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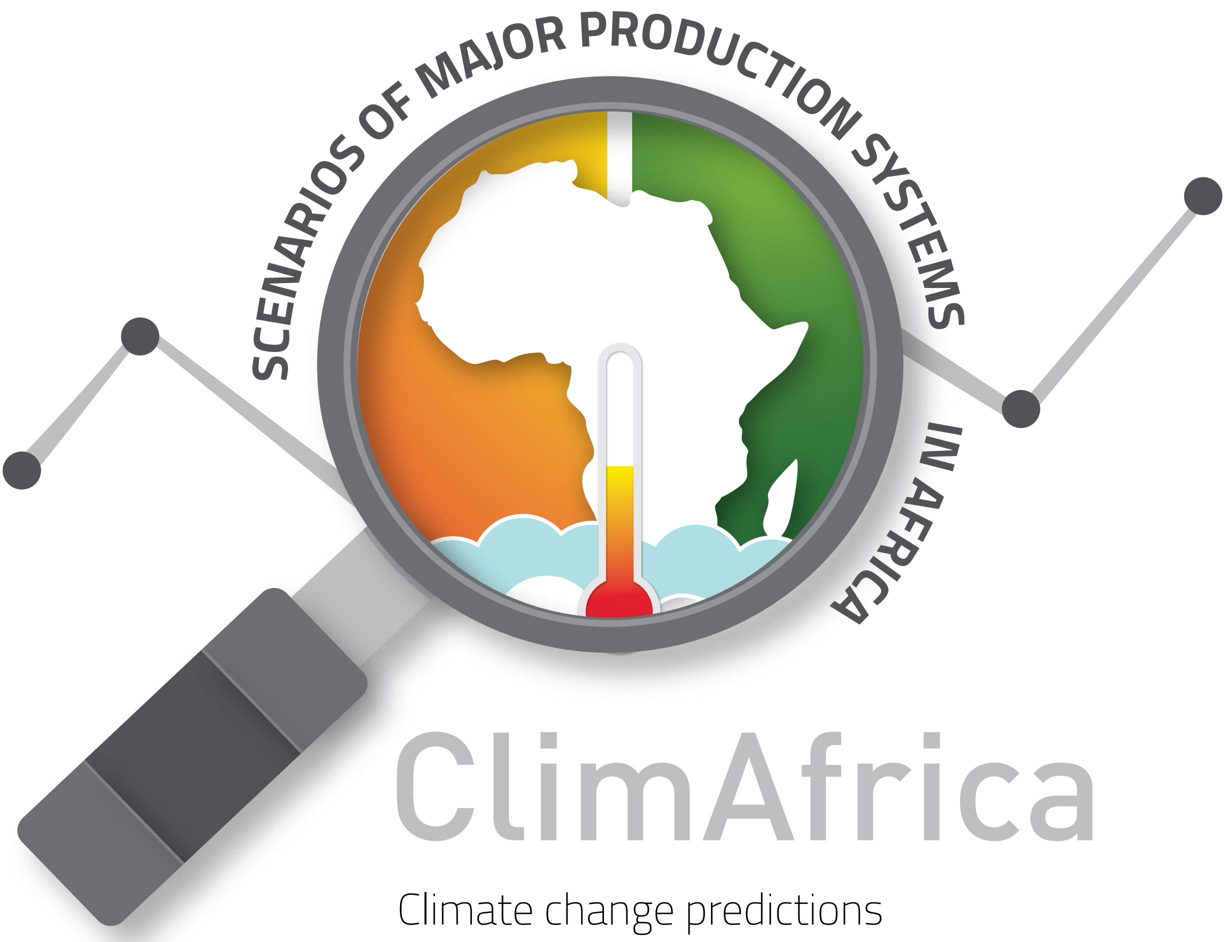

ClimAfrica

Climate change predictions in sub-Saharan Africa: impacts and adaptations

Scenarios of the major production systems in Africa

ClimAfrica

Climate change predictions in sub-Saharan Africa: impacts and adaptations

Food and Agriculture Organization of the United Nations - Rome, 2017

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1. INTRODUCTION

1.1 Short summary

This document was produced in the frame of the FAO led Work Package no. 4 of the ClimAfrica project, funded by the European Commission. It provides an improved understanding of the current dynamics of major food production systems in Africa (up to 2020) and develop a set of conditional vulnerability scenarios based on current agricultural and socio-economic trends to be used to assess impactsunder the ClimAfrica project. The methodological approach is based on the FAO methodology for framework for land evaluation and agro-ecological zoning to develop scenarios of major production systems in sub-Saharan Africa.

Three main indicators are used to analyse a number of models and scenarios which include dynamic land use, climate, and CO_2 fertilization effects, considering sliding 30 year long-term averages (LTA), such as anomaly analysis (for 3 future periods) for 9 crops (rainfed and irrigated) and 40 parameters derived from the agro-climatic and climatic models outputs; changes suitability analysis for 12 major crops combining the FAO ECOCROP database with the agro-climatic parameters; shifts in Agro-Ecological Zones (AEZ) due to climate change and variability. The outputs of this delivery include a number of spatial datasets, tabular information, metadata and technical report which is included as an Annex to this report. This deliverable provides important information for all the tasks under work package 4 as well as for the tasks of the other work packages.

1.2 Rationale

This document was produced in the frame of the FAO led Work Package no.4 of the ClimAfrica project, funded by the European Commission. It provides an improved understanding of the current dynamics of major food production systems in Africa (up to 2020) and develop a set of conditional vulnerability scenarios based on current agricultural and socio-economic trends to be used to assess impacts under the ClimAfrica project.

The specific tasks include:

- systematically identity and collate relevant variables/indicators with appropriate resolution to be considered for the analysis of the scenarios of major productions systems in Africa. This includes analysis and validation of the data and indicators provided by the other work packages from the ClimAfrica project and other available datasets from other data sources covering climate, biophysical and socio-economic data;
- harmonise the collected data into homogenous database in terms of resolution, mapping units, format etc., and conduct analysis to draw relevant value added indices of agro-climatic indicators and impact indicators;

- develop, test and finalize models to analyse the correlation between various indicators and their predicted impacts to analyse the impacts on major production systems in Africa and offer a number of adaptation options;
- produce high resolution data, metadata and maps of threats the scenarios of major production systems in Africa.

We used the outputs from other ClimAfrica work packages and also uses own data. Moreover, it integrates and harmonizes the deliverables from the other work packages with existing data and information to be used as inputs to develop improved vulnerability assessment and optimal adaptation options. In the process the outputs from other work packages were also validated for consistency and a number of issues with previous versions of the datasets were reported, ultimately contributing the delivery of consistent and harmonized datasets.

2. FULL DESCRIPTION

In order to understand better the current dynamics of major food production systems in Africa under various climate change and variability scenarios we developed a model that examines the impact of projected climate change on major agricultural production systems for 12 crops, for two water regimes, (irrigated and rainfed croplands), 18 agro-ecological zones, 16 farming systems, taking into account protected areas, water bodies, urban areas, barren areas and forest areas at sub-national level for sub-Saharan Africa. Modelled yields are calculated with and without CO_2 fertilization effects.

The study area covers all Africa. However, the presentation of the charts and the analysis of the results focuses on the 10 countries selected for the case studies implementation, i.e. Burkina Faso, Ghana, Togo, Sudan, Ethiopia, Congo, the United Republic of Tanzania, Kenya, Malawi, and South Africa. The data, the methodology and the results of the analysis are presented respectively in sections 2.1, 2.2 and 2.3.

2.1 Data

Climatic data and agro-climatic parameters coming respectively from WP1 and WP3 have been selected for the analysis. Socio-economic datasets coming from WP5 are used in the vulnerability analysis. In addition, FAO internal datasets are used such as the land cover database, global agro-ecological zones, ecocrop, livestock density, population density, stunting index database. External datasets are also considered such as Farming Systems update 2012.

2.1.1 Climate data

The following climatic parameters coming from WP1 are considered: the daily precipitation, the minimum and the maximum air temperature (Tmin and Tmax), and the daily mean temperature, i.e. (Tmax+Tmin)/2. The dataset used is the MIROC5 (RCP8.5) data rescaled to 0.5 degree.

2.1.2 Agro-climatic model outputs

Two models are selected to provide agro-climatic outputs at 0.5 degree: LPJ-Guess and LPJ-ml. Specific agro-climatic parameters coming from the WP3 models are considered (Annex 1). Most of these parameters are provided for nine major crops that are rainfed or irrigated: Rice, Maize, Millet, Pulses, Wheat, Maniok, Sugarbeet, Potatoes, Treenut. They are provided on a monthly, seasonal or annual basis (Annex 1). Two scenarios were used for the agro-climatic projections: B-01 (CO_2 on) and B-02 (CO_2 constant after 2000) for this analysis.

2.1.3 Soil dataset

Six parameters coming from the Harmonized World Soil Database v 1.2 (2012) are used for the suitability analysis and the AEZ changes assessment (see section 2.2.5): the texture, the depth, the drainage, the salinity, the fertility, and dominant soil type.

2.1.4 The ECOCROP dataset

The ECOCROP dataset (http://ecocrop.fao.org/ecocrop/srv/en/cropFindForm) has been used to characterise the suitable (or absolute) and optimum (climate, soil) conditions for 1710 crop types. Twelve crops have been selected for the analysis (section 2.2.4).

2.1.5 Socio-economic data

Three sources have been selected for describing the socio-economic conditions:

- FAOSTAT is used for extracting the annual population from 1961 to present and the projected population up to 2050. Based on these data, the growth rate of population for each 30-year period between 1961 and 2050 (see timelines in section 2.2.1) is derived;
- two parameters from the Food Insecurity, Poverty and Environment Global (FGGD) GIS Database: (i) the prevalence of stunting among children under five, by lowest available subnational administrative unit and (ii) the Global Population Density Estimates, 2015 (FAO 2005) available at FAO GeoNetwork www.fao.org/geonetwork;
- the WP5 outputs were used to characterize the vulnerability of two studies areas: (i) West Africa group: Benin, Burkina Faso, Côte d'Ivoire, Ghana, and Togo, (ii) and East Africa group: Sudan, South Sudan, Uganda.

2.1.6 Other datasets

FAOSTAT yield values are used to correct the values estimated by the agro-climatic models by a corrective factor that integrate other effects than climate.In order to be compatible with the outputs of the models, fresh matter areconverted in dry matter (Annex A). The administrative data used in the analysis arethe GAUL datasets at level 0 (Country) and 1 (Sub-National level). In order to produce a map of Homogeneous Mapping Zones (HMZ) used for the spatial analysis, various datasets are used: the Administrative limits atLevel 1(GAUL), the agro-ecological zones (AEZ) dataset (FAO/IASSA 2012), the Farming Systemdataset (FAO 2012), the global land cover dataset (GLC-SHARE, FAO 2013), the water regime (Irrigated and Rainfed), the population (FAOSTAT), the livestockdataset, and the road density layer. The photoperiod dataset is used for the suitability analysis (section 2.2.4).

2.2 Methodology

The methodology consists of analyzing trends for various parameters (climate, yield, carbon and water fluxes, seasonality) in order to understand the dynamics of major food production systems in Africa and assess the impact of climatic changes on these systems. In order to identify these impacts mainly on water availability and yield, it is first necessary to identify hotspots of changes. For this purpose, three analysis are performed considering the different models and scenarios:

- anomaly analysis (for 3 future periods) for 9 crops (rainfed and irrigated) and 40 parameters derived from the agro-climatic and climatic models outputs;
- suitability analysis (changes) for 12 major crops combining the ECOCROP database with the agro-climatic parameters;
- agro-ecological zones (AEZ) changes between the historical and future periods.

In addition, the causes of changes are identified based on multi-variable regression/correlation maps (e.g. yield vs other factors) and time profiles are extract for the hotspot zones. Prior to the analysis, the yield values are corrected based on a regression analysis using data from FAOSTAT (section 2.2). Then the analysis described above is performed using the Homogeneous Mapping Zones (HMZ) where all the parameters are analyzed based on the indicators derived from the time series products onyield, carbon, water content from the WP1, 3, and 5, and using FAO internal datasets and external datasets.

The outputs of the analysis are then combined in order to identify changes. Hotspots of changes and shifts on major production systems are mapped as areas with significant yield reduction on the major crops primarily in rainfed cultivated, irrigated areas, drop in the crop suitability class, shifts in agro-ecological zones (decrease on LGP-equivalent and soil quality), reduction of water use efficiency (increase on water use demand), projected increase of population, increase of dietary energy supply requirements which have also a high rate of stunting amongst children under five during 2000-2010.

The methodology includes seven steps:

- the data preparation including the timelines and the spatial unit definition;
- the yield correction;
- the anomaly classification;
- the suitability analysis;

- the AEZ changes analysis;
- the regression analysis;
- the identification of hotspots.

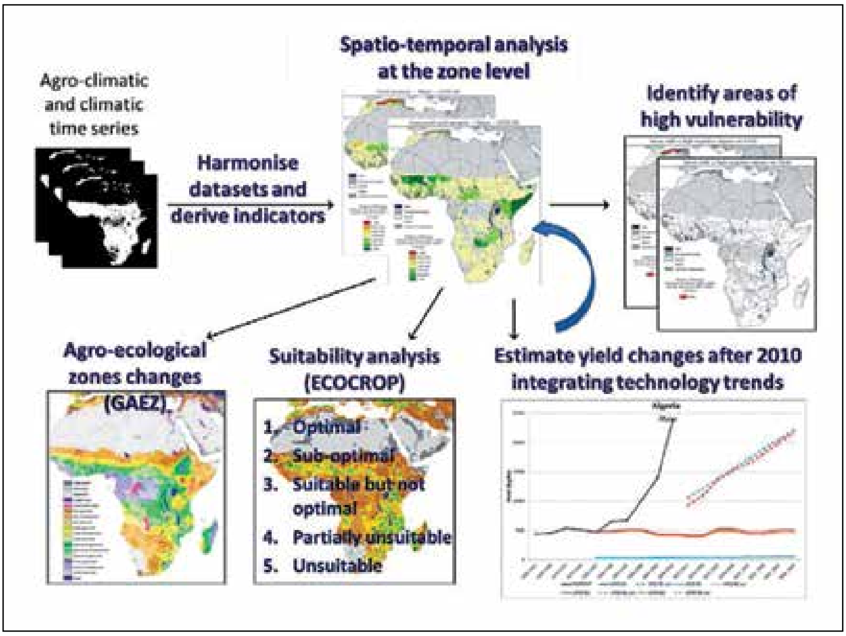


Figure 1. Presentation of the different steps of the methodology.

2.2.1 Data preparation

The analysis required some data preparation that is summarized below. The technical details are given in the Annex. First, the agro-climatic and climatic datasets are harmonised in order to facilitate the automatic processing and the subsequent analysis. This step includes the conversion of format and unit, the geographical and time period subset.

The seasonality is characterized by the start of the season (s), the length of the growing season (lgp), and the harvest date (h) of the season. Different cases are considered according to the number of growing seasons (one or two) and according if the start and harvest date occur during the same year or not (Annex A). New crop specific indicators are derived from the agro-climatic parameters (Annex A):

- the harvested area and production;
- the water use efficiency (WUE) which represents the productivity of the water utilised by the crop for yield;
- the water requirement satisfaction index (WRSI) as an indicator of crop performance based on the availability of water to the crop during a growing season;
- the aridity index (AI) as an indicator of the degree of dryness of the climate. It serves to identify regions that suffer from a deficit of available water;
- the yield values for 11 major crop groups.

