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

Final Report Summary - CLIMAFRICA (Climate change predictions in Sub-Saharan Africa: impacts and adaptations)

Executive Summary:
Africa has been highlighted as one of the most vulnerable continents to climate variability and change. In spite of that, Africa is the least covered continent by cross-continental studies related to the biophysics of climate change, even though it is also a region with a diverse range of agro-ecological and geographical conditions and that this will climate change impacts highly heterogeneous across the continent and even within countries. There is an urgent need for the most appropriate and up-to-date tools to better understand climate change, assess its impacts on African ecosystem and population and develop the most appropriate adaptation measures. CLIMAFRICA aimed to address by applying an integrated, inter-
disciplinary approach that analyse the impacts of climate change in Sub-Saharan Africa (SSA) through
different perspectives and across multiple scales; providing an integrated picture of the of climate change
in SSA and its main impacts. This approach focused on 1- Developing improved climate predictions for
SSA, 2 – Assess climate impacts on key sectors such water resources and agriculture, 3 – Analyse the
potential economic consequences of climate change on agriculture and water resources, 4 – Developing a
Medium-Term Warning System and 5 – Suggest and evaluate measures for climate change adaptation
planning.

Improved seasonal forecast and decadal climate change predictions over SSA were developed. The
introduction of land use and soil moisture on land surface-atmosphere GCM initial conditions increased
the overall skill and accuracy of seasonal forecast in SSA, above all over continents. These projections
were downscaled to the whole African domain to provide climate information relevant to impact studies.
The project found large uncertainty in impact model projections, as results greatly varied depending on the
selection of GCM, impact model or level of CO2 concentrations. Such uncertainties pose a challenge to
adaptation planning. However, some common trend among the models emerged: Ensemble mean
differences for long-term future projections of water runoff suggest an increase in water runoff in some
regions of East Africa and the horn of Africa, and a likely decrease in northern and southern Africa. The
rest of the areas did not show a clear trend in the models. Vegetation productivity is expected to decrease
in general, especially in the south of the Congo Basin; however, an increase is expected in the horn of
Africa. Models also predicted a general reduction of land suitability in Africa for millet, sorghum and maize; except for East Africa again; whose potential maize yield is expected to experience an increase by the end of the century. Analysis combining medium-term (up to 2030) crop projections with vulnerability indicators to food insecurity and others aspects, on the other hand, identified large parts of the Sahel, Ethiopia, and parts of south-east Africa (Malawi, Mozambique) as the most vulnerable areas. Population in this areas, especially rural areas, are expected to be severely affected by these impacts; even if this is not reflected on the national GDP, given its high dependence on climate-sensitive activities to build household income. The project also developed tools that allow a better assessment of vulnerable areas, such as a prototype Medium-Term Warning System, and models to assist in the decision optimal intervention strategies to climate shocks. The project compiled a set of potentially suitable adaptation measures and recommends to include these measures into broader development programmes that address poverty alleviation to be most effective.

Project Context and Objectives:
Africa has been highlighted as one of the most vulnerable continents to climate variability and change, due
to its high exposure, sensitivity and weak adaptive capacity (Niang et al. 2014), intensifying the already
adverse livelihood conditions of many parts of the continent.

Even though Africa is the continent with the lowest contribution to global fossil fuel emissions (Canadell et
al. 2009), its population is expected to be severely hit by the impacts of climate change. In fact, Africa’s
climate is already changing and its effects are already being experienced by the population (Hulme et al.
historical data to draw sound conclusions, there is evidence that mean surface temperatures have
increased by 0.5-2ºC over the past century (Fig. 1), with mean minimum temperatures warming more than
mean maximum temperatures (Niang et al. 2014). Regarding precipitation, available data indicates that
rainfall patterns are significantly changing (Fig. 1). A very likely decline in mean annual precipitation has
occurred over the past century in many parts of western Africa; while in contrast, some parts of southern and eastern Africa have very likely experienced an increase of total average annual rainfall (Niang et al. 2014).

Regardless future emissions, these changes are expected to be amplified in the future as a result of accumulated past emissions, which caused CO2 concentration go above 400 ppm in 2014 for the first time in 3-5 million years (WMO 2014), and the inertia of the climate system. Temperatures in Africa are projected to rise faster than the global average increase, particularly in the more arid regions (James & Washington, 2013). Projections under medium scenarios indicates that mean annual temperature over Africa is expected to increase more than 2ºC by the end of this century, with respect to the mean of the 20th century (Niang et al. 2014). Projected precipitation are not as certain as temperature projections, however, they do suggest a decrease in rainfall in vast areas of northern Africa and southeastern parts of South Africa by the end of the 21th century (Niang et al. 2014). In contrast, average annual rainfall may increase in areas of central and eastern Africa. Higher climate variability is also expected to increase extreme weather events such as heavy rainfall, heat waves and drought (CDKN 2014).

Such changes are likely to affect food security, water availability and natural systems of Sub-Saharan Africa (SSA) because of its high sensitivity to climate conditions. Agriculture, in which rely an estimated 90% of the continent’s population, it is predominantly rain-fed (FAO 2002) and therefore critically depends on sufficiently and timely rainfall for adequate crop production. In fact, a considerable part of arable land in SSA is defined as “dryland” (UNPD; UNSO, 1997); therefore already facing huge stresses such repetitive droughts or poor soil fertility. Many rural communities are also strongly dependant on natural resources from their immediate environment to meet basic livelihood supplies; such as firewood, shelterwood or livestock forage. In such areas, even small changes in temperature and precipitation can have considerable impacts on population wellbeing. This would intensify the already occurring stressors in many parts of rural Sub-Saharan Africa such land degradation, desertification, deforestation, partly as a result of rapid population growth. These impacts have the potential to hinder future economic growth and development and be another source of political instability, given that recent economic development gains have been in climate-sensitive sectors (CDKN 2014).

In spite of that, Africa is the least covered continent by cross-continental studies related to the biophysics of climate change, even though it is also a region with a diverse range of agro-ecological and geographical conditions and that this will climate change impacts highly heterogeneous across the continent and even within countries (Liu et al. 2008). Planners have to deal with considerable uncertainty about future conditions and this hinders the development of effective adaptation strategies that strengthen Africa’s capacity to cope with climate variability and change. Considerable research gaps still constraint long-term decision-making from local to national levels. In particular, the Fourth and Fifth Assessment Report of the Intergovernmental Panel for Climate Change (IPCC, 2007, 2014) identified a set of research needs for the African context. Both reports highlight the need to develop more accurate climate change scenarios that
reduce the uncertainty of climate change predictability. In particular, the need of downscaling General
Circulation Model (GCM) data has been emphasized as it allows a better characterization of the influence
of regional climate drivers in Africa, as well as provides information at a scale that can be meaningful to
understand regional climate processes and assess impacts on hydrology, agriculture and ecosystems.
The IPCC also stresses the necessity to characterize Africa’s groundwater resource potential and
understand the interactions between non-climate and climate drivers as related to future groundwater
resources. The reports also pointed out to the need to improve methodologies to assess and quantify the
effects of climate change on different sectors and systems such as the food system or natural ecosystems,
among others. The need of producing better assessments of the socio-economic consequences of climate
change impacts, was also accentuated, as well as to economically assess certain choices in terms of
mitigation and adaptation to climate change.
These reports also highlight the need of integrated, inter-disciplinary studies that analyse the impacts of
climate change in SSA through different perspectives and across multiple scales; providing an integrated
picture of the of climate change in SSA and its main impacts. This was the guiding motif of the
CLIMAFRICA project.

More specifically, CLIMAFRICA aimed to improve climate model forecast in SSA through better
understand the land-atmosphere feedback that modulate and/amplify the effect of global Ocean Sea
Surface Temperature forcing (i.e. Pacific, Atlantic and Indian Tropical Ocean) over the climatic conditions
of SSA. Land-atmosphere interactions had been, in fact, identified as a component that can potentially
improve forecast quality (Alessandri and Navarra 2008, Jeong et al. 2008, Koster et al. 2010), especially
in regions of strong coupling of climate and land surface such as SSA (Alessandri & Navarra 2008).
Indeed, modelling works have shown that the land surface has a strong potential to contribute to sub-
seasonal and longer climate predictions through the “soil moisture memory” (Koester & Suárez, 2004a,
Koster et al. 2010). The first specific objective of the project was to develop improved climate predictions
on seasonal to decadal climatic scales by estimating the coupling and reciprocal forcing between soil
moisture-vegetation, evapotranspiration and rainfall over SSA using new state-of-the-art datasets
specifically developed for this project. These forecasts have been dynamically and statistically downscaled
to derive meaningful climate forecasts useful for climate impact modelling. These downscaled products
are expected to characterize better the high spatial heterogeneity of SSA. In the process, the project
aimed to compare statistical and dynamical downscaling techniques against each other for the first time in
Africa in order to evaluate the ability of each to reproduce observed climate parameters in terms of spatial
bias across the African continent.

