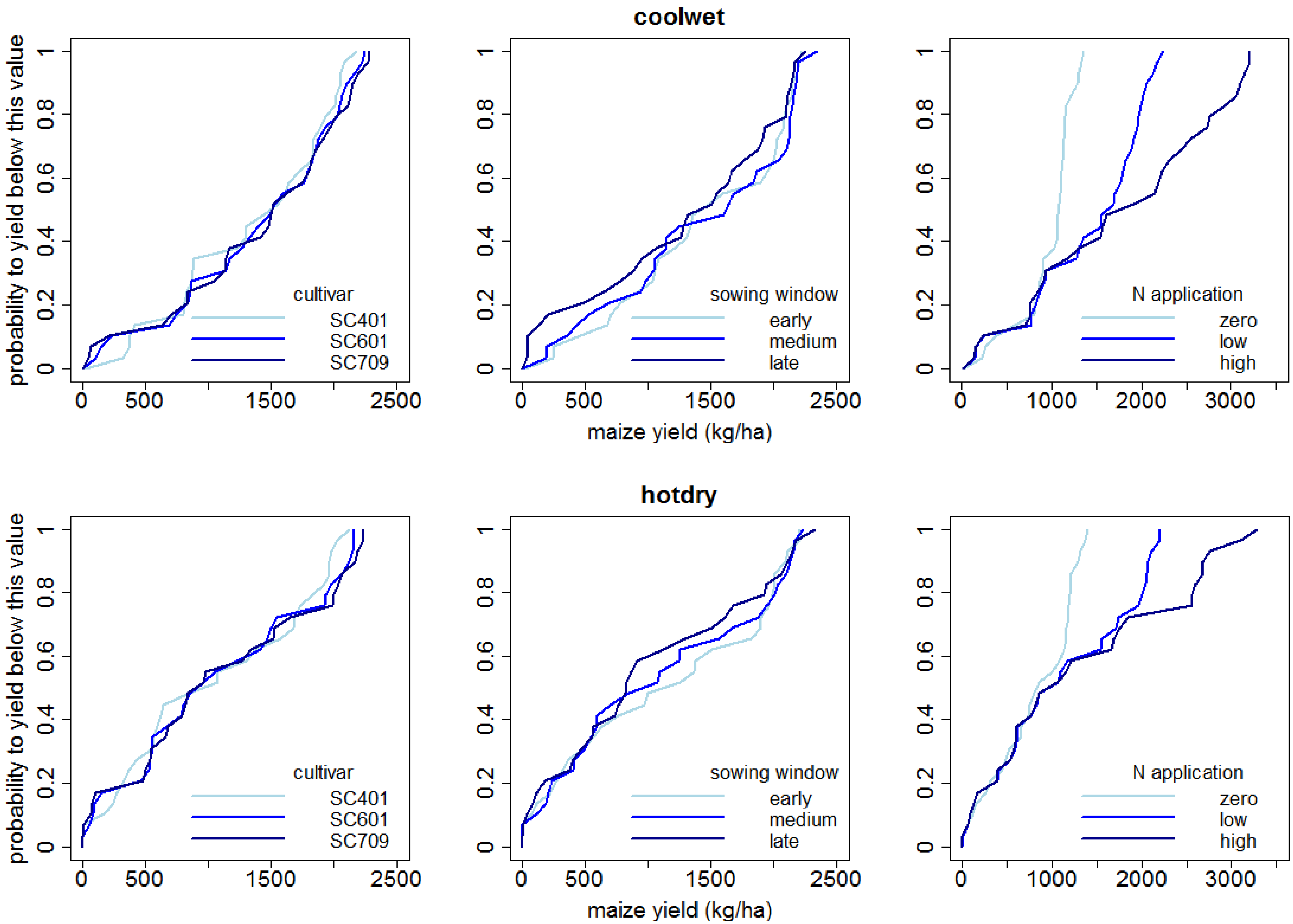
Table 11 p-values for the ANOVA model testing effects of management options on sorghum yield variability. The letters behind significant p-values are results from the Fisher's LSD test. The first letter belongs to the first level of a management option, either 'earlyS', 'early' or 'zero'. The middle and the last letter are the second and last level of a management option. Levels with no letter in common were significantly different according to the Fisher's LSD test.