Additional parameters are derived from the daily climate time series and seasonal outputs from agro-climatic models (Annex A):

- the average of the daily minimum and maximum temperature and of the daily mean temperature over the crop growing season;
- the annual cumulated precipitation;
- the annual average of the minimum and maximum temperature, and of the mean temperature;
- the temperature growing period (LGPt);
- the LGP equivalent;
- the Aridity index over the LGPt season (AI_LGPt).

Based on the previous processes, all the computed parameters are provided at the pixel level and on seasonal or year basis (Annex A). The temporal and spatial averages are computed for facilitating the various analyses.The following timelines (30 Year Long Term Averages) are used for the trend indicators:

- historical reference (1961-1990) (HIS75);
- historical (1971-2000) (HIS85);
- historical (1981-2010) (HIS95);
- current (1991-2020) (CUR);
- future (2001-2030) (FUT15);
- future (2010-2040) (FUT25);
- future (2020-2050) (FUT35).

For each LTA, a number of parameters (Annex A) are generated for two models and two scenarios, for the averages (AVG) and the standard-deviation (STDEV). In addition, 5-year (1961-1965, 1966-1970) averages are computed for the correction of yield projection versus FAOSTAT. Two mapping units are considered:

- for the yield corrections, the country limits are used (level 0) in order to be compatible with FAOSTAT values;
- for the analysis, the Homogeneous Mapping Zones (HMZ) are used.

These are characterized by similar agro-ecological zones, farming systems, land cover and water supply regime at sub-national level (section 2.1.6).

2.2.2 Yield correction

In order to estimate yield changes after 2010, it was necessary to correct the values estimated by the agro-climatic models by a corrective factor that integrate other effects than climate (technology, management, genetic improvements, use of fertilizers and pesticides, mechanization, ploughing techniques). To achieve this objective, a linear regression analysis is done between FAOSTAT time series and the estimated values for the period (1961-2010) on the 5-year averages at the country level for the 2 models, the 2 scenarios and for 9 crop groups. The input data and methodology used for this correction are presented in Annex A.

2.2.3 Anomaly analysis

Four anomaly maps between the current or future average and the historical average are derived from the LTA and STD computed for the 42 seasonal and annual parameters. Then, the spatial statistics are computed per zone and the anomaly values are classified. Based on this classification, the areas of highest changes, i.e. more than 20%, are identified for each crop, and each parameter. The input data and the technical details of the analysis are presented in Annex A.

2.2.4 Suitability analysis

The objective of this analysis is to identify which crops remain or become suitable under climate change scenarios. The methodology occurs in three steps (Annex A):

- analyse the suitability based on climatic conditions (min and max temperature over the growing period, annual cumulated precipitation) using the ECOCROP absolute and optimal conditions;
- analyse the suitability based on soil conditions using five parameters, i.e. texture, salinity, depth, drainage, and fertility;
- combine the suitability results based on climate, soil and the photoperiod.

Twelve crop species have been selected from the 40 first major crops based on the crop production (FAOSTAT 2011) that match with the 9 rainfed crops used in the agro-climatic modeling. Changes are observed between the historical and the future periods for these twelve crops.

2.2.5 AEZ changes

The changes between the historical and the future agro-ecological zones are analysed based on two indicators: the equivalent length of growing period and the AI over the LGPt season (Annex A).

2.2.6 Regression analysis

This step consists of identifying the causes of highest changes (observed in sections 2.2.3 and 2.2.4), thanks to a regression analysis on yields and water availability (WRSI) against other factors (ET, precipitation) on the zonal annual values. This analysis includes three steps:

- spatial average at the zone level on the 5-year files (individual crops);
- regression between Yield and other factors;
- correlation maps at the zone level.

2.2.7 Identification of hotspots areas

In order to identify the areas with a highest impact, the classes of highest changes (>20% and <20%) are identified and combined with the suitability classes. Weights are assigned to according to the suitability class and the combined suitability index is calculated by assigning 90% weight to the most suitable classes and by dropping the weight by 20% for each suitability class as following: 0.9* Very Suitable + 0.7* Suitable + 0.5* Moderately Suitable + 0.3* Marginally Suitable 4 + 0.1* Very Low Suitable (based on the approach of the GAEZ and FGGD). One synthetic map is produced for each crop including both extreme changes (decrease and increase) for two scenarios (pessimistic and optimistic). Then two hotspots maps are produced combining the anomaly yield hotspots of all the crops with the suitability weight.

2.2.8 Vulnerability analysis

In order to identify areas with high vulnerability, the socio-economic factors are analysed and compared with the hotspots zones. The input data are described in section 2.1.7

2.3 Results

2.3.1 Mapping Unit

The 4534 zones used in the analysis are presented in Annex A.

2.3.2 Yield corrections

The yield provided by the two agro-climatic models (lpjg and lpjm) for two scenarios (B1 and B2) have been corrected based on the FAOSTAT yield evolution from 1961 to 2010. Yield from agro-climatic models for the two scenarios are compared with yield values from FAOSTAT and the yield corrected based on FAOSTAT for each crop group (9) by country (Figure 2 and Annex A). These charts show that yield values derived from the agro-climatic models are often very different from statistics in term of level and trend. The trends can also be very different from one model to another.

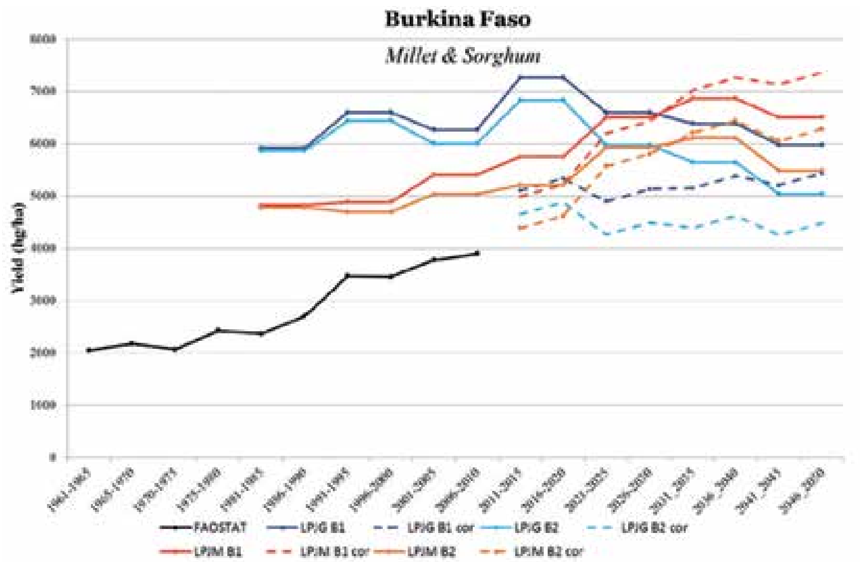


Figure 2. Comparison between yield from agro-climatic models (lpjm and lpjg) for two scenarios (B1 and B2) and yield from FAOSTAT for two crop groups, i.e. Millet & Sorghum and Maize.

The FAOSTAT data often show a high increase of yield which starts in the eighties. This increase due to technology evolution is not taken into account in the agro-climatic modelling. Therefore it is important to integrate this evolution in the yield projections. Moreover, the modelled outputs have to be calibrated with more realistic values. The projected yield values corrected with FAOSTAT are more consistent with FAOSTAT values. However, they can still be twice or 3 times FAOSTAT values in 2010. This can be explained by the slope of FAOSTAT evolution from 1961 to 2010 that can be very high and lead to unrealistic values in the future. Therefore, the corrections have not been applied when the projected values are more than twice the value of FAOSTAT in 2005-2010 or when the projected values are negative.

2.3.3 Anomaly maps

The anomaly maps represent the change (in percentage) observed between the historical period and the future period. Five classes are proposed for each parameter and each crop, from a high decrease (below 30%) to a high increase (above 30%). The normal situation is between -10% and 10%. The anomaly classifications have been produced for the 42 climatic and the agro-climatic parameters.

For all the agro-climatic parameters, they have been produced for all the crops (individual and groups), both models, and for the two scenarios. Some results are presented in Annex. The full database is available in digital format. The anomaly values for the climatic parameters, i.e. annual precipitation, mean temperature, minimum and maximum temperature, are presented in the Annex A. The results show that the highest increases for the temperature are observed in Libya and Egypt for the mean, max, and min temperatures, and in South-Africa only for the max temperature. Annex A shows examples of the evolution of these parameters in comparison with yield for the Western Cape district in South-Africa where the anomaly of the maximum temperature is high (in red on the anomaly map, Annex). The highest decreases for the precipitation are observed in North-Africa.

The yield anomalies are computed for the non-corrected values and the corrected values per individual crop for both models and scenarios. The comparison between the non-corrected and corrected values (examples in Annex A, Figures A6, A7, A8, A9) show large differences when integrating the technology trend in the yield evolution as already observed in the time profiles (section 2.3.2 and Annex A). Anomaly maps for other agro-climatic parameters are also presented in Annex A (Figure A4).

2.3.4 Suitability Analysis

The suitability analysis allowed identifying a suitability class to each crop, based on the climate conditions derived from WP5 and WP3 outputs as well as on the soil quality (Annex A).Both climate and soil classes have been combined in order to produce one suitability map for each crop and each 30-year period (historical, current, and the 3 future periods).

Based on the suitability classes for each crop, a suitability index has been derived for the twelve major crops by attributing a weigh to each suitability class (see section 2.2.7). Changes between the historical and the future periods have been identified. Figure 3 presents these changes over the suitability index for the period (2020-2050) and show that these are negligible as the majority of changes observed are below 5%. The highest decreases of suitability are observed in South-Africa (Free State and Mpumalanga districts), Botswana (Masvingo district), Algeria (Sidi Bel Abbes) and Ethiopia (Somali), whereas the highest increases of suitability are observed in Mali (Segou and Mopti) and Algeria (Bejaia).

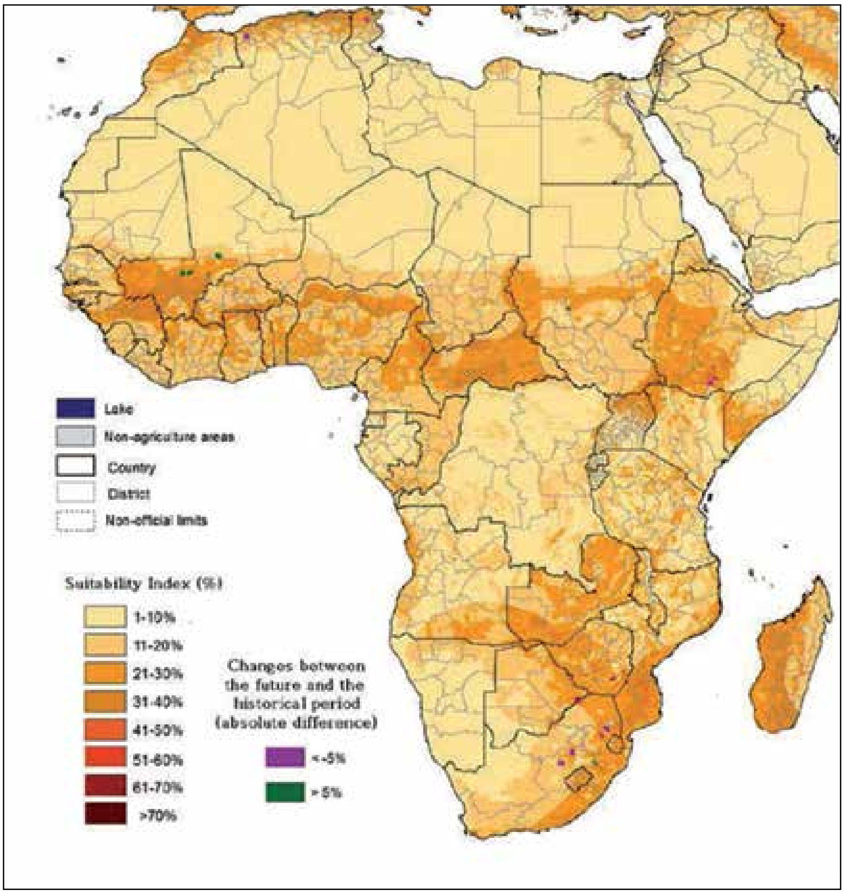


Figure 3. Suitability index for the rainfed crops in the future (2020-2050) based on the soil and climate conditions for the 12 major crops, and the changes observed between the future and the historical period.

2.3.5 Mapping shifts in AEZ due to climate change

The AEZ classification is a combination of soil and climatic conditions. The variable parameters are the agro-climatic conditions that determine the moisture regimes. These conditions are derived from the WP3 and WP5 outputs by using the LGP equivalent and the Aridity Index over the LGPt season. This analysis is done for one model (lpjm) and two scenarios as the potential evapotranspiration is provided only for lpjm.

The evolutions of moisture regimes based on the LGPeq and the AI over LGPt are respectively presented at the Figures A1 and A2 of Annex A. These classifications are quite different in particular for the humid conditions. The moisture regime classification has been combined with the soil quality index, the slope and the water regime for producing the AEZ classification for each period.The changes between the future

and the historical period have been identified for both classifications (Figure 4). The drier areas are mainly located in Ethiopia (Amhara, North of Benishangul Gumuz, DNNP, and extreme south of Oromia), Botswana, Zimbabwe, south of Mozambique and South-Africa whereas the more humid areas are mainly located in West Africa (from Mali to Sudan), Kenya and North Mozambique.

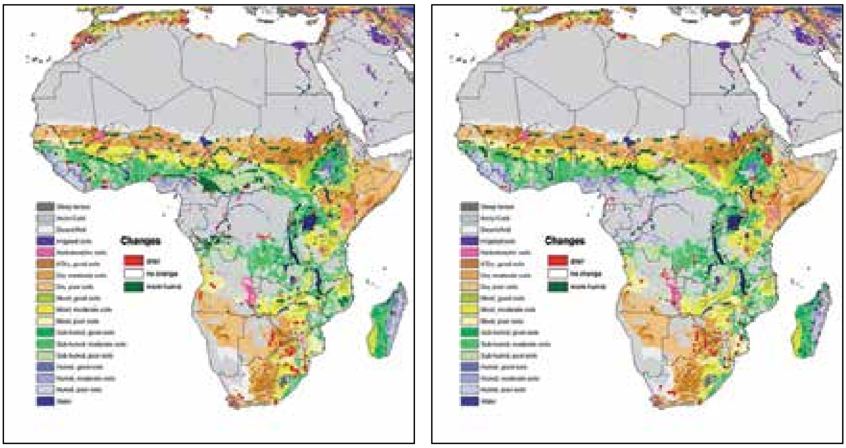


Figure 4. Changes in AEZ classes based on the LGP equivalent (left) and the AI over the LGPt.

