RESPONDING TO CLIMATE CHANGE IN MOZAMBIQUE

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MINISTRY OF STATE ADMINISTRATION
NATIONAL INSTITUTE OF DISASTER MANAGEMENT

Instituto Nacional de
Gestão de Calamidades

National Institute for Disaster Management (INGC)
PHASE II

THEME 6

Agriculture

THEME 6

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EXECUTIVE SUMMARY

Most of the Mozambican agriculture is practiced in a totally non-irrigated regime depending on rains and soil humidity (non-irrigated agriculture). Climate change has resulted in increased temperatures, change in the rain standards and increased concentrations of carbon dioxide (CO_2) and of ozone (O_3) on the earth's surface. This study is intended to quantify the impacts of these changes on the agricultural productivity all over the national territory and focusing on six main crops (cotton, groundnuts, cassava, sorghum and soy).

In this regard, the impacts of the changes on rain and temperature standards in the crop water balance and its potential yielding for six crops were first studied. The individual effects of temperature change, of concentration of carbon dioxide (CO_2) and of ozone (O_3) on the potential yielding of crops were also studied.

In order to simulate climate change, seven general templates of circulation of atmosphere (GCMs), which resulted in daily temperature data (maximum and minimum), as well as the 1961 – 2000 rainfall (calibration) and that of the 2046 - 2065 period (projection) were used for 47 seasons within and around Mozambique. It is based on these data that the study on climate change impacts (past from 1961 to 2000 versus future from 2046 to 2065) was conducted on the six crops at stake.

CliCrop, which estimates the yields based on soil humidity daily diary, was the template used for studying the impacts of the changes of rain and temperature standards on the non-irrigated agricultural yields for six crops (cotton, groundnuts, cassava, sorghum, maize and soy). Climate change effects on yields differ from crop to crop, maize being the most affected crop with an average projected reduction in the country of 11.1%, followed by soy with a projected reduction of 6.4%, then groundnuts with a reduction of 4.6%, cassava with 4.2%, sorghum with 3.5% and cotton as the least affected crop in the order of 2.9% of the current yields. The yielding reduction is split into different geographic zones of crop yielding reduction starting as a cluster in the western zone of Tete province in relation with cotton crop, growing towards the coastal and southern area, with the most affected crops being sorghum, groundnut, cassava and soy, finally followed by maize as the most affected crop covering a larger area in Mozambique. The crop yields may reduce up to 30% of the current production in the most affected areas such is the case of maize in some areas of Tete province.

The increased daily temperature results in positive impact for cassava yielding and it is expected that there will be an increase in the order of 6.0%, and negative effects for the remaining crops, cotton, groundnut, sorghum and soy, with a decrease of 11.0%.

The increased concentrations of CO_2 results in a positive impact on all crops, with a projected increase of 27.0% for cotton, 20% for soy, 10% for groundnut and cassava, 7% for crops such as maize and sorghum.

The increased concentration of O_3 results in a negative impact on all crops, with an expected reduction do 37.0% for cotton, 28% for soy, 14% for groundnut and cassava and 9% for crops such as maize and sorghum.

Table A summarises the expected impacts for the 2046 - 2065 period arising from climate change on the different crops and different factors. The increased concentration of ozone (O_3) is the factor with more negative impact, followed temperature increase. The increased concentration of carbon dioxide (CO_2) results in a positive impact, but it is unable to counter balance the negative effects of the others.

Table A: Climate change effect (rain, temperature, CO_2 and O_3 changes) on crop yielding in the 2046 – 2065 period.

Crop	Rain and temperature	Temperatura	CO_2	O_3	Total
Cotton	- 2.9 %	- 11.0 %	+ 27.0 %	- 37.0 %	- 23.9 %
Groundnut	- 4.6 %	- 11.0 %	+ 10.0 %	- 14.0 %	- 19.6 %
Cassava	- 4.2 %	+ 6.0 %	+ 10.0 %	- 14.0 %	- 2.2 %
Sorghum	- 3.5%	- 11.0 %	+ 7.0 %	- 9.0 %	- 16.5 %
Maize	- 11.1 %	- 11.0 %	+ 7.0 %	- 9.0 %	- 24.1 %
Soy	- 6.4%	- 11.0 %	+ 20.0 %	- 28.0 %	- 25.4 %
Average	- 5.5%	- 8.2 %	+ 13.5 %	- 18.5 %	- 18.6 %

The effects presented arise from average estimates taken all over the country. However, there are variations from region to region. As stated earlier, the effects vary from region to region and, in case of maize in the region surrounding Tete, such effects may reach a total decrease in the order of 45.0 %. These effects may be exacerbated by increased occurrence and intensity of disasters (droughts, floods, cyclones and uncontrolled bushfire, which result in total loss of the production in the affected zones.

The Agrarian Sector Development Strategy (PEDSA 2011-2020) aims to double the goals of annual crop yielding of 7% by 2020. In order to attain these goals, considering the climate change impacts, it is necessary refer to an increased crop yielding of 2,5 times. Although there are already some adaptation measures that can be implemented, still there is a need to develop a specific agenda of agriculture aimed at dealing with climate change.

Possible measures of adaptation to climate change include, among others:

- Irrigation, rain water catchment and conservation techniques;
- Change of the sowing seasons in order to avoid increased concentration of O_3;
- Bacilli inoculation a soil fertility management to increase the tolerance to increased O_3;
- Avoid bushfire (NO_2) changing to cold bushfire in order to avoid increased emissions of NO2 and the consequent production of ozone (O_3);
- Genetic improvement for production of material that is tolerant to increased concentrations of ozone.

CONTENTS

Figures & Tables

PART 1

AGRICULTURE

Impacts of Climate Change on the Agricultural Productivity in Mozambique

Part 1: Rui Brito

Part 1. Agriculture. Impacts of Climate Change on the Agricultural Productivity in Mozambique

INTRODUCTION

The study of the National Institute for Disaster Management (INGC) on the Impact of Climate Change on Disaster Risk in Mozambique is a very deliberate and meticulous study that assesses and quantifies current vulnerability to extreme climate events (flooding, cyclones, and sea-level rise). Vulnerability is then assessed against seven potential future climate scenarios in an attempt to fully capture the full variability of potential impacts and risks associated with climate change.

Most of the food-crop agriculture in Mozambique is dry-land or rainfed agriculture meaning that it is completely reliant on precipitation and resonant soil moisture to satisfy the crop water demand. In times of droughts, precipitation is infrequent and soil moisture is low thus increasing the water stress during crop growth and severely reducing crop yield. Very high temperatures can also effectively decrease crop yields independent of water availability meaning that if drought conditions coincide with abnormally high temperatures, crop losses are very likely. A substantial drought in Mozambique occurring between 1981 and 1985 affected more than 16 million people and is credited with killing more than 100 000 due to substantial water stress on drinking water sources and subsistence agriculture. Current trends in Global climate suggest that drought frequency, drought length, and average temperatures are all increasing.

WORK DONE IN PHASE I OF INGC STUDY

The INGC study during phase I examines Mozambique's crop yield vulnerability by directly modeling crop yield percentages and their sensitivity to climate variability. The current and potential scenarios on land utilization types suitability classification has been assessed with a dynamic and automated land evaluation system (ALES), which operates on the basis of a decision-tree model for each land utilization type, matching its eco-physiological and socio-economic requirements, with the relevant land and environment attributes, i.e. soil, terrain and climate characteristics and qualities.

Such system results in the simulation of crop yields/performance under different levels of management, where observed yields are associated with prevailing small holder traditional low input farming systems, and potential yields corresponding to limitation free highly managed commercial crop production systems.

The selected crops for the study included cassava, maize, soybean, sorghum, cotton and groundnut, giving a combination of different crops grown mostly under rainfed conditions, and representing different crop types that react different to changes in temperature and rainfall patterns. These selected crops where used to produce the suitability maps under current conditions, and the suitability maps under climate change for three different general circulation models (IPSL, ECHAM, and GFDL) under the SRES A2 emission scenario.

Each of the maps resulting from the climate change (ECHAM, IPSL and GFDL) were then compared to the current conditions and classified into five different classes:

- *Significant Reduction in Risk*, equivalent to a change to a better suitability class in two levels;
- *Slight reduction risk*, equivalent to a change to a better suitability class in one level;
- *No Significant Change*, equivalent to no change in the suitability class;
- *Slight Increase Risk*, equivalent to a change to a worst suitability class in one level, and
- *Significant Increase in Risk*, which is equivalent to a change to a worst suitability class in two levels.

Figure 10 to *Figure* 13 show the result for the three different models (ECHAM, IPSL and GFDL), and the average change resulting from all three models.

Figure 1: Land suitability changes for maize under climate for IPSL model (INGC, 2009)/.....

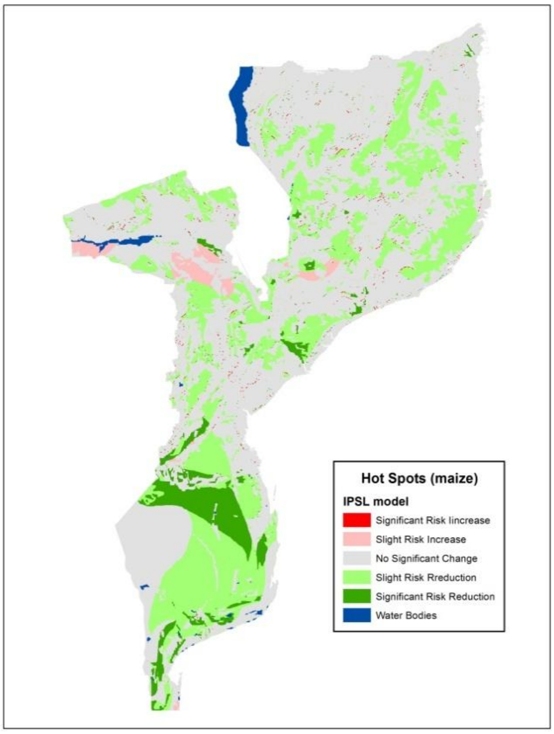

Figure 1: Land suitability changes for maize under climate for IPSL model (INGC, 2009).

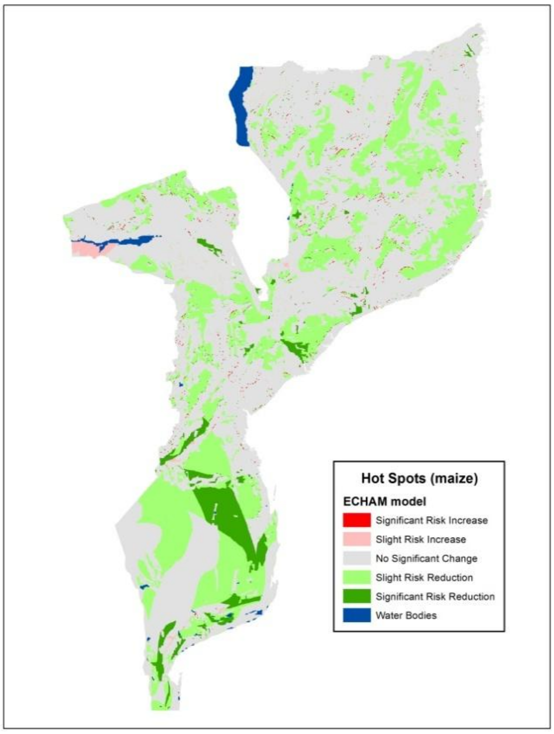

Figure 2: Land suitability changes for maize under climate change for ECHAM (MPI) model (INGC, 2009).

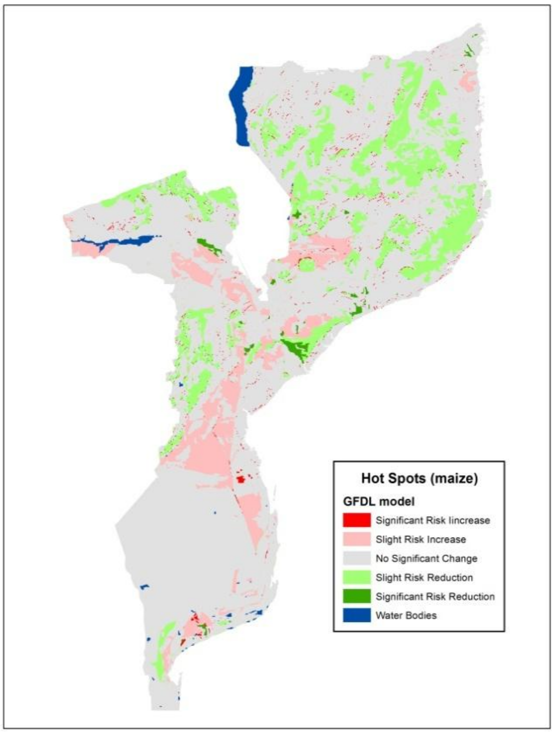

Figure 3: Land suitability changes for maize under climate change for GFDL model (INGC, 2009).

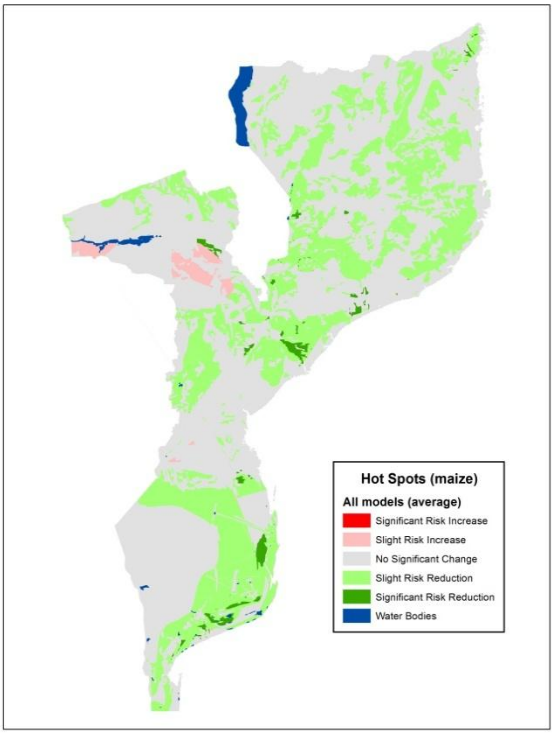

Figure 4: Average land suitability changes for maize under climate change for all three models (INGC, 2009).

It was based on these maps and associated changes that the climate change impacts were discussed and analyzed during the first phase of the study.

Conclusions from the analysis are very insightful and provide a detailed look into what areas of Mozambique are at significant risk for a reduction in suitable cropland. However, the analysis may be dramatically underestimating the risk. The model uses a simple water balance based on monthly average values for the rainfall and temperature, and neglects the effects of daily balances and excess and deficit of water in the system during shorter periods. Excess water in the form of "ponding" and soil saturation and deficit of water during short dry spells can reduce crop yields and stunts its growth. In order to account to daily values of the rainfall and for the negative effects of excess water and deficit of water during shorter periods, a new crop model must be used that can balance soil water status in a daily basis.

MODELLING CROP YIELDS

In September of 2009 a team of consultants from the World Bank arrived in Maputo to begin the study for Mozambique on the "Economics of the Adaptation to Climate Change" (EACC). The study focuses on attaching an economic cost/benefit to Mozambique for predicted climate change until 2050. A significant part of this study is the agriculture component as Mozambique's economy is strongly based on agriculture production and the quality of agricultural production is strongly correlated with climatic conditions at the time of agriculture production. Therefore, adequately predicting changes in agriculture production as a result of climate change is one of the most important factors of the EACC and is one that the National Institute for Disaster Management (INGC) had already done significant work on as a part of their report the "Study on the Impact of Climate Change on Disaster Risk in Mozambique: Main Report".

At the time of the World Bank team's arrival the INGC study was starting its second phase. Previously, the INGC report had only examined the vulnerability of Mozambique's cropland to climate change by examining cropland "suitability" under current and potential future climate change conditions. The second phase of the study proposed to attribute quantifiable results (i.e. actual crop yields) to these changes in land suitability which happened to be one of the goals of the EACC study, leading to the collaborative effort between INGC and the World Bank.

The EACC study proposed to use a crop model called CliCrop, which is a generic crop model used to calculate the effect of changing daily precipitation patterns on crop yields and irrigation water demand. The model was developed in response to available crop models that only use monthly average rainfall and temperature to produce crop outputs. These monthly models do not capture the effects of daily changes in precipitation patterns, which might greatly impact crop production. For example, most of the General Circulation Models (GCM) accepted by the International Panel for Climate Change (IPCC) predicts that total annual precipitation will decrease in Africa, but extreme precipitation events will increase in frequency. CliCrop is built to account for these extreme events specifically because it models at a daily time-step. Extreme precipitation events can be very detrimental to crop production as too much water at one time can actually "suffocate" a crop and inhibit crop growth. Therefore, CliCrop takes into account the phenomenon of "water logging" which describes the period of time when the ground in an area of crop production is completely saturated with water. At this time, crop growth is stunted or even stopped which in effect lengthens the growing season and can reduce overall yields if the phenomenon persists.

CliCrop model is used to examine future agricultural performance with past production under an array of potential climate futures, for an array of crops and soil types. To do this CliCrop model is run using climatic inputs from the same seven General Circulation Models (GCMs) as the first phase of the INGC study with both past (1961 to 2000) and future (2046 to 2065) daily data, 30 soil profiles characteristic to Mozambique, 47 locations in and around Mozambique, and six crops, cassava, cotton, groundnuts, maize, sorghum and soybean. This results in almost 20 000, spatially dependent, 20 year simulations per crop and a robust look at future crop yield potential.

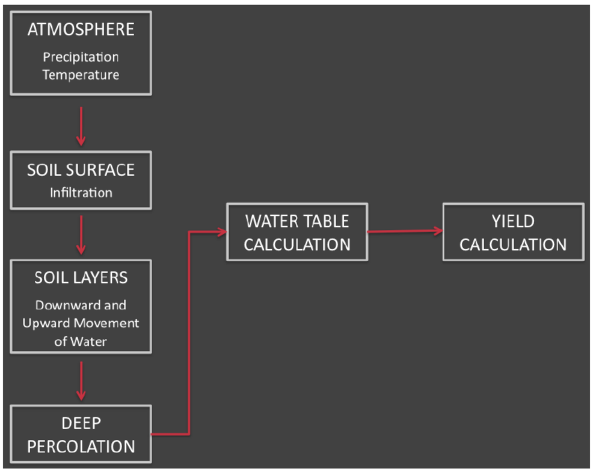

Figure 5: Flow diagram of the procedures followed by CliCrop.

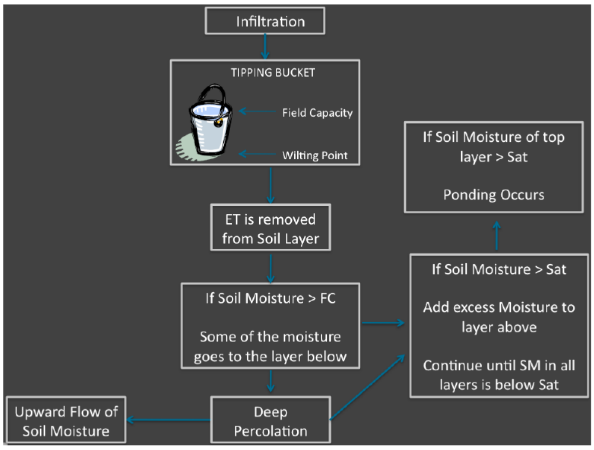

Figure 6: Schematic of the soil moisture process used by CliCrop

Basically CliCrop models the effects of the atmosphere indirectly in the soil layer through the extraction of ET and the infiltration into the soil layers (Figure 5). Then the model uses the soil properties and precipitation amount to calculate the infiltration using the USDA Curve Number method, and it computes the soil moisture in each soil layer. It then calculates the amount of moisture allowed percolating into the deep soil layers, the water table is then measured and a crop yield is calculated based on the daily soil water conditions at the root zone (Figure 6). For more detailed information on CliCrop model, please refer to the M.Sc. thesis (Fant, 2008).