Effects	*climate scenario*					
	Baseline	**future cool/dry**	**future cool/wet**	**future hot/dry**	**future hot/wet**	**future middle**
Cultivar	**0.00** b-a	**0.00** b-a	**0.00** b-a	**0.00** b-a	**0.00** b-a	**0.00** b-a
sowing window	**0.01** b-b-a	**0.00** c-b-a	**0.01** b-ab-a	**0.00** b-b-a	**0.00** b-b-a	**0.00** c-b-a
N application	**0.00** c-b-a	**0.00** c-b-a	**0.00** c-b-a	**0.00** c-b-a	**0.00** c-b-a	**0.00** c-b-a

Table 12: p-values for the ANOVA model testing effects of management options on food self-sufficiency when sorghum is grown. The letters behind significant p-values are results from the Fisher's LSD test. The first letter belongs to the first level of a management option, either 'earlyS', 'early' or 'zero'. The middle and the last letter are the second and last level of a management option. Levels with no letter in common were significantly different according to the Fisher's LSD test.

Effects	*climate scenario*					
	Baseline	**future cool/dry**	**future cool/wet**	**future hot/dry**	**future hot/wet**	**future middle**
Cultivar	0.70	0.07	**0.04** a-b	0.20	0.37	**0.01** a-b
sowing window	**0.00** a-a-b	**0.00** a-b-c	**0.00** a-a-b	**0.03** a-ab-b	**0.00** a-b-c	**0.00** a-b-c
N application	0.18	0.22	0.71	**0.01** b-a-a	0.44	0.18


baseline
probability to yield below this value
0
0.2
0.4
0.6
0.8
1
0
500
1500
2500
cultivar
SC401
SC601
SC709
sowing window
early
medium
late
maize yield (kg/ha)
1000
2000
3000
N application
zero
low
high
cooldry


coolwet
hotdry
probability to yield below this value
maize yield (kg/ha)
cultivar
SC401
SC601
SC709
sowing window
early
medium
late
N application
zero
low
high
0
0.2
0.4
0.6
0.8
1
0
500
1500
2500
1000
2000
3000