Another important component of the project was to improve the understanding of the sensitivity of Sub-
Saharan African agriculture, forestry, pastoral and water resources. CLIMAFRICA has applied a multi-
model approach built on newly developed, sate-of-the-art data assimilation and process-based models to
identify hotspots of particular vulnerability and sensitive crop types by considering the likelihood, strength
and interaction of climate change impacts across biosphere properties at various spatial scales.

Another objective of the project was to assess the potential implications of these impacts, particularly the
ones on crop yield, on national African economies; as well as to evaluate the costs and benefits of
irrigation as one main instrument to adapt to adverse climate change effects. A theoretical model was
developed that modelled the socio-economic permeation of negative climatic shocks over large areas
Finally, and even though it was not an specific objective of the CLIMAFRICA project; it is worth mentioning that project activities and cooperation with African scientists allowed to organize a series of technical training workshops that helped to improve the capacity of the African project partners to assess climate change impacts. This constitutes an important co-benefit of the project.

Project Results:
3.1 Improvement of seasonal to decadal climate modelling projections in Sub-Saharan Africa and downscaling.

3.1.1 Seasonal to decadal climate projections for Sub-Saharan Africa.

One of CLIMAFRICA’s main objectives was to improve previous seasonal forecast and decadal climate predictions over Sub-Saharan Africa by improving the understanding and quantification of land surface-atmosphere feedbacks in Global Climate Models. This was based on the fact that prior research identified land surface as a component of strong potential to contribute to sub-seasonal and longer climate predictions through the “soil moisture memory” (Koster et al. 2004b, 2004c; Ferranti & Viterbo, 2006), and identify western and central Africa as regions of strong coupling between soil moisture and precipitation (Koster, 2004b). This work clearly displayed the potential for a reliable soil moisture and vegetation initialization to improve rainfall prediction over SSA lands, which is the most difficult climate parameter to predict.

With this in mind, the project developed a state-of-the-art land use and soil moisture datasets to be included in the initialization of the CMCC Seasonal and Decadal Prediction System, and therefore better represent land surface initial conditions.

The land use datasets produced in the project were composed by three components: a) annually resolved vegetation fractions (both natural and anthropogenic) for continental Africa and globally at 0.5° from 1901-2007, b) harvested area of 26 major crop types for the year 2000, all crop types being stratified by irrigation vs. rain-fed agriculture and c) historical evolution of crop and pasture area until 2007. The first product was originally produced by CLIMAFRICA while the rest were secondary data produced by Portman et al. 2010 and Ramankutty & Foley 1999 (updated), respectively. The final resolution of the product was 0.5°.

The soil moisture product consisted in a new observational-based, global gridded multilayer dataset of water reservoir stored in the surface soil for the past 30 years. To develop the product, we started from the dataset developed as part of the European Space Agency program Climate Change Initiative (CCI)
initiated in 2010 for a period of 6 years (Liu et al. 2011). This dataset blends active and passive microwave satellite estimates, producing a global database of soil moisture from 1979 to 2010. However, spatial gaps were still substantial in densely forested areas and in snow-covered regions during the winter. To sort this out, we generated a hybrid product by merging the satellite observed record with soil moisture simulations by global land surface models. The hybridization was based on training a machine learning method (Random Forests, Breiman (2001)) on regional windows using the satellite data as target variable, and the soil moisture simulations as predictors. The trained models were then used to fill the gaps in the satellite product using the simulations as input. This hybrid product was then further profiled to deeper soil layers to achieve a multilayer soil moisture product that was later used for initializing the GCM. Finally, we validated the product using a set of in-situ soil moisture measurements from the International Soil Moisture Network (ISMN, Dorigo et al. (2011)). The final dataset covers the period 1979-2010, with temporal resolution of one day and spatial resolution of 0.25 degree (Fig. 2). This product is unprecedented and will likely have impact also for the scientific community outside CLIMAFRICA.

Figure 2. Original soil moisture dataset (called ESA-CCI) (left panel) and the more complete, CLIMAFRICA developed dataset (called SM-ECVplus) (right panel) for the climatological June.

Hindcast analysis showed that the introduction of these datasets on land surface-atmosphere initial conditions in the most recent version of the Centro Euro-Mediterraneo sui Cambiamenti Climatici Seasonal Prediction System (CMCC-SPSv2, Borrelli et al. 2012) increased the overall skill and accuracy of seasonal forecast in SSA. The model captured reasonably well the seasonality of the West African Monsoon, its inter-annual variability in terms of intensity (Fig. 3) and the average amount of precipitation. However, compared with observations, the model tends to produce fewer precipitation south of 15°N, while simulated rainfall overextends northward, draining semi-arid regions (Fig. 4).

Figure 3. West African Monsoon Index, anomaly from the mean value. This index represents the intensity of the WAM during summer in the region depicted on the right. The blue line represents the index simulated by the CMCC CPS, the red line the index in the observation. Correlation between the two curves is about 66%.

Figure 4. Precipitation (mm per day) over Africa during boreal summer. CMCC-SPS simulation on the left, observation on the right.

Results indicated that soil moisture and precipitation are highly associated to each other, showing large interdependence due to the role of latent heat in connecting them. We found that their reciprocal effect is largely season-dependent: in general, coupling is mostly active during time characterized by high precipitation variability. During Monsoon season, there is a clear effect of precipitation on soil moisture in northern tropical Africa, with particular regards to Sahel and east African highlands, where up to 60% of its variance is explained. On the other hand, the impact of local soil moisture accounts for 6-10% of the total precipitation variability in central-west Sahel, with peaks up to 12-15% on the Atlantic coast and part of the rainforest. Land-atmosphere coupling occurs in central-west Sahel, already identified as a “hot-spot” in the
GLACE experiment (Koster et al. 2006). In the OND (October-November-December) season, coupling is particularly robust in eastern equatorial Africa, where precipitation explains up to 75% of overall soil moisture variance, while the soil moisture forcing on rainfall counts for 6-15% of the total variability, with higher peaks along the coast and the highlands. A relevant amount of precipitation variability in the dense rainforests of central Africa and northern Madagascar may be attributed to soil moisture, most likely through high vegetation evapotranspiration rates in the wet season.

In addition, results of anomaly correlation analysis showed that the impact of initialization of land surface on seasonal prediction is mainly observed over continents, implying that the non-local effect of land surface is fairly small, while over the ocean the contribution of atmospheric initial conditions seem predominant. Figure 5 points out the added value provided by land surface initialization to seasonal forecast, by examining twelve key regions covering a wide spectrum of climatic areas. Comparing SPS1 (only ocean initialized) versus SPS1.5 (ocean and atmosphere initialized), it is possible to single out the contribution of the atmosphere initialization. Analogously, the difference between SPS1.5 and SPS2 (land, atmosphere and ocean initialized) identifies the role of land surface, as atmosphere and ocean models are identically initialized in the systems.

Fig. 5. Anomaly correlation averaged in different regions, seasonal forecast for the November start date. Colors refer to the three versions of the CMCC-CPS, bars indicate target seasons (LS0 = Nov-Dec-Jan, LS1 = Dec-Jan-Feb, etc.)

3.1.2 Downscaling of climate projections.

Because the grid resolution of the GCM is very coarse, it is necessary to apply a procedure whereby finer-scaled information relevant to impact studies can be extracted. This scale conversion is referred to as downscaling. Downscaling proposes that the local scale climate is primarily a function of the large scale climate modified by some local forcing such as topography, continentality, proximity to oceans and lakes, among others. There are two main types of downscaling; dynamical and statistical.

Previous research has shown that there are benefits and shortcomings inherent in both downscaling methodologies. Dynamical models attempt to simulate atmospheric processes, land-surface and land-sea interactions as well as atmosphere-vegetation interactions. Compared to the statistical downscaling results the numerical models have much larger spatial biases and the wet and dry biases are spatially heterogeneous. However, on the positive side, dynamical models provide a suite of output variables that are physically consistent so it is possible to identify sources of bias in the models and take these into account. Statistical downscaling, in contrast, develops statistical relationships between the observed rainfall at a station or in a grid cell and the driving synoptic circulation. Overall the results from the statistical downscaling are very much better than dynamical models across almost all regions and the addition of the SD results to the regional climate model ensemble mean improved the ensemble mean in all regions. Multi-downscaling ensemble mean should be used if possible as it spans a wider range of rainfall variability, especially if used in an impact model. Previous research suggested that both downscaling approaches are of comparable skill, although providing different attributes of regional
The CLIMAFRICA project applied both, statistical and dynamical techniques to produce a set of downscaled climate projections for the whole African domain, divided in three sets: western, eastern and southern Africa. In addition to that, the project also contrasted the two downscaling techniques to evaluate the ability of each to reproduce observed rainfall in terms of spatial bias of monthly rainfall across the African continent in order to contribute to the understanding of the strengths and weaknesses of the different techniques. Overall the results from the statistical downscaling are much better and downscaling produces rainfall fields that are much closer to the observed field than dynamically downscaled results across almost all regions and the addition of the SD results to the regional climate model ensemble mean improved the ensemble mean in all regions.