MODEL INPUTS

Data inputs for the CliCrop model are more demanding than that for the previous phase of the study. Meteorological data (precipitation, minimum and maximum temperatures) is provided at a daily basis instead of the monthly to account for the daily water balance. Table 1 shows the list of required inputs for the CliCrop model.

Table 1 : Required inputs for the model CliCrop

Inputs	Unit
Daily Precipitation	mm/dia
Daily Maximum Temperature	°C/dia
Daily Minimum Temperature	°C/dia
Clay/Sand Fraction	%
Soil Layers/Stratification	mm
Crop Coefficients (K_c)	Factor (1)
Crop Stage Duration	Days (2)
Yield Coefficients	Factor (3)

We used daily precipitations and daily maximum and minimum temperatures for 47 meteorological stations from which 27 are in Mozambique (Figure 7). This study used the 27 stations inside of the country that were used in the first INGC report, with an additional of 20 more stations in neighboring countries, to get better estimations in neighboring areas away from the coast where there are no stations.

Daily weather data is used to better represent the crop-soil-climate interaction. The model used during the first phase of the study relied on monthly values to represent the characteristic growing season, failing to recognize the importance of individual precipitation events. It is not unlikely that one intense precipitation event can account for most of a month's average precipitation leaving the remainder of the month relatively dry and not optimal for crop growth. A monthly average will not take this into account and may characterize a month as unusually good for crop growth where as it may very well have been the opposite.

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(1) These are constants used to derive the potential evapotranspiration for a particular crop. Each crop has three coefficients specific to a crop growing stage. They are derived by FAO and used directly in the model.

(2) This is the length in days of the four stages of crop growth. Like the crop coefficients, these too are derived by FAO and used directly in the model.

(3) This is used to weight the effects of water losses on the yield for each of the four stages of growth. Like the crop coefficients and crop stage durations, these are derived by FAO.

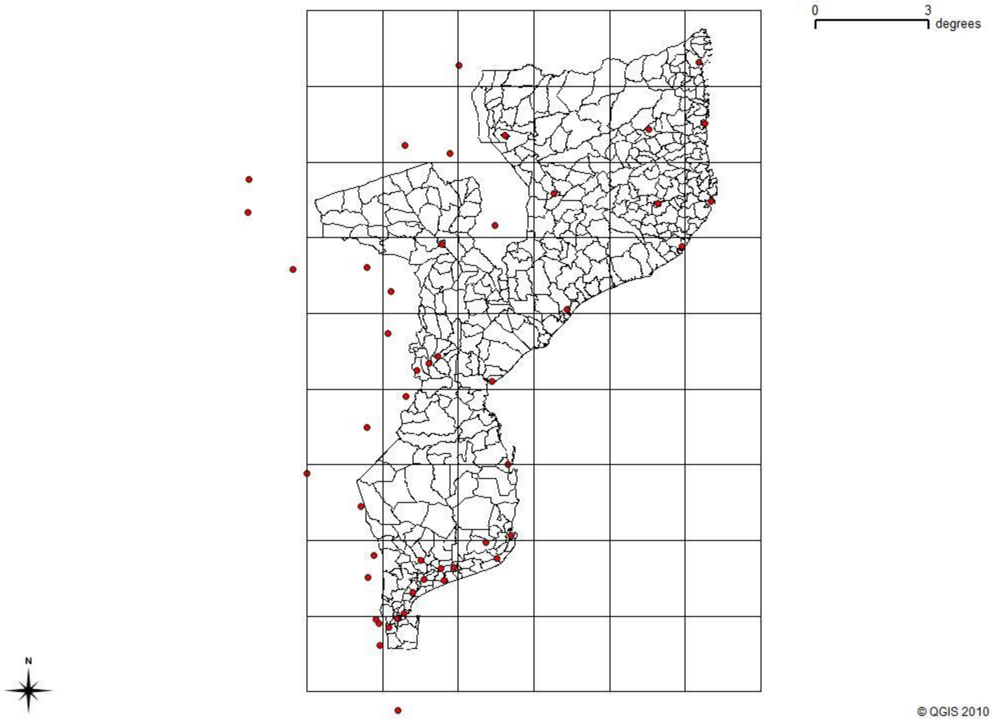


Figure 7: Location of the 47 meteorological stations used in this study.

CliCrop was run for 30 different soil types that were used to try to capture heterogeneous soil conditions throughout Mozambique. Soil permeability is an important part of the CliCrop water balance as it will govern when and how long soil will remain water-logged. The soil layers/stratification describes the vertical heterogeneity of the soil profile, delineating sections of soil with different clay/sand fractions.

The 30 soil types used in this report can be grouped in four Major Land Systems distinguished at the first classification level within the INIA/DTA (1995) National Soil Map a scale of 1:1 000 000, namely:

(i) Alluvial and fluvial-marine zones: it refers to all zones with deposits at the surface resulting from the river action or combined action from river and sea (estuaries), thus including those laid down in river channels, floodplains, estuaries, local depressions temporally inundated, alluvial fans at the foot of mountain slopes. The most representative soil types are the clayey alluvial soils (code FG) and the coarser or medium textured stratified alluvial soils (code FS).

(ii) The main limitations for agricultural use are drainage, sometimes salinity and sodicity and risk of flooding (soil units FG and FS).
    - Sedimentary basin: it refers to the basin of sedimentary rocks and metamorphosed sedimentary rocks and other zones with aeolian deposits, like the coastal and inland dunes. In this zone and based on their parent material of origin six subgroups are distinguished:
    - inland dune and aeolian sandy deposits represented by the whitish sandy soils (code AB); the yellowish colored sandy soils (code AA) and the orange colored sandy soils (code AJ);
    - red "Grés" and red sands of late Tertiary origin (code G);
    - mananga (within 100 cm; often covered by sandy aeolian deposits), mananga in situ (code MA, MM); colluviums of mananga (code MC);
    - soils derived from the post-mananga deposits occupying colluvial slopes along valleys (codes PA, PM);

- platforms of rolled gravel (within 100 cm depth) of the mananga base – originated soils (code SC);
- weathering material from sedimentary rocks of Karroo, Cretaceous or Tertiary origin developed soil types like (codes WV, WP, WM and WK).

The main limitations for agricultural use are low water and nutrient retention (soil units AB, AA, AJ, G, MA, MM); soil hardness and permeability, sodicity and sometimes salinity (soil units MM, MC); salinity, sodicity, drainage and inundations (soil unit MC).

(iii) Volcanic rock zones: it refers to the areas in Mozambique where volcanic rocks (rhyolite and basalt) are encountered at or near the surface and form the parent rock. Six dominant phases occur in this zone but only four soil types are the most important in terms of agricultural use namely:

- reddish colored soils derived from “in situ” weathered rock (code RV);
- reddish colored soils derived from “in situ” weathered basaltic rock (code BV);
- black soils derived from “in situ and deposition” weathered basaltic rock (code BP);
- colluvial soils derived from weathered basaltic rocks (code BC).

The main limitations for agricultural use are soil erosion (slopes) soil depth (< 100cm) soil unit RV; sometimes soil depth (BV); sodicity, sometimes soil depth, land preparation (BP); soil depth, sometimes salinity and sodicity, drainage (BC).

(iv) Pre-Cambrian socle zone: referring to the zones where rocks of Pre-Cambrian origin are at or near the surface from which the main soil types are derived. The Pre-Cambrian socle term sometimes also is indicated as crystalline socle or African surface. The main soil types are subdivided in nine units being the texture the major diagnostic criteria for their differentiation and these soil units are:

- colluvial soils type of fine texture (code CG); colluvial soils type of medium texture (code CM); colluvial soils type of coarse texture (code CA);
- red and fine textured soils developed “in situ” - weathered rock (code VG); red and medium textured soils developed “in situ” – weathered rock (code VM); and those of coarser texture (code VA).
- brown and fine textured soils developed “in situ” – weathered rock (code KG); brown and medium textured soils developed “in situ” – weathered rock (code KM); and those of coarser texture (code KA).

The main limitations for agricultural use are drainage (CG, CM); drainage and fertility (CA); germination conditions, erosion risk (VG, VM, KG, KM); water retention capacity and fertility (VA, KA).

The crop coefficients (Table 3 and Table 4), crop-stage durations (Table 2), yield coefficients (Table 6) and rooting depth (Table 5) are empirical variables describing the growth cycles and other characteristics of each crop in relation to evapotranspiration and yields. They are used based on the FAO’s database (FAO Irrigation and Drainage Paper No. 56 Crop Evapotranspiration, Allen, *et al*. 1998).

Table 2 : Lengths of crop development stages (days) for six crops (Allen et al. 1998).

Crop	Initial	Development	Mid	Late	Total
Cassava	150	40	110	60	360
Cotton	30	50	60	55	195
Groundnut	35	35	35	35	140
Maize	30	50	60	40	180
Sorghum	20	35	45	30	140
Soybean	20	30	60	25	140

Table 3 : Single crop coefficients (Kc) and mean maximum plant heights for six crops (Allen et al. 1998).

Crop	Kc ini	Kc mid	Kc end	crop height (m)
Cassava	0.30	1.10	0.50	1.5
Cotton	0.35	1.15 to 1.20	0.50 to 0.70	1.2 to 1.5
Groundnut	0.40	1.15	0.60	0.40
Maize	0.30	1.20	0.60	2.0
Sorghum	0.30	1.00 to 1.10	0.55	1.0 to 2.0
Soybean	0.40	1.15	0.50	0.5 to 1.0

Table 4 : Basal crop coefficients (Kcb) for six crops (Allen et al. 1998).

Crop	Kcb ini	Kcb mid	Kcb end
Cassava	0.15	1.00	0.45
Cotton	0.15	1.10 to 1.15	0.40 to 0.50
Groundnut	0.15	1.10	0.50
Maize	0.15	1.15	0.50
Sorghum	0.15	0.95 to 1.05	0.35
Soybean	0.15	1.10	0.30

Table 5 : Maximum effective rooting depth and soil water depletion factor for six crops (Allen et al. 1998).

Crop	Maximum Root Depth	Depletion fraction
Cassava	0.70 to 1.00	0.40
Cotton	1.00 to 1.70	0.65
Groundnut	0.50 to 1.00	0.50
Maize	1.00 to 1.70	0.55
Sorghum	1.00 to 2.00	0.55
Soybean	0.60 to 1.30	0.50

Table 6 : Coeficientes de rendimento para seis culturas. (CropWat 4.3)

Crop	Ky ini	Ky dev	Ky mid	Ky late	Ky
Cassava	0.40	0.60	0.80	0.60	0.80
Cotton	0.40	0.40	0.50	0.40	0.85
Groundnut	0.40	0.60	0.80	0.40	0.70
Maize	0.40	0.40	1.30	0.50	1.25
Sorghum	0.20	0.40	0.55	0.20	0.90
Soybean	0.40	0.80	1.00	0.40	0.85

MODEL OUTPUTS

CliCrop model is capable of producing a suite of outputs applicable to agricultural production and agriculture water management. Table 7 shows all of the outputs from the CliCrop model and their units. Special attention should be paid to the potential that the drainage and water deficit outputs might add to the study. With these, it may be gathered how efficiently water is being, or will be, used for crop production, thus adding a water resource dimension to the study.

Table 7 : CliCrop list of Outputs.

OUTPUT	UNIT
Crop Yield	fraction
Drainage	mm
Water Deficit	mm
Length of the Growing Season	days
Planting Date	day of the year (1 to 365)
Potential Evapotranspiration (PET)	mm
Actual Evapotranspiration (ET)	mm
Precipitation	mm

Crop yield is presented as a fraction of the maximum possible unit production. A yield fraction of 1.00 means that perfect growing conditions existed and 100% of the planted unit area produced to its maximum potential. A value of 0.0 means none of the planted unit of area produced any harvestable crop. Figure 17 gives the average crop yields (fraction) computed by CliCrop for maize under rainfed agriculture in Mozambique for the period going from 1961 to 2000 (past). According to the map, predicted yields for maize under rainfed agriculture, ranges from a maximum more than 0.9 (> 90 %) in the northern part of the country where rainfall is good, to a minimum of less than 0.1 (<10 %) in the arid and semi-arid regions of the country. For comparison it is also presented the agro-climatic yield potential for maize under low input conditions based on the report Assessment of Land Resources for Rainfed Crop Production in Mozambique (FAO/UNDP, 1982a) which was produced based on a more detailed information (climate stations). From both pictures it can be seen that they show the same general pattern with some differences in certain locations. The IIAM map is based on a denser network of 108 stations inside of Mozambique and also based on height, and several other factors which were not included in CliCrop. CliCrop is based on 43 stations from which only 27 are inside of Mozambique. So some attention has to be used when interpreting the maps from this study specially when scaling down results to specific locations. The results are comparable in the southern and northern parts of the country, with certain differences in the center of the country where the relief is more heterogeneous in shorter distances.

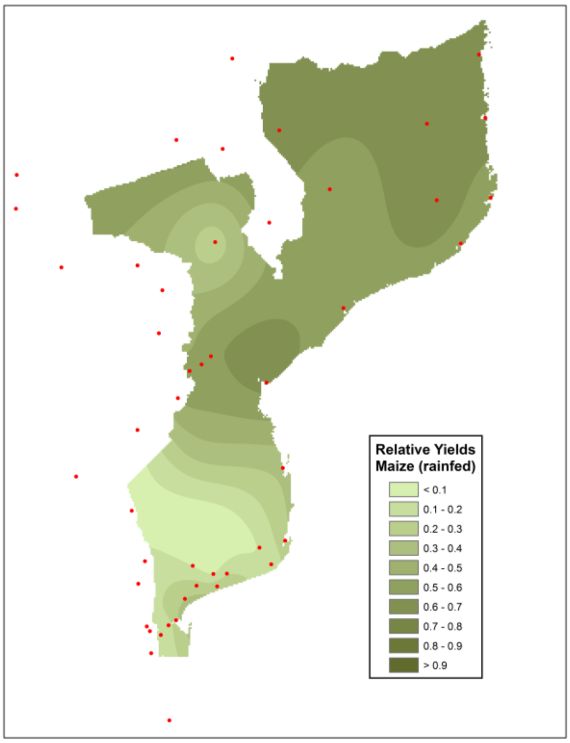


Figure 8: CLICROP average relative yields for maize during 1961 to 2000.

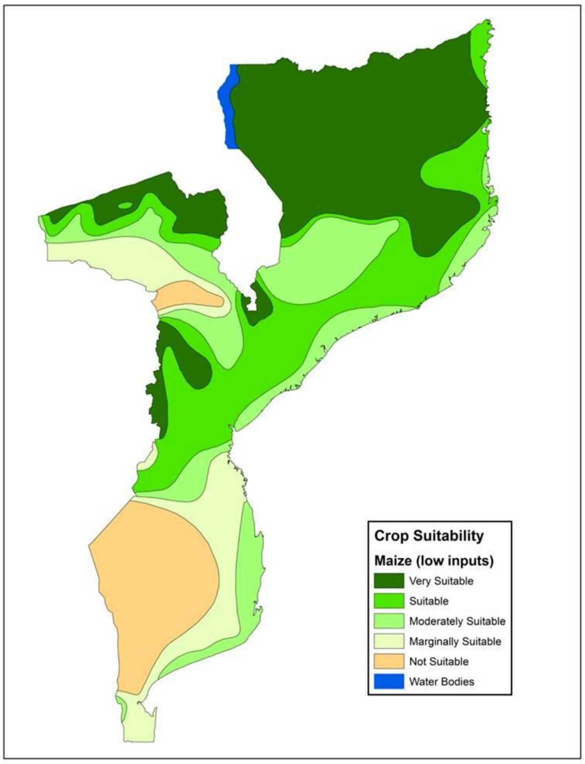


Figure 9: Agro-climatic suitability for maize (low input) (adapted from FAO/UNDP, 1982 b)

Drainage is the amount of water that has percolated the root zone joining the groundwater, expressed in mm per unit area. Water deficit is the water that the crop lacks for optimal growing conditions. It too is expressed in mm. By simultaneously looking at drainage and water deficit it is possible to examine the efficiency with which water is used for agriculture production.

The length of the growing season is the number of days with which a crop takes to complete the growing cycle. Planting Date is the day on which the crop is planted ranging from 1 to 365 or 366 in leap years. In the CliCrop simulation runs, the planting date is decided based on rainfall accumulation during the start of the rainy season that starts during October. If there is an accumulated rain during tow consecutives days of 25 mm or more, CliCrop assumes that farmers planted their crops. Day one equals January 1st and day 365/366 equals December 31st.

Potential Evapotranspiration (PET) represents the maximum amount of water in mm that the crop may transpire into the atmosphere on any given day. This too, can be used to examine the efficiency of water use.

MODELING CLIMATE CHANGE IMPACTS

CliCrop is used to produce a suite of results geared towards analyzing the quality of annual agricultural yields governed by potential climate futures and compare them to predicted yields from past climate. The study uses the seven General Circulation Models (GCMs) listed in Table 8 to predict daily time series for rainfall, and maximum and minimum temperatures. The GCMs are used to predict twenty years of future climate from 2046 through 2065 based on the past climate from 1961 through 2000 (INGC, 2009).

Table 8: General Circulation Models (GCMs) used to produce climate data (INGC, 2009).

Originating Group(s)	Country	I.D.	Name used in this report
Canadian Centre for Climate Modeling & Analysis	Canada	CCCMA3.1(T63)	CCCMA
Météo-France/Centre National de Recherches Météorologiques	França	CNRM-CM3	CNRM
CSIRO Atmospheric Research	Australia	CSIRO-Mk3.0	CSIRO
Max Planck Institute for Meteorology	Germany	ECHAM5/MPI-OM	MPI
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA	GFDL-CM2.1	GFDL
NASA / Goddard Institute for Space Studies	USA	GISS-ER	GISS
Institute Pierre Simon Laplace	France	IPSL-CM4	IPSL

Table 9 to Table 14 present for six cassava, cotton, groundnut, maize, sorghum and soybean, the potential yields (ton/ha) expected for Mozambique for different levels of inputs and different agro-climatic conditions (FAO/UNDP, 1982b). There are five suitability classes: very suitable, suitable, moderately suitable, marginally suitable and not suitable. The values presented in the tables are based on the agro-climatic suitability methods recommended by FAO. Rainfed agriculture practiced by the majority of farmers in Mozambique, referred as class “Low” in the table, show the lowest yields resulting from minimum agriculture inputs (no fertilizers) and based only on the rainfall. These yields are the potential yields for a specific crop under local climatic conditions (mainly temperatures in its relation to evapotranspiration, and rainfall), limited by low inputs. It is based on these values that this study projects actual yields in ton/ha for each of the six crops. The other classes (medium and high) could also be used but the scope of the study is rainfed agriculture for small scale farmers.

Table 9: Potential yields for Cassava in Mozambique for three different levels of inputs.