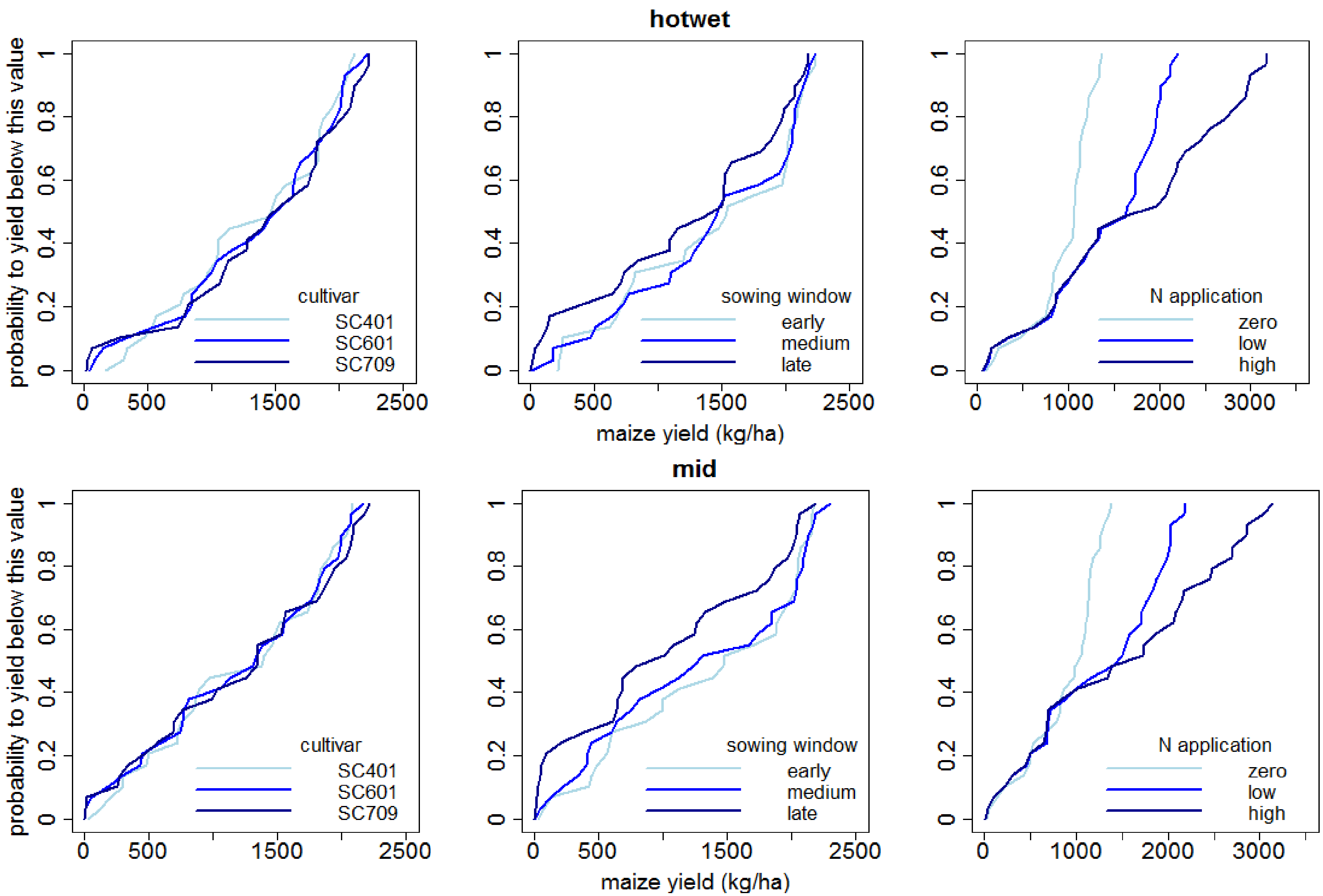
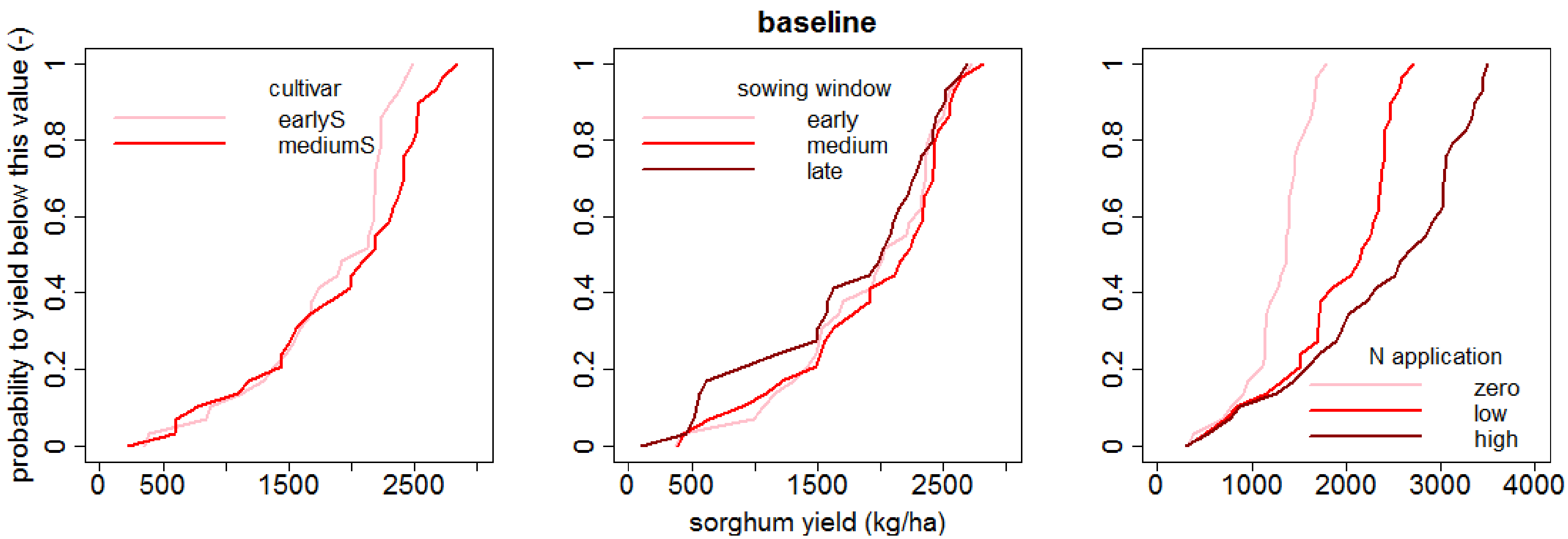