3.2 Analysis of climate impacts on key ecosystem services.

An important component of the project was devoted to assess the potential impacts of the previously described climate change scenarios on key ecosystem services. The analysis focused on water resources, vegetation productivity, and agricultural production, and proxies of vulnerability to food insecurity. The combinations of this information allowed CLIMAFRICA to identify hotspots regions of climate change impacts.

3.2.1 Characterization of African water resources: retrospective and prospective analysis.

Previous described climate predictions are very likely to have an impact on African water resources. To assess this, an important part of the project focused on characterizing the current African water resources, analyse past trends and forecast potential climate change impacts. More specifically, the analysis consisted in assessing current and future water runoff and retrospective major African lake level variations.

Runoff is the amount of local rainfall that does not evaporate or is stored in the soil. Over longer time periods, it is equal to the difference between precipitation and total evapotranspiration. Runoff therefore constitutes the freshwater resource that can be available to anthropogenic uses as ground or surface water. The CLIMAFRICA project used 149 mean annual runoff station measurements whose gauged area captures the majority of relevant (non-desert) African land surface to produce a spatially explicit estimate of runoff for the entire continent. We integrated the runoff measurements with four different rainfall data sets (GPCC, GPCP, WorldClim & TRMM) and various land surface characteristics using the Budyko framework (Roderick & Farquhar 2011). We first estimated the Budyko parameter for each catchment and rainfall product and then trained the Random Forest machine learning technique (Breiman 2001) to predict the between catchment variability of this coefficient. Based on cross-validation, we found that this approach captures the spatial variability of runoff very well, as residual analysis did not reveal a coherent spatial bias pattern. This method of measurement of mean annual runoff allowed us to generate spatially explicit estimates of mean annual water balance components: precipitation, evapotranspiration and runoff (Fig. 6).

The analysis showed that total integrated runoff over the continent is 3708 km3 per year, which is
approximately 20% of total African rainfall. The remaining 80% are lost to the atmosphere via evapotranspiration. Runoff is largest in regions with largest rainfall, especially at West African coasts and the eastern Congo basin.

The analysis also indicates that the spatial pattern of mean annual evapotranspiration is strongly associated with rainfall, which is consistent with the expectation that water supply rather than energy demand limits evapotranspiration over most regions of Africa. The comparatively low runoff in the northern and southern savanna and grassland ecosystems shows the efficiency of the land surface in evaporating the available water.

CLIMAFRICA used three agro-dynamic vegetation models (LPJmL, LPJ-GUESS, ORCHIDEE) to investigate climate change derived trends and associated uncertainties in water resources in Africa at a continental scale for the year 2100. Climate change was assessed using three different climate models for the RCP 8.5 scenario, each downscaled to 0.5 degree resolution by three different downscaling methods. From the possible 27 combinations of climate model, downscaling method, and agro-DVM, three were infeasible because not all input variables for ORCHIDEE could be provided by one of the downscaling methods. For all other combinations simulations with increasing and constant atmospheric CO2 concentration were carried out, yielding a total number 48 simulations. In addition to the presentation of results in terms of model agreement, we perform an analysis of variance (ANOVA) in an attempt to determine the relative contribution of these three steps in the modeling chain to overall ensemble uncertainty. The generated ensemble of simulations provided a comprehensive set of future scenarios projections and allows assess all major sources of uncertainty in the modeling chain.

Figure 7 shows the projected mean difference of runoff change for the year 2100. Water runoff projections seemed to be almost insensible to the CO2 scenario. Although transpiration rate of individual leaves is expected to decrease under elevated CO2 due to increased CO2 uptake efficiency through stomata, the effect appears to be balanced by the increased amount of standing biomass, which results in a more or less constant canopy conductance.

There were however large differences in projected runoff change among different ensemble members, suggesting large uncertainties in the projections. Analysis showed that in most regions, the dominant source of ensemble variation originated from climate models and downscaling methods. Only in northern and southern tips of the continent agro-DVMs were the major source of uncertainty.

Over almost all Africa runoff is projected to decrease in the worst case and to increase in the best case combination. Exceptions were some regions East Africa and the Horn of Africa where runoff is projected to increase or remain at least constant in all ensemble members and some regions in northern and southern Africa where runoff is projected to decrease or remain at best constant. In most other regions runoff is projected to decrease in 25% of the ensemble members but agreement on a decrease usually does not
Figure 7. Ensemble mean difference in simulated runoff and its variance between the year 2100 and current climate assuming constant CO2 (top left) and transient CO2 (top right). Relative uncertainty contributions of climate models, downscaling methods and impact models are shown in the bottom left figure for constant CO2 and bottom right for transient CO2.

In addition to water runoff, the project also placed emphasis on lake water levels. Indeed, lakes represent key water reservoirs and an important source of economic income through fishing, agriculture and tourism, among others. CLIMAFRICA analysed 40 major lakes and its water level dynamics as derived from remotely sensed SAR altimetry between 1993 and 2011. Figure 8 shows exemplary monthly lake level variations of six lakes as a north-south gradient of Sub-Saharan Africa (Tana, Turkana, Kyoga, Victoria, Tanganyika & Malawi). Results of the analysis showed that a high inter-annual and inter-decadal water lake levels. Beside the strong increase around 1998, due to preceding periods of intense droughts and a subsequent increase in precipitation and extreme rainfall in late 1997 no systematic pattern of change along the north-south transect can be found.

Figure 8. Harmonized lake level variations based on GOHS/LEGOS altimetry (Crétaux et al. 2011); ENVISAT altimetry and TOPEX/Poseidon/Jason-1 & Jason-2/OSTM (USDA et al. 2012). Lake levels are highly variable over the years, recognizable due to the rise and fall in lake levels above and below the mean lake level line (zero line), and are subject to substantial decadal scale variability (red line).

Inter-annual variability of lake level variation (absolute mean of all lake levels) did show however a high correlation with the occurrence of the coupled ocean-atmosphere phenomenon the El Niño/Southern Oscillation (ENSO) (Fig. 9), represented by the Multivariate ENSO Index (MEI) (Wolter et al. 1993, Wolter et al. 1998). This confirms the previous research findings that link the development of wet and dry periods in SSA to the global Ocean Sea Surface Temperature (SST) forcing and the ENSO. It is therefore expected that future ENSO variations will also affect lake water levels in SSA.

Figure 9. Interannual variability of lake level variations in Africa (absolute mean of all lakes) vs. Multivariate ENSO Index (Wolter et al. 1993, Wolter et al. 1998).

Finally, lake level datasets were tested for significant positive and negative trends by using Mann-Kendall tests, which is a non-parametric test to detect significant trends in time series over the period 1993-2012 (Mann 1945, Kendall 1975). The trend test revealed an increase in lake levels for Volta, Turkana, Kwania, Mweru, Malawi, Cabora Bassa and Kariba. Lake levels of Nasser, Chad, Tana, Victoria, Tanganyika and Rukwa show a negative trend. However, there is virtually no coherent spatial pattern in lake level trends, which might indicate that these lake level variations are strongly influenced and managed by humans.

3.2.2 Characterization and potential climate change impacts on African vegetation productivity.

An important component of the project was devoted to characterize general patterns of vegetation productivity in Africa and improve the understanding of the sensitivity of vegetation to climate change.
Indeed, vegetation productivity represents a key ecosystem service that directly influences agriculture, pastures and forestry systems.

In this sense, the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) (Gobron et al. 2006) has been identified as an indicator of the presence and productivity of vegetation and the intensity of the terrestrial carbon sink. Changes in FAPAR are also an indicator of desertification and the productivity of agricultural, forest and natural ecosystems.

The project used the state-of-the-art satellite derived 0.5º monthly FAPAR product from 1998-2010 from the SeaWiFS (Gobron et al. 2006) and MERIS (Gobron et al. 2008) sensors to characterize vegetation productivity in Africa. FAPAR was found to be strongly linked to soil water availability across continental Africa. In fact, we identified that a FAPAR model based on only two variables can explain about 80% of the spatial and temporal FAPAR variability of Africa. Therefore, remotely sensed FAPAR provides a good proxy for ecosystem relevant moisture variations over Africa. When analysing inter-annual variability, the spatial pattern shows a clear hotspot in eastern Africa, roughly stretching along the Great Rift Valley. This region has been identified before to be also a hotspot of IAV of carbon fluxes in Africa (Weber et al. 2009) and it is among the hotspots of IAV of the global land (Jung et al. 2011). A second IAV hotspot was found in the Okavango domain (Fig 10).