Suitability Class	Level of inputs and fractions to the maximum potential yields					
	High		Medium		Low	
	ton/ha	fraction	ton/ha	fraction	ton/ha	fraction
Very Suitable	> 25.0	1.00	> 13.8	1.00	> 7.5	1.00
Suitable	18.5 - 25.0	0.74 - 1.00	10.2 - 13.8	0.73 - 1.00	5.6 - 7.5	0.75 - 1.00
Moderately suit	14.0 - 18.5	0.56 - 0.74	7.7 - 10.2	0.55 - 0.73	4.2 - 5.6	0.56 - 0.75
Marginally suit	8.5 - 14.0	0.34 - 0.56	4.7 - 7.7	0.34 - 0.55	2.6 - 4.2	0.34 - 0.56
Not suitable	< 8.5	< 0.34	< 4.7	< 0.34	< 2.6	< 0.34

Table 10: Potential yields for Cotton in Mozambique for three different levels of inputs.

Suitability Class	Level of inputs and fractions to the maximum potential yields					
	High		Medium		Low	
	ton/ha	fraction	ton/ha	fraction	ton/ha	fraction
Very suitable	> 1.8	1.00	> 1.00	1.00	> 0.5	1.00
Suitable	1.5 - 1.8	0.83 - 1.00	0.8 - 1.00	0.80 - 1.00	0.4 - 0.5	0.80 - 1.00
Moderately suit.	1.2 - 1.5	0.66 - 0.83	0.6 - 0.8	0.60 - 0.80	0.3 - 0.4	0.60 - 0.80
Marginally suit.	0.7 - 1.2	0.38 - 0.66	0.4 - 0.6	0.40 - 0.60	0.2 - 0.3	0.40 - 0.60
Not suitable	< 0.7	< 0.38	< 0.4	< 0.40	< 0.2	< 0.40

Table 11: Potential yields for Groundnut in Mozambique for three different levels of inputs.

Suitability Class	Level of inputs and maximum potential yields					
	High		Medium		Low	
	ton/ha	fraction	ton/ha	fraction	ton/ha	fraction
Very suitable	> 2.5	1.00	> 1.4	1.00	> 0.8	1.00
Suitable	2.0 - 2.5	0.80 - 1.00	1.1 - 1.4	0.78 - 1.00	0.6 - 0.8	0.75 - 1.00
Moderately suit.	1.6 - 2.0	0.64 - 0.80	0.9 - 1.1	0.64 - 0.78	0.5 - 0.6	0.62 - 0.75
Marginally suit.	1.0 - 1.6	0.40 - 0.64	0.6 - 0.9	0.42 - 0.64	0.3 - 0.5	0.37 - 0.62
Not suitable	< 1.0	< 0.40	< 0.6	< 0.42	< 0.3	<0.37

Table 12: Potential yields for Maize in Mozambique for three different levels of inputs.

Suitability Class	Level of inputs and maximum potential yields					
	High		Medium		Low	
	ton/ha	fraction	ton/ha	fraction	ton/ha	fraction
Very suitable	> 4.5	1.00	> 2.9	1.00	> 2.0	1.00
Suitable	4.2 - 4.5	0.93 - 1.00	2.7 - 2.9	0.93 - 1.00	1.6 - 2.0	0.80 - 1.00
Moderately suit.	2.9 - 4.2	0.64 - 0.93	1.9 - 2.7	0.65 - 0.93	1.3 - 1.6	0.65 - 0.80
Marginally suit.	1.9 - 2.9	0.42 - 0.64	1.2 - 1.9	0.41 - 0.65	0.9 - 1.3	0.45 - 0.65
Not suitable	< 1.9	< 0.42	< 1.2	< 0.41	< 0.9	< 0.45

Table 13: Potential yields for Sorghum in Mozambique for three different levels of inputs.

Suitability Class	Level of inputs and maximum potential yields					
	High		Medium		Low	
	ton/ha	fraction	ton/ha	fraction	ton/ha	fraction
Very suitable	> 3.0	1.00	> 2.0	1.00	> 1.4	1.00
Suitable	2.5 - 3.0	0.83 - 1.00	1.6 - 2.0	0.80 - 1.00	1.1 - 1.4	0.78 - 1.00
Moderately suit.	1.9 - 2.5	0.63 - 0.83	1.2 - 1.6	0.60 - 0.80	0.9 - 1.1	0.64 - 0.78
Marginally suit.	1.2 - 1.9	0.40 - 0.63	0.8 - 1.2	0.40 - 0.60	0.5 - 0.9	0.35 - 0.64
Not suitable	< 1.2	< 0.40	< 0.8	< 0.40	< 0.5	< 0.35

Table 14: Potential yields for Soybean in Mozambique for three different levels of inputs.

Suitability Class	Level of inputs and maximum potential yields					
	High		Medium		Low	
	ton/ha	fraction	ton/ha	fraction	ton/ha	fraction
Very suitable	**> 2.0**	**1.00**	**> 1.7**	**1.00**	**> 1.5**	**1.00**
Suitable	1.7 - 2.0	0.85 - 1.00	1.4 - 1.7	0.82 - 1.00	1.2 - 1.5	0.80 - 1.00
Moderately suit.	1.4 - 1.7	0.70 - 0.85	1.1 - 1.4	0.64 - 0.82	1.0 - 1.2	0.66 - 0.80
Marginally suit.	0.8 - 1.4	0.40 - 0.70	0.7 - 1.1	0.41 - 0.64	0.6 - 1.0	0.40 - 0.66
Not suitable	< 0.8	< 0.40	< 0.7	< 0.41	< 0.6	< 0.40

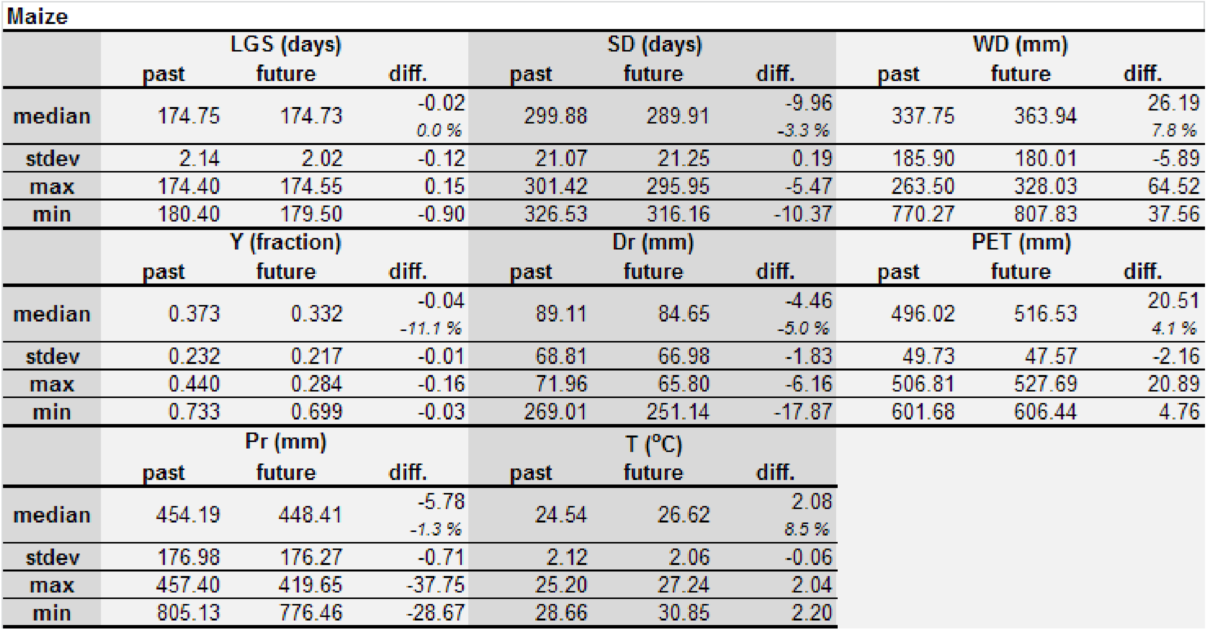
CliCrop looks at the specific case of water stress (excess or deficit) which is dependent on the rainfall and temperature but also on the specificities of the soils (in particular the hydraulic conductivity, water retention characteristics of the different soil layers, and soil depth). It means that yields can vary for a specific location from a maximum to a minimum value depending on the soil characteristics under study. The values presented and discussed in this report are based on the results for the best soils used to run CliCrop simulations. It means that the soil is not a limiting factor in terms of hydraulic or other physical properties like root depth. The study used this option to make the analysis of impacts of climate change simpler with fewer factors, avoiding the inclusion of an extra factor (soil types) that would mask the impacts and would complicate the analysis. So this report speaks only about effects of the changes in temperatures and rainfall on projected yields for the best soils in Mozambique.

IMPACTS OF CLIMATE CHANGE IN MAIZE

To study the impact of climate change in rainfed agriculture and reduce the number of variables under analysis the study only used the results from the best soils. Using all soils would mask the effects of changing rainfall and temperatures, making it difficult to pinpoint the causes of changes in the yields.

Table 15 gives the outputs from CliCrop for maize for the past (1961 to 2000) and for the future (2046 to 2065). These are the median values of all the seven GCM models, all the 47 stations, and the best soils. The variables presented are the Length of the Growing Season (LGS) in calendar days, the Sowing Date (SD) in calendar days, the Water Deficit during the growing period (WD) in mm, the Yields (Y) expressed as a fraction, the Drainage during the growing period (Dr) in mm, the Potential Evapotranspiration during the growing period (PET) in mm, the Precipitation during the growing period (Pr) in mm, and the average daily Temperature during the growing period (T) in ^{o}C. It also shows the differences in relation to the past expressed in the same units, and for the specific case of the median, we also show in brackets the difference expressed as a percentage. The same tables are presented in annex I for all the six crops (cassava, cotton, groundnut, maize, sorghum and soybean).

Table 15: Mozambique maize average values from CliCrop for the seven GCMs and 47 meteorological stations soils.



Maize									
	LGS (days)			SD (days)			WD (mm)		
	past	future	diff.	past	future	diff.	past	future	diff.
median	174.75	174.73	-0.02 *0.0 %*	299.88	289.91	-9.96 *-3.3 %*	337.75	363.94	26.19 *7.8 %*
stdev	2.14	2.02	-0.12	21.07	21.25	0.19	185.90	180.01	-5.89
max	174.40	174.55	0.15	301.42	295.95	-5.47	263.50	328.03	64.52
min	180.40	179.50	-0.90	326.53	316.16	-10.37	770.27	807.83	37.56
	Y (fraction)			Dr (mm)			PET (mm)		
	past	future	diff.	past	future	diff.	past	future	diff.
median	0.373	0.332	-0.04 *-11.1 %*	89.11	84.65	-4.46 *-5.0 %*	496.02	516.53	20.51 *4.1 %*
stdev	0.232	0.217	-0.01	68.81	66.98	-1.83	49.73	47.57	-2.16
max	0.440	0.284	-0.16	71.96	65.80	-6.16	506.81	527.69	20.89
min	0.733	0.699	-0.03	269.01	251.14	-17.87	601.68	606.44	4.76
	Pr (mm)			T (ºC)					
	past	future	diff.	past	future	diff.			
median	454.19	448.41	-5.78 *-1.3 %*	24.54	26.62	2.08 *8.5 %*			
stdev	176.98	176.27	-0.71	2.12	2.06	-0.06			
max	457.40	419.65	-37.75	25.20	27.24	2.04			
min	805.13	776.46	-28.67	28.66	30.85	2.20			

From the results (median of seven GCMs and 47 stations) it is expected in the future the yields for maize under rainfed production to decrease in 11.1 % overall, and the average temperature to increase in 2.1 oC (8.5% increase) during the growing season.
The results also show for maize to expect in the future (2046 to 2065):

- an overall increase of 26.2 mm in water deficit during the growing period (7.8 % increase);
- an overall decrease of 4.5 mm in drainage during the growing period (5.0 % decrease);
- an overall increase of 20.5 mm in potential evapotranspiration during the growing period (4.1 % increase);
- an overall decrease of 10.0 days in the sowing dates (3.3% decrease) meaning that planting dates will happen later, and
- no significant changes in the precipitation during the growing period (overall decrease of 5.8 mm in precipitation corresponding to 1.3 % decrease).

It is clear that final crop water balance in the future will be negative as a result of increasing evaporative demands associated to increasing temperatures, and no significant changes in the overall precipitation during the growing period.

The effectiveness of rainfall for agricultural can be inferred from the results, and it becomes apparent that it is expected in the future a decrease of effective rainfall for agricultural, resulting from the combination of an increase in rainfall intensity (heavier rains), and a decrease in the number of rainy days. Another outcome is the decrease in drainage water that will join the groundwater (5.0 % decrease) affecting this important water resource that replenishes river flows during the dry season.

The values presented are the result of an arithmetic computation (median) based on the results for the 47 locations and seven GCMs, and they do not represent an average value for the country, which should be based not only on location, but also linked to production areas and the geographical distribution associated to the soils. Nevertheless, the results show an overall tendency of 11.1 % decrease in the potential yields of maize under rainfed production in the country as a result of climate change (temperature in relation to evapotranspiration, and rainfall).

Figure 10 presents the expected changes in future temperatures (2046-2065). It gives the change of the median of all 7 GCMs for the average daily temperatures (oC) during the maize growing period. Along the coast expected changes are on the order of +1.9 oC and in the high interior near Zimbabwe can reach values up to +2.4 oC, showing the effect of the sea in attenuating temperatures. To have an idea on differences among the different GCM models, figure gives the distribution of temperature changes for all models and for the extremes. The line in blue is the distribution of the median of all models in the past for the temperature, the line in green gives the same values in the future. The two green lines with dots give the extremes of the 7 GCMs (highest and lowest increase) in the future. It is clear that all models predict an increase in average temperatures.

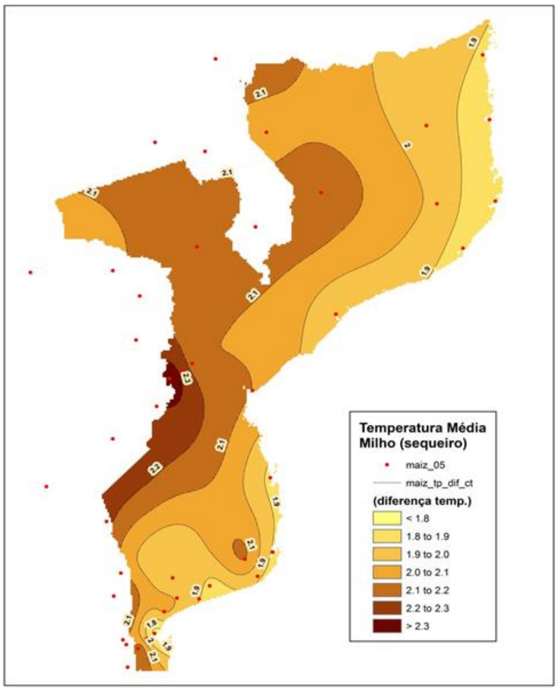


Figure 10: Expected changes in the future (2046-2065) in the median of all 7 GCMs for the average daily temperatures during maize growing period, expressed in °C.

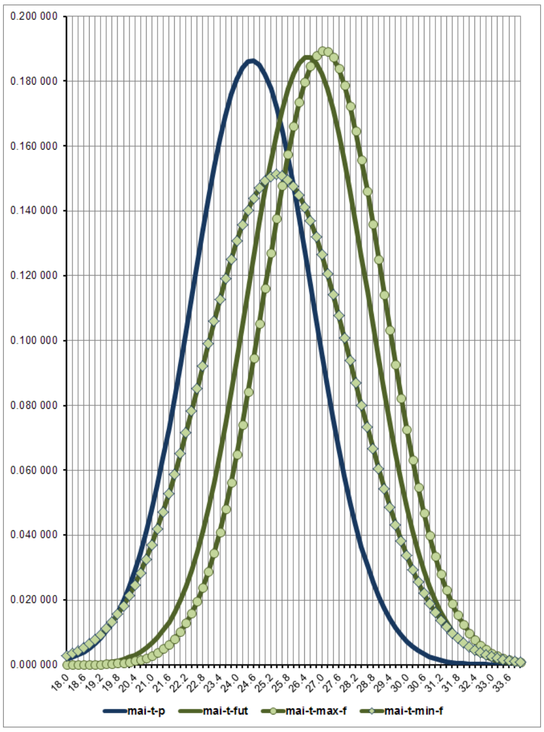


Figure 11: Changes in the distribution of overall temperatures in the country (past in blue, and future in green) based on all GCMs, and for the two extremes (smallest increase and largest increase in green with dots).

Depending on location (Figure 12), rainfall could increase in the future (2046-2065) up to 300 mm during the maize growing season in some central areas of Mozambique as well as some northern areas. It could decrease up to 300 mm in the northern interior of the country and up to 150 mm in some central areas of the country. We should be cautious with rainfall once this is the behavior of the median for all 7 models that show different tendencies.

The tendencies in rainfall changes can be contradictory as shown in Figure 13. The line in blue is the distribution of the median values of all models in the past for rainfall, the line in green gives the same values in the future. The two green lines with dots give the extremes of the 7 GCMs (largest increase and largest decrease in rainfall) in the future. It is clear that models show different predictions, some predict an increase in overall rainfall and some a decrease.

The lower extreme predicts a decrease during the growing period, from an average of 480 mm in the past to an average of 390 mm in the future (decrease of around 20%). The higher extreme predicts an increase during the growing period for maize, from an average of 480 mm in the past to an average of 630 mm in the future (increase of around 30%). The median of all the models is an insignificant decrease of around 20 mm. So some cautious should be used when discussing changes in rainfall where both extreme scenarios are possible.

These differences reflect our present knowledge and understanding of expected changes in rainfall in the region with different models giving different and even contradicting tendencies. If we look at the IPCC 4th report, our region is part of the area where rainfall changes are not yet well understood and modeled with different models not agreeing in the outcomes. Because of that it is difficult to establish recommendations based on average results from different models. In these cases the analysis and recommendations should be based on possible extreme outcomes coming from the different models and also the uncertainty linked to them.

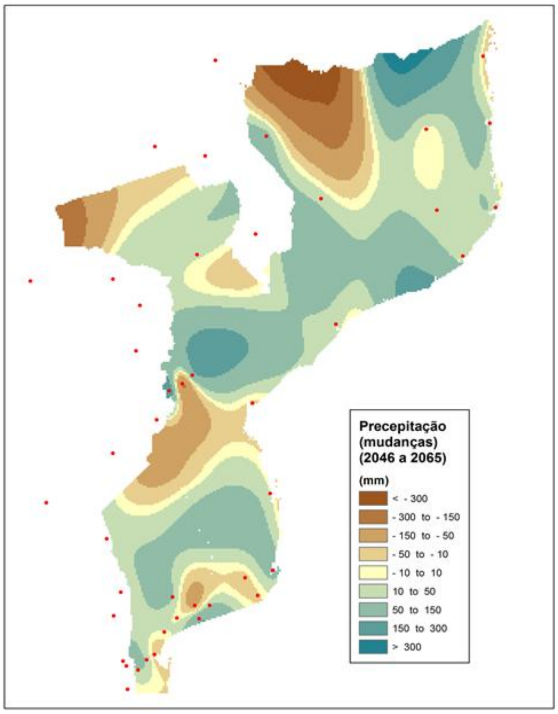


Figure 12: Expected changes in the future (2046-2065) in the median of all 7 GCMs for rainfall during maize growing period, expressed in rainfall mm.