2.3.6 Hotspots

Based on the anomaly classes, hotspots zones have been identified for each agro-climatic and climatic parameter and future period. For each crop and each period, the hotspots are represented by 5 classes (Annex A):

- zones with a high decrease (>20%) for at least one scenario;
- zones with a high decrease (>20%) for at least two scenarios;
- zones with a high increase (>20%) for at least one scenario;
- zones with a high increase (>20%) for at least two scenarios;
- zones with a contradictory information between models.

The hotspots zones of all the rainfed crops have been combined with the suitability classes as follow. The number of crops with a yield increase or decrease of more than 20% has been computed considering two suitability thresholds: one above 0% and another one above 40%. The results have been mapped (Figures 5 and 6) showing the areas with positive impact in green and the areas with a negative impact in red. One map has been produced considering at least one scenario showing the same trend and the other one considering at least two scenarios showing the same trend.

These maps show the districts where the impact of climate while considering the technology evolution should be positive or negative in the future. If we consider a relatively high suitability threshold (40%) and an agreement of two scenarios, the areas with the highest expected decrease are: the district of Savanes in Togo and the district of Melaky in Madagascar. If we consider just one scenario, we can add the districts of Lira, Kitgum, Kumi and Soroti in Uganda, Addis Ababa in Ethiopia, Sud Bandama in Cote d'Ivoire, Koulikoro in Mali, and Volta and Upper East in Ghana.

The areas with the highest expected increase are: the northern part of Ghana and the south-east part of Burkina Faso if we consider an agreement between scenarios. If we consider just one scenario, we can add the districts of Segou and Kayes in Mali, Ghana, Mamou and Labe in Guinea, a major part of Burkina Faso, the north of Nigeria.

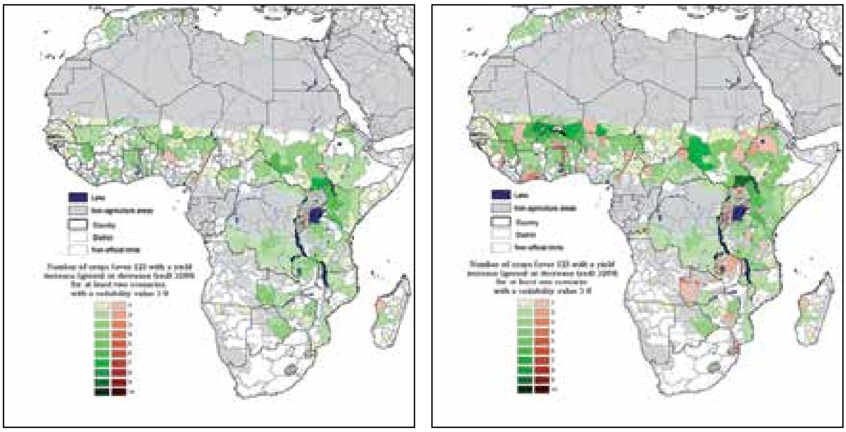


Figure 5. Hotspots zones in the future (2020-2050) for the major rainfed crops when considering at least two scenarios (left) or only one scenario (right) showing the same extreme yield changes. The intensity of the color represents the number of crops with a yield increase or decrease above 20% and with a suitability value above 0%. The red colors represent a yield decrease whereas the green colors represent a yield increase.

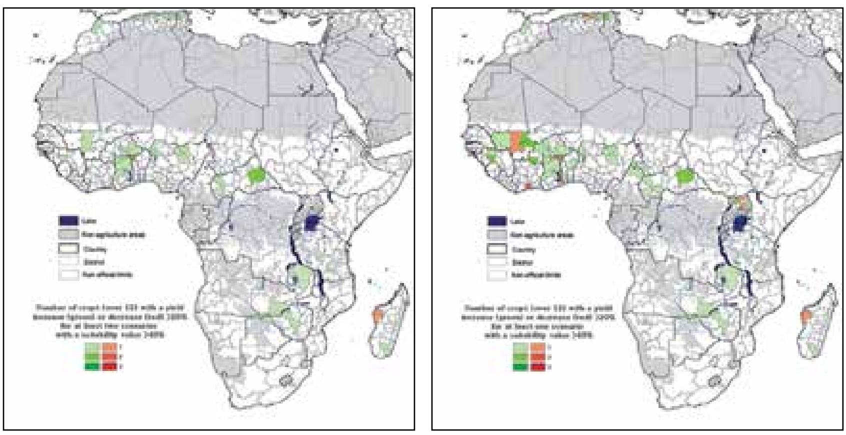


Figure 6. Hotspots zones in the future (2020-2050) for the major rainfed crops when considering at least two scenarios (left) or only one scenario (right) showing the same extreme yield changes. The intensity of the color represents the number of crops with a yield increase or decrease above 20% and with a suitability value above 40%. The red colors represent a yield decrease whereas the green colors represent a yield increase.

2.3.7 Changes per country

The anomaly values (relative difference) for all the parameters, for both models and scenarios and for all the crops have been extracted at the country level. Tables synthetizing these figures have been produced for each country (Annex A). Only the more represented crops, i.e. more than 500 ha, are represented.

2.3.8 Regression analysis

The correlation coefficients between Yield and other factors have been computed at the zone level and classified in 5 classes (Annex A). These correlations allow identifying the causes of a negative or positive impact of climate on yield. In particular, we can observe that the increase of temperature has a positive impact notably in Ethiopia, in the south of South-Africa, in the western part of Kenya and Angola, whereas it has a negative impact on yield in Congo, in the eastern part of Madagascar, and from Senegal to South-Sudan between 3° and 14° North. In particular, in the district of Savanes in Togo, the high yield decrease observed is mainly due the temperature increase (coefficient of correlation of -0.83 with Tmin). Similarly in the Northern district of Sierra Leone, a high correlation is observed between the yield decrease for Maize and the increase of temperature (coefficient of correlation -0.92 with Tmin). The evolution of these two factors in comparison with the precipitation is presented in Annex A. At the opposite, in the district of Amhara in Ethiopia, the increase of temperature lead to a yield increase for Maize (0.92 with Tmin).

On the other hand, the precipitation changes (increase or increase) are highly correlated with yield in higher latitudes between 9° and 15° mainly in Senegal, North of Mauritania, Sudan and Eritrea, as well as in the United Republic of Tanzania. In particular, in the district of Dodoma in the United Republic of Tanzania, the yield increase observed for Maize is mainly due to precipitation increase (coefficient of correlation of 0.8) whereas in the district of Southern Kordofan in Sudan, the yield for Maize has been affected by the reduction of precipitation (coefficient of correlation of 0.77).

2.3.9 Vulnerability analysis

Three socio-economic factors have been selected at the national and sub-national level: the annual population growth derived from the FAOSTAT dataset (current and future), the vulnerable population from FGGD and from WP5 for two studies areas and the density population from FGGD. The countries that are characterized by a high annual population growth, a high prevalence of stunting among children under five and a high population density are Nigeria and Ethiopia. The United Republic of Tanzania and the Democratic Republic of Congo are also characterized by a high annual population growth and a high prevalence of stunting among children under five but the population density is lower.

Based on these factors, Nigeria and Ethiopia are higly vulnerable. However these are not characterized by high yield decrease for the crops that are more suitable. In Nigeria, the FCT Abuja district should present a high decrease for Maize and Wheat but the suitability for these crops is respectively 35% and 10%. In Ethiopia, the Amhara district should present a high decrease for Wheat but the suitability for this crop is only 21% and the district of Benishangul Gumuz should present a high decrease for Rice but the suitability is only 24%. However, it is important to mention that these two districts should be affected by drier conditions with regards to the agro ecological zones analysis (see section 2.4.6).

The districts that are characterized by the highest yield decrease for the more suitable crops, i.e. Savanes in Togo and Melaky in Madagascar are also characterized by a high percentage of stunted children (respectively 48% and 39%), and a relatively high population density for Togo (129 persons per square kilometre in the north of the district).

Many districts in Uganda are also characterized by a high yield decrease, a high density population and between 30 and 40% of stunted children. The district of Sud Bandama in Cote d'Ivoire that could be affected by a high decrease of yield (according to one scenario) is not characterized by a high density population or vulnerable population. On the other side, the district of Koulikoro in Mali is quite vulnerable as it could be affected by a high yield decrease and is already characterized by 36% of stunted children.

The districts of Volta and Upper East in Ghana could be also affected by a high decrease of yield (according to one scenario) and are characterized by a relatively high density population, respectively 36% and 25% of stunded children, and a vulnerable population according to WP5. Finally, amongst the vulnerable populations, it is important to mention areas where the population is considered as vulnerable but where the impact of climate and technology evolution should be positive in the future:

- the northern part of Ghana that is characterized by 39 of stunted children, should present a high yield increase considering two scenarios;
- the Est district of Burkina Faso (characterized by 35% of stunted children) should present a high yield increase considering two scenarios;
- the districts of Kebbi, Jigawa, Kano, Bauchi in the north of Nigeria (characterized by a high percentage of stunted children, and a high growth population) should present a high yield increase but considering only one scenario.

3. CONCLUSION

The objective of the WP 4.1 consisted of understanding the current dynamics of major food production systems in Africa (up to 2050), and develop a set of conditional vulnerability scenarios based on current agricultural and socio-economic trends to be used to assess impacts under the ClimAfrica project. The main goal for this output was to prepare the methodological framework for the analysis of scenarios of major production systems in Africa. However, the current available datasets are found to be at a very coarse resolution and the limited number of crops available is a limitation in the interpretation of the actual results. It is suggested that the spatial resolution of the datasets from the other work packages is further enhanced using various methodologies for downscaling.

Relevant variable/indicators with appropriate resolution to be considered for the analysis of the scenarios of major productions systems in Africa have been identified and collected. This included the analysis and validation of the data and indicators provided by the other work packages from the ClimAfrica project (mainly WP1, 3 and 5) and other available datasets from other data sources covering climate, biophysical and socio-economic data. All the internal and external datasets have been harmonised into homogenous database in terms of resolution, mapping units, format etc., and relevant value added indices of agro-climatic indicators and impact indicators have been computed.

Appropriate models have been developed, tested and finalized to analyse the trends of 43 climatic and agro-climatic parameters (precipitation, yield, carbon and water fluxes, seasonality) in order to identify hotspots of changes. Prior to the analysis, the values estimated by the agro-climatic models have been corrected based on a regression analysis with FAOSTAT values. The objective was to integrate other effects than climate (technology, management, genetic improvements, use of fertilizers and pesticides, mechanization, ploughing techniques) in order to come with more realistic trends and yield estimations.

Then, hotspots of changes have been identified based on **three types of analysis** performed considering the different models and scenarios, at the pixel, the zone and the country level:

- **anomaly analysis** (for 3 future periods) for 9 crops (rainfed and irrigated) and 43 parameters derived from the agro-climatic and climatic models outputs;
- **suitability changes analysis** for 12 major crops combining the ECOCROP database with the agro-climatic parameters;
- **agro-ecological zones (AEZ) change analysis**.

The outputs of these analysis have been combined in order to identify the highest changes. Hotspots of changes and shifts on major production systems have been mapped as areas with significant yield reduction on the major crops primarily in rainfed cultivated, irrigated areas, drop in the crop suitability class, shifts in agro-eco-

logical zones (decrease on LGP-equivalent and soil quality), and reduction of water-use efficiency (increase on water use demand). In addition, the causes of changes have been identified based on a regression analysis (yield vs other factors) and time profiles have been extracted for the hotspot zones. Finally, socio-economic factors (increase of population, the vulnerable population, and the density population) have been analysed, mapped, and compared with the hotspots areas in order to identify vulnerable populations.

The anomaly maps (representing the relative changes observed between the historical period and the future period) allowed to identify the areas where the impact of climate (combined with the technology trend for the yield parameter) is the highest for both models, the two scenarios, and for all parameters. The comparison between the non-corrected and corrected values has shown large differences when integrating the technology trend in the yield evolution.

The analysis of changes in suitability has shown negligible changes. Preliminary results with the limitations on the datasets explained earlier indicate that the highest decreases of suitability for the main rainfed crops are observed in South-Africa (Free State and Mpumalanga districts), Botswana (Masvingo district), Algeria (Sidi Bel Abbes) and Ethiopia (Somali), whereas the highest increases of suitability are observed in Mali (Segou and Mopti) and Algeria (Bejaia).

The analysis of changes in agro-ecological zones has shown areas with drier and more humid conditions based on two indicators, i.e. the LGP equivalent and the Aridity Index over the LGPt season. Drier areas (between the future and the historical period) are mainly located in Ethiopia (Amhara, North of Benishangul Gumuz, DNNP, and extreme south of Oromia), Botswana, Zimbabwe, south of Mozambique and South-Africa whereas the more humid areas are mainly located in West Africa (from Mali to Sudan), Kenya and North Mozambique.

The regression analysis allowed identifying the individual effects of each climate factor on yield. In particular, the analysis highlighted the areas where the increase of temperature has a positive impact on yield and the areas where the increase of temperature has a negative impact on yield. Similarly the areas where the precipitation changes have a positive or negative impact on yield have been identified.

The hotspots zones of all the rainfed crops have been combined with the suitability classes as follow. The number of crops with a yield increase or decrease of more than 20% has been computed considering two suitability thresholds: one above 0% and another one above 40%. The results have been mapped showing the areas with positive impact in green and the areas with a negative impact in red. One map has been produced considering at least one scenario showing the same trend and the other one considering at least two scenarios showing the same trend.

The combination of all the results with the socio-economic factors allowed identifying districts where a vulnerable population will have to face off negative impacts of climate despite the technology evolution. These districts are: Savanes in Togo, Melaky in Madagascar, the districts of Soroti, Kitgum, Lira, and Kumi in Uganda, the district of Koulikoro in Mali, and the districts of Volta and Upper East in Ghana.

On the other hand areas where the population is considered as vulnerable but where the impact of climate and technology evolution should be positive in the future have also been identified: the northern part of Ghana, the Est district of Burkina Faso, and the districts of Kebbi, Jigawa, Kano, Bauchi in the north of Nigeria. Despite a comprehensive approach combining a large number of data, from different sources to come with final hotspots areas, these results should be interpreted with caution. Indeed, the analysis is still limited by the quality of the input data, i.e. coarse spatial resolution, few number of crop types, incomplete dataset, the inacurracy of some model outputs values and/or their inconsistency with realistic values. The methodology has been developed in order to reduce some of these limitations but some inaccuracies still remain. Finally, the methodology developed is quite flexible in some improvements could be considered in the future, like the integration of more scenarios or models, and the use of uncertainties.