Figure 10. Observed FAPAR and FAPAR Interannual Variability.

To anticipate how vegetation productivity may change may change with future climate change, we first developed a empirical model through a non-parametric Random Forest machine learning tool (Breiman et al. 2000) to predict FAPAR based on primarily climate data. The trained model was then applied to three GCM (MIROC5, Can-ESM2, GFDL-ESM2) from the CMIP5 archive to simulate FAPAR response to future climate conditions by 2100. To validate the approach the entire procedure was repeated but using three land surface models (LSMs) for comparison LPJmL (Bondeau et al. 2007), LPJ-GUESS (Smith et al. 2001), and Orchidee (Krinner et al. 2005). The models were forced with the same climate data sets as the empirical model and with scenarios of constant and transient CO2, resulting in 6 simulations per model.

Figure 11. Corroboration of trend patterns in simulated fAPAR from the empirical Random Forests model, and LSM simulations with constant and transient CO2. Shown is the median trend of three different climate simulations for Random Forests, the median trend of 18 land surface model simulations (3 LSMs x 3 GCMs x 2 CO2 scenarios) for LSMs (constant and transient CO2), and the median trend of 9 land surface simulations (3 LSMs x 3 GCMs) for LSMs with constant and transient CO2 respectively.

The result of the empirical simulations approach is presented in the left map of figure 11. Even though the FAPAR trend patterns differed quite a lot among the different climate projections some general patterns emerge: (1) All three show overall more negative than positive FAPAR trends, (2) the horn of Africa showed positive FAPAR trends (3) south of the Congo basin shows negative FAPAR trends. FAPAR trend patterns in central Africa and the northern savannas are somewhat equivocal and dependent on the choice of climate model simulation. When the results of the empirical approach were compared with the LSMs simulations, some common patterns arose, such as positive FAPAR trends in the Horn of Africa and
negative FAPAR trends in West Africa and south of the Congo basin. However, if LSM simulations are stratified by constant and transient CO2 runs a contrasting pattern emerges. In the constant CO2 runs the LSMs predicted negative FAPAR trends over vast areas of Africa (except for the horn of Africa and the Namib), particularly in West Africa, south of the Congo basin, and south-eastern Africa. If the LSMs were forced with rising CO2 most of the negative FAPAR trends disappeared or reversed to positive trends. The horn of Africa, again, showed clearly positive FAPAR trends with the rising CO2 scenario. Increasing CO2 concentrations have a direct physiological effect in the LSMs by increasing the ecosystem’s water use efficiency. Therefore, the effect of increasing dryness in the future is compensated or even over-compensated by the increase in water use efficiency in the models. In other words, the CO2 effect determines if Africa will turn brown or green until 2100 in the LSMs.

3.2.3. Climate Change effects on agriculture and potential consequences to food security.

CLIMAFRICA assessed the potential impacts of future climate change on African agriculture at continental and local scale through a combination of crop yield forecasts and the analysis of future land suitability and other agro-climatic indices. These projections were combined with a spatial dataset of proxies to vulnerability to food insecurity to identify areas of particular concern.

The impact of climate change and future CO2 concentrations on future long term crop yields at continental scale was evaluated for rain-fed maize, the most important cereal crop in Africa (FAOSTAT), applying the same methodological approach as for water runoff. We simulated future yield using the same global Agro-DGVM models (LPJ-GUESS, LPJmL and ORCHIDEE), climate projections (MIROC5, Can-ESM2, GFDL-ESM2), and statistical downscaling techniques. For one of the downscaling techniques not all climate variables needed to force the ORCHIDEE model were available. Running the model with the three AgroDGVMs assuming either constant or transient CO2 thus generated (3 GCMs x 2-3 downscaling methods x 3 Agro DGVMs x 2 CO2 scenarios) 48 model runs. However, all simulations were conducted without accounting for different agricultural management intensity. Hence, projected yield changes presented here are changes in potential yields, which may differ from changes in actual yields.

Projections results indicated that changes in yields are clearly sensitive to increasing CO2 concentrations with less negative or stronger positive yield changes in the increased CO2 scenarios; increasing CO2 would therefore benefit maize through an increase of water efficiency thorough stomata. Also, projected yields highly varied depending on the type of Agro-DVM, GCM and climate downscaling technique used. In many cases the agro-DVMs are the main source of projection uncertainty. Looking at the ensemble mean for constant CO2, however, some general patterns emerged (Figure 12; top left). Potential maize yield was projected to generally decrease in many parts of Africa, except for parts of east and the horn of Africa were yield is projected to increase. If one instead looks at simulated yield assuming transient CO2 a largely different picture emerges, with a stronger positive trend in large parts of east and southern Africa (Figure 12; top right). However, it may be possible that Agro-DVM overestimates the CO2 fertilization effect, as the random forest model used for FAPAR, trained for current climate and CO2 trends, displayed a result that was closer to the median of all runs (both transient and constant CO2).

CLIMAFRICA also assessed future suitability for maize, sorghum and millet using diagnostic models. This was done using future projected trends in climate in combination with soil data. The results generated one
suitability map for each crop, time period and climate input (GCM), where suitability ranges from suitable to unsuited. Results of the model predict a general reduction of land suitability in Africa for millet, sorghum and especially maize, which seems to be much more sensitive to changes in climate. These maps could be useful as an aid for future adaptation in relation to crop selection.

Figure 12. Ensemble mean difference in simulated yield and its variance between the year 2100 and current climate assuming constant CO2 (top left) and transient CO2 (top right). Relative uncertainty contributions of climate models, downscaling methods and impact models are shown in the bottom left figure for constant CO2 and bottom right for transient CO2.

Some of these trends were confirmed when climate change impact on crop yields was evaluated at the local scale. CLIMAFRICA used DSSAT-CSM (Decision Support System for Agrotechnology Transfer-Cropping System Model) (Jones et al. 2003; Hoogenboom et al. 2010), a dynamic, process-oriented, software that allows the simulation of crop growth and development over time on a uniform surface of land, under certain conditions of crop management (ordinary or assumed) to simulate potential future scenarios of crop yields for the most important crops of six study areas selected for the project. Crop simulation models implemented into DSSAT-CSM were parameterized at the field scale, inside the case study areas, using data from field experiments and information on ordinary agronomic crop management. The parameterized models were then used to simulate crop phenology and yield under rainfed and irrigated conditions, and different management options. DSSAT-CSM was forced with the three GCMs, statistically (SOMD) and dynamically (SMHI-RCM) downscaled for simulation of current and future yields at these sites, with both constant and transient CO2 concentration.

Figure 13. Average changes in crop yield (%) in each case study area for 2025 (2011-2040), 2055 (2041-2070), and 2085 (2071-2100) respect to baseline (1981-2010), considering the three GCMs (CANESM2, GFDL and MIROC5) statistically (SODM) and dynamically (SMHI-RCM) downscaled, with transient CO2 (according to RCP 8.5).

DSSAT predicted a decrease in crop yield in simulations with constant CO2 (380ppm), especially for 2055 and 2085. The largest yield declines were projected, again, for maize (especially in Ghana and Togo). A positive trend of yield projections in Kenyan study area, even if the increase in crop yield is high in % terms, but small in absolute terms. This is in consonance with previously described continental scale FAPAR and crop yield scenarios that predict higher future crop yields in many parts of eastern Africa. Considering transient CO2 (according to RCP 8.5) the impacts on yield are lower, especially in C3 species as cassava and rice (Fig. 13).

3.2.4. Medium-term vulnerability to food insecurity in Sub-Saharan Africa.

In addition to the long term (end of the 21st century) agricultural production projections previously explained, the project also analysed medium-term vulnerability to food insecurity in SSA by combining information on yield projections for several major crops in Africa for 2030, with datasets of proxies of current vulnerability to food insecurity. The combination of both datasets allowed to develop hotspots maps of potential food security risk by 2030.
This combination of vulnerability and yield is deeply important because socio-economic vulnerability is a key component of overall food security. In fact, it is actually possible to have high food insecurity in regions that are highly productive, through food accessibility and utility being low despite availability being high through food distribution issues, export activities and assignment of food to other regions than that of production.

An initial data trawl to develop a continental-scale vulnerability map to food insecurity identified seventeen proxies for modelling and predicting stunting; however, only five of them were available at the required extent and resolution. The final list of proxies used consisted in: 1) Stunting for children under five years old, 2) Road density, 3) 2010 Oversea Development Assistance net per capita, 4) Population under five years old and 5) Total population. These variables were normalized and combined to construct the vulnerability map. The minimum mapping unit was set at GAUL 1 or district level.