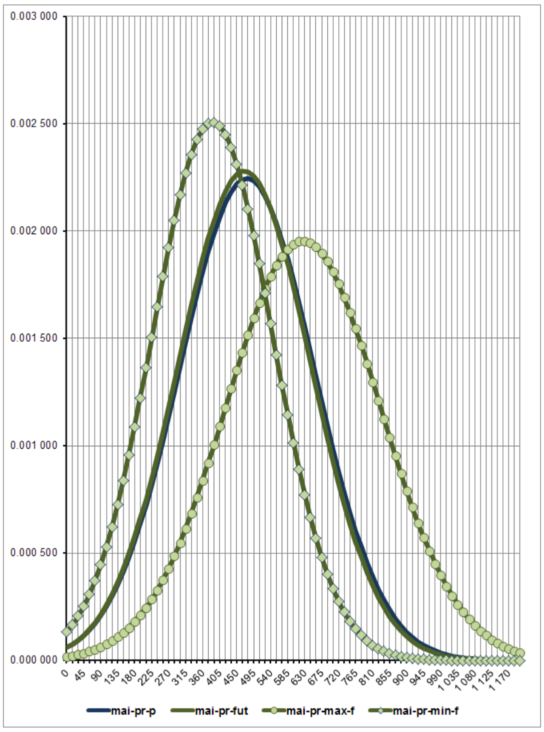


Figure 13: Changes in the distribution of overall average rainfall in the country (past in blue, and future in green) based on all GCMs, and for the two extremes (largest decrease and largest increase in green with dots).

The changes in crop yields for maize (% of present yields), resulting from changes in temperatures in relation to evapotranspiration and changes in rainfall are presented in Figure 13. Depending on location, crop yields under rainfed production could increase in the future (2046-2065) up to 25 % of present yields in a relatively small area in the south dry interior, or could decrease more than 25% in central areas of Mozambique along the Zambezi valley as well as in the coast around Inhambane and Vilankulo.

We should also be cautious with the results once the expected changes are based on the median of all 7 models. As with rainfall, the tendencies in crop yield can be, dependent on the model, contradictory as is shown in Figure 14. The line in blue is the distribution of the median values of all models in the past for maize yields, the line in green gives the expected median values in the future. The two green lines with dots give the extremes of the 7 GCMs (highest and lowest increase in crop yields) in the future.

It is clear that models show different predictions, some predict an increase in overall crop yield, and some a decrease. The lowest extreme predicts an average decrease of crop yields of around 33 %. The highest extreme predicts an average increase of around 35 %. The average result for all the models is a decrease of around 11% as presented previously (Table 15). So some cautious should be used when discussing changes in crop yields once extreme scenarios are possible with a strong uncertainty linked to the results.

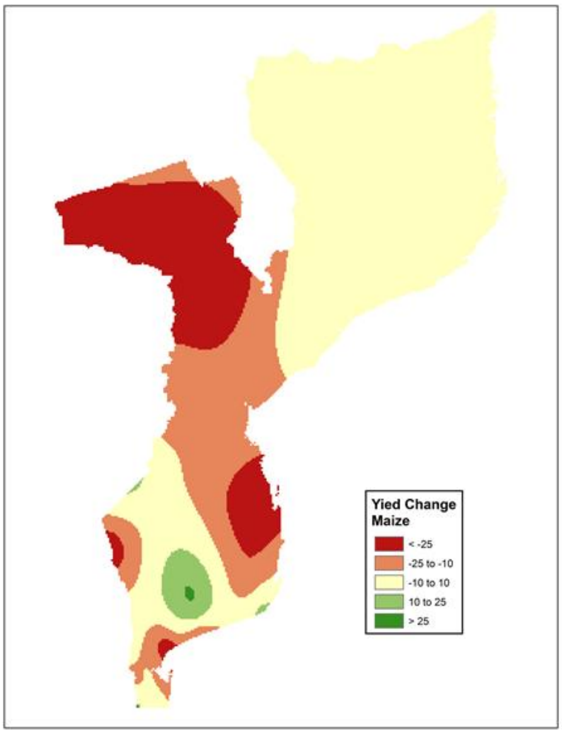


Figure 14: Expected changes in the future (2046-2065) for maize (median of all 7 GCMs), expressed in % of present yields.

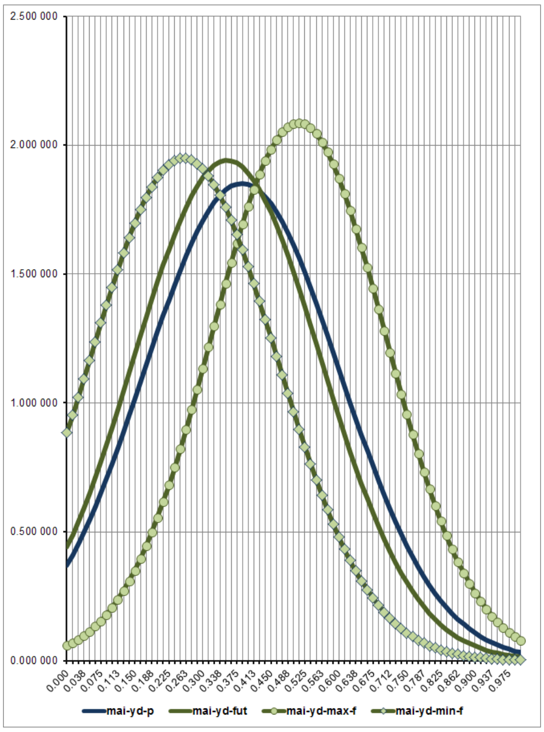


Figure 15: Changes in the distribution of the overall crop yields for maize in the country (past in blue, and future in green) based on all GCMs, and for the two extremes (largest decrease and largest increase in green with dots).

The results discussed here refer to all the seven GCMs. It is difficult to speak in an average expectation of all the models once they show different tendencies and one is not more probable then the other. We should look at the results of each individual model to get better insights on related to risks in the future. Figure 16 shows the ratios between expected future yields (2046 to 2065) and the past yields (1961-2000) for each of the models (cccma, cnrm, csiro, gfdl, giss, ipsl, and mpi), and for the same ratio of the median of all models (all).

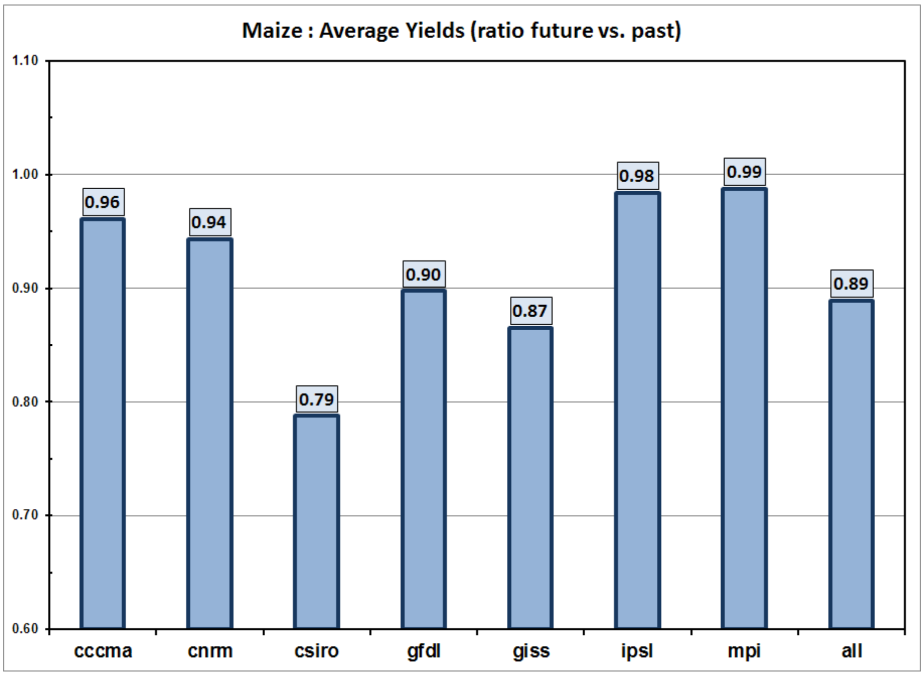


Figure 16: Ratio of average yields for each General Circulation Model (GCM).

All the models show ratios inferior to 1.0 meaning that future yields in maize are expected to decrease. The case of all models (all) shows a ratio of 0.89, equivalent to a decrease in 11.1 % as mentioned previously. Looking at each of the models, the mpi model (ratio of 0.99 equivalent to 1.2 % decrease) gives the least changes, close to ipsl (ratio of 0.98 equivalent to 1.6 % decrease), followed by cccma (ratio of 0.96 equivalent to 3.9 % decrease) and cnrm (ratio of 0.94 equivalent to 5.7 % decrease). Then gfdl (ratio of 0.90) giving an expected change on the order of 10.2 % decrease, the giss (ratio of 0.87) with an 13.5 % decrease and finally csiro (ratio of 0.79) giving the worst scenario with a decrease on the order of 21.3 %. The projected changes in present yields (in %), range from 1.2 % to 21.3 % decrease with the median value around 11.1 % yield decrease for maize.

If we want to express expected changes in terms of actual yields (in kg/ha), and not changes in relative to present yields, we can cross the information of expected changes in present yields (Figure 14) with the present potential yields (Table 12 and Figure 9). Crossing that information we get the expected changes for maize expressed in kg/ha as presented in Figure 17.

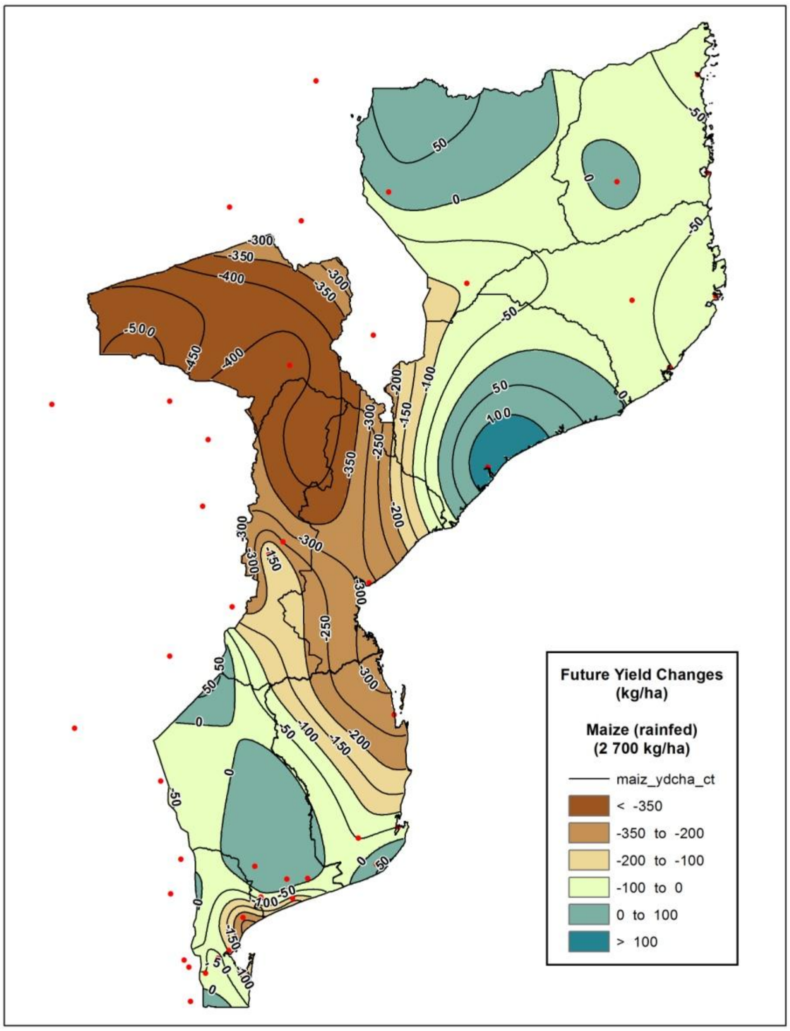


Figure 17: Expected changes in the future (2046-2065) for maize (expressed in kg/ha) under rainfed agriculture based on the median of all 7 GCMs.

According to the map (Figure 17) summarizing the impacts (expressed in kg/ha) of climate change in rainfed agriculture, it is expected a reduction of crop yields on the order of 350 kg/ha or larger for maize under rainfed production in the center part of the country along the Zambezi valley. This area stretches towards the Punguè and Buzi basins and part of the Save basin towards the coast of Inhambane with expected reduction on the order of 100 to 350 kg/ha. The area around Quelimane expects an increase up to 100 kg/ha, and in the northern interior, some parts of the southern interior and in the coast around Zavala, projects a light increase (0 to 50 Kg/ha) in crop yields. In the rest of the country it is expected light decreases in yields on the order of 0 to 50 kg/ha. Overall the country the projected reduction is on the order of 11.1 % of present yields.

The first phase of the INGC study carried out by IIAM used only three models, the echam model which we refer in this study as the mpi model, the ipsl model, and the gfdl model. The ratios for these models, as presented in Figure 16, are respectively 0.99, 0.98, and 0.90, missing the two lower extremes (giss and csiro) and including the two less sensitive models the mpi (echam) model and the ipsl model. Comparing their results with this study, the gfdl model projects yield decrease trends (Slight Risk Increase) along the Zambezi valley stretching towards the south similar to the trends presented in this study for maize under rainfed conditions.

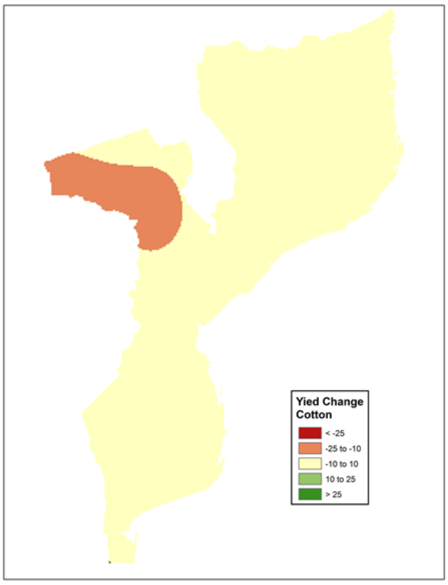
IMPACTS OF CLIMATE CHANGE IN OTHER CROPS

For the other crops, cassava, cotton, groundnut, sorghum and soybeans, this report presents only the final results. Table 16 summarizes the results for all six crops showing expected changes in the future for the average temperature and rainfall during the growing season, and respective crop yields. In terms of crop yields, maize is the most sensitive to climate change with yields decreasing on the order of 11.1 %, followed by soybeans with a projected decrease of 6.4 %, then groundnut with a decrease of 4.6 %, cassava with 4.2 %, sorghum with 3.5 % and then cotton the least affected crop with a projected decrease of 2.9 % of present yields.

Table 16: Projected changes for 2046 to 2065 in average temperatures (°C) during the crop growing season, crop yields (%) under rainfed conditions, and rainfall (mm) during the crop growing season for cassava, cotton, groundnut, maize, sorghum and soybeans.

Crop	Changes in Temperature			Changes in Yield			Changes in Rainfall		
	median (past)	change in future		median (past)	change in future		median (past)	change in future	
	°C	°C	%	mm	mm	%	mm	mm	%
Cassava	23.8	2.0	8.5	0.397	- 0.02	- 4.2	633.7	- 17.3	- 2.7
Cotton	24.1	2.1	8.5	0.517	- 0.02	- 2.9	610.0	- 20.0	- 3.3
Groundnut	24.5	2.1	8.5	0.599	- 0.03	- 4.6	487.9	- 5.1	- 1.1
Maize	24.5	2.1	8.5	0.373	- 0.04	- 11.1	454.2	- 5.8	- 1.3
Sorghum	24.6	2.1	8.5	0.572	- 0.02	- 3.5	438.9	- 3.9	- 0.9
Soybeans	24.6	2.1	8.4	0.217	- 0.03	- 6.4	377.4	- 4.5	- 1.2

The geographic distribution of the changes in crop yields under rainfed conditions are presented in Figure 18 to Figure 27, expressed either as relative changes of present potential yields in %, or changes in actual crop yields in kg/ha. Figure 18 and Figure 19 present the results for cotton, Figure 20 and Figure 21 for sorghum, Figure 22 and Figure 23 for groundnut, Figure 24 and Figure 25 for cassava, and Figure 26 and Figure 27 for soybeans.



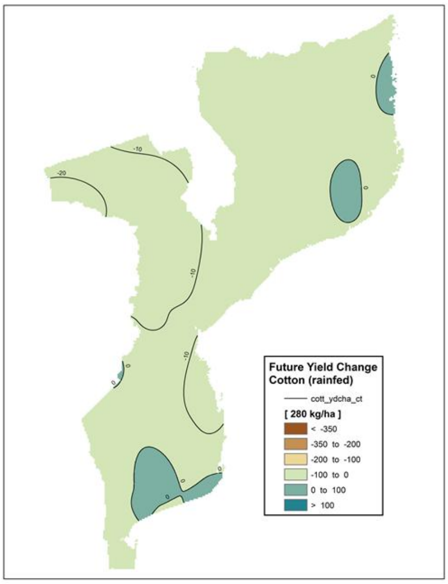
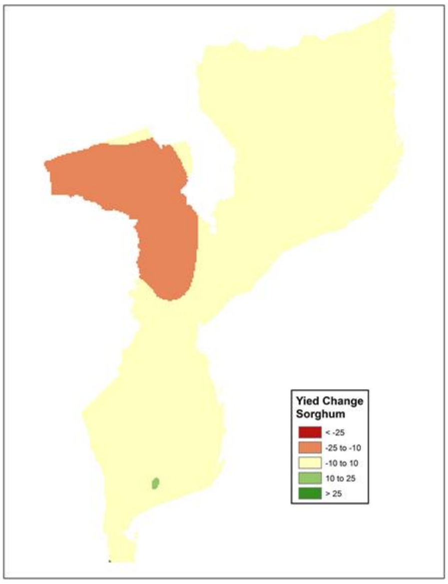


Figure 18: Projected changes in the future (2046-2065) for cotton (median of all 7 GCMs), expressed in % of present yields.

Figure 19: Projected changes in the future (2046-2065) for cotton (median of all 7 GCMs), expressed in kg/ha.



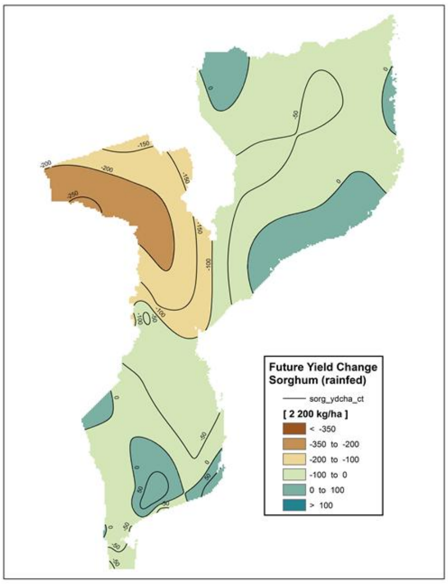
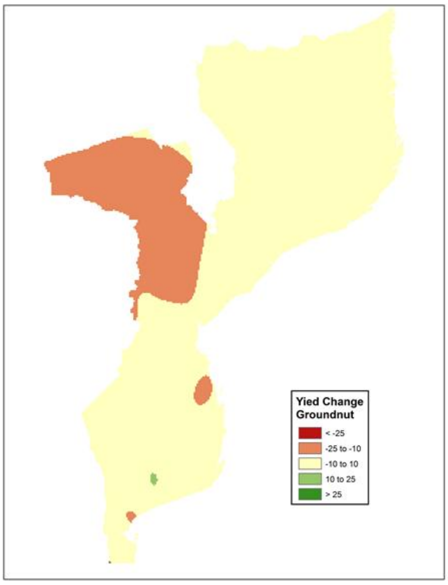


Figure 20: Projected changes in future (2046-2065) for sorghum (median of all 7 GCMs), expressed in % of present yields

Figure 21: Projected changes in the future (2046-2065) for sorghum (median of all 7 GCMs), expressed in kg/ha.