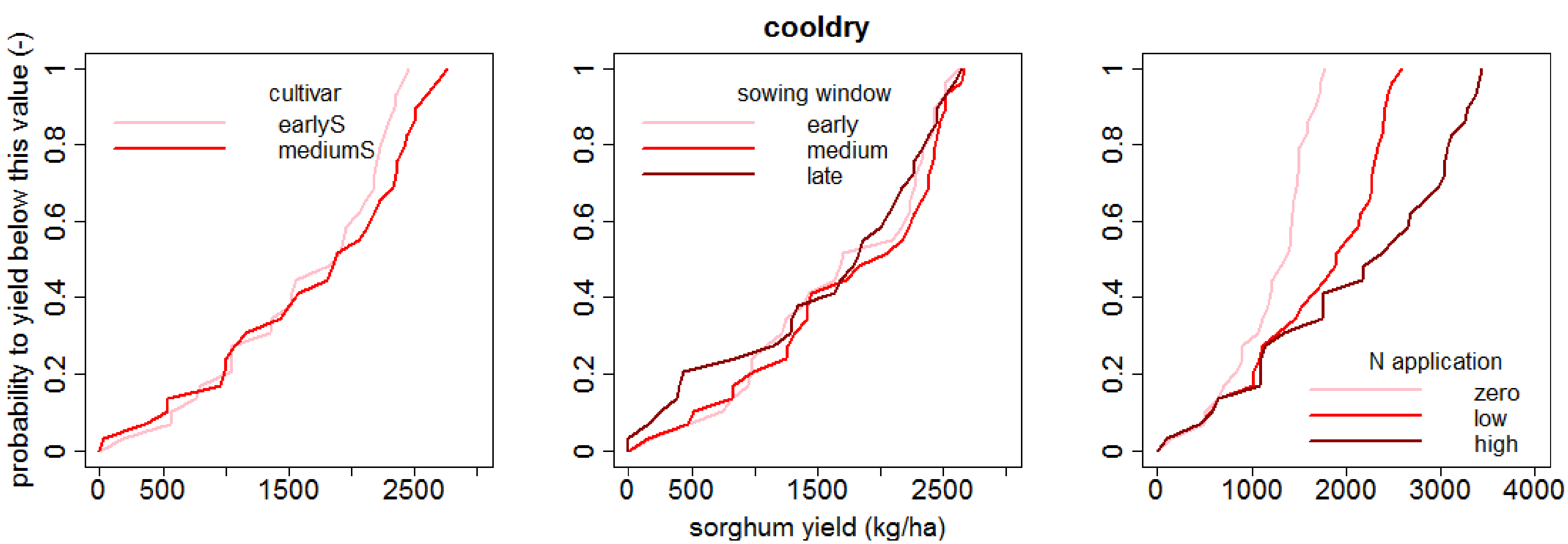