A map of future crop production scenario for 2030 was developed based on two dynamical vegetation model projections (LPJ-Guess and LPJ-ml) for the following crops: common wheat, barley, maize, paddy rice, sorghum, millet, pulses, sugar beet, potatoes, manioc (cassava) and peanuts. The modelled agricultural outputs were calculated for two different scenarios: B-01 (CO2 on) and B-02 (CO2 constant after 2000), resulting on 4 different combinations of models/scenarios. These maps were compared to current estimates of crop production to estimate yield change trends and normalized and mapped at GAUL1 level. Finally, a mean value of the four model/scenarios results was calculated for all crops combined.

The average of the normalized values for the two datasets were calculated and a map (Figure 14) was produced.

Figure 14. Combination map of future crop change for 2030 with current vulnerability to food insecurity.

Green indicates administrative boundaries with a projected increase of crop production, where stunting is low. Red indicates areas of concern with a projected decreased crop production, with high stunting. Figure 14 essentially shows that regions that are already suffering from stunting are likely to come under more pressure with the change in climate.

The results of this work provide an excellent starting point for the prioritisation of focus when it comes to areas of sub Saharan Africa that will require input in the future. However, a phase of detailed research within these specific regions will be needed in order to develop a higher resolution understanding of the socio-economic and agricultural related status and potential futures in the areas of concern. The current work is a useful oversight but will need to be finessed at a high resolution in future work.

3.2.5. Hotspots of biophysical climate change impacts in Sub-Saharan Africa.

Some of the projections described above were combined with new measures of biophysical impacts of climate change in order to identify areas that overlap spatially and develop a continental-scale composite impact measure to identify hotspots of high exposure to negative climate change impacts by the end of the
21st century. Positive climate impacts were not considered in this analysis. This analysis aimed to provide a wider single picture that combined several types of biophysical impacts as a consequence of climate change.

We focused on biosphere properties relevant to African societies: such as flooding probability, dry periods, total surface freshwater availability, water requirements for cropland irrigation, ecosystem productivity, and crop yield and simulated with the process-based impact model LPJmL at a daily resolution on a global 0.5*0.5º grid. We simulated annual net primary production (NPP) as a measure of ecosystem performance, monthly river discharge as an indicator of surface freshwater availability and the risk of seasonal droughts or inundation, annual irrigation water requirements as an indicator of difficulties in crop management, and crop yields as an indicator of agricultural productivity, driven by a broad range of climate scenarios. Changes were only considered if future projections are significantly different from the reference period (1991–2000) at the 5% significance level according to the Welch’s t-test. Absolute changes were normalized by the maximum change per biosphere property, if positive changes are considered damaging (flooding, dry periods, irrigation requirements); relative changes were capped at 100%, which happens only in regions with very low reference values (Fig. 15).

Figure 15. High-end impact in biosphere properties in the 2080s for (a) total surface freshwater availability, (b) flooding probability, (c) occurrence of dry periods, (d) irrigation water requirements on currently irrigated areas, (e) ecosystem productivity and (f) crop yields. The measure d is a composite of absolute and relative change rates to reflect the importance of large relative changes for the local population and of large absolute changes for the region.

Results indicated that parts of West Africa including the western Sahel, the eastern Sahel, the region around Lake Victoria, and parts of the large rivers, Congo, Niger, Nile, Okavango, and Zambezi are hotspots of climate change impacts (Fig. 15). These hotspot regions are characterized by a combination of relatively high likelihoods of negative impacts in all biosphere properties, the possibility of extreme impacts, and that negative impacts are strong on average. However, the driving factors differ between these hotspot regions. For instance, the Sahel is a hotspot region because of its susceptibility to negative climate change impacts on total water availability and its variability (risk of flooding, seasonal water shortages), as well as on ecosystem productivity and crop yields. For further information on the methodology and results of this study, the reader is referred to Müller et al. (2014).

3.3. Socio-economic implications of climate change impacts and analysis of adaptations and coping measures in Sub-Saharan Africa.

An entire work package of the project focused on assessing the economics impacts of the predicted changes in crop yield due to medium-term climate change and developing a model that describes the spatial spread of climatic shocks in larger areas.

3.3.1. Economic effects of climate change impacts on water and agriculture

CLIMAFRICA developed a national scale macro-economic assessment of climate change impacts in Sub-Saharan African countries by 2030 basically based on the impacts of climate change on crop yields and water resources. To do that, the project incorporated two new models structures in ICES (Intertemporal
Computable Equilibrium System), a recursive dynamic general equilibrium model developed with the main purpose to assess the final welfare implication of climate change impacts on an economic system (Eboli et al. 2010), to better assess the impacts of future crop yields on national African economies. Firstly, the project adapted the farmers’ production function and included a decision process to account for a realistic substitution between the two technologies as a response to changes in relative price of primary factors as well as water shortage induced by climate change. This implied a refinement of the economic database characterizing the benchmark year through the explicit definition of the economic value of land and capital used for irrigation, by crops and countries worldwide.

In addition to that, we also modified the methodology to simulate the effects of increased irrigation because of planned adaptation, to cope with crop yields reduction. We first computed the financial investment required in case of climate change affects negatively agricultural production and GDP, considering the differentials in unitary yields of rain-fed and irrigation technologies (net of over time variations induced by climate change) in each country and by crops to compute how much irrigation is required, and then applying unitary costs per hectare to get the overall investments at country level. Then, this bottom-up spreadsheet procedure is complemented by a top-down modelling to introduce such investments in a coherent macro-economic framework. In fact, more irrigation requires more investment in the agricultural sectors, crowding out the overall investment at country level that is exogenously subtracted to the economic system as a whole. This represents the adaptation costs to be confronted with the benefits by the increased productivity due to the replacement of rain-fed with irrigated land/crops.

Results come from the comparison of a “no climate change” with the “climate change” scenarios in which the changes in yield due to climate change are inserted in the macro-economic model to evaluate its marginal contribution in terms of GDP, sectorial production, prices, international trade and other macro-economic variables. This depends on the share of agricultural value added in the economic system as well as the flexibility of the market system to switch to cheaper production (e.g. imports) when the domestic output becomes too costly. The general equilibrium model allows capturing the inter-connections within the economic system (input-output relationships), this way considering also the effects in non-agricultural sectors that are anyway connected with agriculture.

In general, climate change impacts on the agricultural sector are positive in Western Africa, and negative in the rest of Sub-Saharan Africa. However, the macroeconomic general equilibrium analysis allows considering the so-called market-driven or autonomous adaptation. This reflects at which extent economic agents (landowners, farmers, other productive sectors, consumers) react to the pure effect of climate change that in economic terms works through changes in relative prices leading to changes in purchase behaviours (including changes in import-export dynamics). This is one main limitation of the partial equilibrium models. The map below represents the outcomes in terms of overall country performance, typically measured by change in Gross Domestic Product. We only report in the picture below the case without considering CO2 fertilization effect. When the latter is switched on, we observe a generalised increased in output production in the agricultural sector. These results however, have to be taken with caution given the previously mentioned potential overestimation of the CO2 effect.

Figure 16. Impacts on GDP in Sub-Saharan Africa in 2030 (% change wrt “no climate change” SSP5 scenario)
Moving to adaptation, the table below reports main findings of the analysis, showing how much adaptation is required to recover the agricultural production lost from the climate change impact economic assessment and the total amount of investment required at country level.