ANNEX 1

TECHNICAL DOCUMENTATION

1. List and description of agro-climatic parameters selected for the analysis

	Name	Model	Description	Fq	Unit	Crop Specific
1	Co_2	lpjm-lpjg	Co_2	annual	ppm	
2	harea_sea	lpjm	harvest area	year 2000	% of pixel	y
3	hdate_sea	lpjm-lpjg	harvest date for the two growing seasons	seasonal	julian day	y
4	lgpxx_sea	lpjm-lpjg	lenght of the growing season	seasonal	julian day	y
5	yield_sea	lpjm-lpjg	yield	seasonal	kg C (dry) m-2	y
6	moff_sea	lpjm-lpjg	runoff	seasonal	mm	y
7	vegcx_sea	lpjm-lpjg	total carbon (vegetation at harvest)	seasonal	kg C m-2	y
8	swcn1_sea	lpjm-lpjg	soil water content - surface	seasonal	mm	y
9	swcn2_sea	lpjm-lpjg	soil water content - baseflow	seasonal	mm	y
10	swcn3_sea	lpjm	soil water content - drainage	seasonal	mm	y
11	etotx_sea	lpjm-lpjg	actual evapotranspiration	seasonal	mm	y
12	petxx_sea	lpjm-lpjg	potential evapotranspiration	seasonal	mm	y
13	petxx_mon	lpjm	potential evapotranspiration	monthly	kg m-2 s-1	n
14	irrig_sea	lpjm-lpjg	irrigation supply	seasonal	mm	y
15	gppx_sea	lpjm-lpjg	ground primary productivity	seasonal	kg C dry m-2	y

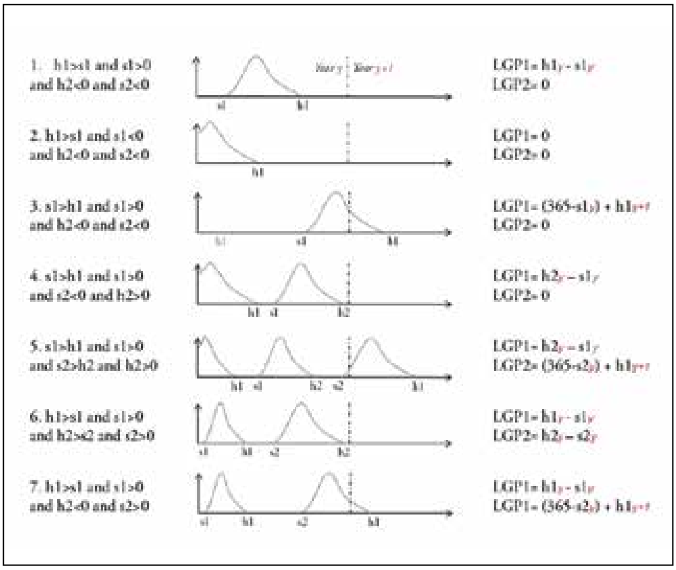
2. Conversion rates from fresh matter to dry matter for each FAOSTAT crop

Crop FAOSTAT	Conversion Factor
Rice, paddy	0,875
Wheat	0,875
Millet	0,9
Sorghum	0,88
Fonio	0,8875
Maize	0,87
Barley	0,8875
Popcorn	0,8875
Rye	0,8875
Oats	0,8875
Buckwheat	0,8875
Triticale	0,8875

Crop FAOSTAT	Conversion Factor
Canary seed	0,8875
Mixed grain	0,8875
Cereals, nes	0,8875
Pulses, Total + (Total)	1
Roots, tubers, Total + (Total)	0,3
Sugar beet	0,14
Quinoa	0,3
Jute & jute-like fibres + (Total)	0,35
Fibre crops Primary + (Total)	0,35
Treenuts, Total + (Total)	0,35
Oilcrops Primary + (Total)	0,225
Vegetables Primary + (Total)	0,15

Crop FAOSTAT	Conversion Factor
Vegetables & melons, Total + (Total)	0,15
Fruit escl. melons, Total + (Total)	0,15
Citrus fruit, Total + (Total)	0,15
Oilcakes Equivalent + (Total)	0,225
Rapeseed	0,9
Sunflower	0,9
Soybean	0,9
Cotton	0,35
Oil palm	0,225
Ground nut	0,67

3. Illustration of the 7 possible seasonality cases considering maximum 2 growing seasons



4. Computation and description of new indicators

Three indices related to crop water requirements and use efficiency are derived from the agroclimatic parameters: the Water Use Efficiency (WUE), the water requirement satisfaction index (WRSI), and the aridity index (AI).

- The WUE represents the productivity of the water utilised by the crop for yield, and has been often taken as an important comprehensive index (Eck, 1986; Wang, 1987; Turner, 1987; You and Wang, 1992; Hunsaker et al., 1996). One of the goals in water-saving farming is to seek a high value of WUE.
  WUE_sea = yield_sea /etot_sea.

- The water requirement satisfaction index (WRSI) is an indicator of crop performance based on the availability of water to the crop during a growing season. Verdin and Klaver (2002) and Senay and Verdin (2003) demonstrated a regional implementation of WRSI in a grid cell

based modeling environment. WRSI for a season is based on the water supply and demand a crop experiences during a growing season.

WRSI_sea = (etot_sea / pet_sea) X 100.

- The aridity index (AI) is an indicator of the degree of dryness of the climate. It serves identifying regions that suffer from a deficit of available water. Two AI are calculated, a seasonal index and an annual index.

  AI_sea = prec_ann / pet_sea (crop specific)

  AI_ann = prec_ann / pet_ann (non-crop specific)

  where pet_sea is the potential evapotranspiration over the growing season (crop specific), pet_ann the potential evapotranspiration over the year (per gridcell) and prec_an is the average annual precipitation (UNEP, 1992).

The crop area and production values are computed per pixel using the harvest area and yield value as follows:

- Crop Area (ha/pixel) = (5000 X lufrac) X cftfrac
- Production (hg/pixel) = Crop Area X yield X 10000 (m^2 to ha) X 10 (kg to ha)

The production is computed in hg in order to be comparable with FAOSTAT yield values.

The production and crop area for the 18 rainfed and irrigated crops are clustered in 11 groups as described in the following table.

	Group name	Abbreviation	FAOSTAT crop types	FAO code
1	Rice	TrRi rf+ir	Rice paddy	27
2	Maize	TeCo rf+ir	Maize	56
3	Tropical Cereals (Millet, Sorghum)	TrMi rf+ir	Millet, Sorghum, Fonio	79, 83, 94
4	Temperate Cereals (Wheat, Barley)	TeWW rf+ir	Barley, Wheat, Mixed grain, Oats	44, 15, 89, 101, 108 103, 75, 68, 71, 97
5	Pulses	TePu rf+ir	Pulses	1726
6	Root Crops	TrMa, TeSb, TeSo rf+ir	Roots and Tubers	1720
7	Others (Oil crops, Fibre crops, fruits...)	TrPe rf+ir	Fruits, Fibre Crops, Treenuts Vegetables, Oilcrops...	others
8	C4 crops	TeCo, TriMi rf+ir	Maize, Millet, Sorghum, Fonio	56, 79, 83, 94
9	C3 crops	TriPe, TePu, TrRi, TeWW, TeSb TrMa, TeSo rf+ir	all axcept C4 crops	all minus (56, 79, 83, 94)
10	Tot irrigated	Tot ir		
11	Tot rainfed	TrPe, TePu, TrRi, TeWW, TeSb TrMa, TeSo, TeCo, TrMi rf		

The clustering consists of summing the production and crop area of the different crops on a yearly basis.

Additional parameters are derived from climate time series and seasonal outputs from agro-climatic models:

- **the average of the daily minimum temperature** (tmin_sea) from the daily (meteo) time series (at the pixel level) for the crop growing season (determined by lgp crop specific, see section 2.2.1b);
- **the average of the daily maximum temperature** (tmax_sea) from the daily (meteo) time series (at the pixel level) for the crop growing season (determined by lgp crop specific, see section 2.2.1b);
- **the average of the daily mean temperature** (tavg_sea) from the daily (meteo) time series (at the pixel level) for the crop growing season (determined by lgp crop specific, see section 2.2.1b);
- **the annual cumulated precipitation** (prec_an) from the daily (meteo) time series (at the pixel level);
- **the annual average of the minimum temperature** (tmin_an) from the daily (meteo) time series (at the pixel level);
- **the annual average of the maximum temperature** (tmax_an) from the daily (meteo) time series (at the pixel level);
- **the annual average of the mean temperature** (tavg_an) from the daily (meteo) time series (at the pixel level);
- **the temperature growing period** (LGPt) is calculated with reference to a temperature threshold, below which there is a no growing period, in this case 5°C (278.15K). It is derived from the daily mean temperature;
- **the LGP equivalent (LGPeq):**

$$LGPeq = \begin{cases} 14.0 + 293.66 \times \left(\frac{P}{ETo}\right) - 61.25 \times \left(\frac{P}{ETo}\right)^2 & ; \quad when \left(\frac{P}{ETo}\right) \leq 2.4; \\ 366 & ; \quad when \left(\frac{P}{ETo}\right) > 2.4; \end{cases}$$

P is defined as the annual cumulated precipitation (prec_an) and ETo like the potential evapotranspiration during the year (pet_ann);

- **the Aridity index over the LGPt season** (AI_LGPt) is the aridity index averaged over the temperature growing period. It is derived from the daily precipitation, the mean temperature, and the monthly the potential evapotranspiration (converted in daily value but constant over the month).

5. List and description of the parameters used for the analysis

	Name	Model	Description	Fq	Unit	Scale	Crop Specific
1	Co_2	lpgm-lpjg	Co_2	annual	ppm		n
2	harea_sea	lpjm	harvest area	year 2000	% of pixel		y
3	carea_sea	lpjm	crop area = harvest area *5000	year 2000	ha		y
4	carea_sea	lpjm	crop area per group (11) = sum of ind. crop areas	year 2000	ha		y
5	hdate_sea	lpjm-lpjg	harvest date for the two growing seasons	seasonal	julian day		y
6	lgpxx_sea	lpjm-lpjg	lenght of the growing seasons	seasonal	julian day		y
7	sdate_sea	lpjm-lpjg	sowing date for the two growing seasons	seasonal	julian day		y
8	yield_sea	lpjm-lpjg	Yield	seasonal	hg/ha		y
9	prodx_sea	lpjm-lpjg	production = carea X yield	seasonal	hg (dry)		y
10	prodx_sea	lpjm-lpjg	production per group (11) = sum of ind. crop productions	seasonal	hg	/100	y
11	ycorx_sea	lpjm-lpjg	yield corrected based on FAOSTAT	seasonal	hg/ha		y
12	rnoff_sea	lpjm-lpjg	runoff	seasonal	mm		y
13	vegcx_sea	lpjm-lpjg	total carbon (vegetation at harvest)	seasonal	hg/ha		y
14	swcn1_sea	lpjm-lpjg	soil water content - surface	seasonal	% of pore volume	x100	y
15	swcn2_sea	lpjm-lpjg	soil water content - baseflow	seasonal	% of pore volume	x100	y
16	swcn3_sea	lpjm	soil water content - drainage	seasonal	% of pore volume	x100	y
17	etotx_mon	lpjm	actual evapotranspiration	monthly	mm/day	x10	n
18	etotx_sea	lpjm-lpjg	actual evapotranspiration	seasonal	mm		y
19	etotx_ann	lpjm	actual evapotranspiration (derived from monthly values)	annual	mm	x10	n
20	petxx_mon	lpjm	potential evapotranspiration	monthly	mm/day	x10	n
21	petxx_sea	lpjm-lpjg	potential evapotranspiration	seasonal	mm		y
22	petxx_ann	lpjm	potential evapotranspiration (derived from monthly values)	annual	mm*10	x10	n
23	irrig_sea	lpjm-lpjg	irrigation supply	seasonal	mm		y
24	gppx_sea	lpjm-lpjg	ground primary productivity	seasonal	hg/ha		y
25	WUExx_sea	lpjm-lpjg	Water Use Efficiency = yield sea/aet_sea	seasonal		x1000	y
26	WRSIx_sea	lpjm-lpjg	Water Requirement Satisfaction Index = aet_sea/pet_sea	seasonal		x1000	y
27	AIxxx_sea	lpjm_lpjg	Aridity index = precx_an/pet_sea	seasonal		x1000	y

	Name	Model	Description	Fq	Unit	Scale	Crop Specific
28	AIxxx_ann	lpjm	aridity index = precx_an/petxx_ann	annual		x1000	n
29	AIlgp_sea	lpjm	aridity index over the LGPt season	seasonal		x10	n
30	LPGtx_an	mir5	temperature growing period	annual	julian day		n
31	LGPeq_an	lpjm	the LGP equivalent (derived from Aixxx_ann)	annual		x10	n
32	tminx_daily	mir5	daily minimum temperature	daily	Kelvin		n
33	tmaxx_daily	mir5	daily maximum temperature	daily	Kelvin		n
34	tavgx_daily	mir5	daily mean temperature	daily	Kelvin		n
35	precx_daily	mir5	daily precipitation	daily	mm		n
36	tminx_sea	ipjm-lpjg	minimum temperature over the growing seasons	seasonal	Kelvin	x10	y
37	tmaxx_sea	lpjm-lpjg	maximum temperature over the growing seasons	seasonal	Kelvin	x10	y
38	tavgx_sea	lpjm-lpjg	mean temperature over the growing seasons	seasonal	Kelvin	x10	y
39	precx_an	lpjm-lpjg	annual cumulated precipitation	annual	mm		n
40	tminx_an	lpjm-lpjg	annual minimum temperature	annual	Kelvin	x10	n
41	tmaxx_an	lpjm-lpjg	annual maximum temperature	annual	Kelvin	x10	n
42	tavgx_an	lpjm-lpjg	annual mean temperature	annual	Kelvin	x10	n

6. Simplifications in version 1

The dataset used in the analysis was unfortunately not the final one and some simplifications have to be considered:

- The period of interest that should goes from 1961 to 2050 goes actually from 1981 to 2050 as the agro-climatic outputs cover only this period (in version 1).
- Because of this period reduction, the corrective factors used in the yield correction have been adapted as follows: the slope of the differences has been replaced by the slope of the FAOSTAT values that covers the period of interest (1961-2010).
- Because of this period reduction, the historical period used as reference for the anomaly maps is the period HIS95 (1981-2010) instead of HIS75 (1961-1990), and only two anomaly maps are computed: the relative difference between FUT25 and HIS95, and the relative difference between FUT35 and HIS95.
- Only one growing season has been considered as only one harvest date is provided in the agro-climatic outputs.

- The mapping unit used in this study consists of sub-national limits (districts from GAUL level 1) instead of the Homogeneous Mapping Zones foreseen in the methodology (see section 2.2.1.i). The reason is that the spatial resolution of the climafrica input data (version 1) is too coarse compared to the size of the zones.

7. Yield correction approach

The input data used in the yield correction are:

- FAOSTAT 5-year yield values covering the period (1961-2010) averaged for 9 crop groups (Table 2) at the country level, used to compute the corrective factor;
- 5-year yield values covering the period (1961-2050) for the 9 crop groups (see section 2.2.5), spatially averaged per country (production/crop area).

A linear regression analysis is done between FAOSTAT time series and the estimated values for the period (1961-2010) on the 5-year averages at the country level for the 2 models, the 2 scenarios and for the 9 crop groups. The corrective factors (slope and intercept of the differences between FAOSTAT and the model outputs) corresponding to each model, scenario and crop group are identified. Then the corrections are applied at the pixel level on the individual crop yield values.

In order to avoid some unrealistic projections, the outliers are removed from the outputs. If the future projection overcomes the double of the yield observed in 2010 (FAOSTAT value) and/or if the future projection is a negative value, the correction is not applied and the class "no data" is attributed in the anomaly classification. For each country and each crop group, a chart is produced showing the yield estimated by the agro-climatic models in comparison with the yield from FAOSTAT (1961-2010) and the new estimations (based on WP3 and FAOSTAT regression analysis). These graphs should show the impact of climate change on yield with and without technological trend correction.