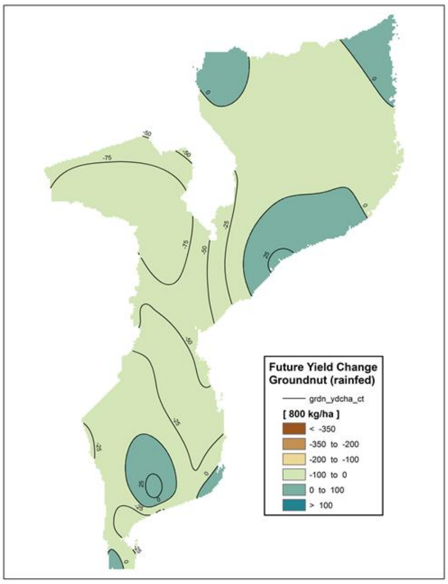
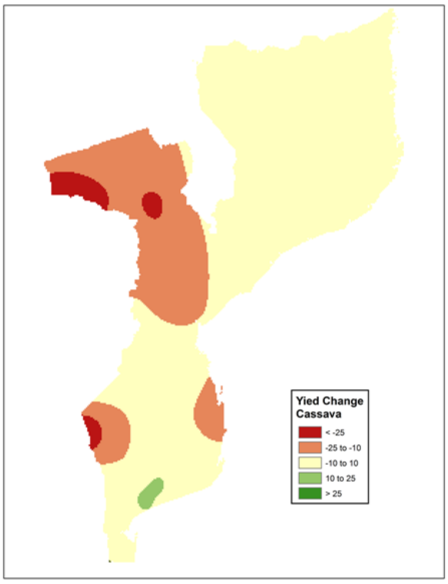


Figure 22: Projected changes in the future (2046-2065) for groundnut in % of present yields.

Figure 23: Projected changes in the future (2046-2065) for groundnut in kg/ha).



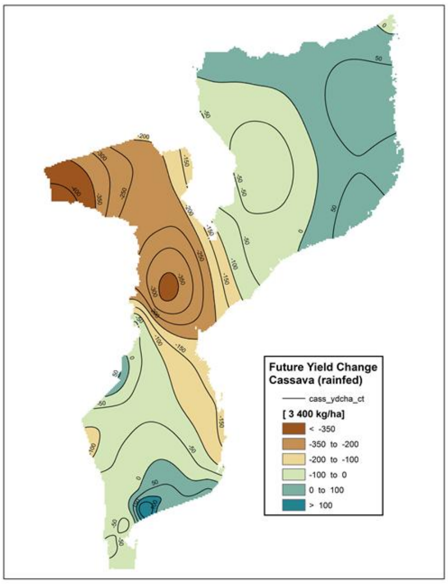


Figure 24: Projected changes in the future (2046-2065) for cassava in % of present yields.

Figure 25: Projected changes in the future (2046-2065) for cassava in kg/ha.

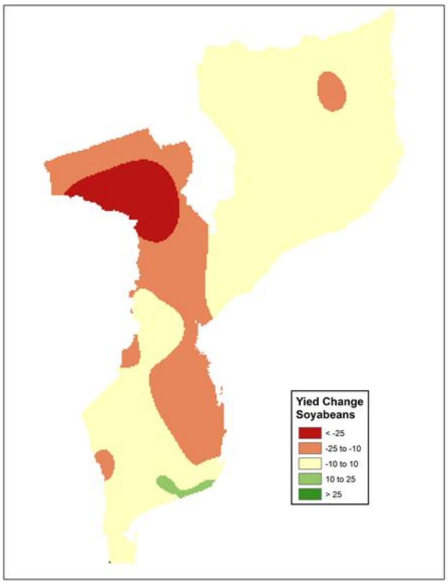


Figure 26: Projected changes in the future (2046-2065) of soybean yields in % of present yields.

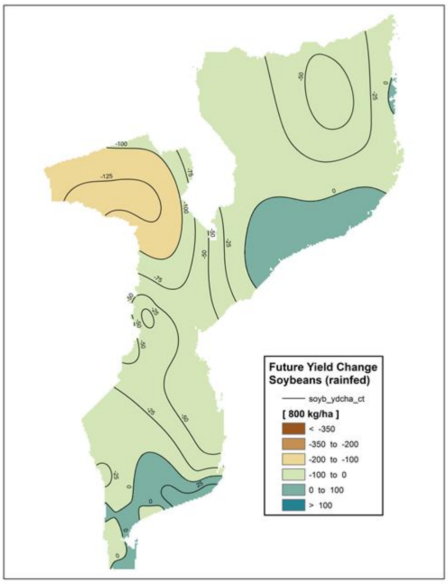


Figure 27: Projected changes in the future (2046-2065) for soybeans in kg/ha.

Looking at all the crops, the most sensitive crop to climate change (changes in temperatures in relation to evapotranspiration, and in rainfall), is maize, followed by soybeans, groundnut, cassava, sorghum, and then cotton as the least sensitive. If we look at the maps, the decrease in relative yields starts with a pocket in the west side of the province of Tete (cotton in Figure 18), then grows towards the coast and the south, sorghum in Figure 20, then groundnut in Figure 22, then cassava in Figure 24, then soybeans in Figure 26, and then maize as the most affected crop in Figure 14.

ADAPTATION TO CLIMATE CHANGE

Climate change is a global phenomenon resulting from the changes in the concentrations of greenhouse's gas in the atmosphere. These changes the energetic balance in the atmosphere changing temperatures and rainfall patterns. This study looks at changes based on the SRES A2 emission scenario.

There are two ways to deal with climate changes, one is trough mitigation which looks at practices to decrease the emission of greenhouse's gases, practices very relevant to the developed countries that have great responsibilities on emission of gases, and the other looking at adaptation to climate change that are more relevant to developing countries that are less responsible for greenhouse's gas emissions but are the ones that in most cases are more affected by climate change as is the case of Mozambique one of the least developed countries.

This study looks at possible impacts in agriculture crop yields (resulting from changes in rainfall and temperature in its relation to evapotranspiration) and looks at possible adaptation measures to deal with this situation.

The agricultural sector that is crucial to the development of Mozambique, sets in its strategic plan for 2011 to 2020, an average growth of 7% which will be achieved by doubling crop yields and increasing

25% the cultivated area for the most important crops, guaranteeing at the same time a sustainable use of the natural resources.

Besides the effect of changes in temperatures and rainfall, crop yields could decrease substantially across Mozambique due to increased frequency and intensity of natural disasters, in particular droughts affecting the semi-arid and arid regions of the country, floods affecting the rich valleys of the rivers where population density and economic activities are concentrated, and cyclones affecting the coastal zones of Mozambique where the majority of people leaves.

Freshwater resources, on which the viability of agriculture depends, are vulnerable and are strongly impacted by climate change, with present water management practices not sufficiently adapted to cope with these impacts (FAO, 2008a). As a consequence of these impacts, climate change is likely to aggravate food insecurity in Mozambique putting in risk the country's effort to reduce poverty. Under this perspective, adaptation measures are crucial to increase agricultural productivity and reduce the impacts of climate change.

Adaptation as defined by IPCC is an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. There are different types of adaptation including ***autonomous*** adaptation most practiced by people with livelihoods depending on agriculture and that have used this mechanisms to cope with climate variability, ***anticipatory*** adaptation that takes place before impacts of climate change occur that, together with technology innovation, attempts to improve resilience to future and uncertain impacts but implies trade-offs between optimization in current conditions and minimizing vulnerability to anticipated shocks, and ***planned*** adaptation that is the result of a deliberate policy decision taken based on the recognition that conditions have changed or are about to change and that action is required. (FAO, 2008b).

Adaptation to climate change requires making anticipatory adjustments to prepare for expected climate variability and changing average climate conditions, in order to moderate harm and exploit beneficial opportunities (IPCC, 2007). So in Mozambique we have to start to introduce adaptation measures at the community level to promote resilience and prepare for future challenges where climate change plays a major role.

The scope of this study is the effect of climate change on the water budget of the crops and its impact on crop yields. We have seen that temperature rises and changes in rainfall will decrease crop yields under rainfed production and will increase water consumption under irrigated condition making water management a crucial aspect of climate change adaptation. The different options of adaptation measures in water and agriculture that we have to look are:

- Managing soil moisture at field level in rainfed areas:
  Here refers to accessible technologies and investments to assist farmers to establish better control and management of intermittent water supplies that are crucial during dry spells that occurs where rainfall is variable like in the semi-arid and arid regions of the country, and resulting in frequent crop losses. The techniques involves in situ water harvesting together with improving soil water holding capacity in the root zone to deal with the temporary water deficit that occurs during the dry spells. These investments should be accompanied by optimizing the use of fertilizer, seeds and other key inputs in rainfed settings when soil moisture management practices are developed (Rockström, 2000).

- Investing in small-scale water harvesting infrastructure:
  Water harvesting refers to any practice that collects runoff from the rainfall and stores for agricultural productive uses. These techniques involve three components, a watershed area to produce runoff, a storage facility to store water, and a target area for the use of the water that in this case is for agriculture. There are two different types one that is in-situ harvesting that involves adjusting the surface of the soil to route surface runoff water to the root zone, in this case the watershed area and the storage and target area are in the same place with the root zone functioning as the water reservoir. The second water harvesting techniques involves the construction of small reservoirs and the watershed, storage and target area are located in different places. In this case the different water harvesting systems can be classified according to the scale of runoff collection, from small check dams and water retention structures to larger external systems collecting runoff from watersheds. Storage options in rainwater harvesting include surface or subsurface tanks and small dams.

  The first technique, in-situ water harvesting techniques have been successfully used in some of the districts in the semi-arid and arid regions of Mozambique where they have been introduced together with conservation agriculture, resulting in significant yield increase when compared to local agriculture techniques. The second one has also been used in Mozambique more oriented for domestic and/or animal use. These techniques are much more technological demanding in the design and most of the initiative in Mozambique have had technical flaws and ended up in failure with frequent destruction after heavy rains or have never been filled up. Nevertheless these techniques are very relevant to reach better water management under water stress conditions, and there is still scope for better dissemination of a wide range of water harvesting technologies that are available but relatively little known outside their areas of origin.

  There is a large potential for poverty reduction using rainwater harvesting techniques in smallholder settings in semi-arid and sub-humid areas. Small interventions in water harvest and storage can have big impacts on the livelihoods in rural areas. Typically providing a 1 000 m^3 of extra water per hectare per season for supplementary irrigation improve farmers' resilience to dry spells, and, in combination with improved soil, nutrient and crop management can substantially increase the productivity of small-scale rainfed agriculture (Rockström et. al., 2007).

- Developing community based small scale irrigation,
  Rainfed agriculture is extensively practiced all over Mozambique and is negatively affected by the low and erratic rainfall. In the semi-arid areas, the risk of dry land crop failure is high, while along the river valleys flooding is more likely to happen during the wet years resulting in aggravated risk of crop failure.

  There is a very large potential for irrigation development in Mozambique, where most of the rivers have flows that can easily sustain large areas of irrigation once appropriate infra-structure is built (water storage dams). For small scale irrigation development, it is only worth to consider areas that have a reliable water source within an economical distance and height of pumping. The main limiting factors for irrigation development in the area are the floods during the wet years, access to markets, and technological know-how in agricultural production. The strategy for the introduction of community based small scale irrigation must go together with other measures to improve agricultural productivity. These measures can be summarized in the acronym CROP meaning C for good Crops where good seeds and other inputs are crucial, R for good Roads to transport the products, O for good Outlets to sell the products, and P for a good Price to recover the investments.

To enhance development in small scale irrigation, it is proposed to stratify the interventions based on four distinct regions:

(i) The lower valleys along the rivers. This region is characterized by a tropical dry savanna with average annual rainfalls ranging from 600 to 1 000 mm, and with reliable sources of water in the rivers, lakes or shallow groundwater. The strategy is the introduction of irrigation pumps (treadle, diesel or electrical pumps) together with other measures to improve agricultural productivity.

(ii) The higher plateaus in the country characterized by tropical rains with average annual rainfalls ranging from 1 000 to 1 600 mm as the only source of water. It is suggest to promote soil and water conservation techniques to increase water storage in the soil, and water harvesting associated to supplementary irrigation to decrease the risk of crop failure due to water stress, and improve agricultural productivity;

(iii) The transition between both regions with average annual rains ranging from 800 to 1 000 mm, with in some areas relatively higher slopes, and small rivers most of the time non-perennial. It is proposed to promote soil and water conservation measures to promote soil storage and prevent soil erosion, to promote water harvesting, and in those places with a reliable source of water and potential for gravity irrigation, the construction of diversion weirs, and

(iv) The semi-arid and arid regions with rainfall below the 500 mm where development of water storage infra-structure should be oriented for livestock production and domestic use once these are regions permanently water stressed not appropriate to development of irrigated agriculture. In the areas where water is reliable, small scale irrigation can be developed linked to agricultural productivity and access to markets,

- Improving existing irrigation systems and developing new irrigation systems:
  Mozambique has a huge potential for development of large irrigation systems with still available good agricultural soils along major rivers that, together with the development of large dams can assure the large amounts of water needed to develop irrigated agriculture at a large commercial scale. Here it is important to mobilize resources to develop large public investments in the construction of large dams and irrigation systems, and attract and involve a strong private sector to make these large investments profitable and link them with the small scale farmers organized associations and the small scale private growers as shown by the very successful experience with the sugar cane development in Mozambique.

Climate change will also bring more intense rains and for that special attention should be given to soil erosion control techniques both for small and large scale agriculture, and drainage in agriculture to control water logging in the river valleys together with flood protection measures to avoid flood damage.

Besides these mentioned initiatives, Mozambique should also look at other forms of risk transfer like insurances in agriculture to cope with the naturals disasters (droughts, floods and cyclones) that are becoming more frequent and intense. Other important aspect is to introduce prevention mechanisms of wild fires that under hotter climate conditions and stronger winds have a larger destruction power. These should involve community based control and prevention mechanisms, and the introduction of monitoring, prevention and control mechanisms in larger forested areas.

CONCLUSIONS AND RECOMMENDATIONS

This study covers the effect of climate change (increase in temperatures and changes in rainfall patterns) on crop water balance and crop yields under rainfed agriculture in Mozambique. It used daily precipitations and daily maximum and minimum temperatures for 47 meteorological stations from which 27 are in Mozambique. It modeled the daily crop water balance and its impact in crop yields for six different crops (cassava, cotton, groundnut, maize, sorghum and soybean) and for seven different general circulation models downscaled to Mozambican conditions.

The effects of climate changes on crop yields differs from crop to crop, with maize being the most affected crop with a projected average decrease in the country of 11.1 % in crop yields, followed by followed by soybean with a projected decrease of 6.4 %, then groundnut with a decrease of 4.6 %, cassava with 4.2 %, sorghum with 3.5 % and then cotton the least affected crop with a projected average decrease on the order of 2.9 % of present yields.

The projected yield decreases are geographically different distribute with the decrease in relative yields starting with a pocket in the west side of the province of Tete with cotton, then growing towards the coast and the south, with sorghum, groundnut, cassava, and soybean, and then maize as the most affected crop covering a wider area in Mozambique. Crop yields can decrease in the most affected areas up to 30 % of present yields as is the case of Maize in some areas of the province of Tete.

These effects of climate change can be exacerbated by the increase in frequency and intensity of natural disasters (droughts, floods, cyclones and wild fires) that could revert the efforts of the country in reducing poverty and reaching an average 7% growth in the agriculture sector by doubling crop yields and increasing 25% of the cultivated area for the most important crops.

The massive development and adoption of adaptation mechanisms in the agriculture sector is crucial to make Mozambican communities and society more resilient to climate change, requiring a strong coordination mechanisms in the sector, the development of local adaptation measures and fast dissemination mechanisms, involving both the private sector and large producers as well the small scale farmers. It requires a strong leadership from the government and the channeling of funds to investments that will have strong impacts in the present and in the future. It will require that all relevant sectors (universities, research institutions, policy makers, extension services, and producers) will channel their efforts and resources in a coordinated manner towards the same goal, increase agricultural productivity and resilience to climate change.

In this endeavor, water management is crucial once climate change together with development and population growth will bring higher demand for the water that is becoming less and less available. It will require from the agricultural sector the adoption of mechanisms and technologies that will make a better use of water with more crops per drop, and the improvement of water storage mechanisms at the plant level, community level, and at water basin level, to cope with water scarcity.