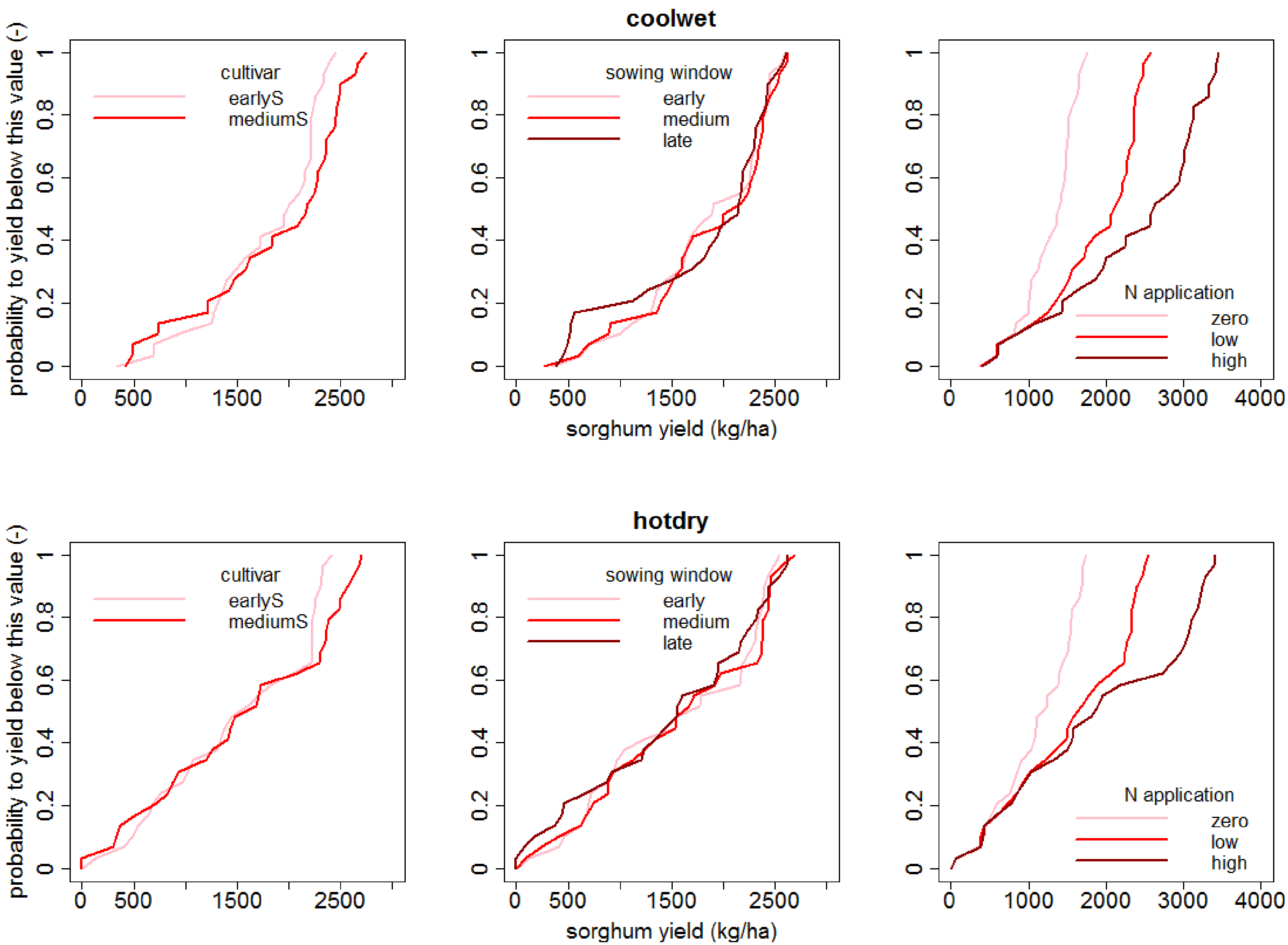
Figure 24: Probability plots of maize yields under all levels of the three different management options, for all climate scenarios. Yields compared between levels of one management options were averaged across all levels of the other management options.