8. Anomaly analysis

Four anomaly maps (at the pixel level) are derived from the LTA and STD computed in a previous step:

- the baseline anomaly, i.e. the relative difference between the current average/std (CUR) and the reference average/std (anomLTA_CUR05_HIS75 & anomSTD_CUR05_HIS75);

- the future anomaly 2015, i.e. the relative difference between the future average FUT15 and the reference average (anomLTA_FUT15_HIS75 & anomSTD_FUT15_HIS75);
- the future anomaly 2025, i.e. the relative difference between the future average FUT25 and the reference average (anomLTA_FUT25_HIS75 & anomSTD_FUT25_HIS75);
- the future anomaly 2035, i.e. the relative difference between the future average FUT35 and the reference average (anomLTA_FUT35_HIS75 & anomSTD_FUT35_HIS75).

The relative difference is the difference between the current or future average and the historical average divided by the historical average. Then, for the 36 seasonal or annual parameters (see table 3), the spatial statistics are computed **per zone** (see section 2.2.8). Finally, the (mean) **zonal anomaly values for the 30-year averages** are classified in 7 classes: <-30%, -30 to -20%, -20 to -10%, + 10%, 10-20%, 2-30%, >30%, except for the temperature that is classified as follows: <0.03%, -0.03 to -0.02%, -0.02 to -0.01%, + 0.01%, 0.01 to 0.02%, 0.02 to 0.03%.

Based on this classification, the areas of highest changes, i.e. more than 20%, are identified for each crop, and each parameter. For each crop, 5 classes are produced:

- one class for the positive changes when at least one scenario shows a high increase;
- one class for the positive changes when at least two scenarios or models show a high increase;
- one class for the negative changes when at least one scenario shows a high increase;
- one class for the negative changes when at least two scenarios or models show a high increase;
- one class for the zones where a conflicting information is observed, i.e. one model shows a decrease when the other shows an increase or inversely.

9. Suitability analysis

The methodology occurs in three steps:

- analyse the suitability based on climatic conditions
- analyse the suitability based on soil conditions
- combine the suitability results based on climate, soil and the photoperiod.

a) Suitability by climatic conditions

The analysis uses the following input data:

- The average of the daily minimum temperature and the average of the daily maximum temperature over the growing period (see section 2.2.1f) for each reference period (see section 2.2.1g) and each rainfed crop (9).
- The cumulated precipitation from the daily (meteo) time series (at the pixel level) for each reference period (see section 2.2.1.f).
- The ECOCROP dataset with a selection of 12 major crop species. These crops have been selected from the 40 first major crops based on the crop production (FAOSTAT 2011) that match with the 9 rainfed crops used in the agro-climatic modeling.

For each 30-year period, a suitability class is assigned to each pixel for each crop, based on the ECOCROP absolute and optimal conditions:

NAME	Abb.	TMIN	TOP MN	TOP MX	T MAX	RM IN	ROP MN	ROP MX	RMAX	PP MIN	PP MAX	TE XT	TEX TR	DEP	DEPR	DRA	DRAR	SAL	SALR	FER	FERR
Maniok (Cassava)	TrMa	10	20	29	35	500	1000	1500	5000	12	14	LM	WO	M	M	W	WE	L	L	M	L
Maize	TeCo	10	18	33	47	400	600	1200	1800	12	14	MO	W	M	S	W	WE	L	M	H	L
Rice paddy (J aponica)	TrRi1	10	20	30	36	1000	1500	2000	4000	0	0	W	W	M	S	I	I	L	L	H	M
Rice paddy (Indica)	TrRi2	16	25	35	38	1000	1500	2000	4000	12	12	W	W	M	S	I	I	L	L	M	L
Potato	TeSo1	7	15	25	30	250	500	800	2000	0	0	MO	W	M	S	W	WE	L	L	M	L
Wheat (common)	TeWW	5	15	23	27	300	750	900	1600	12	14	MO	MH	M	S	W	W	L	M	H	M
Sorghum (low alt.)	TrMi1	8	27	35	40	300	500	1000	3000	12	12	MH	W	M	M	W	IE	L	M	M	L
Potato yam	TeSo2	12	20	30	38	900	1200	2600	4000	12	12	M	LM	D	M	W	W	L	L	H	M
Millet, common	TrMi2	15	20	32	45	200	500	750	1000	12	14	M	W	M	S	W	WE	L	L	M	L
Sugar beet	TeSb	4	15	25	35	500	650	900	1200	14	14	M	MH	D	M	W	W	L	M	H	M
Cowpea	TePu1	10	20	35	40	400	600	1500	4100	12	14	M	W	M	S	W	WE	L	L	M	L
Bean, common	TePu2	7	16	25	32	300	500	2000	4300	12	14	MO	W	M	S	W	W	L	L	M	L

The following classificationis applied to each 30-year period:
1. Optimal, 2. Sub-optimal, 3. Suitable but not optimal, 4. Partially unsuitable, 5. Unsuitable

	< Tmin	[Tmin; TopMin[	[TopMin; TopMax]	]TopMax; Tmax]	> Tmax
< Rmin	5	4	4	4	5
[Rmin; RopMin[	4	3	2	3	4
[RopMin; RopMax]	4	2	1	2	4
]RopMax; Rmax]	4	3	2	3	4
> Rmax	5	4	4	4	5

b) Suitability by soil conditions

The analysis uses a soil dataset including five parameters, i.e. Texture, Salinity, Depth, Drainage, and Fertility, and occurs in two steps:

- For each soil parameters, a suitability class is assigned according to the following classification: 1. Optimal, 3. Suitable but not optimal (i.e. absolute but not optimal conditions), 5. Unsuitable (not absolute, not optimal).
- The five parameters are combined and five classes of soil suitability are assigned for each crop as follows:
  1. **optimal**: the five parameters are optimal;
  2. **sub-optimal**: at least 3 parameters are optimal, the others are suitable;
  3. **suitable** but not optimal: all parameters are suitable but not optimal;
  4. **partially unsuitable**: at least 3 parameters are suitable or optimal, the others are unsuitable;
  5. **unsuitable**: at least 3 parameters are unsuitable.

c) Agro-climatic suitability

Finally, the 5 classes of suitability for climate and soil conditions are combined according to the following classification:

		SOIL				
		Optimal	**Sub-optimal**	**Suitable**	**Partially unsuitable**	**Unsuitable**
CLIMATE	**Optimal**	1	2C	3C	4C	5C
	Sub-optimal	2S	2	3C	4C	5C
	Suitable	3S	3S	3	4C	5C
	Partially unsuitable	4S	4S	4S	4	5C
	Unsuitable	5S	5S	5S	5S	5

The photoperiod is also taken into account as the class number is decreased by one if the photoperiod is unsuitable. Five classes are considered at the end corresponding tot the 5 numbers presented in the table. Finally, changes are observed between the historical and the future periods for the 12 crops.

10. Mapping AEZ shifts

In the framework of the AEZ project (FAO/IIASA 2012), the following Agro-ecological zones have been produced for the period (1961-1990).

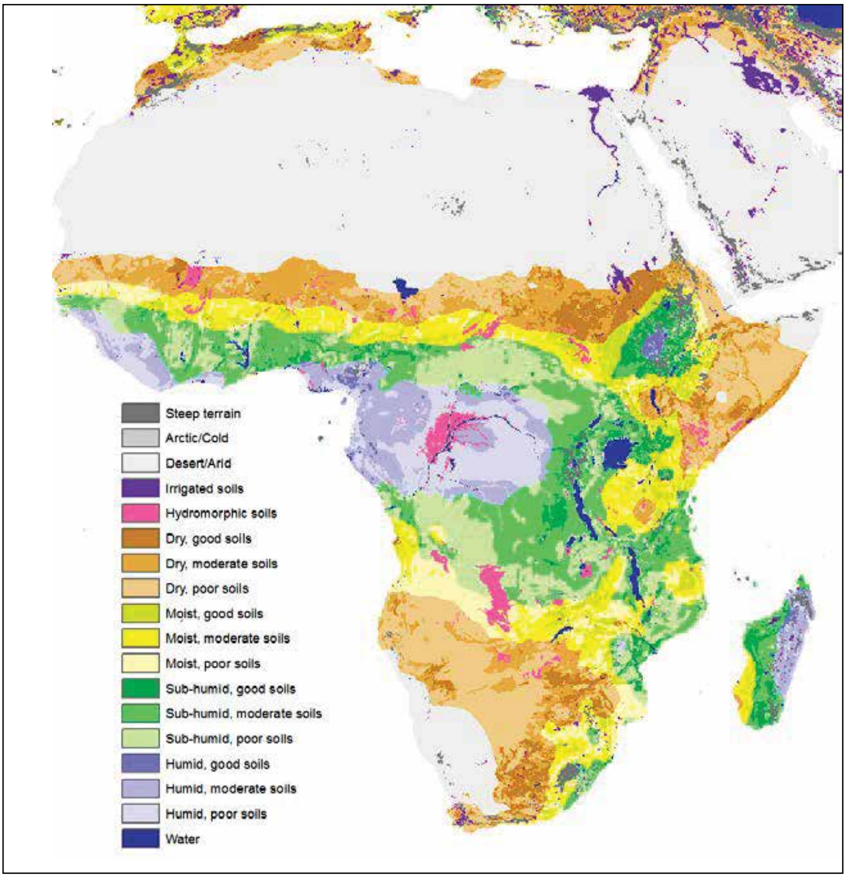


Figure A1 Agro-ecological zones produced for the period 1961-1990

The Climafrica AEZ changes analysis combines the soil classes of the baseline agro ecological zones (1961-1990) with the following agro-climatic inputs for the 30-year periods:

- the equivalent length of growing period (LGPeq) (derived from AI_ann);
- the aridity index over the LGPt season (AI_LGPt).

These inputs are provided for 2 scenarios and one model (lpjm) and are classified as follows in order to determine the soils qualities by moisture regimes:

1. Desert/Arid: AI_LGPt < 0.15 or LGPeq < 60 days;
2. Dry conditions: AI_LGPt between 0.15-0.40 or LGPeq between 60–120 day;
3. Moist conditions: AI_LGPt between 0.40-0.65 or LGPeq between 120-180 days;
4. Sub-humid conditions: AI_LGPt between 0.65-1.15 or LGPeq between 180-270 days;
5. Humid conditions: AI_LGPt > 1.15 or LGPeq > 270 days.

The moisture regimes (dry, moist, subhumid, and humdid) outputs are then resampled at the same resolution as the AEZ layer, i.e. 10km (0,083333333°) and combined with the soil classes (good, moderate and poor soils, irrigated and hydromorphic soils), and the slope in order to obtain the following agro-ecological classification schema for each 30-year period:

- Steep terrain: Terrain slopes > 16% for more than two-thirds of grid cell;
- Arctic/Cold: LGPt < 60 days;
- Desert/Arid;
- Irrigated soils: > 20% of grid cell irrigated (according to GMIA);
- Hydromorphic soils: Grid-cells with >50% hydromorphic soil types in flat terrain;
- Dry, good soils;
- Dry, moderate soils;
- Dry, poor soils;
- Moist, good soils;
- Moist, moderate soils;
- Moist, poor soils;
- Sub-humid, good soils;
- Sub-humid, moderate soils;
- Sub-humid, poor soils;
- Humid, good soils;
- Humid, moderate soils;
- Humid, poor soils;
- Water.

11. Homogeneous Mapping Zones

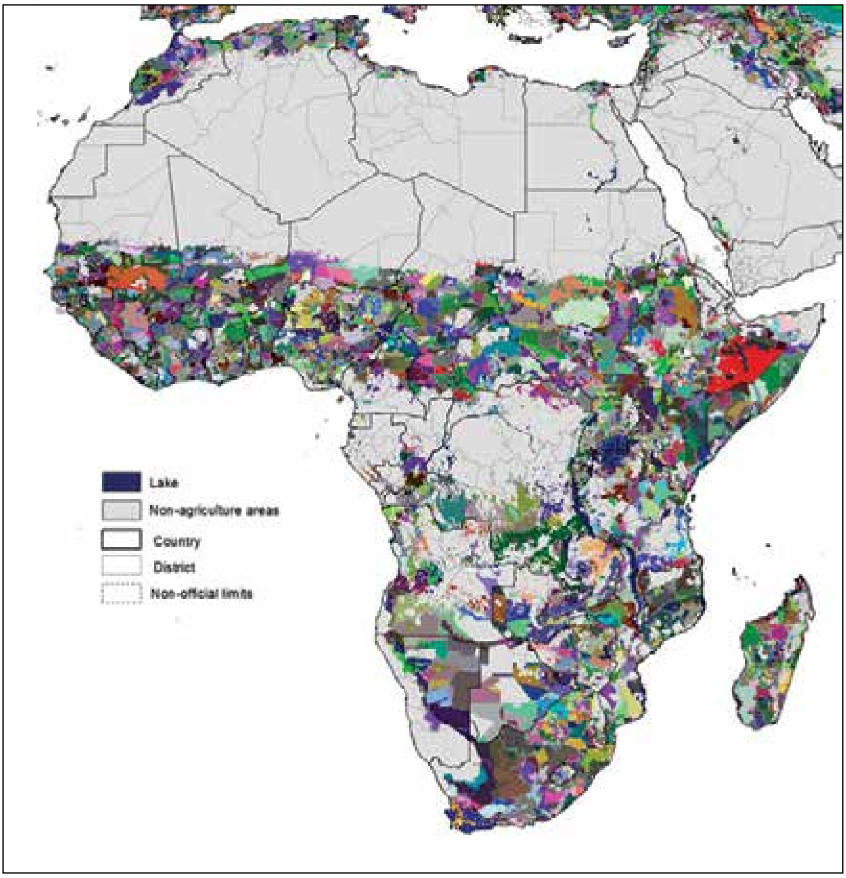
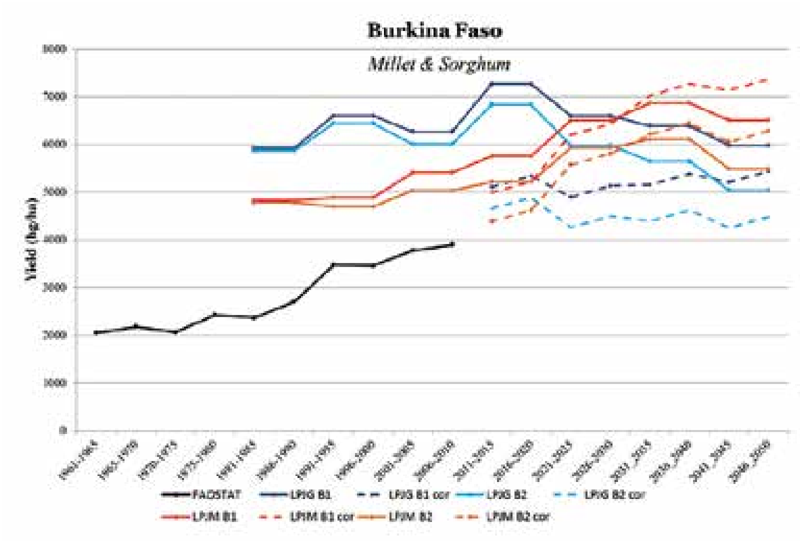


Figure A2 The 4534 Homogeneous Mapping Zones (HMZ) derived from the combination of different datasets (2.2.1 & 2.1.6) and used in the analysis with the mask of non-agriculture areas (in grey) are presented below.