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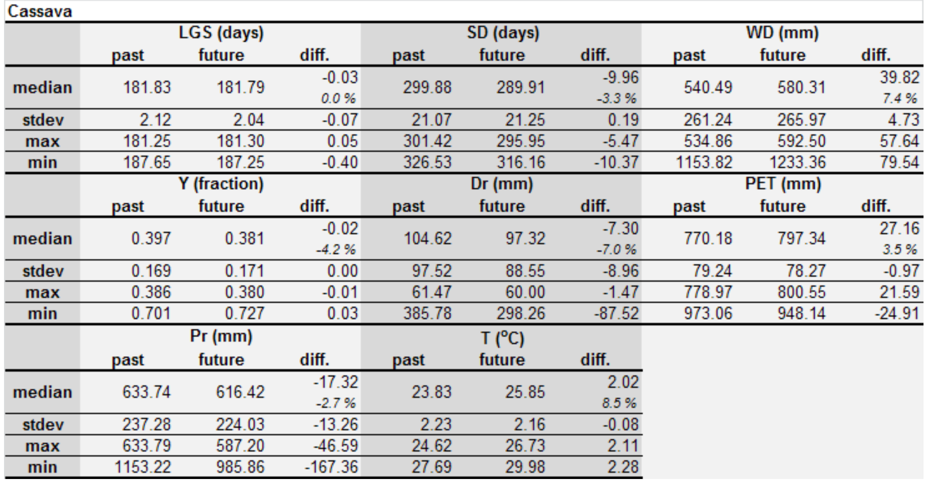
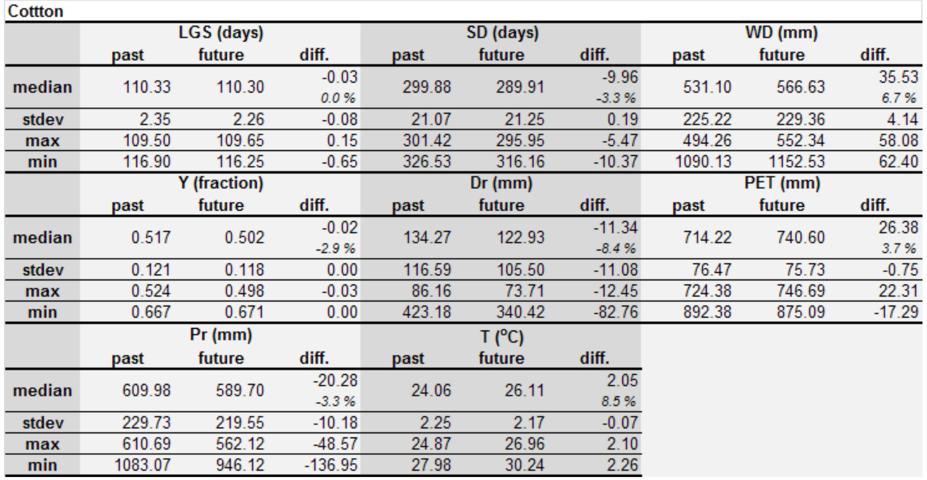
Annex I: Average values of the CliCrop model for Mozambique (based on the median) for seven General Circulation Models (GCMs), 47 meteorological stations and six different crops (cassava, cotton, beans, maize, sorghum and soya)



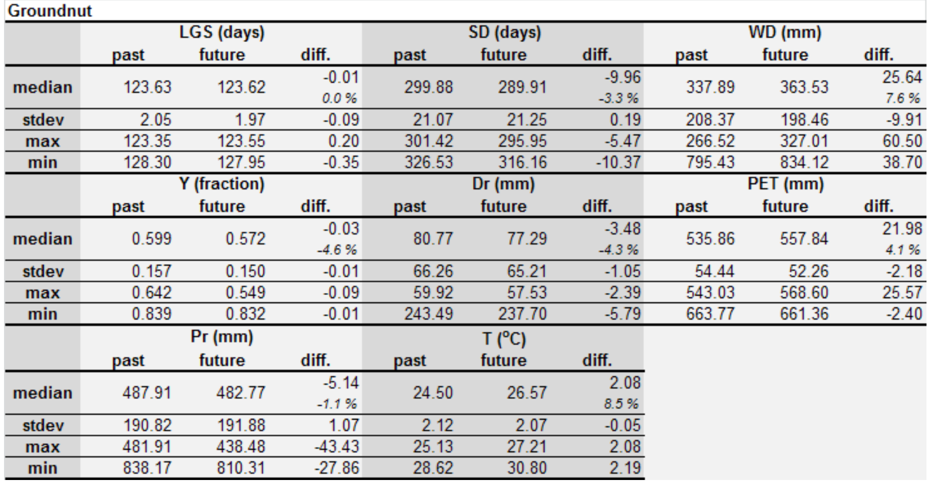
Cassava									
	LGS (days)			SD (days)			WD (mm)		
	past	future	diff.	past	future	diff.	past	future	diff.
median	181.83	181.79	-0.03 *0.0 %*	299.88	289.91	-9.96 *-3.3 %*	540.49	580.31	39.82 *7.4 %*
stdev	2.12	2.04	-0.07	21.07	21.25	0.19	261.24	265.97	4.73
max	181.25	181.30	0.05	301.42	295.95	-5.47	534.86	592.50	57.64
min	187.65	187.25	-0.40	326.53	316.16	-10.37	1153.82	1233.36	79.54
	Y (fraction)			Dr (mm)			PET (mm)		
	past	future	diff.	past	future	diff.	past	future	diff.
median	0.397	0.381	-0.02 *-4.2 %*	104.62	97.32	-7.30 *-7.0 %*	770.18	797.34	27.16 *3.5 %*
stdev	0.169	0.171	0.00	97.52	88.55	-8.96	79.24	78.27	-0.97
max	0.386	0.380	-0.01	61.47	60.00	-1.47	778.97	800.55	21.59
min	0.701	0.727	0.03	385.78	298.26	-87.52	973.06	948.14	-24.91
	Pr (mm)			T (ºC)					
	past	future	diff.	past	future	diff.			
median	633.74	616.42	-17.32 *-2.7 %*	23.83	25.85	2.02 *8.5 %*			
stdev	237.28	224.03	-13.26	2.23	2.16	-0.08			
max	633.79	587.20	-46.59	24.62	26.73	2.11			
min	1153.22	985.86	-167.36	27.69	29.98	2.28			

Cassava



Cottton									
	LGS (days)			SD (days)			WD (mm)		
	past	future	diff.	past	future	diff.	past	future	diff.
median	110.33	110.30	-0.03 *0.0 %*	299.88	289.91	-9.96 *-3.3 %*	531.10	566.63	35.53 *6.7 %*
stdev	2.35	2.26	-0.08	21.07	21.25	0.19	225.22	229.36	4.14
max	109.50	109.65	0.15	301.42	295.95	-5.47	494.26	552.34	58.08
min	116.90	116.25	-0.65	326.53	316.16	-10.37	1090.13	1152.53	62.40
	Y (fraction)			Dr (mm)			PET (mm)		
	past	future	diff.	past	future	diff.	past	future	diff.
median	0.517	0.502	-0.02 *-2.9 %*	134.27	122.93	-11.34 *-8.4 %*	714.22	740.60	26.38 *3.7 %*
stdev	0.121	0.118	0.00	116.59	105.50	-11.08	76.47	75.73	-0.75
max	0.524	0.498	-0.03	86.16	73.71	-12.45	724.38	746.69	22.31
min	0.667	0.671	0.00	423.18	340.42	-82.76	892.38	875.09	-17.29
	Pr (mm)			T (ºC)					
	past	future	diff.	past	future	diff.			
median	609.98	589.70	-20.28 *-3.3 %*	24.06	26.11	2.05 *8.5 %*			
stdev	229.73	219.55	-10.18	2.25	2.17	-0.07			
max	610.69	562.12	-48.57	24.87	26.96	2.10			
min	1083.07	946.12	-136.95	27.98	30.24	2.26			

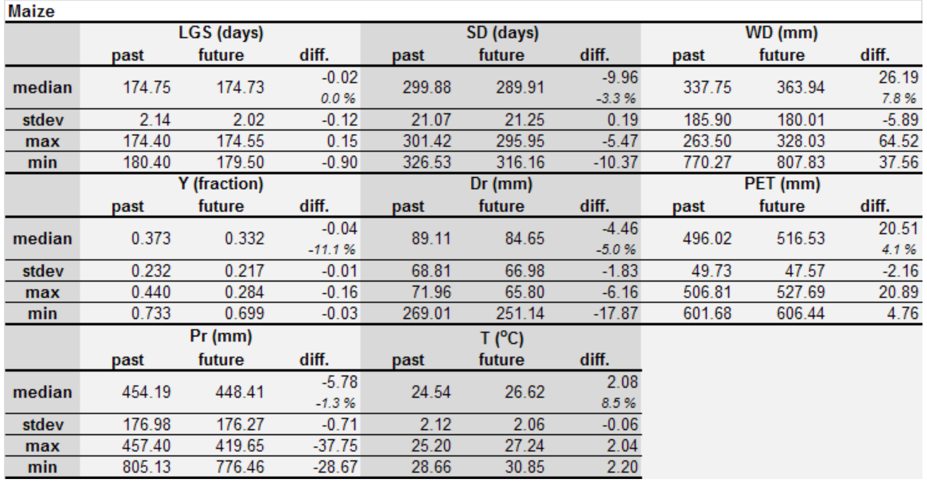
Cotton



Groundnut

	LGS (days)			SD (days)			WD (mm)		
	past	future	diff.	past	future	diff.	past	future	diff.
median	123.63	123.62	-0.01 *0.0 %*	299.88	289.91	-9.96 *-3.3 %*	337.89	363.53	25.64 *7.6 %*
stdev	2.05	1.97	-0.09	21.07	21.25	0.19	208.37	198.46	-9.91
max	123.35	123.55	0.20	301.42	295.95	-5.47	266.52	327.01	60.50
min	128.30	127.95	-0.35	326.53	316.16	-10.37	795.43	834.12	38.70
	Y (fraction)			**Dr (mm)**			**PET (mm)**		
	past	future	diff.	past	future	diff.	past	future	diff.
median	0.599	0.572	-0.03 *-4.6 %*	80.77	77.29	-3.48 *-4.3 %*	535.86	557.84	21.98 *4.1 %*
stdev	0.157	0.150	-0.01	66.26	65.21	-1.05	54.44	52.26	-2.18
max	0.642	0.549	-0.09	59.92	57.53	-2.39	543.03	568.60	25.57
min	0.839	0.832	-0.01	243.49	237.70	-5.79	663.77	661.36	-2.40
	Pr (mm)			**T (ºC)**					
	past	future	diff.	past	future	diff.			
median	487.91	482.77	-5.14 *-1.1 %*	24.50	26.57	2.08 *8.5 %*			
stdev	190.82	191.88	1.07	2.12	2.07	-0.05			
max	481.91	438.48	-43.43	25.13	27.21	2.08			
min	838.17	810.31	-27.86	28.62	30.80	2.19			

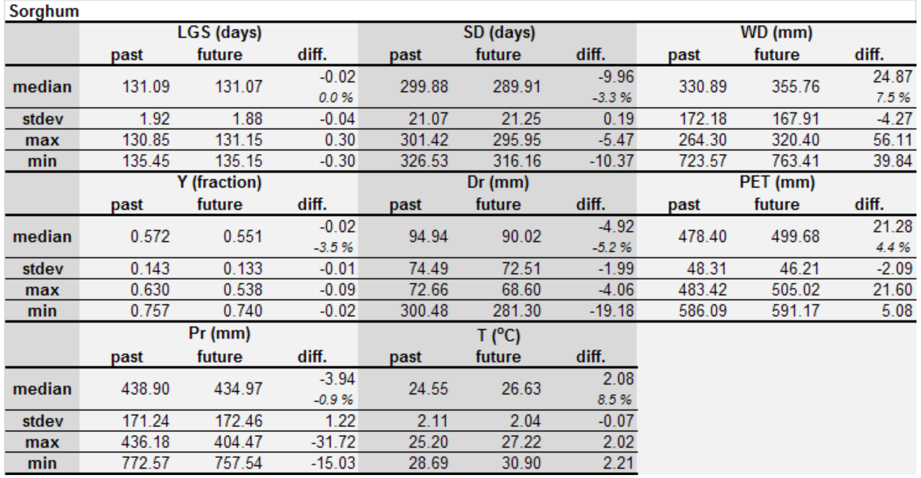
Beans



Maize

	LGS (days)			SD (days)			WD (mm)		
	past	future	diff.	past	future	diff.	past	future	diff.
median	174.75	174.73	-0.02 *0.0 %*	299.88	289.91	-9.96 *-3.3 %*	337.75	363.94	26.19 *7.8 %*
stdev	2.14	2.02	-0.12	21.07	21.25	0.19	185.90	180.01	-5.89
max	174.40	174.55	0.15	301.42	295.95	-5.47	263.50	328.03	64.52
min	180.40	179.50	-0.90	326.53	316.16	-10.37	770.27	807.83	37.56
	Y (fraction)			**Dr (mm)**			**PET (mm)**		
	past	future	diff.	past	future	diff.	past	future	diff.
median	0.373	0.332	-0.04 *-11.1 %*	89.11	84.65	-4.46 *-5.0 %*	496.02	516.53	20.51 *4.1 %*
stdev	0.232	0.217	-0.01	68.81	66.98	-1.83	49.73	47.57	-2.16
max	0.440	0.284	-0.16	71.96	65.80	-6.16	506.81	527.69	20.89
min	0.733	0.699	-0.03	269.01	251.14	-17.87	601.68	606.44	4.76
	Pr (mm)			**T (ºC)**					
	past	future	diff.	past	future	diff.			
median	454.19	448.41	-5.78 *-1.3 %*	24.54	26.62	2.08 *8.5 %*			
stdev	176.98	176.27	-0.71	2.12	2.06	-0.06			
max	457.40	419.65	-37.75	25.20	27.24	2.04			
min	805.13	776.46	-28.67	28.66	30.85	2.20			

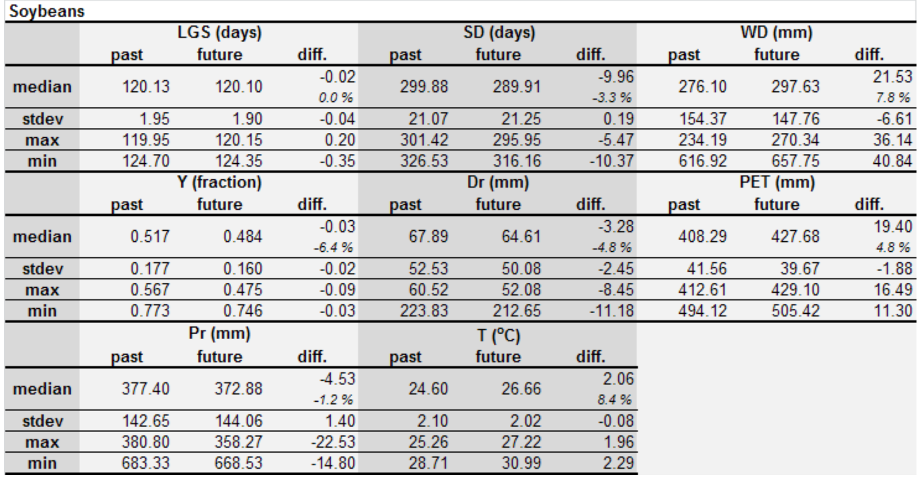
Maize



Sorghum

	LGS (days)			SD (days)			WD (mm)		
	past	future	diff.	past	future	diff.	past	future	diff.
median	131.09	131.07	-0.02 *0.0 %*	299.88	289.91	-9.96 *-3.3 %*	330.89	355.76	24.87 *7.5 %*
stdev	1.92	1.88	-0.04	21.07	21.25	0.19	172.18	167.91	-4.27
max	130.85	131.15	0.30	301.42	295.95	-5.47	264.30	320.40	56.11
min	135.45	135.15	-0.30	326.53	316.16	-10.37	723.57	763.41	39.84
	Y (fraction)			**Dr (mm)**			**PET (mm)**		
	past	future	diff.	past	future	diff.	past	future	diff.
median	0.572	0.551	-0.02 *-3.5 %*	94.94	90.02	-4.92 *-5.2 %*	478.40	499.68	21.28 *4.4 %*
stdev	0.143	0.133	-0.01	74.49	72.51	-1.99	48.31	46.21	-2.09
max	0.630	0.538	-0.09	72.66	68.60	-4.06	483.42	505.02	21.60
min	0.757	0.740	-0.02	300.48	281.30	-19.18	586.09	591.17	5.08
	Pr (mm)			**T (ºC)**					
	past	future	diff.	past	future	diff.			
median	438.90	434.97	-3.94 *-0.9 %*	24.55	26.63	2.08 *8.5 %*			
stdev	171.24	172.46	1.22	2.11	2.04	-0.07			
max	436.18	404.47	-31.72	25.20	27.22	2.02			
min	772.57	757.54	-15.03	28.69	30.90	2.21			

Sorghum



Soybeans

	LGS (days)			SD (days)			WD (mm)		
	past	future	diff.	past	future	diff.	past	future	diff.
median	120.13	120.10	-0.02 *0.0 %*	299.88	289.91	-9.96 *-3.3 %*	276.10	297.63	21.53 *7.8 %*
stdev	1.95	1.90	-0.04	21.07	21.25	0.19	154.37	147.76	-6.61
max	119.95	120.15	0.20	301.42	295.95	-5.47	234.19	270.34	36.14
min	124.70	124.35	-0.35	326.53	316.16	-10.37	616.92	657.75	40.84
	Y (fraction)			**Dr (mm)**			**PET (mm)**		
	past	future	diff.	past	future	diff.	past	future	diff.
median	0.517	0.484	-0.03 *-6.4 %*	67.89	64.61	-3.28 *-4.8 %*	408.29	427.68	19.40 *4.8 %*
stdev	0.177	0.160	-0.02	52.53	50.08	-2.45	41.56	39.67	-1.88
max	0.567	0.475	-0.09	60.52	52.08	-8.45	412.61	429.10	16.49
min	0.773	0.746	-0.03	223.83	212.65	-11.18	494.12	505.42	11.30
	Pr (mm)			**T (ºC)**					
	past	future	diff.	past	future	diff.			
median	377.40	372.88	-4.53 *-1.2 %*	24.60	26.66	2.06 *8.4 %*			
stdev	142.65	144.06	1.40	2.10	2.02	-0.08			
max	380.80	358.27	-22.53	25.26	27.22	1.96			
min	683.33	668.53	-14.80	28.71	30.99	2.29			

Soya

PART 2

Modeling the impact of midcentury climate change on crop yield in Mozambique: Effect of rise in temperature, back ground ozone and atmospheric CO_2, a layer approach

Part 2: Edwin Holman

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Modeling the impact of midcentury climate change on crop yield in Mozambique: Effect of rise in temperature, back ground ozone and atmospheric CO_2, a layer approach

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Abstract

This work is part of the INGC - Project *Responding to Climate Change in Mozambique* - theme 6 - Phase II. A layer approach is presented to evaluate and add the effects of up to 6°C temperature rise, up to 60 ppb ground level ozone rise and up to 300 ppm atmospheric CO_2 increase on actual average crop yield of six selected crops: cassava, cotton, ground nut, maize, sorghum and soybean in Mozambique. Within the ranges as set by these figures, the individual and combined outcome on crop yield change of 550 ppm atmospheric CO_2, 1.7 to 2.4°C temperature increase and 15 to 30 ppb ground level ozone increase, as associated with Mozambique´s midcentury climate change, is explicitly calculated.

Actual modeling attempts often tend to apply a threshold value for ozone, underestimate the yield suppressing effect of ground level ozone, overestimate 'the feeding effect' of CO_2 and apply traditional Q_{10} temperature responses derived from short term (hours) measurements in mature organisms [27][28][29][31][32]. In our work, an updated vision and consequent approach are put forward as to how temperature, ground level ozone and CO_2 interactively modulate yield-outcome. To elucidate the actual and future yield gap, we principally combine the findings of three pioneering research teams: (1) the work on dual CO_2 - ground level ozone interaction on crop yield from the USDA research team led by Prof. Dr. Edwin Fiscus, (2) the work on Carbon Use Efficiency (CUE) from Prof. Dr. Marc van Iersel and colleagues at the Georgia and Utah State University and (3) the work on ozone modulated epigenetic memory effects and the recently peer-reviewed discovery in this area from Crops Advance Brazil [48]], showing us:

(1) the end of a paradigm: extra atmospheric CO_2 basically doesn´t feed crops' yield, but acts as an oxidative stress // ozone 'detox',
(2) the CUE paradox: although variable, Crops Carbon Use Efficiency tends to be fixed,
and as opposed to short term changes, long term temperature change little interferes with CUE,
(3) the CUE paradox explained: crops in their juvenile phase memorize and fix for life their respirational efficiency which is modulated by ozone.

- **Yield is basically modulated by ground level ozone as opposed to atmospheric CO_2**
- **There applies no threshold or 'safe value' for ozone exposure**
- **Ground level ozone generates *a false signal of metabolic perturbation***
- **Ground level ozone at the moment of (trans)planting defines the maximum yield-outcome**

Modeling ground level ozone increase versus change of actual yield

- Crops on average are expected to have their actual yields reduced by 0.5% per ppb '1st month of planting-average' ground level ozone increase (memory effect on CUE),
- Crops on average are expected to have their actual yields further reduced by 0.5% per ppb 'crop-cycle-average' ground level ozone increase (dynamic influence on CUE and carboxylation),
- For the individual crops, a sensitivity factor applies.

Modeling atmospheric CO_2 increase versus change of actual yield

- for the sensibility factor = 1, for 50, 60 and 70 ppb ground level ozone the projected yield increases are 0.074%, 0.096% and 0.117% respectively for every 1 ppm CO_2 increase.

Modeling atmospheric temperature increase versus change of actual yield

- For **annual crops** on average, the combined outcome of Growing Degree Days (GDD) increase and crop cycle reduction on yield is an expected 5% yield reduction for every $1^{o}C$ of average temperature increase,
- For **the perennial cassava**, on average a 2.9% yield increase for every $1^{o}C$ average temperature increase is projected.