baseline
probability to yield below this value (-)
cultivar
earlyS
mediumS
sowing window
early
medium
late
N application
zero
low
high
sorghum yield (kg/ha)



cooldry
probability to yield below this value (-)
cultivar
earlyS
mediumS
sowing window
early
medium
late
N application
zero
low
high
sorghum yield (kg/ha)


coolwet
probability to yield below this value (-)
cultivar
earlyS
mediumS
sowing window
early
medium
late
N application
zero
low
high
sorghum yield (kg/ha)
hotdry
probability to yield below this value (-)
cultivar
earlyS
mediumS
sowing window
early
medium
late
N application
zero
low
high
sorghum yield (kg/ha)

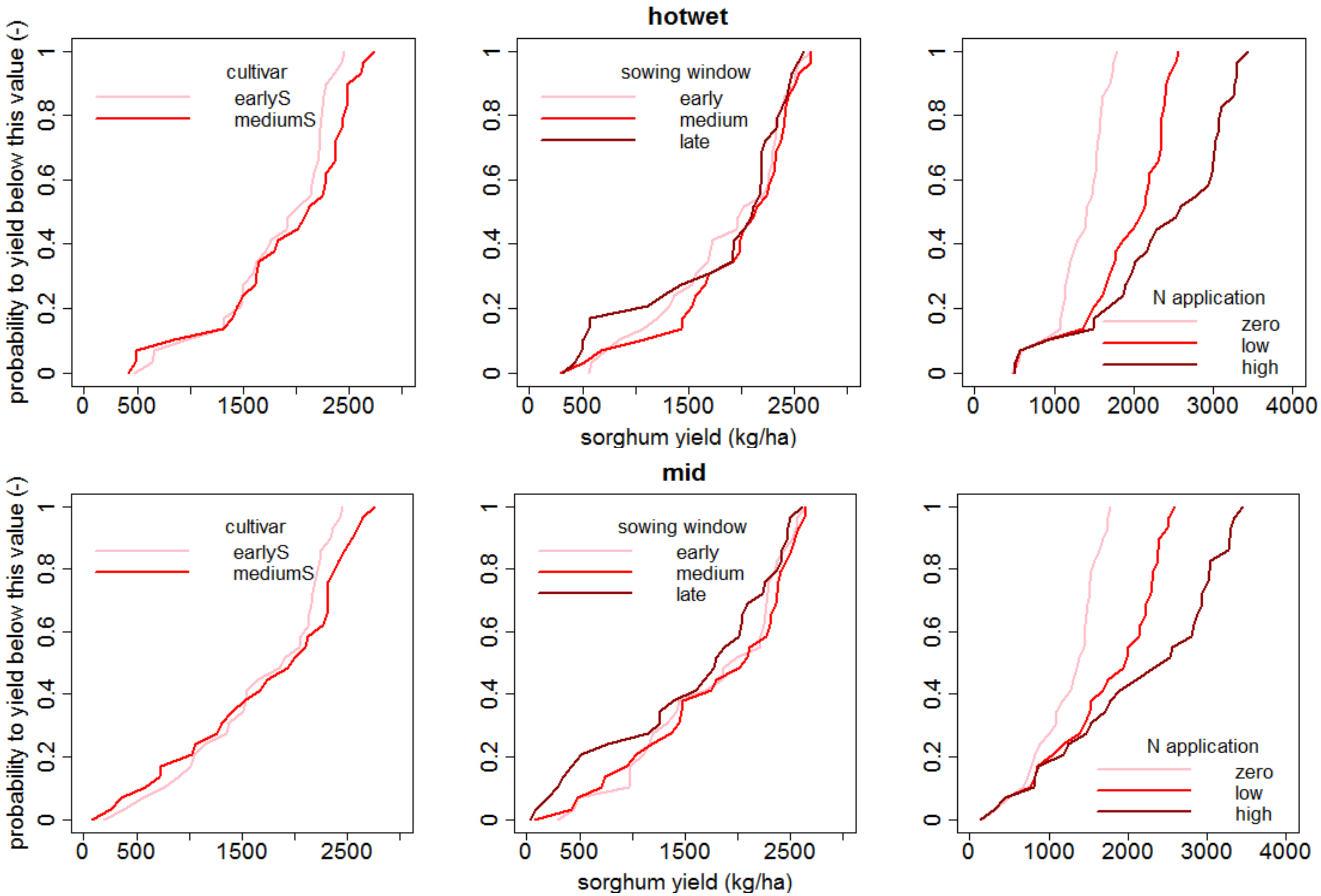


Figure 25: Probability plots of sorghum yields under all levels of the three different management options, for all climate scenarios. Yields compared between levels of one management options were averaged across all levels of the other management options.