12. Yield correction results

The yield provided by the two agro-climatic models (lpjg and lpjm) for two scenarios have been corrected based on the FAOSTAT yield evolution from 1961 to 2010. Yield from agro-climatic models for two scenarios (B1 and B2) are compared with yield values from FAOSTAT and the yield corrected based on FAOSTAT for each crop group (9) by country.

The following charts present the comparison between yield from agro-climatic models (lpjm and lpjg) for two scenarios (B1 and B2) and yield from FAOSTAT for two crop groups, i.e. Millet & Sorghum (above) and Maize, and for two countries.



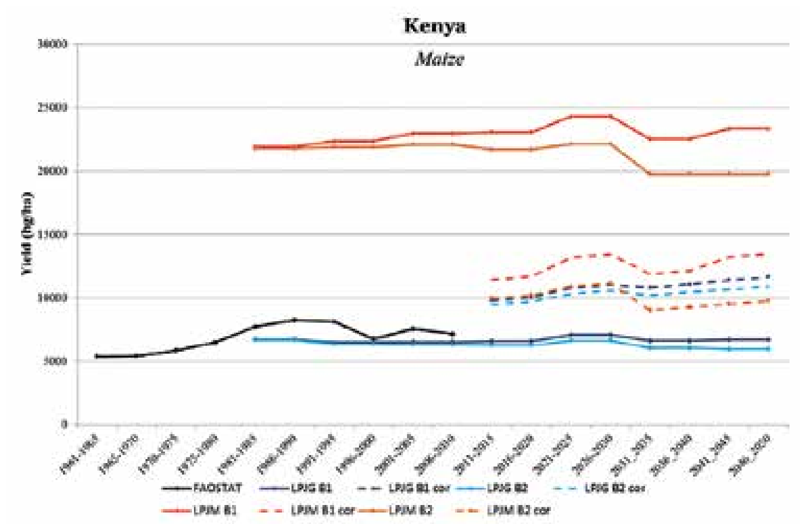
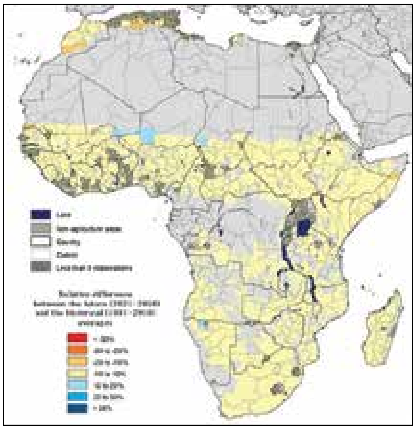


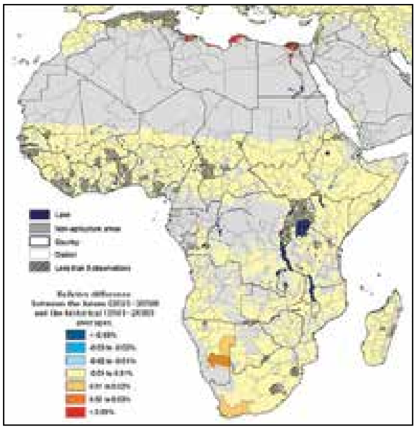
Figure A3 Comparison between yield from agro-climatic models (lpjm and lpjg) for two scenarios (B1 and B2) and yield from FAOSTAT for two crop groups, i.e. Millet & Sorghum and Maize and for two countries.

These charts show that yield values derived from the agro-climatic models are often very different from statistics in term of level and trend. The trends can also be very different from one model to another. The FAOSTAT data often show a high increase of yield which starts in the eighties. This increase due to technology evolution is not taken into account in the agro-climatic modelisation. Therefore it is important to integrate this evolution in the yield projections. Moreover, it is important to calibrate the modelled outputs with more realistic values.

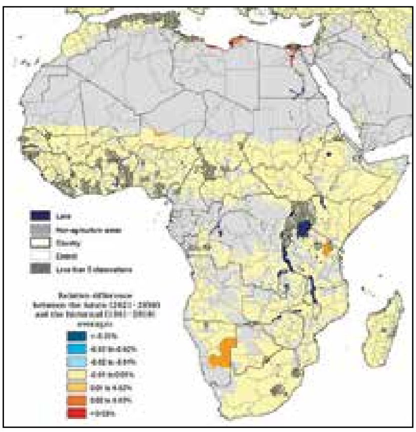
13. Anomaly maps for the climatic parameters



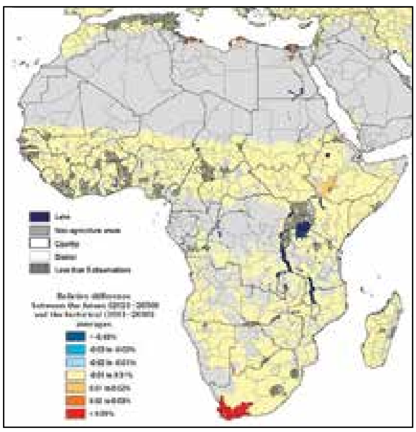
Precipitation Anomaly



Mean Temperature



Temperature minimum



Temperature maximum

Figure A4 Anomaly maps for climatic parameters.

14. Evolution of the climatic parameters

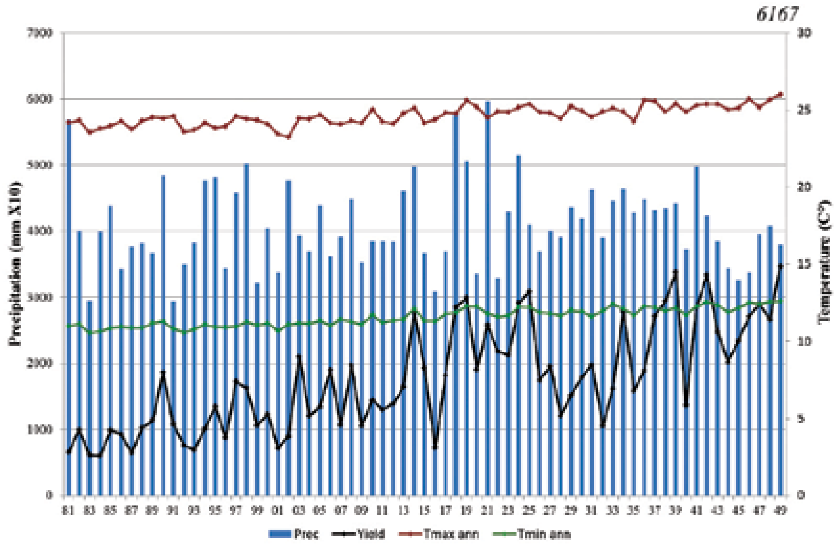
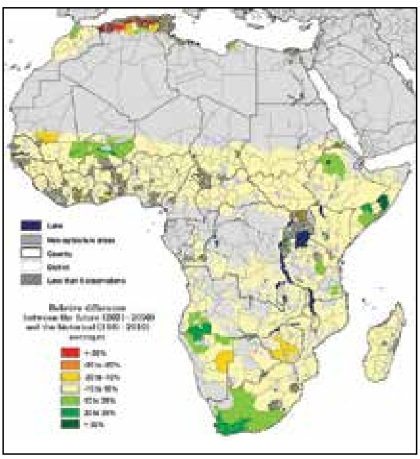


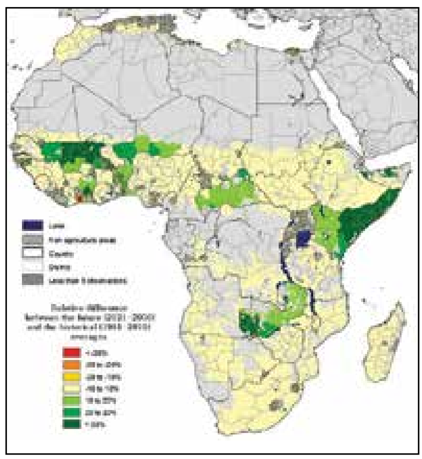
Figure A5 Evolution of the climatic parameters in comparison with the yield for the Western Cape District zone in South-Africa where the increase of maximum temperature is relatively high.

15. Yield anomaly maps

1. Comparison between the non-corrected and corrected yield values for the rainfed maize, for the lpjm model and the pessimistic scenario (B2):



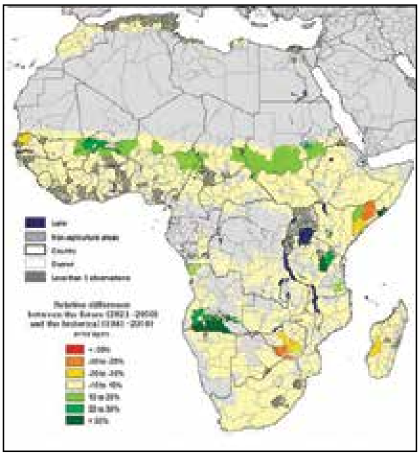
Yield anomaly - Maize - LPJM B2



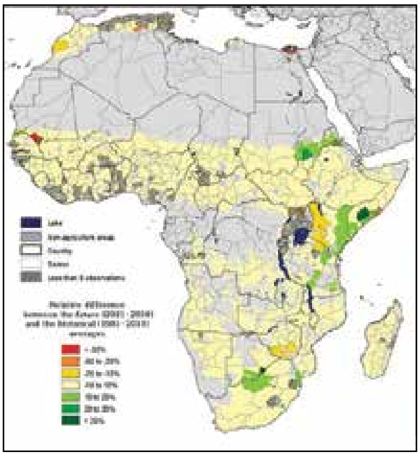
Corrected yield anomaly - Maize - LPJM B2

Figure A6 Non-corrected and corrected yield values for the rainfed maize, for the lpjm model and the pessimistic scenario (B2).

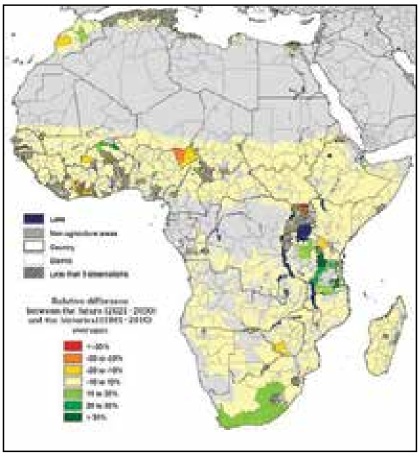
2. Anomaly maps for the non corrected yield for four different crops, for the lpjm model and the optimistic scenario (B1):



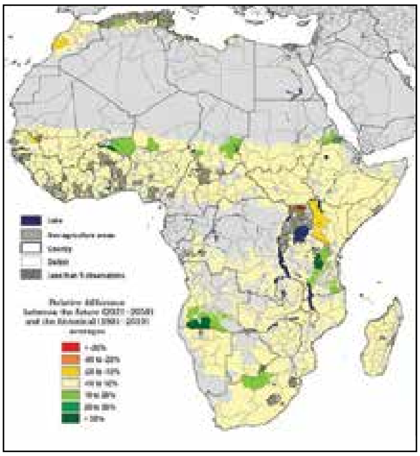
Yield anomaly - Rainfed Maniok - LPJM B1



Yield anomaly - Rainfed Wheat - LPJM B1



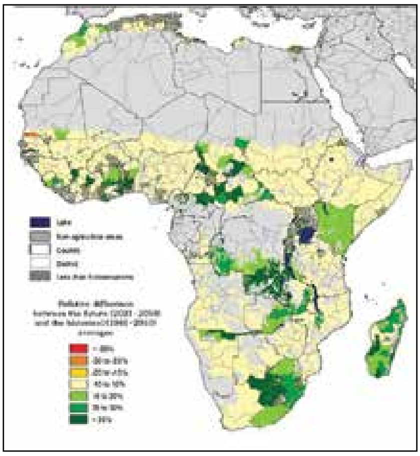
Yield anomaly - Rainfed Potatoes - LPJM B1



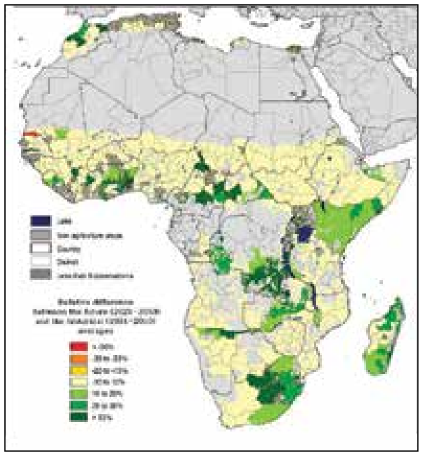
Yield anomaly - Rainfed Sugarbeet - LPJM B1

Figure A7 Anomaly maps for the non-corrected yield for four different crops, for thelpjm model and the optimistic scenario (B1).

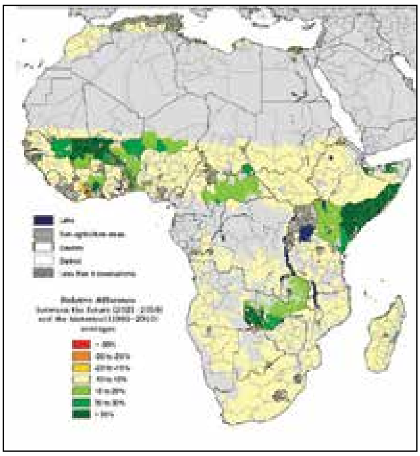
3. Anomaly maps for the non corrected yield for Maize, for the lpjg and lpjm model and the optimistic scenario (B1):



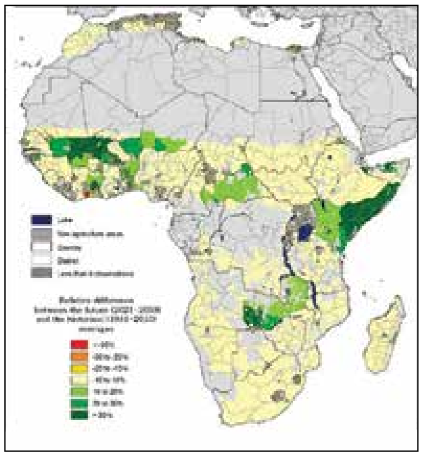
Corrected yield anomaly - Maize - LPJG B1



Corrected yield anomaly - Maize - LPJG B2



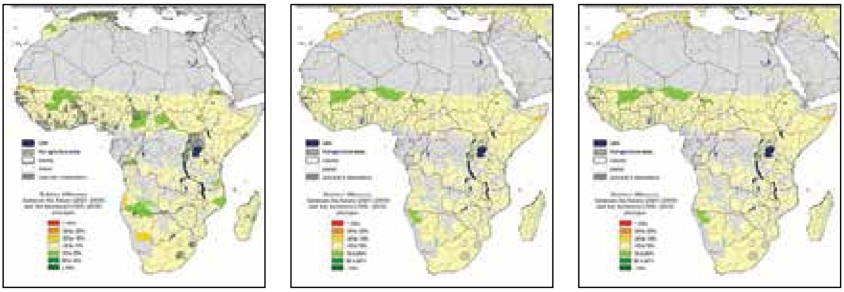
Corrected yield anomaly - Maize - LPJM B1



Corrected yield anomaly - Maize - LPJM B2

Figure A8 Anomaly maps for the non-corrected yield for Maize, for the lpjg and lpjm model and the optimistic scenario (B1).