Introduction

Part of the 'Theme 6 contribution' to Phase II of the Mozambican National Institute for Disaster Management (INGC) Project *Responding to Climate Change in Mozambique*, this complementary article addresses the rationale for modeling the effects of *temperature rise* and *ground level ozone rise* on crop yield and includes their mathematical approaches.

INGC Phase I recommended that additional crop modeling be required to improve the robustness of findings of yield changes resulting from climate change [1]. Phase II therefore continued the analysis, applying all seven instead of a selected three Global Climate Models (GCMs) [ref. 1, p.21, Table 1.10] and a new calibrated crop model (Clicrop) for the six selected crops: cassava, cotton, ground nut, maize, sorghum and soybean. Phase I and initially Phase II isolated the combined effect of water availability and temperature on *crop transpiration* as the main restricting factor to yield.

In the course of Phase II, it was recognized that under changing climate, crop Carbon Use Efficiency (CUE), that is the carbon sequestered or the Net Primary Production (NPP), as percentage of the total carbon initially captured in the overall process of photosynthesis or Gross Primary Production (GPP), can no longer be considered a constant physiological property. Subject to temperature rise and ground level ozone rise, both photosynthesis (NPP, PS_{brutto}) and respiration (R) are foreseen to readjust (NPP↓, R↑) and as we will show, to the extent that rising atmospheric carbon dioxide content through it's 'feeding effect' in general can't compensate for the negative effects of respiration and photosynthesis on yield.

$$NPP = GPP - R \qquad \text{(Formula 1)}$$

$$CUE = \frac{NPP}{GPP} \qquad \text{(Formula 2)}$$

Changes in CUE have a direct and potentially high impact on crop yield as formula 3 below shows for the initial exponential growing phase. $P_{(d)}$ = accumulated production at day (d) expressed as gram Carbon (gC), IG = initial weight (gC), PS_{brutto} = gross photosynthesis ($gC.gC^{-1}.d^{-1}$), CUE = Carbon Use Efficiency.

$$P_{(d)} = IG \times e^{PS_{brutto} \times CUE \times d} \qquad \text{(Formula 3)}$$

Other studies confirm that temperature changes have strong impact on yields. Lobell & Burke [17] conclude that progress in understanding crop responses to temperature and the magnitude of regional temperature changes are two of the most important needs for climate change impact assessments and adaptation efforts for agriculture. The European Environment Agency in addition identifies ground level ozone as a factor projected to have significant negative impacts on agriculture [16][20].

Furthermore, timing of seasonal events or the phenological response of crops is, next to day-length, principally triggered by temperature. Temperature increase can extend a by low temperature limited growing season. This is potentially beneficial to season's yield as the growing season is the farmer's window to produce. The crop cycle on the other hand is the plant's window to produce, strongly correlates positively with yield and tends to be reduced with increased temperatures as thus will yield. Data from Quadir *et al*. [6] for example show that for Sunflower production every 1°C average temperature increase reduces the crop cycle with 9.3 days, reducing yield with a 5.7% from optimum yield realized. For annual crops, on single planting basis, temperature increase is associated with shortened crop cycle and yield reduction. If applicable, adaptive measures therefore include advancing of the agricultural calendar which will interfere with day-length and likely involves selecting suitable varieties [15][16]. Yield response to temperature change of perennial crops like cassava having a crop-cycle of more than one year will be approached differently (see perennials, page 7).

It was therefore decided to further upgrade our modeling by including *temperature* and *ground level ozone* as separate factors.

It is our objective to predict the influence of climate change on change of actual yields in Mozambique as reflected by the influence of change by the selected major climate factors (1) rainfall, (2) temperature and (3) ground level ozone.

- **In our simulations, coupling the influence of the weather components rainfall, temperature & ground level ozone individually or in combination with crop growth and yield we implicitly assume that the influence of all other omitted factors including factors like farm management and socioeconomic factors are constant.**

For our modeling approach the key-word is "change", which implies technical modeling benefits. The actual yield data serve as the basis that reflects and confirms the influence of *all factors involved* as actually present. Yield change per factor change (keeping all other factors constant) is simulated on the basis of changes in:

The considered dependent eco-physiological processes:

(1) phenological development,
(2) transpiration,
(3) CO_2 assimilation,
(4) respiration,
(5) dry matter formation,
(6) partitioning of assimilates to the harvestable organs.

The considered six crops of interest are:

- cassava, cotton, ground nut, maize, sorghum and soybean.

Base map – actual yields

- Six maps, one per crop, showing actual average annual yields.

  Using the actual yield data of the six crops of interest as the basis or mathematical point of departure greatly alleviates the model that can restrict itself solely to the dynamics of yield change influenced by change of a single factor.

In *a layer approach*, next to transpiration, we add temperature & ground level ozone individually, making it possible to superimpose them individually as well as in combination on *the base maps, per map giving the present actual average annual yield per culture* in Mozambique.

Layer one – Transpiration

- Two forms of presentation per crop, one showing projected yield & the other showing yield change, due to transpiration change.

  Rainfall (I) & temperature (II) change have been predicted by applying the seven GCMs. The combined effects of rainfall & temperature change on transpiration (2) have been predicted by applying the calibrated crop model *Clicrop*. Linking the combined effects on CO_2 assimilation (2), dry matter formation (5) & partitioning of assimilates to the harvestable organs (6) predicts the relation between transpiration change and yield change. The outcome indicates that at this sub-level little change is to be expected on Mozambique's national level.

Layer two – Temperature

- Two forms of presentation per crop; one showing projected yield & the other showing yield change from predicted relative yield change due to temperature change. For annual crops our approach is epidemiological. Per crop we correlate historical temperature to yield event patterns, without explaining the underlying physics, nor trying to feed a multiple variable model.

Layer three – Ground level ozone

- Two forms of presentation per crop; one showing projected yield & the other showing yield change from predicted relative yield change due to ground level ozone change.

The layer approach also has practical benefits. It facilitates the evaluation of the impact of the individual factors in their contribution to yield change. We feel this will help prioritize adaptive measures that focus on

- mitigating the impact of **rainfall** changes on present potential crop yield,
- mitigating the impact of **temperature** changes on present potential crop yield,
- mitigating the impact of **ground level ozone** changes on present potential crop yield.

Mathematical approach

1. **Temperature rise - yield *change* related to general temperature *change***
2. **Ground level ozone rise - yield *change* related to general ground level ozone *change***

Observation: The period is used as the decimal mark.

1. Temperature rise - yield change related to general temperature change

Crop growth and yield correlate positive and linear with accumulated heat during the growing season. For non-perennial crops, Growing Degree Days (GDD) is a simple mathematical expression for the heat accumulation and a modeling tool to help predict plant developmental progress along the crops cycle as will be explained below [6][7][8][14][15][16]. Ref. perennial crop, see paragraph “perennials” at page 6. The crops cycle or number of days between planting and harvest reflects the time for the crop to accumulate carbon that is its time-window to come to yield. The crop cycle is not only crop and variety depending but is also a function of temperature. When, for the same planting-date, the climate tends to be slightly hotter, the crop cycle tends to be shorter [16]. A substantial data base should be used for the analyses to get a good impression of this effect, combining data of various plantings with varying planting dates. An example of the possible outcome is formula (1) at page 5: Crop cycle (days) = -9.34 × average daily GDD (^{o}C) + 264. By simply comparing two plantings that have their day of planting in different seasons will give the false impression of the opposite trend to be truth. This, because it also is *the distribution of heat along the crops cycle* that strongly defines cycle length and yield-outcome.

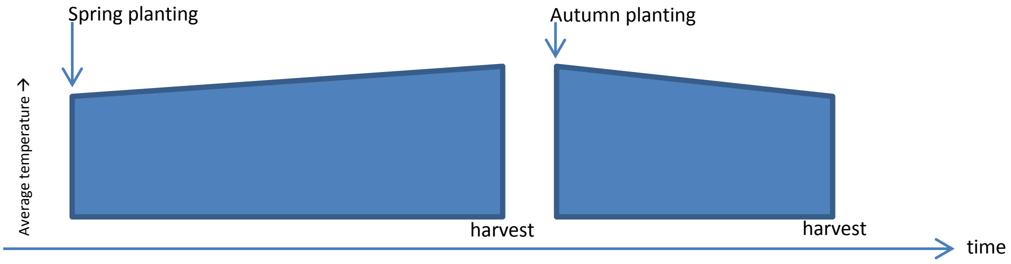

Figure 1 : ***Distribution of heat along the crop cycle strongly defines cycle length & yield-outcome.***

The influence of temperature on the partitioning of assimilates to the roots, stems, leaves and the storage organs is a function of the developmental stage of the crop [15]. A spring planting, having a relatively cool start at planting and building-up to a relatively hot finish at harvest is likely to give the longest crop cycle with the highest accumulated GDD and the highest yield-outcome. The opposite goes for an autumn planting [6][23]. For example, by integrating data form Quadir *et al.* [6] for sunflower when expressing the temperature distribution (TD) by T_{amp} / T_{amh} , whereby T_{amp} = average temperature of month of planting and T_{amh} = average temperature of month of harvest, for TD we find a range of 0.5 to 1.8 inversely and linearly correlating with cycle length (n=8, R^2=0.88), GDD (n=8, R^2=0.95) & yield (n=8, R^2=0.95).

GDD therefore encloses three dependent variables:

(1) The temperature, expressed as average above threshold or base temperature (T_b) of maximum and minimum daily temperature (T_{max} & T_{min}):

$$GDD = \sum_{i=l}^{n}\left(\frac{T\max + T\min}{2} - Tb\right)$$

(formula 4)

, that is a measure for the effectively accumulated heat that contributed to the development and growth to yield of the crop along its cycle,

(2) The gradient of temperature distribution along the crops cycle,

(3) The number of growing days between planting and harvest that is the actual crop cycle.

In calculating the GDD, a daily average temperature below T_b is accounted for as T_b to yield 0 GDD for that day. Within the practical range of temperatures up to approximately 40^{o} C, for C3 as opposed to C4 crops a cut-off value of for example 30^{o}C is normally applied to T_{max} that is a temperature limit above which temperature is considered not to contribute any further to growth and development. For $T_{max} > T_{cutoff}$, the cut-off temperature is used in calculating the GDD.

- Within the scope of our study it is important to realize that relative yield *reduction* due to a general temperature *rise* is the net effect of crops cycle reduction partially compensated for by daily GDD increase.

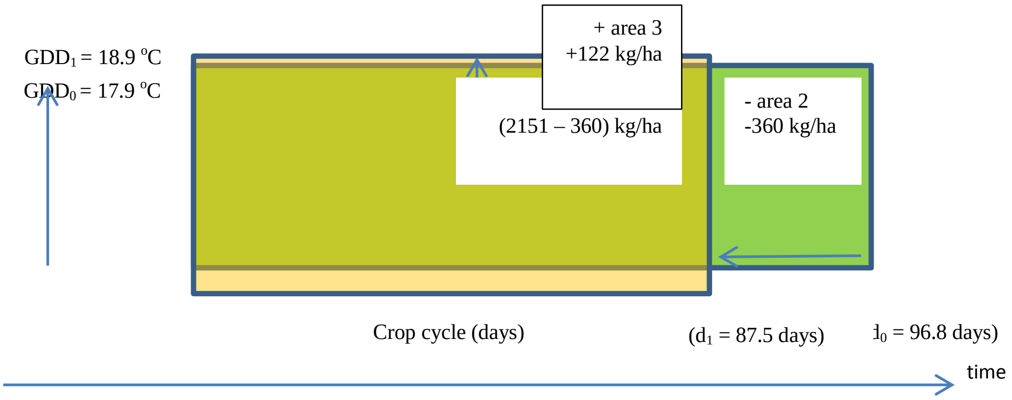

***Figure 2 :** Yield change of sunflower due to a 1^{o}C average temp rise.*

Per crop, we want to define three linear relationships: (1) crops cycle as a function of average daily GDD which will give us the crop cycle change per unit of temperature rise, (2) yield as a function of crop cycle which will give us the component of the yield reduction per unit of temperature change & (3) yield as a function of accumulated GDD which will give us the component of the yield increase per unit of temperature change. The two components of yield change have opposite signs and for temperature rise the net out-come is negative that is yield reduction. (4) Additionally, we want to know the actual average daily GDD.

For example, by integrating data form Quadir *et al*. [6] for sunflower we find (1)→(2)→(4)→(3):

(1) Crop cycle (days) = **-9.34** × average daily GDD (^{o}C) + 264
(2) Yield (kg/ha) = **38.5** × crop cycle (days) – 1591

- The component of the yield change per unit of temperature change = -9.34 × 38.5 = -360 kg/ha per +1^{o}C increase.

(4) Actual average daily GDD = **17.9 ^{o}C** → in (1) gives actual Crop cycle = 96.8 days.
(3) Yield (kg/ha) = **2,72** × total accumulated GDD (^{o}C) - 2562

- New crop cycle = 96.8 – 9.34 = 87.5 days with +1^{o}C GDD per day extra = accumulated 87.5 ^{o}C extra → (3) 87.5 × 2.72 = +238 kg/ha per +1^{o}C increase.
- Net to yield change: -360+238 = -122 kg/ha per 1^{o}C increase.
- Initial yield is (3) 2.72 × 17.9 × 96.8 – 2562 = 2151 kg/ha

- Relative yield change per unit of temperature change = -122/2151 = -0.057 or:

  - -5.7% per +1^{o}C
  - Temperature change of +1.5 ^{o}C to +5.7 ^{o}C is expected to affect relative sunflower yield by -9% to -33%.

Sunflower	y = ax+b			
	Y	x	A	B
(1)	Crop cycle (days)	Average daily GDD (^{o}C)	-9.34 (*A*)	264 (*B*)
(2)	Yield (kg/ha)	Crop cycle (days)	38.5 (*C*)	-1591
(3)	Actual average daily GDD (^{o}C)	-	-	17.9 (*D*)
(4)	Yield (kg/ha)	Total accumulated GDD (^{o}C)	2.72 (*E*)	-2562 (*F*)

$$\text{Relative yield change per unit of temperature change} = \frac{AC + E\,(AD + B + A)}{ED\,(AD+B) + F} \times 100\% = -5{,}7\ \%\ ({}^{o}C^{-1})$$

Table 1 : The calculation of relative yield change per unit of temperature change.

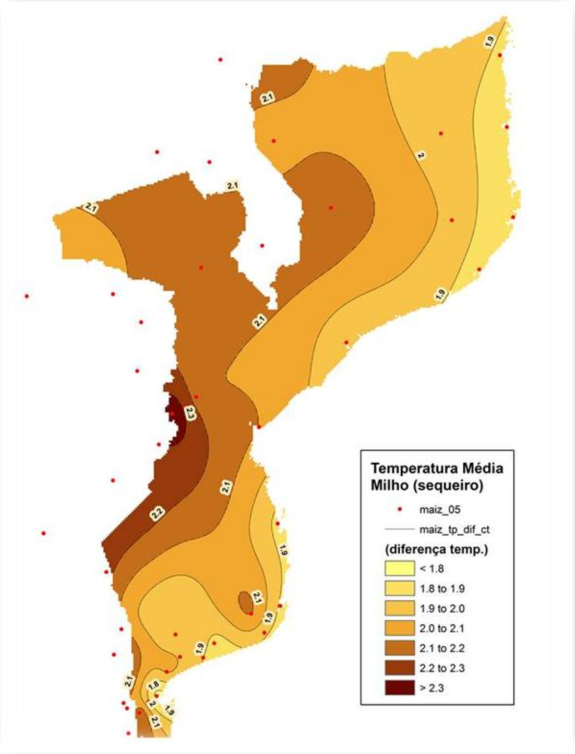

Figure 3 : Average midcentury temperature change for the planting season (of for example corn), ranging from 1.7 to 2.4^{o}C.

In the same way we find the relative yield change (ΔY_{rel}) due to temperature change, per unit of temperature change (ΔT) and applied to the predicted range of +1.7°C to +2.4°C for average midcentury planting season's temperature change:

Crop	Relative yield[*] change per temperature change ($\Delta Y_{rel}/\Delta T$)			
	Unit +1°C	+1.7°C	Mean +2.1°C	+2.4°C
Sunflower	-5.7%	-9.7%	-11.7%	-13.7%
Groundnut	-5.0%	-8.5%	-10.3%	-12.0%
Maize	-6.1%	-10.4%	-12.5%	-14.6%
Sorghum	-4.7%	-8.0%	-9.6%	-11.3%
Median	**-5.4%**	-9.1%	-11.0%	-12.9%
Cassava[**]	+2.9%	+4.9%	+5.9%	+7.0%
Soybean[***]	-5.4%			
Cotton[***]	-5.4%			

Table 2 : Relative yield change per unit of temperature change for selected crops.

[*] Observation 1: "Yield" principally refers to yield per crop cycle. If, under the assumption as put forward at page 2, the crop calendars don´t change, the percentage of yield change also applies to yield in general, e.g. per season or per year.

[**] Observation 2: The logic as summarized in table 1 doesn´t apply to perennial crops like Cassava. For the explanation see paragraph "Perennials" below.

[***] For Soybean and Cotton, due to incomplete data, we use the average results of sunflower, groundnut, maize & sorghum as indicative estimate for the influence of temperature increase on yield change.

Table 2 summarizes the predicted yield changes under the assumption as put forward in bold at page 3 **that nothing changes but the average temperature (!)**. By for instance jointly assuming a backward shift in time of the planting calendar, yield reduction can be alleviated and numbers will become more positive, potentially giving a false impression of the temperature effect on yield, especially when the numbers start a life of their own without proper reference to their underlying basic assumptions.

Calculating layer 2 - temperature

$\Delta Y_{rel}/\Delta T$ = the relative yield change under unit temperature change (Table 2).

For a *projected local average temperature change* ($\Delta T_{p.avg.local}$) of the actual local average temperature, the *projected* local average relative yield is: $Y_{p.avg.rel.local} = (1 - (\Delta Y_{rel}/\Delta T \times \Delta T_{p.avg.local}))$. This is relative to local actual average absolute yield ($Y_{a.avg.abs.local}$) so in absolute terms the *projected* local average absolute yield becomes: $Y_a \times Y_{p.rel.local}$.

Example: [Ref. 1, main report INGC, table 4.2, p.101] Sunflower average yield 2006-2007 = 0.5 to 1.5 t/ha. For the projected midcentury average temperature change of +1.5 to +5.7°C the average yield will consequently suffer -9% to -32% change. Relative yield will be 91% to 68% of actual yield.

- Sunflower actual average yield expectancy = 0.5 to 1.5 t/ha.
  Projected midcentury absolute yield becomes 'best case' (95% likeliness to be worse):
  0.5 × 91% to 1.5 × 91% = 0.5 to 1.4 t/ha.
- Projected midcentury absolute yield becomes 'worst case' (5% likeliness to be worse):
  0.5 × 68% to 1.5 × 68% = 0.3 to 1.0 t/ha.
- Projected midcentury absolute yield becomes 'average case' (50% likeliness to be worse):
  0.5 × 80% to 1.5 × 80% = 0.4 to 1.2 t/ha.

Perennials

Perennial crops like cassava are plants that by nature live for more than two years. As opposed to annual crops like sunflower or groundnut, the perennial life-cycle is not restricted to a temperature dependent window of generally 3 to 4.5 months with a, for the farmer to assert, ideal date of planting if to maximize yield-outcome. Some perennials like cassava are 'evergreens', carrying leaves and sequestering carbon year round. The approach of estimating average yield change as a function of average temperature increase by influencing cycle reduction, to perennials is not applicable.