<table>
<thead>
<tr>
<th>Country/Macro-Region</th>
<th>Total cultivated area (1000 ha)</th>
<th>Current irrigated hectares (1000 ha)</th>
<th>Share current irrigated / total cultivated areas</th>
<th>Additional irrigated hectares required (1000 ha)</th>
<th>Total (current + required) (1000 ha)</th>
<th>Irrigation potential (1000 ha)</th>
<th>Investment costs (million $2000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Malawi</td>
<td>3135</td>
<td>73.5</td>
<td>2.3</td>
<td>9.4</td>
<td>82.9</td>
<td>162</td>
<td>58.6</td>
</tr>
<tr>
<td>Mozambique</td>
<td>5350</td>
<td>118.1</td>
<td>2.2</td>
<td>181.4</td>
<td>299.5</td>
<td>3072</td>
<td>995.6</td>
</tr>
<tr>
<td>Tanzania</td>
<td>11650</td>
<td>184.3</td>
<td>1.6</td>
<td>49.2</td>
<td>233.5</td>
<td>2132</td>
<td>507.6</td>
</tr>
<tr>
<td>Zambia</td>
<td>2984</td>
<td>155.9</td>
<td>5.2</td>
<td>2.0</td>
<td>157.9</td>
<td>523</td>
<td>12.6</td>
</tr>
<tr>
<td>South Africa</td>
<td>12413</td>
<td>1670.0</td>
<td>13.5</td>
<td>3.6</td>
<td>1673.6 na</td>
<td>22.7</td>
<td>10700</td>
</tr>
<tr>
<td>Rest of South Central Africa</td>
<td>11140</td>
<td>92.8</td>
<td>0.8</td>
<td>78.6</td>
<td>171.4</td>
<td>10700</td>
<td>128.8</td>
</tr>
<tr>
<td>Rest of Eastern Africa</td>
<td>31508</td>
<td>2246.9</td>
<td>7.1</td>
<td>20.6</td>
<td>2267.5 na</td>
<td>128.8</td>
<td>491.0</td>
</tr>
</tbody>
</table>

Table 1. Current, required, potential irrigation and required investment costs for climate change offsetting

3.3.2 Spatial modelling of socio-economic effects of climate shocks.

CLIMAFRICA also aimed to improve current knowledge of optimal intervention strategies to food shortage shocks by developing a theoretical model for the spreading of climate shocks over large areas. This model can be a useful tool to design optimal intervention strategies and minimize the spreading of disaster at given costs and available resources. While most climate-related research focuses on direct impact of climate change on the spot, and considers individual coping and prevention strategies, this work focused on the impact that coping may have on regions outside the primary focus area.

Occurrence of abrupt climatic shocks like flooding or sudden extreme drought often require either preventive measures or immediate interventions like food aid, shelter, vaccination campaigns or medical care that have to be organized at the higher levels. However, in both cases the allocation of scarce available resources is not an easy task because the directly affected victims are interconnected with other persons and areas through social and biophysical networks that depending on their endowments and resilience can either assist in absorbing the shocks or become affected as well. For example, social networks will ensure the individual’s possibility to turn to his neighbors, family or clan members for support in times of hardship. Strong religious and/or cultural norms usually enforce these obligations, and make it virtually impossible to refuse calls for assistance, even if the household itself is also experiencing hardship. This may, in turn, force that household to resort to their network, and the spreading starts.

Biophysical networks allow responding to crises by visiting adjacent areas like in migration – with or without herds – which may also harm others outside the original disaster area. Hence, in all cases, it is vital to understand and model the linkage between people and/or locations to provide policy advice on how
best to intervene from the point of view of the entire system rather than the individual in isolation.

The analysis under was carried out in Western and Eastern Africa at a sub-national scale, at a resolution of 10x10 km cell. For each cell, the composition of the population in terms of being very vulnerable, vulnerable, nearly vulnerable and not vulnerable was determined through the analysis of social indicators of vulnerability. The main innovation in the model is the representation of the spread of havoc through relations between populations. Empirical support for the assumptions made was found through the field data collection carried out for CLIMAFRICA. In the West Africa region, rural populations are connected to other rural populations at most 10 km (1 cell) away; urban areas are linked to other urban areas at most 20 km away, while rural-urban links (one-way only) can extend up to 80 km, to reflect the fact that household members may have migrated from rural areas to urban centers, but still remain important for the household in times of need. For East Africa, rural areas are linked up to 20 km (to reflect the larger distances between populated areas in large part of the East Africa study region as compared to West Africa and the possibility of migration), while urban links and rural-urban (one-way) links are assumed to spread 20 km, and 80 km, as for West Africa.

Figure 17. Example of optimal intervention in West Africa

The model shows how different shocks in productive capacity of household permeates differently through the system and affects other households as well, especially the weaker ones. The extended non-linear structure model accommodates, next to, space and state of household, also a temporal dimension and facilitates an embedding in more comprehensive models that seek an optimal setting of both prevention and coping interventions that meet the policy makers’ objectives while remaining within the affordable (budget) constraints.

3.4. Medium-Term Warning System

An important objective of the CLIMAFRICA project was to develop a methodology for the creation of a prototype Medium-Term Warning System (MTWS) that will allow to identify areas of concern in the next 40 years due to climate change. The analysis was performed using five time steps: one reporting current situation (in, or around, 2010) and four future time steps: 2020, 2030, 2040 and 2050. The areas of concerns for food security have been characterized by significant changes of the climatic variables and by the local human/environmental systems sensitivity and/or by the inability to mitigate and adapt to such changes.

This definition of the area of concern followed the widely accepted definition of climate change vulnerability. Thus, a region’s vulnerability to climate change is described by three elements: exposure, sensitivity and adaptive capacity, as follows: (i) exposure can be interpreted as the direct danger (i.e. the stressor), and the nature and extent of changes to a region’s climate variables (e.g. temperature, precipitation, extreme weather events); (ii) sensitivity describes the human–environmental conditions that can worsen the hazard, ameliorate the hazard, or trigger an impact; (iii) adaptive capacity represents the potential to implement adaptation measures that help avoid potential impacts. The MTWS utilizes a
specific set of indicators to measure each one of three the previously defined components of vulnerability by computing indices, averages or weighted averages and capture the multi-dimensionality of vulnerability. The result of indicators approach has a pyramidal structural:

- At the top there is a single index highlighting the areas of concern (i.e. vulnerable) for climate change;
- At the intermediate level there are three sub-indexes that summarise the information about the three vulnerability’s component (i.e. exposure, sensitivity and adaptive capacity); and finally
- At the lowest level there are indicators that coincide with more specific socio-economic and bio-physical aspects of the studied system

The selection of indicators was done through an extensive review of previous works (Gbetibouo & Ringler 2009, Moss et al. 2001, Cutter et al. 2003, Lucas & Hilderink 2004, Brooks et al. 2005, Thorton et al. 2006, Ehrhart et al. 2009, Birkmann et al. 2010, Davies et al. 2011, Wheeler 2011, Simelton et al. 2012 and Busby et al. 2013). Further selection of the indicators were pragmatically assess in relation to data sources, in particular implemented according the availability of update and consistent dataset, and finally selecting those indicators that match the target of this assessment. Table 2 describes the final list of indicators considered in the MTWS.

<table>
<thead>
<tr>
<th>ID</th>
<th>Component Name of indicator</th>
<th>Unit</th>
<th>Time step</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Exposure Calories demand</td>
<td>Kcal/pixel</td>
<td>2010 – 2050</td>
</tr>
<tr>
<td>2p</td>
<td>Exposure Precipitation anomalies</td>
<td>Mm</td>
<td>2010 – 2050</td>
</tr>
<tr>
<td>2t</td>
<td>Exposure Temperature anomalies</td>
<td>°K</td>
<td>2010 – 2050</td>
</tr>
<tr>
<td>3</td>
<td>Sensitivity Crowding cropland</td>
<td>Ha/1 000 people</td>
<td>2010 – 2050</td>
</tr>
<tr>
<td>4</td>
<td>Sensitivity Livestock per capita</td>
<td>LSU/ 1 000 people</td>
<td>2010 – 2050</td>
</tr>
<tr>
<td>5</td>
<td>Sensitivity Agricult. Res. per capita</td>
<td>Not dimensional number</td>
<td>2010 – 2050</td>
</tr>
<tr>
<td>6</td>
<td>Sensitivity Food satisfaction index</td>
<td>Percentage of caloric intake satisfied by local production</td>
<td>2010 – 2050</td>
</tr>
<tr>
<td>7</td>
<td>Sensitivity Crop diversification index</td>
<td>Percentage</td>
<td>2010 – 2050</td>
</tr>
<tr>
<td>8</td>
<td>Adapt. Cap. Richness International USD purchasing power parity</td>
<td></td>
<td>2010 – 2020</td>
</tr>
<tr>
<td>9</td>
<td>Adapt. Cap. Access to market Travel minute to nearest large city</td>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>10</td>
<td>Adapt. Cap. Access to health facilities Percentage of assisted delivery</td>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>11</td>
<td>Adapt. Cap. Access to water sources Percentage of household with water access</td>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>12</td>
<td>Adapt. Cap. Access to sanitation Percentage of household with sanitation facilities</td>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>13</td>
<td>Adapt. Cap. Infant mortality Death per 1 000 live births</td>
<td></td>
<td>2010 – 2030</td>
</tr>
<tr>
<td>14</td>
<td>Adapt. Cap. Underweighted prevalence Percentage of underweighted children</td>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>15</td>
<td>Adapt. Cap. Stunting prevalence Percentage of stunted children</td>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>16</td>
<td>Adapt. Cap. HIV prevalence Percentage of population living with HIV</td>
<td></td>
<td>2010</td>
</tr>
<tr>
<td>17</td>
<td>Adapt. Cap. Malaria EIR Number of infects mosquito bites per night</td>
<td></td>
<td>2010</td>
</tr>
</tbody>
</table>

Table 2. Indicators used in the MTWS.