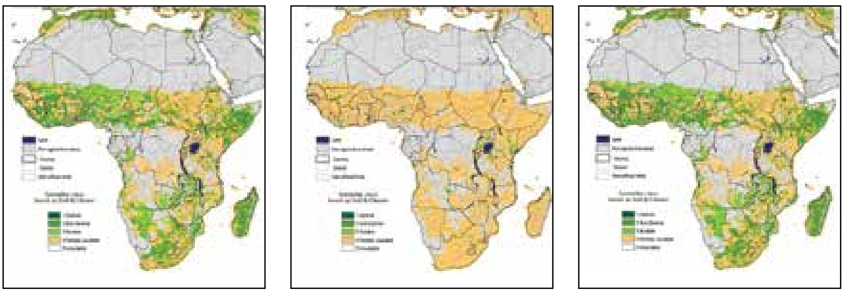
4. Anomaly maps of the runoff, the Actual Evapotranspiration and the Water Use Efficiency for the lpjm model and the pessimistic scenario.



Runoff anomaly - LPJM B2 | AET anomaly - LPJM B2 | WUE anomaly - Maize - LPJM B2

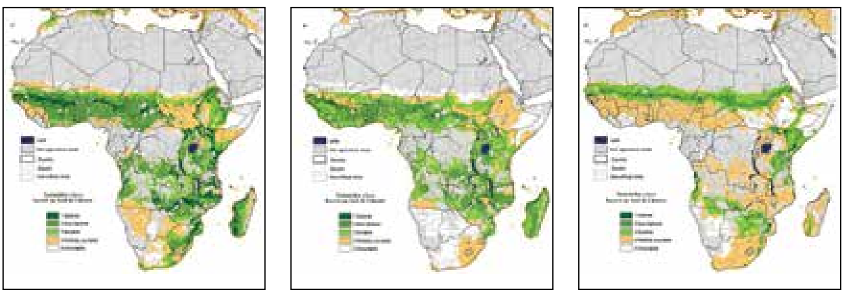
Figure A9 *Anomaly maps of the runoff, the Actual Evapotranspiration and the Water Use Efficiency for the lpjm model and the pessimistic scenario.*

16. Suitability Analysis



Suitability (2020-2050) Rainfed Maize | *Suitability (2020-2050) Rainfed Maniok* | *Suitability (2020-2050) Rainfed Millet*

Figure A10 *The suitability classes based on the Soil conditions for rainfed Maize, Manioc and Millet.*

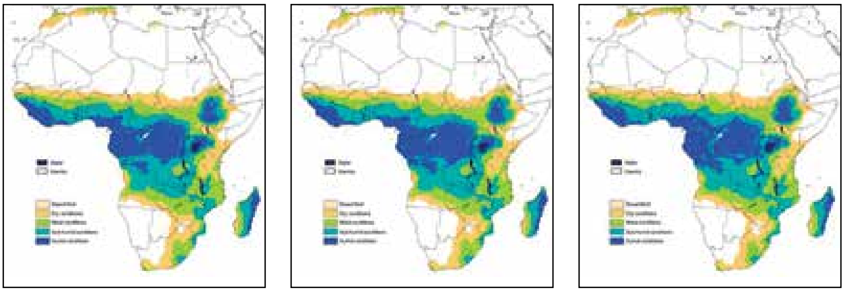


Suitability (2020-2050) Rainfed Maize | *Suitability (2020-2050) Rainfed Maniok* | *Suitability (2020-2050) Rainfed Millet*

Figure A11 *The suitability classes based on the Climate conditions for the same crops.*

17. AEZ shift

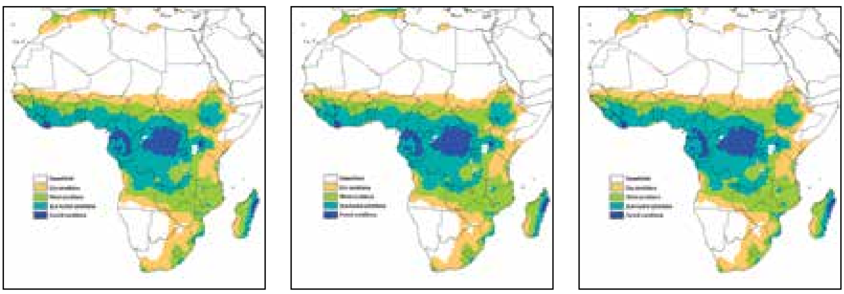
1. Evolution of the moisture regimes based on the LGPeq classification for the lpjm model and the optimistic scenario:



Moisture regimes - LPJM - HIS95 *Moisture regimes - LPJM - FUT15* *Moisture regimes - LPJM B1 - FUT35*

Figure A12 The moisture regimes based on the LGPeq classification.

2. Evolution of the moisture regimes based on the AIlgpt classification for the lpjm model and the optimistic scenario:

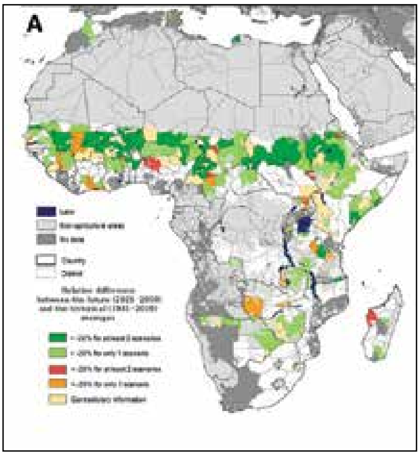


Moisture regimes - LPJM - HIS95 *Moisture regimes - LPJM - FUT15* *Moisture regimes - LPJM B1 - FUT35*

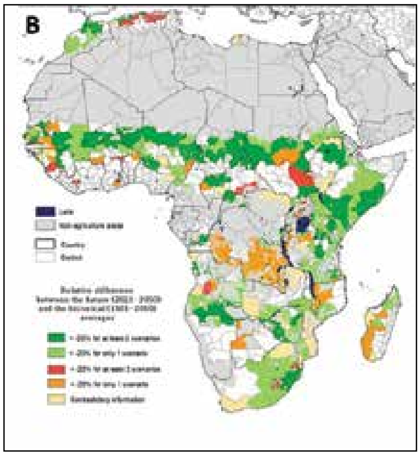
Figure A13 The moisture regimes based on the Allgpt classification.

18. Hotspots based on yield anomaly values

1. Yield corrected (A) and non-corrected (B) hotspots zones for Maize



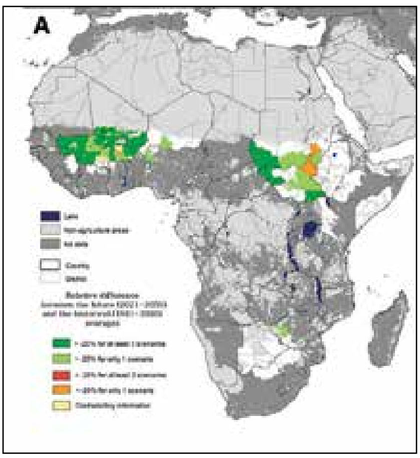
Hotspots - Rainfed Maize



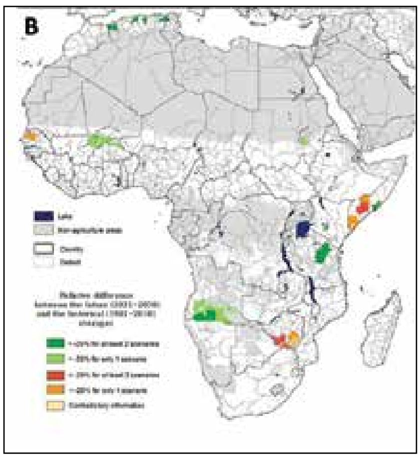
Hotspots - Rainfed Maize

Figure A14 *Hotspots zones for Rainfed Maize.*

2. Yield corrected (A) and non-corrected (B) hotspots zones for Maniok



Hotspots - Rainfed Maniok



Hotspots - Rainfed Maniok

Figure A15 *Hotspots zones for Rainfed Maniok.*

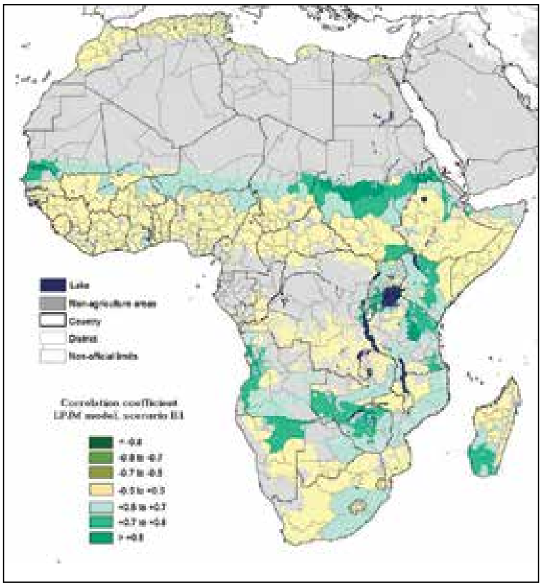
19. Aggregated changes by country

The relative difference (in %) between the future (2020-2050) and the historical (1981-2010) periods for various parameters, and Crop area (in ha) are presented below for two countries: Ethiopia and Burkina Faso.

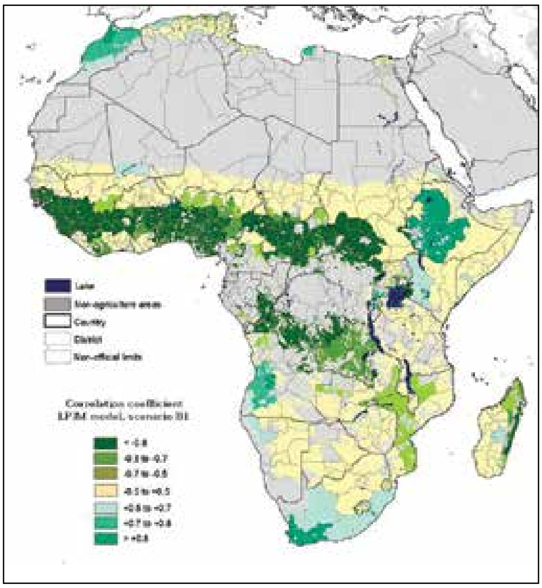
ETHIOPIA			Yield	Yield cor	GPP	WRSI	WUE	Als	Veg C	PET	AET	LGP	Rnoff	SWC1	SWC2	AI LGPt	Prec	Tmin	Tmax	Area (ha)	Co_2
Maize	LPJG	B1	50.4	-5.2	74.1	-0.1	1.4	3.5	66.6	-1.5	-1.7	-0.6	18.2	10.8	10.8	-1.7	0.8	0.0	0.0	13525.0	20
		B2	-16.4	43.0	95.4	-0.4	1.4	3.0	-5.8	-1.0	-1.5	-0.6	18.0	11.5	11.5	-1.7	0.8	0.0	0.0	13525.0	2
	LPJM	B1	79.8	30.4	74.4	0.8	8.7	2.6	83.3	-0.3	0.3	-0.6	5.7	0.0	1.2	-1.7	0.8	0.0	0.0	13525.0	20
		B2	60.4	6.1	79.3	0.9	7.8	2.6	61.1	-0.3	0.4	-0.6	5.5	0.5	1.2	-1.7	0.8	0.0	0.0	13525.0	2
Millet	LPJG	B1	-20.7	60.5	105.1	0.2	0.6	3.3	23.4	-1.2	-1.2	-0.8	14.3	11.0	11.0	-1.7	0.8	0.0	0.0	13810.0	20
		B2	30.4	35.0	110.1	-0.2	-0.3	2.7	70.2	-0.7	-1.0	-0.8	13.9	10.4	10.4	-1.7	0.8	0.0	0.0	13810.0	2
	LPJM	B1	3.1	-3.6	52.0	0.8	2.2	3.4	77.0	-0.7	-0.3	-0.9	6.4	0.0	1.6	-1.7	0.8	0.0	0.0	13810.0	20
		B2	3.2	0.4	58.8	0.9	0.9	3.4	55.0	-0.7	-0.2	-0.9	6.4	0.6	1.6	-1.7	0.8	0.0	0.0	13810.0	2
Potatoes	LPJG	B1	0.0	0.3	0.0	0.0	0.0	-0.1	0.0	0.0	-0.1	0.0	-0.6	-0.2	-0.2	-1.7	0.8	0.0	0.0	1065.0	20
		B2	-0.1	0.3	-0.1	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	-0.5	-0.1	-0.1	-1.7	0.8	0.0	0.0	1065.0	2
	LPJM	B1	-1.3	-0.4	49.2	1.1	3.3	2.9	9.6	-1.5	-0.4	-1.7	7.1	0.0	1.6	-1.7	0.8	0.0	0.0	1065.0	20
		B2	-23.3	0.0	87.1	1.1	0.6	2.9	49.7	-1.5	-0.4	-1.7	7.1	0.3	1.6	-1.7	0.8	0.0	0.0	1065.0	2
Pulses	LPJG	B1	-20.3	0.0	53.9	-0.7	2.4	2.1	70.9	-0.3	-1.2	-0.1	15.1	5.6	5.6	-1.7	0.8	0.0	0.0	11340.0	20
		B2	43.0	0.0	118.9	-0.9	-1.9	2.5	117.3	-0.5	-1.8	-0.1	14.8	6.9	6.9	-1.7	0.8	0.0	0.0	11340.0	2
	LPJM	B1	40.6	5.4	106.8	0.7	15.0	2.1	90.0	-0.6	0.1	-0.9	6.8	0.0	1.2	-1.7	0.8	0.0	0.0	11340.0	20
		B2	16.4	-0.3	86.2	0.7	11.1	2.1	74.1	-0.6	0.1	-0.9	6.7	0.2	1.2	-1.7	0.8	0.0	0.0	11340.0	2
Wheat	LPJG	B1	22.5	0.0	58.6	-1.9	-1.1	0.9	44.4	-1.7	-2.7	-1.3	12.1	1.1	1.1	-1.7	0.8	0.0	0.0	16770.0	20
		B2	65.0	0.0	101.1	-2.2	-2.7	0.8	93.4	-1.9	-3.2	-1.3	12.7	1.3	1.3	-1.7	0.8	0.0	0.0	16770.0	2
	LPJM	B1	46.8	-0.3	72.0	0.2	2.2	2.5	101.2	-0.3	-0.2	-0.7	5.9	0.0	1.1	-1.7	0.8	0.0	0.0	16770.0	20
		B2	6.8	0.3	73.5	0.3	-0.4	2.5	84.9	-0.3	-0.2	-0.7	5.9	0.2	1.1	-1.7	0.8	0.0	0.0	16770.0	2
Treenut	LPJG	B1	-3.1	0.0	-1.1	-0.5	-0.7	3.3	-1.7	-1.1	-1.9	-0.9	19.9	7.3	7.3	-1.7	0.8	0.0	0.0	1415.0	20
		B2	-6.3	0.0	-4.2	-1.0	-3.0	3.8	-5.0	-1.5	-2.9	-0.9	21.4	8.5	8.5	-1.7	0.8	0.0	0.0	1415.0	2
	LPJM	B1	28.2	0.5	125.8	1.4	8.2	2.5	72.0	-0.4	0.7	-0.8	5.1	0.6	1.2	-1.7	0.8	0.0	0.0	1415.0	20
		B2	48.9	-0.3	99.3	1.4	5.4	2.5	14.0	-0.4	0.7	-0.8	5.1	0.6	1.2	-1.7	0.8	0.0	0.0	1415.0	2