Cassava

Cassava is a perennial evergreen and chilling-intolerant crop. It is rare to see cassava survive in areas with minimum temperatures of 15°C or less. Temperatures below 20°C close stomata of cassava. High temperatures up to approximately 30°C tend to open them [24]. Low temperatures provoke excessive levels of oxidative stress as is reflected by the stomatal behavior in relation to temperature. The phytohormone abscisic acid (ABA) induces stomatal closure by inducing hydrogen peroxide (H_2O_2) production and both ABA & H_2O_2 inducing nitric oxide (NO) production by the enzyme nitrate reductase (NR). It is the NO signal that induces stomatal closure (with or without H_2O_2) [25]. As H_2O_2 induces NO production, it is the 'false H_2O_2 signal' from ozone that also triggers stomatal closure.

Ground level ozone rise - yield *change* related to general ground level ozone *change*

For a given crop, past ontogenetic phase, its carbon use efficiency (CUE) defined as carbon sequestered over carbon captured and realized yield seems constant and immune to temperature variation. Now realizing it is principally ozone that up-regulates the AOX relative to COX therefore making ATP production more carbon – costly, not being compensated by photosynthesis, reducing the carbon use efficiency we have three major levels to be combined:

(1) **Ozone↑** → Respiration↑ & Photosynthesis↓= CUE↓, Crop cycle↓:
Overall effect: all crops: **yield↓**

(2) **Temperature↑** → GDD↑ & Crop cycle↓, Respiration↑ & Photosynthesis ↓or↑ depending on actual temperature: Overall effect: annual crops: **yield↓**,
perennials: **yield↑**

(3) **CO_2↑** → "Ozone-effect"↓, CUE↑: Respiration↓ & Photosynthesis↑,
Leaf-temperature↑, GDD↑ & Crop cycle↑ (!), Partitioning of
sequestered carbon to harvested organs↓:
Overall effect: all crops: **yield↑**

Actual modeling attempts often tend to apply a threshold value for ozone, underestimate the yield suppressing effect of ground level ozone, overestimate 'the feeding effect' of CO_2 and apply traditional Q_{10} temperature responses derived from short term (hours) measurements in mature organisms [27][28][29][31][32]. In our work, an updated vision and consequent approach are put forward as to how temperature, ground level ozone and CO_2 interactively modulate yield-outcome.

A paradigm is broken by Fiscus' team: The 'feeding effect' of increasing atmospheric CO_2 is principally due to *CO_2 counteracting the oxidative signal from ground level ozone*. The carboxylating enzymes Rubisco and PEPC responsible for the incorporation of CO_2 are redox sensitive by having cysteine groups of which the oxidation state modulates the enzymes activity explaining the enzymes sensitivity to ozone induced oxidative signals, principally through hydrogen peroxide [22][33][34]. Increasing CO_2 favors the by β-carbonic anhydrase and superoxide dismutase (SOD) facilitated reduction of hydrogen peroxide by oxidation of NADPH [39]. For Barley, it was demonstrated that the hydrogen peroxide scavenging enzyme catalase (CAT) and SOD increased rapidly after plants were transferred from elevated CO_2 (700 ppm) back to ambient levels [35], offering a strong rationale for the observed 'anti ozone' effect from atmospheric CO_2 increase. We conclude that the rate of carboxylation is a function of the atmospheric [CO_2/O_3] flux ratio into leaves. For cotton, rice, soybean, wheat, groundnut, snap bean and potato, Fiscus demonstrates that under low ozone conditions (25 ppb) a doubling of actual atmospheric CO_2 (372 to 706 ppb) will on average only marginally increase yield (+3%) whereas under high ozone conditions (60 ppb) a doubling of atmospheric CO_2 will give considerable *relative* yield increase (+35%) although in absolute terms *the yield is merely restored to its 'low ozone level' yield* (!) [27][28][29].

- **Yield is basically modulated by ground level ozone as opposed to atmospheric CO_2**
- **No threshold or 'safe value' applies for ozone exposure**

A reference for data on the effects of CO_2 application on crop production is the Dutch research station for floriculture and glasshouse vegetables [46]. For a greenhouse crop at 372 ppm CO_2 and under the circumstances that only atmospheric CO_2 is considered the limiting factor for growth and under full light conditions their most positive projection is 25% dry matter increase for CO_2 increasing to 706 ppm. For every extra 100 ppm CO_2 on top of 706 ppm CO_2, projected dry matter increase is less than 4%. Using data from Fiscus, a 25% yield increase at 706 ppm CO_2 relative to *372 ppm CO_2 and 15 ppb ground level ozone* is projected if the greenhouse air at 706 ppm CO_2 contains approximately 45 ppb ozone. Dutch greenhouse air is mostly enriched with CO_2 from gas combustion. Low NO_x ($NO_x = NO + NO_2$) equipment produces approximately 20 ppm NO_x (with the alarm set at 30 ppm) at 11.7% CO_2. If used to maintain 706 ppm CO_2 in a closed greenhouse environment, this mixture supplies (volume parts) 121 ppb NO_x of which 35 ppb are NO_2. NO_2 in the light dissociates to NO + ozone. 35 ppb NO_2 is the equivalent of 35 ppb O_3 (!). If the cleaned combustion gasses contain as little as 10 ppb ozone we have the expected 45 ppb. The limit for ozone from combustion gasses in the greenhouse environment is set at 30 ppb.

So why is it that in the professional production of flowers and vegetables, the greenhouse atmosphere is enriched with CO_2? Basically, because in the greenhouse environment projected to keep all growing factors at their optimum, the lack of CO_2 (defined as below environmental concentrations, to date about 400 ppm) reduces productivity significantly. At 300 ppm CO_2, average productivity is reduced by 13% and at 200 ppm CO_2 the average reduction is about 38%. Within the objective to keep CO_2 at 400 ppm to feed the crop, due to the oxidative load present in the greenhouse air, the optimum concentration for CO_2 is about 700 ppm to largely compensate for the 'ozone effect'. Outside air in the Netherlands (as goes for the whole of Europe) for that sake is no alternative as during day-time the '7 hour average' is very likely to be above 35 ppb ozone [20][21][47].

Like CO_2, **ground level ozone** is absorbed by all crops through the stomata. Intra-cellular, absorbed ozone is converted into hydrogen peroxide (H_2O_2) that acts as a diffuse intra- and inter-cellular oxidative signal. It triggers cell-protecting feedback mechanisms which includes the up-regulation of the mitochondrial alternative oxidative pathway (AOX). Electrons that are deviated from their normal cytochrome oxidative pathway (COX) into the AOX, will not contribute to further ATP generation but have their energy dissipated as heat. Cell-protecting feedback mechanisms, like the AOX, are normally activated upon oxidative stress from proper cellular metabolic perturbation. Understanding that cellular metabolic processes functionally use trans-boarding H_2O_2 as a signal for back-coupling to **process functional** oxidative activity, it becomes clear that H_2O_2 from ozone, which is generated 'at the out-side of the cellular reaction vessels' and presenting itself directly to the redox sensors, mimics increased oxidative overflow of from cellular functional activity and triggers technically unnecessary negative feedback to the cells functional oxidative processes. Crops Advance therefore concluded that

- **Ground level ozone generates *a false signal of metabolic perturbation***

The list of un-seen negative effects is extensive. H_2O_2 from ground level ozone 'non-functionally' triggers: reduction of chlorophyll content, reduction of carboxylation capacity & activity and up-regulation of respirational activity with reduced efficiency. For electrons taking the AOX pathway, the final number of ATP generated per O_2 respired is 11 to 6. For electrons taking the COX pathway the final number of ATP generated per O2 respired is 29 to 6. Electrons that terminate (combine with oxygen) over the AOX pathway are only 38% efficient. Mitochondria work to maintain ATP generation up to demand. In the event of AOX up-regulation mitochondria will consequently consume more carbohydrates to maintain the cell fueled. Increased carbohydrate consumption reduces dry matter production that is yield. 60 ppb ground level ozone increase is shown to augment total dark respiration in sugarcane with 24% and in cotton with 29%, principally due to AOX up-regulation [31][48]. Simulation studies on grasses and rose demonstrate that a 30% increase of total dark respiration in the leaves and stems is associated with 25% to 46% yield reduction [31][48].

Memory effect: When AOX up-regulation happens during the crops juvenile or early developmental phase, the up regulation is set and fixed for life causing permanently reduced respirational efficiency and consequent yield reduction (!). This was in a professional greenhouse production setting in the state of Minas Gerais – Brazil for the first time demonstrated by Crops Advance. The perennials rose and carnation gave up to a factor 4 variation between individual plantings in their 'four months average' yield (January – April, 2007). After 23 individual plantings of 5000 m^2 each were grouped by the month of their planting, the group-average productivity correlated $r^2=0.97$ with the local average ozone exposure* at the month of planting. * Expressed as NASA´s satellite tropospheric ozone column values in Dobson Units (DU) and for the location of planting [45]. Additionally to the memory effect, over a full year cycle, leaf-chlorophyll content and accumulated dry matter inversely followed the trend of ground level ozone. A **factor 1.6** increase of tropospheric ozone (28 to 45 DU), on average reduced leaf- chlorophyll content in rose with a **factor 1.6** (56 → 35 CCI, 2003 – 2005, n=79) and accumulated dry matter in the flower of carnation with a **factor 1.6** (2.01 → 1.26 g/flower, Feb 2007 – Feb 2008, n=54). A very sharp decline in both leaf chlorophyll content and accumulated dry matter was observed at the onset of the sugarcane burning season at the end of the August [45][48].

- **Ground level ozone at the moment of (trans)planting defines the maximum yield-outcome**

Modeling ground level ozone increase versus change of actual yield

Increasing ground level ozone is therefore expected to further reduce carbon capture *and* carbon use efficiency (CUE), both amplifying each other's effect on yield reduction.

- Crops on average are expected to have their actual yields reduced by 0.5% per ppb '1st month of planting-average' ground level ozone increase (memory effect on CUE) and additionally

- Crops on average are expected to have their actual yields further reduced by 0.5% per ppb 'crop-cycle-average' ground level ozone increase (dynamic influence on CUE and carboxylation)

For the individual crops, a sensitivity factor applies. In order of ozone sensitivity:

cotton	1.6
soybean	1.2
ground nut	0.6*
cassava	0.6*
maize	0.4
sorghum	0.4

*Ground nut and Cassava (estimate) are grouped with Sugar beet, Potatoes, Rape and Tobacco = 0.6. Sorghum is grouped with Millet, Corn and Rice = 0.4, Sunflower (estimate) = 1.2, Fresh vegetables in general = 1.0, Tomato = 1.4, Watermelon = 3.1, Hops 0.9 [21].

Modeling atmospheric CO_2 increase versus change of actual yield

In the above it is elucidated why the effect of CO_2 increase on actual yield can't appropriately be evaluated separately from projected ground level ozone. In our modeling, per crop, a combination of CO_2 increase relative to 'CO_2 increase for maximum yield effect' with the projected ground level ozone value and the crops ozone sensibility factor are combined to project the yield increasing effect of atmospheric CO_2 increase, for example yielding:

- for the sensibility factor = 1, for 50, 60 and 70 ppb ground level ozone the projected yield increases are 0.074%, 0.096% and 0.117% respectively for every 1 ppm CO_2 increase.
- The relation between ground level ozone (in ppb // $O_{3\,ppb}$) and expected relative yield increase (as a fraction // dY_{rel}) per ppm CO_2 increase is described by the function:
- $dY_{rel} = 363^{-1} \times ([0.0078 \times O_{3\,ppb} + 0.88] - 1)$

The CO_2 effect on ozone inhibition and yield improvement is assumed to be linear. 363 ppm atmospheric CO_2 increase is projected to give the maximum yield benefit. Atmospheric CO_2 and ground level ozone have opposing effects on length of crop developmental stages and total crop cycle [36][37][38]. In soybean 550 versus 372 ppm CO_2 delayed reproductive development and final maturation by 3 days although seed-filling was accelerated. Over three growing seasons seed yield increased by 15% to 16%, principally due to ozone suppression. A 13 ppb ground level ozone increase on the other hand shortened the growing season and reduced seed yield (seed weight and number of pods) by 15% [36]. The effect on crop cycle length on actual yield change is incorporated within the projected effects of CO_2 and ground level ozone increase.

Modeling atmospheric temperature increase versus change of actual yield

For the purpose of modeling the impact of **temperature rise** on actual yield, the selected crops have been divided into annuals (cotton, ground nut, maize, sorghum and soybean) and perennial (cassava). Under temperature rise, annual-crops' yield principally suffers from *crop cycle shortening*. Although increasing temperatures raise the daily accumulated growing degrees (GDD), which in general is associated with yield increase, overall yield is reduced due to the stronger effect of crop cycle reduction on yield.

- For **annual crops** on average, the combined outcome of GDD increase and crop cycle reduction on yield is an expected 5% yield reduction for every 1°C of average temperature increase.

The perennial cassava is both C3 and C4, an evergreen and due to average temperature increase expected to have its yield on average increased, principally due to increased average minimum temperatures mitigating associated oxidative stress. The crop cycle of perennials is not expected to change under increasing temperatures and alleviation of low temperature stress is expected to contribute positively to yield-outcome.

- For **the perennial cassava**, on average a 2.9% yield increase for every 1°C average temperature increase is projected.
- The average yield (dY_{rel}) increase per +1°C increase is a function of the average actual leaf temperature ($T_{leaf\text{-}avg\text{-}act}$). $T_{leaf\text{-}avg\text{-}act}$ is calculated as the average of the maximum and minimum daily leaf temperature: $T_{leaf\text{-}avg\text{-}act} = [T_{leaf\ max} + T_{leaf\ min}]/2$.
- $dY_{rel} = 0.66 \times T_{leaf\text{-}avg\text{-}act}^{-1}$.
- As an estimation, actual average leaf temperature can be derived from the actual average air temperature minus 3°C.

Conclusions

A Resume in table-form which brings us back to the title of this document: "Impact of midcentury climate change on crop yield in Mozambique. Effect of rise in temperature, back ground ozone and atmospheric CO2, a layer approach".

Crop	Sensitivity factor for ozone	Back ground Ozone +15 a 30 ppb			Atmospheric CO_2 +178 ppm (550 ppm)			Surface Air Temperature +1.8 a 2.4 °C			Sum		
		+15 ppb O_3	**+23 ppb O_3**	+30 ppb O_3	+15 ppb O_3	**+23 ppb O_3**	+30 ppb O_3	+1.8 °C	**+2.1 °C**	+2.4 °C	Min total	**Med total**	Max Total
Cotton	1.6	-24%	**-37%**	-48%	+21%	**+27%**	+33	-9%	**-11%**	-13%	-12%	**-21%**	-28%
Soybean	1.2	-18%	**-28%**	-36%	+16%	**+20%**	+25	-9%	**-11%**	-13%	-11%	**-19%**	-24%
Groundnut	0.6	-9%	**-14%**	-18%	+8%	**+10%**	+12	-9%	**-10%**	-12%	-10%	**-14%**	-18%
Cassava	0.6	-9%	**-14%**	-18%	+8%	**+10%**	+12	+5%	**+6%**	+7%	+4%	**+2%**	+1%
Maize	0.4	-6%	**-9%**	-12%	+5%	**+7%**	+8	-10%	**-13%**	-15%	-11%	**-15%**	-19%
Sorghum	0.4	-6%	**-9%**	-12%	+5%	**+7%**	+8%	-8%	**-10%**	-11%	-9%	**-12%**	-15%

Table 3 : Resume: Impact of midcentury climate change on crop yield in Mozambique. Effect of rise in temperature, back ground ozone and atmospheric CO2, a layer approach.

Although ground level Ozone and atmospheric CO2 are given their individual column or "layer", it has become clear that these two factors are inter-linked and therefore not independent when it comes to their effect on crop yield. The "feeding" or "ozone-compensating" effect of +178 ppm CO2 on yield is therefore presented per expected minimum, average and maximum back ground ozone increase. The figures show that the projected minimum increase of +15 ppb for mid-century back ground ozone already annuls the effect of 178 ppm atmospheric CO2 increase on yield. This challenges the peace of mind. One might think to have found in the CO_2 component of the greenhouse effect a merely crop yield increasing. The negative effects on crop yield of ground-level ozone increase above +15 ppb and the full negative effect of temperature increase go uncompensated by the expected atmospheric CO_2 increase (!).

Einstein: “It is the theory that decides what we can observe”.

If we accept the net result of photosynthesis and respiration as the process responsible for turning our earth atmosphere aerobic and maintaining it at actual levels, perturbation of the carbon use efficiency must be expected to reverse this dynamic balance. Although we graphically “see” a link between the anthropogenic CO_2 production and the atmospheric CO_2 increase, the causal link can be the associated anthropogenic oxidative loading of the atmosphere responsible for reducing vegetation carbon use efficiency. In other words, atmospheric CO_2 increases mainly due to perturbed carbon use efficiency.

Recommendations
Depending on the feasibility, humanity will timely come to understanding and jointly succeed in reducing their cumulative loading of the atmosphere with components, principally NOx & NH4 that cause oxidative stress in terrestrial vegetation including crops.

- For Mozambique and neighboring countries the focus should be on NOx reduction, stopping *uncontrolled* hot-combustion processes, principally biomass burning.

Alternatively it has priority to find solutions that help to maintain or even increase yield under the circumstances of projected climate change.

- Crop selection together with cultural measures that increase crops tolerance towards oxidative stress should have priority.

As total oxidative stress is the sum of the individual components responsible, including back ground ozone, cassava is an example of how mitigation of oxidative stress from low-temperatures can result in actual yield-increase.

1. Mitigation of oxidative stress from low-temperatures (e.g. Cassava).

A shift from rain-fed towards irrigated agriculture is a measure that reduces oxidative stress from drought, increasing the tolerance towards other oxidative stress components.

2. Mitigation of oxidative stress from drought: shift from rain-fed towards irrigated agriculture (All Crops).

As crops are specifically sensitive towards oxidative stress during their juvenile phase, mitigation of high ozone events from for example periods of large scale biomass-burning can result in significant conservation of their yield-potential.

3. Mitigation of oxidative stress from ozone: Early planting, before the start of the burning season (All Crops).

A shift from rain-fed towards irrigated agriculture makes it possible to select low ozone seasons for planting that otherwise would be limited due to lack of water.

4. Mitigation of oxidative stress from ozone: by shifting from rain-fed towards irrigated agriculture selecting a low ozone season for planting (All Crops).

In plant nutrition as well as in human nutrition, a joint selective group of micro-elements including but not limited to zinc, selenium and sulphur, is associated with anti-oxidant capacity. Under the circumstances of predicted climate change it becomes increasingly critical to assure adequate levels of these elements. Soil analyses should include these elements and attention should be given as to how to interpret and translate the numbers into area specific fertilizer programs.

5. Soil analyses should include the elements associated with anti-oxidant capacity (including but not limited to Zn, Se, S) and attention should be given as to how to interpret and translate the numbers into area specific soil corrections and fertilizer programs (All Crops).

We should also realize crops not only provide food in a caloric sense but are at the start of the food-chain also to assure sufficient availability of essential elements up-chain thereby preventing perturbations associated with deficiency of these elements. UNICEF states: “Zinc deficiency has been identified as a significant public health problem contributing to the deaths of about 450,000 children each year, and approximately 800,000 deaths overall. Worldwide, some 2 billion people are at risk of zinc deficiency.” [49].

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