The MTWS combines the values from the three different components to produce a single layer that identifies future areas of concern in SSA using PCAs, in which each component of the vulnerability framework above described, is weighted according to its contribution to the overall variance in the data. One of the advantages of this structure is that it is easily amendable and can be further improved by the inclusion on new and/or updated indicators in each of the three components.
Future vulnerability was assessed using three different GCMs (MIROC5, GDFL and CANESM2). Preliminary WTMS for the three global circulation models were relatively consistent among them, with some variations. The most vulnerable areas identified were the Sahel (especially the East part between Sudan and Chad), Ethiopia, the Congo River Basin and a belt from North of Mozambique to North of Angola and South of Democratic Republic of Congo.

Figure 18. A sample snapshot of the WTMS (Above). Areas of Concerns (AOCs) expressed in-terms of integrated vulnerability index. The maps show comparison between the difference in vulnerability (2050 – 2010) according to CGM CANESM2 (scenario rcp 8.5) model. Analysis was conducted with an assumption that no economic or insignificant economic development (baseline) and with a scenario of economic development considered through interpolation (Below).

3.5 Local-scale assessment of climate change vulnerability using a case study approach

In addition to the continental and regional scale vulnerability analysis exercises described above, CLIMAFRICA also assessed vulnerability to climate change at local-scale level in order to evaluate the importance of local biophysical and socio-economic conditions in modulating the effects of impacts occurring at broader scales. To do that, CLIMAFRICA selected a set of case study areas in six African countries – Ghana, Togo, Burkina Faso, Republic of Congo, Sudan, Kenya and Malawi – that altogether constitutes a good representation of some of the main agro-ecosystems of the continent.

The study revealed that vulnerability was mainly a function of exposure (the expected physical change in climatic conditions) and sensitivity (the susceptibility of the agro-ecosystem to be affected by the expected climatic changes) because adaptive capacity (the ability of the human communities to adapt and cope to impacts caused by the expected climatic changes) was generally low in all the study areas, as a result of the high levels of poverty, lack of access to credit, low level of education, among other factors. Cognitive barriers to adaptation (God's will) were also common in many study areas.

Picture 1. Household survey in Ankasa (Ghana)

Vulnerability was mainly determined by the expected change in climate and the local biophysical factors of the study area. As an example, the study area of Kiboko, in Kenya, which showed low levels of adaptive capacity, was identified as one of the less vulnerable areas due to the positive projections regarding local climate (i.e. higher levels of rainfall) and relatively good natural resources (i.e. high soil fertility). Other areas, like Sanmatenga in Burkina Faso, Togodo in Togo or Gedaref in Sudan were identified as the most vulnerable due to the projected negative local climate projections and severity of current stressors (land degradation, nutrient depletion, etc.). Other areas however, were found to be more resilient due to the higher diversity of income sources. The case of Kissoko-Tchizalamou in Congo is paradigmatic: the poor soil conditions for agriculture, combined with the proximity to the sea and relatively good transport infrastructures due to the proximity to the capital of the country, has caused a strong diversification of livelihood activities in the study area; probably increasing the resilience to the projected climate change scenarios.
3.6 Evaluation of best practices guides and measures for climate change adaptation planning

Previously described climate change projections highlights the importance of improving the resilience of socio-ecological systems of rural African communities and their ability to adapt to future challenges.

Societies, organizations and individuals achieve such resilience through adaptation and coping measures, defined by the IPCC (2001) as an adjustment in ecological, social, and economic systems in response to observed or expected changes in climate and its effects and impacts in order to alleviate adverse impacts and take advantage of future opportunities. Adaptation, therefore, may be viewed as choices, within a response space, that include both short term and long term adaptation actions, and define success as those actions that decrease vulnerability and increase resilience overall (van Aalst et al. 2008).

CLIMAFRICA evaluated and compiled a set of potentially suitable adaptation strategies to address the vulnerabilities identified as a result of previous project activities. The list of adaptation measures and policy recommendations was obtained through bibliographical and database research of case studies of strategies that have been proved successful in similar areas affected by similar problems.

The study stressed that climate change adaptation programs still need to address adaptation at various scales: the local level, at which the most impacts of climate change are felt; and at the national level, to address policy issues that may hinder adaptation at local level. Insecure land tenure was identified as one of the most important obstacles standing in the way of effective climate change adaption. Insecure land rights discourage farmers willing to implement measures that do not provide direct benefits in the short term, such as agroforestry measures. The lack of a coordinated network of extension services that would be responsible for building the necessary capacity of the local population to implement these strategies was also identified as an important obstacle that could only be addressed at regional or national levels. To be most effective, adaptation must proceed at several spatial levels simultaneously.

The evaluation also stressed that widespread poverty conditions common in many parts of rural Sub-Saharan Africa and also in the case study sites studied in the project, is one of the main limiting factors at the local scale. It is because of this reason that the project placed a strong emphasis in adaptation measures related to conservation agriculture and Ecosystem-based Adaption (EbA), such as agroforestry as conservation tillage techniques; as they represent suitable solutions of relatively low implementation costs with benefits not only at household level but also in terms of general ecosystem goods and services.

However, to effectively increase climate change resilience of rural population, it is absolutely necessary to reduce poverty. In this sense, we stress that climate change adaption measures are more likely to be effective if they are integrated into broader development programs that addresses poverty, land tenure/usufruct stability, access to peer-to-peer learning, gender-oriented extension and credit and markets to increase resilience and avoid maladaptation.

Potential Impact:
4.1 Potential impact of the results and their exploitation

Most of the ClimAfrica results are of scientific relevance, and so their potential impact is mainly at level of the research community. The studies on the uncertainty of seasonal predictions and the analysis on the
criticalities of decadal predictions are contributing to the global scientific discussion on the right
decisions for climate predictions and the best options for improvements; of paramount importance is
that ClimAfrica is among the few efforts working on the African context. Also in the impacts modelling
community there is an ongoing discussion on the model performances, depending on the crops systems,
the scale, the geographical context, etc., and the ClimAfrica results that are going to be published will
significantly contribute to the scientific discussion.

Even if those results have a primary impact on the scientific community, they are also contributing to the
improved knowledge on climate change related issues in SSA and have therefore a great potential impact
on other sectors than science. In effect, the information provided by the improved performance of climate
predictions and impacts models, as well as the other project’s results and products, like the medium term
warning system, the datasets at continental and local scale, the socio-economic analysis, etc., even if not
fully ready at operational level, are of practical use also outside the scientific context. These results,
integrated by other sources of data and information, can be used for improved planning in response to
climate change, impacting other communities, like professionals on environmental management (agro-
climatologists, etc.), farmers and decision makers and finally also the civil population.

ClimAfrica has indeed organized four training sessions on different aspects (field data sampling, socio-
economic analysis, data processing, models use) in order to form the personnel of different African
research institutions and environmental agencies to exploit the project results and improve their skills in
managing relevant data, tools and information also external to our project. This is the first step to move
from the scientific understanding and analysis to proper planning of management strategies of water
resources and agricultural systems. But further training efforts are needed to form and set up a higher
number of specialised professional teams.

The MTWS together with the socio-economic results can be then used to identify the areas of concerns, in
terms of vulnerability of ecosystems and civil population (identifying also the most vulnerable groups),
were to concentrate further studies on impacts of variability and changes of climate and the needed
adaptation planning. A comprehensive analysis of the ClimAfrica results integrated with other results can
be used to assess the resilience to climate change of water resources and different crops systems, and
propose better land uses and risk management practices that diminish negative impact. All the above, if
associated with appropriate capacity building initiatives, will allow better preparedness to climate change
at any level, until civil population, and can support the development of resilient communities.

A further step in the use of project results can be the development of interactive user-friendly tools on
climate change predictions at seasonal to decadal scale, and the impacts on crop productivity, dedicated
to African farmers, to be used for planning climate smart agriculture practices, based on recommendations
of crop species or varieties, seeding time, water inputs and other strategies.

More in general, besides the scientific community, the farmers and the professionals from environmental
agencies, the project results have significant impacts at level of environmental policies, from the level of
decision makers to the field level of farmers, and general awareness on the climate change problem.

ClimAfrica contributed to bridging the gap between the scientific results and the policy needs. Some
decision makers were already involved in the project through the events and activities dedicated to the
stakeholders, and so already know about the available results and their potential impacts. In general, decision makers can use them for policies at country level on adaptation and management of water resources and agricultural systems. The ingestion of the ClimAfrica results in the countries’ communication strategies will increase the awareness on climate change and risks, but also on what can be done, by the civil population.

The ultimate effect of a comprehensive strategy for integrating and using climate related results at any level, from science to policy, will be civil protection, at least in terms of food security and water resources preservations.