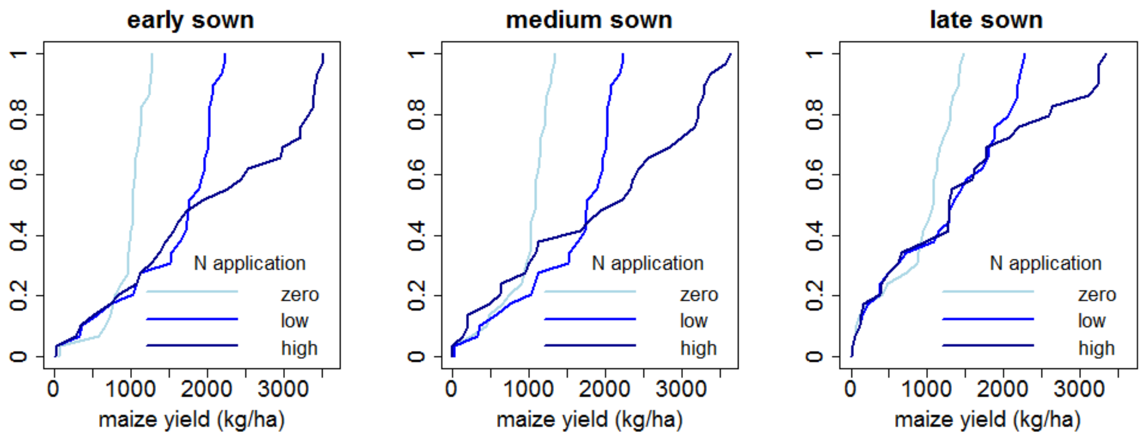


Figure 26: Probability plot of maize yield in the baseline climate scenario, for different levels of N application and sown in different windows, averaged across all cultivars.

12.4 ADITTIONAL FIGURES AND TABLES

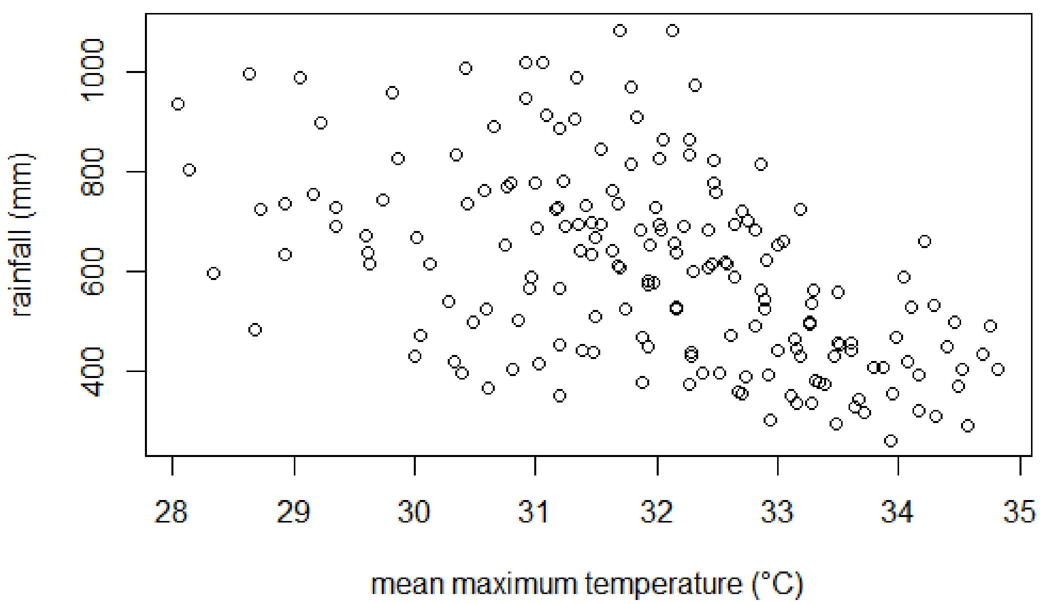


Figure 27: Mean maximum temperature in the rainy season plotted against the rainy season rainfall.

Table 13: The average time to maturity for maize and sorghum across all management strategies, for the different climate scenarios.

Crop	*time to maturity (days)*					
	baseline	**future cool/dry**	**future cool/wet**	**future hot/dry**	**future hot/wet**	**future middle**
maize	118	126	114	121	115	122
sorghum	109	116	104	110	101	108

Table 14: The average maximum temperature during the whole growing period and during the 20 days after sowing for early, medium and late sown maize.

sowing window	*average maximum temperature during growing period of maize*	*average maximum temperature during 20 days after sowing*
	°C	°C
early	30.1	32.3
medium	29.6	30.4
late	29.3	29.6

Table 15: The average biomass of maize crops that yielded below 750 kg ha^{-1}, for the three levels of N application.

N application	*maize biomass*
	kg ha^{-1}
zero	2226
low	2528
high	2582