BURKINA FASO			Yield	Yield cor	GPP	WRSI	WUE	Als	Veg C	PET	AET	LGP	Rnoff	SWC1	SWC2	Al LGPt	Prec	Tmin	Tmax	Area (ha)	Co_2
Rice	LPJG	B1	28.6	42.9	125.0	1.7	4.9	5.2	91.3	0.4	2.2	1.3	11.9	2.3	2.3	5.3	5.9	0.0	0.0	580.0	20
		B2	5.5	-1.0	58.8	0.9	2.0	6.1	-4.6	-0.4	0.4	1.3	12.8	2.4	2.4	5.3	5.9	0.0	0.0	580.0	2
	LPJM	B1	51.0	26.4	129.1	5.5	10.0	5.8	47.2	-0.2	5.4	-0.5	6.2	1.2	3.7	5.3	5.9	0.0	0.0	580.0	20
		B2	4.4	9.9	48.0	5.4	6.9	5.8	99.3	-0.2	5.3	-0.5	6.1	1.2	3.8	5.3	5.9	0.0	0.0	580.0	2
Maize	LPJG	B1	68.2	183.0	101.5	2.0	1.0	6.0	33.5	-0.1	1.8	0.0	19.0	12.2	12.2	5.3	5.9	0.0	0.0	3260.0	20
		B2	52.7	0.0	30.5	1.4	0.4	5.7	12.3	0.2	1.6	0.0	20.0	11.0	11.0	5.3	5.9	0.0	0.0	3260.0	2
	LPJM	B1	97.1	-9.8	73.7	6.2	4.2	6.3	188.4	-0.4	5.9	-0.4	8.0	0.0	2.8	5.3	5.9	0.0	0.0	3260.0	20
		B2	58.0	55.3	108.3	6.3	3.6	6.3	134.7	-0.4	5.9	-0.4	7.9	1.8	2.8	5.3	5.9	0.0	0.0	3260.0	2
Millet	LPJG	B1	32.5	1.0	77.0	2.3	1.8	6.1	74.1	-0.2	2.1	0.0	18.9	12.2	12.2	5.3	5.9	0.0	0.0	33230.0	20
		B2	38.7	0.1	3.3	1.8	1.1	5.8	44.0	0.1	1.9	0.0	20.5	12.6	12.6	5.3	5.9	0.0	0.0	33230.0	2
	LPJM	B1	11.5	13.2	102.3	6.6	6.0	5.9	82.5	0.0	6.8	-0.7	7.8	0.0	3.8	5.3	5.9	0.0	0.0	33230.0	20
		B2	10.7	14.5	211.1	6.6	5.1	5.9	95.4	0.0	6.8	-0.7	7.8	1.5	3.8	5.3	5.9	0.0	0.0	33230.0	2
Pulses	LPJG	B1	47.9	0.0	32.3	2.1	3.9	5.4	62.4	0.5	2.6	0.0	13.3	1.1	1.1	5.3	5.9	0.0	0.0	9285.0	20
		B2	40.3	0.0	31.6	0.9	0.6	6.3	6.2	-0.4	0.6	0.0	14.7	1.2	1.2	5.3	5.9	0.0	0.0	9285.0	2
	LPJM	B1	33.0	24.7	66.7	7.1	16.5	5.4	29.7	0.3	7.8	-0.6	8.3	0.0	4.1	5.3	5.9	0.0	0.0	9285.0	20
		B2	11.9	15.3	-15.3	7.0	7.9	5.4	38.3	0.3	7.7	-0.6	8.2	1.4	4.0	5.3	5.9	0.0	0.0	9285.0	2
Treenut	LPJG	B1	6.1	9.3	4.6	1.8	3.4	5.0	5.4	0.9	2.7	0.0	11.4	0.8	0.8	5.3	5.9	0.0	0.0	3585.0	20
		B2	0.0	9.3	-0.2	0.2	0.0	6.3	-0.2	-0.3	-0.1	0.0	12.8	0.9	0.9	5.3	5.9	0.0	0.0	3585.0	2
	LPJM	B1	13.5	16.3	69.7	6.2	9.5	6.2	59.7	-0.3	5.9	-0.5	6.9	1.4	3.7	5.3	5.9	0.0	0.0	3585.0	20
		B2	-18.2	10.9	68.6	6.2	6.0	6.2	53.5	-0.3	5.8	-0.5	6.9	1.4	3.7	5.3	5.9	0.0	0.0	3585.0	2

20. Correlation between yield and precipitation, yield and Tmin for Maize for the lpjm model (scenario B1)



Hotspots - Rainfed Maniok



Hotspots - Rainfed Maniok

Figure A16 Correlation between yield and precipitation, yield and Tmin for Maize, for the lpjm model (scenario B1).

21. Evolution of yield for the Northern disict of Sierra Leone, for the lpjm model (scenario B1)

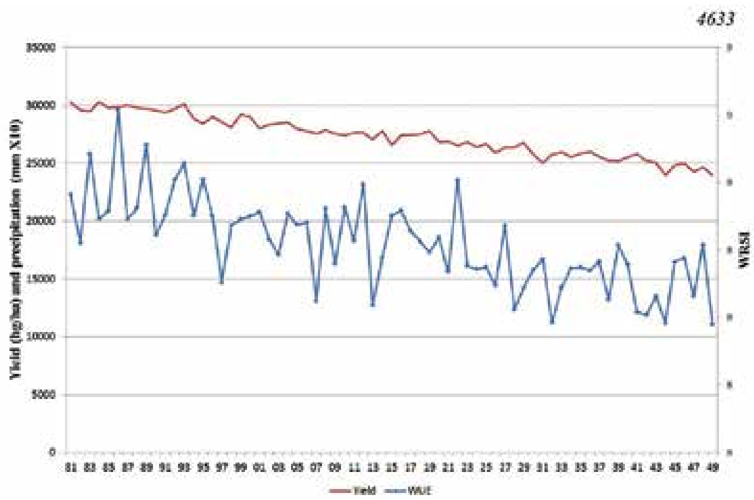


Figure A17 Evolution of yield with climate factors - lpjm model (scenario B1).

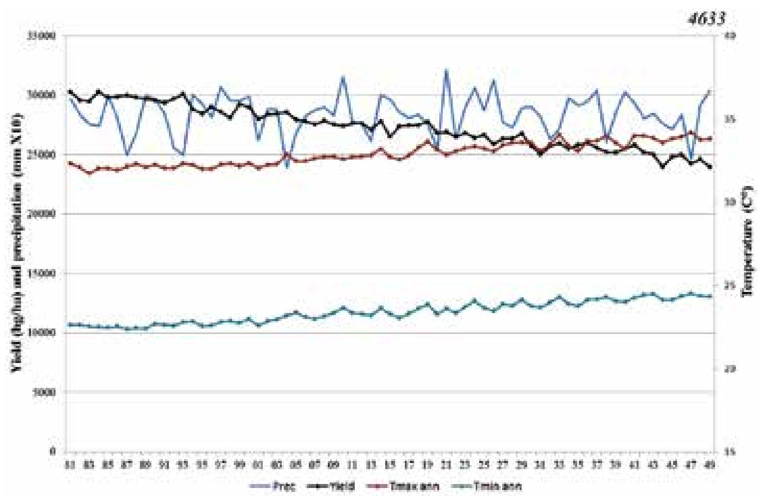


Figure A18 Evolution of yield with the water use efficiency index - lpjm model (scenario B1).

22. Annual population growth from 1961 to 2050

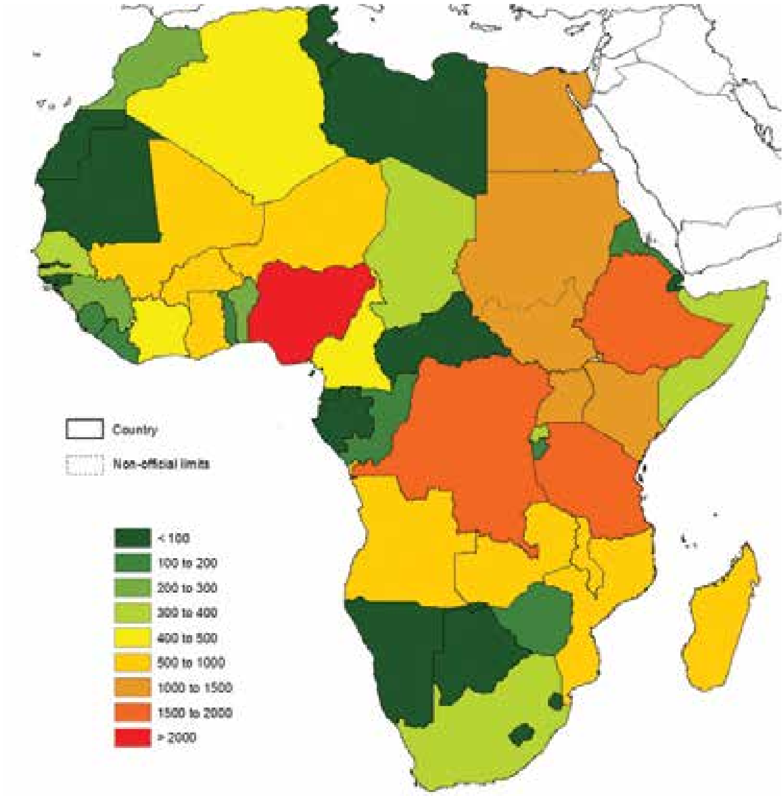


Figure A19 Source FAOSTAT

23. Prevalence of stunting among children under five

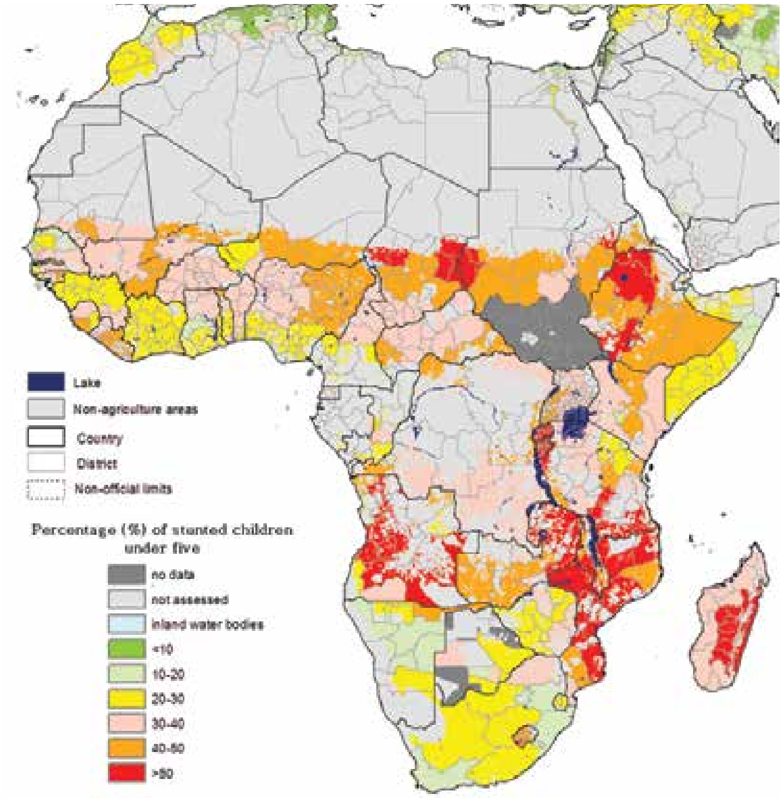


Figure A20 *Source FGGD*

24. Population density estimates for 2015

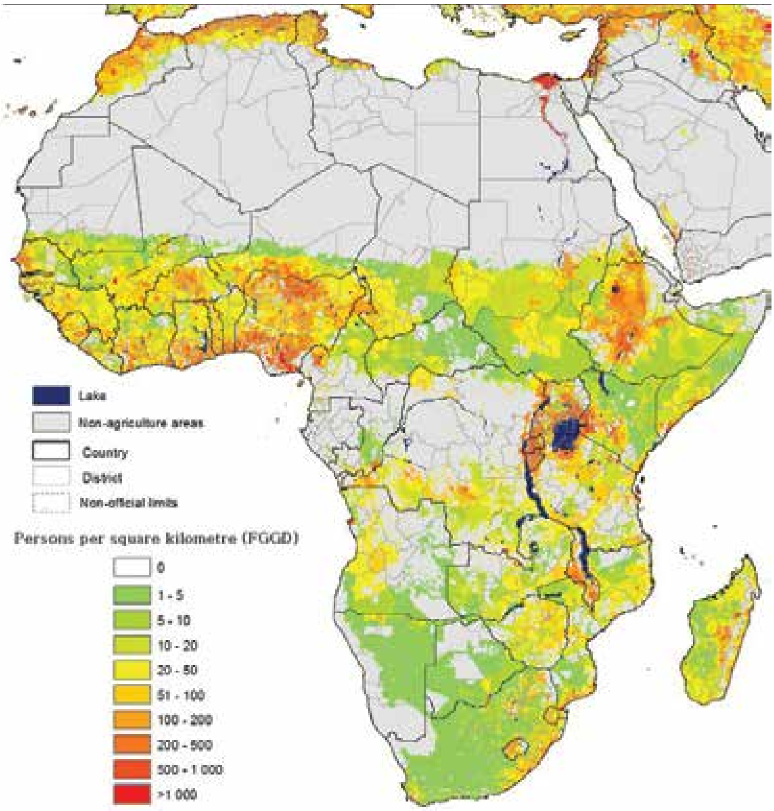


Figure A21 *Source FGGD*

25. Vulnerable population in East and West Africa

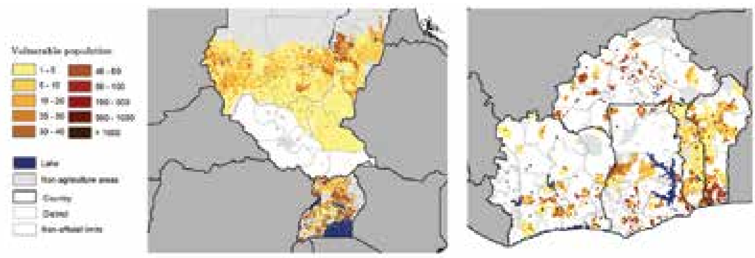


Figure A22 *Source WP5*

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