4.2 Dissemination activities

To ensure the widest dissemination of the ClimAfrica results and their following fully a set of dissemination activities, coordinated in the frame of the dissemination plan (Deliverable 8.5) were implemented, and are listed here below.

Web Site
The most direct dissemination tool is the project Web Site. The website contains easily available data and products on the project and enable the dissemination of the information to all interested stakeholders that have access to the internet. Project activities, related documents and results, published materials (like presentations, training materials and reports) and events announcements are regularly uploaded.

Video
A 15 minutes video on “Climate Change in Africa” was produced. This video introduces climate change issues in Africa, focusing on two related EU FP7 projects addressing the research (ClimAfrica) and the dissemination (AfriCAN Climate) aspects. It is available on the ClimAfrica website and also on YouTube, at: https://www.youtube.com/watch?v=oD5wld96kJs&feature=c4-overview&list=UUC4NNzAqqjLk3p58JkOucVw.

Publications (articles, newsletters, brochures)
The main results from the ClimAfrica research activities are being published in international, peer reviewed, scientific and technical journals with a good distribution and easy accessibility (e.g. free online journals, etc.), especially in Africa. The publication of articles in journals is coordinated by the dissemination team in order to avoid any conflicts created by disagreements among partners. The respect of the Special Clause 39 is ensured. Beneficiaries make their best efforts to ensure that electronic versions of their publications are freely available as soon as possible.
The project brochure was produced during the 1st reporting period.

An article on ClimAfrica, with the project description and further details and interviews, was published in the “International Innovation” Journal: see pages 91-93. The pdf version is also available on the ClimAfrica website: http://www.climafrica.net/downs/docs/pubs/International_Innovation_ClimAfrica.pdf Furthermore periodical newsletter are being produced when relevant information (about project activities, progress and achievements) is available.
Management of intellectual property
The management of the intellectual property is defined in the consortium agreement and the respect of the Special Clause 29 is ensured. In any case, ClimAfrica aims at sharing data and the produced knowledge and will promote the free dissemination of the knowledge produced by the project.

Being accessible to the widest audience the ClimAfrica results will support the further scientific and technical development of climate predictability and adaption options beyond the duration of the ClimAfrica project.

Conferences and Workshops
Besides the two Stakeholders Workshops (described here below) we have also organized 4 training events to train in particular the African collaborators in understanding and using the project models and tools, but also to follow a common methodology for field samplings and data analysis. All these events are described also in the Deliverable 8.7.
- from 6 to 15 June 2011, Dakar (Senegal), "ClimAfrica Case Studies Workshop and field training " aimed at standardizing the methods and techniques and define the protocols to be used for biophysical data collection in WP6 (Figure 3);
- from 16 to 17 January 2012, Accra (Ghana), "Training Workshop for Socio Economic Assessment in WP6", aimed at training and discussion on the different methods for local-scale socio-economic assessment;
- from 5 to 7 October 2012, Alghero (Italy), fall school on “Modeling climate change impacts on water and crops at different scales”. The following topics were covered and laboratory sessions were held in conjunction with lectures: i) Climate modeling and downscaling techniques; ii) Models and tools for the assessment of climate change impacts on agriculture and evaluation of changes in crop management as adaptation/mitigation strategies; iii) Socio-economic issues. The course had a focus on Africa and financial support was provided to fully cover the participation of the African partners;
- from 17 to 18 June 2013, Mombasa (Kenya), "Training Course on Statistical Data Analysis" aimed at giving concepts, elements and tools for the analysis of field data collected in the frame of the WP6’s Case Studies.

Participation in external events
As part of the dissemination plan, the ClimAfrica project and its results have been presented – at project level – by the project coordinator during different events, most of them listed here below and described also in D8.7:
- 2 June 2011 in Bonn (Germany), UNFCCC SBSTA34 Workshop on Research: oral presentation to discuss emerging research projects in the area of climate change;
- 17-19 October 2011 in Addis Ababa (Ethiopia), First Conference on Climate Change and Development in Africa (CCDA-I): poster presentation to start contacts and collaboration with relevant stakeholders;
- 28 November-9 December 2011 in Durban (South Africa), UNFCCC-COP17: oral presentation of the ClimAfrica project at the EC Side Event on 28 November 2011. ClimAfrica also organized its own side event about “Regional information for climate services in Africa” on 3 December 2011 (Figure 4). The purpose was to underline the need for improved climate services in support to decision makers.
- 22-27 April 2012 in Vienna (Austria), EGU General Assembly 2012: poster presentation of the ClimAfrica project and first results;
- 29-31 August 2012 in Zanzibar (Tanzania), 32nd Greater Horn of Africa Climate Outlook Forum (GHACOF 32): oral presentation "The seasonal prediction system at CMCC: a focus on Africa";
- 17 October 2012 in London (UK), PAERIP meeting on research infrastructure collaboration between Africa and Europe: participation aimed to propose recommendations for improving the Climate-related research infrastructure in Africa;
- 25-27 October 2012 in Geneva (Switzerland), “Global Framework on Climate Service Dialogue”: oral presentation of the ClimAfrica project and its potential application as a climate service;
- 7-8 March 2013 in Brussels (Belgium), high-level conference "Promoting Africa-EU Research Infrastructure Partnerships": the ClimAfrica perspective, tacking stocks also of others relevant EU FP6 (CarboAfrica) and FP7 (ICOS) projects was included in the presentation "African atmospheric and ecosystem observation networks: perspectives on local and global needs and implementation";
- 15-18 October 2013 in Arusha (Tanzania), Africa Climate Conference 2013: oral presentation "ClimAfrica: an international project to improve seasonal to decadal climate predictions and assess climate impacts in Sub-Saharan Africa".

In all the above events information on the project and associated dissemination material was provided by representative of the project.
Finally all the project participants have presented the project, focusing either on their specific results, or at project level, in many relevant meetings at national and international level.

Stakeholders engagement
In order to fulfil the objectives of ClimAfrica it is crucial the connection with the relevant African stakeholders, ranging from key institutions involved in climate change and environmental research and planning in Africa, to decision makers and end users. That is why the dissemination strategy started with the identification of the target stakeholders and their needs. The criteria used for the identification of the ClimAfrica potential stakeholders are listed in the Deliverable 8.4 “List of potential ClimAfrica stakeholders”.
Two Stakeholders Workshop were organized, the first one on 21 June 2013 in Mombasa, the second one on 5 September 2014 in Addis Ababa. The aim was to present the key findings of the ClimAfrica project focusing on the data, products and services that may be of interests to the project’s stakeholders and at developing synergies, collaborations and strategic partnerships to ensure the best use and follow up of the ClimAfrica outcomes. A small numbers of key stakeholders, identified by the ClimAfrica local African partners, actively contributed to the discussion and provided their feedbacks on the ClimAfrica results in order to improve them (after the first workshop) and assess their usefulness also beyond the project (after the second and final workshop).
Those activities aimed at raising public awareness and participation, creating synergies and developing new collaboration. The objective was to increase the visibility of ClimAfrica and maximize the effectiveness of outreach in order to efficiently transfer and share the matured scientific and technical knowledge and the good practices to the potential stakeholders. The final aim was to promote the accessibility and use of the main project outputs beyond the project community and the project lifetime.
The second workshop in particular was the opportunity to take stock of the project results and reinforce the linkages and collaborations also in view of future opportunities. Stakeholders provided their inputs and feedbacks through their participation into the meetings, but also answering to a specific questionnaire, used to feed the final report and deliverables with their useful perspective.
Data Sharing Policy

Finally, as part of the dissemination plan, a data sharing policy, both for internal and external purposes, has been developed and agreed by the project consortium.

4.3 Way forward

The project coordinator and the project manager are permanent staff of CMCC and a light coordination of dissemination activities will be ensured for the next years. The project website will be maintained as well, and relevant updates concerning mainly dissemination and publications, will be regularly uploaded.

As described in the Deliverable D8.6 there is in place a publication plan for a full exploitation of the ClimAfrica scientific results. Leading authors with the collaboration of co-authors, are taking stock of the final and complete results for preparing a number of papers to be published in the next months and/or years. In most cases these papers will regard specific themes at WP level and even below, and will be led by the relevant beneficiaries. In addition, it is planned to write 3 cross cutting papers, integrating the results of different work packages, dealing with water, food, and climate services. Moreover there will be a final synthesis paper overarching the different project results. Both the core group of authorships and the key issues to be addressed has been agreed. Those publications will ensure the continuation during the next years of the widest dissemination of the ClimAfrica main results through the appropriate audience.

All the above activities as well as the stakeholder engagement, the networking, synergies and collaborations developed during the course of the project, laid the foundation for the continuation of the dissemination and exploitation of the results also beyond the project end.

List of Websites:
Website: www.climafrica.net

ClimAfrica Contact details
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Related documents

final1-climafrica-partnership.pdf

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