CLIMATE CHANGE AND FOOD SECURITY IN TROPICAL WEST AFRICA – A DYNAMIC-STATISTICAL MODELLING APPROACH

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With 8 figures and 3 tables
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Summary: The relationships between climate and agricultural production in Benin, tropical West Africa, are elucidated using predictions from a high-resolution regional climate model. The aim is to detect the sensitivity of various mainly alimentary crops cultivated in tropical Africa to changing climate conditions due to increasing greenhouse-gas concentrations and ongoing land degradation. This knowledge is of practical relevance since the predominant cultivation of less vulnerable crops may be an appropriate adaptation strategy in order to maintain or improve food security in Africa. Model output statistics are used to transfer simulated climate variability to changing crop yield. It turns out that the statistical relationships between climate and agricultural production are very strong, amounting in part to more than 50% of explained variance at the interannual time scale. Especially summer monsoon precipitation and relative humidity represent reliable predictors of crop yield. Until 2025, the dryer and warmer climate in tropical Africa may come along with a decrease in agricultural production with respect to most crops. The reduction is in the amount of 5 to 20%, implying severe problems of food security given the increasing population density. However, yams and manioc, as major alimentary crops in Benin, appear to be less sensitive to climate change.

Zusammenfassung: Anhand von Simulationen mit einem hoch auflösenden regionalen Klimamodell wird der Zusammenhang zwischen Klima und landwirtschaftlicher Produktion im westafrikanischen Benin beleuchtet. Das Ziel besteht darin, die Sensitivität verschiedener Nutzpflanzen, die im tropischen Afrika angebaut werden und vorwiegend als Ernährungsgrundlage dienen, gegenüber veränderten klimatischen Rahmenbedingungen zu erfassen. Dabei werden steigende Treibhausgaskonzentrationen und eine fortschreitende Landdegradation berücksichtigt. Die Kenntnis dieser Sensitivität besitzt große praktische Relevanz, da der bevorzugte Anbau von unempfindlichen Nutzpflanzen eine geeignete Anpassungsstrategie zur Ernährungssicherheit in Afrika darstellen könnte. Über so genannte Model Output Statistics wird die simulierte Klimavariabilität in Ernteertragsanomalien umgesetzt. Es zeigt sich ein starker statistischer Zusammenhang zwischen Klima und landwirtschaftlicher Produktion. Teilweise beträgt die erklärte Varianz mehr als 50% auf der interannuellen Zeitskala. Vor allem der Sommermonsunniederschlag und die relative Luftfeuchte bilden zuverlässige Prädiktoren für den Ernteertrag. Bis 2025 wird ein trockeneres und wärmeres Klima im tropischen Afrika simuliert, welches hinsichtlich der meisten Nutzpflanzen mit Ernteeinbußen in Höhe von 5 bis 20% einhergehen könnte. Vor dem Hintergrund der zunehmenden Bevölkerungsdichte ergibt sich damit ein gravierendes Ernährungsproblem. Andererseits erweisen sich Jams und Maniok, die in Benin eine wichtige Nahrungsgrundlage darstellen, als weniger sensitiv gegenüber dem Klimawandel.

Keywords: climate change, Africa, food security, regional climate model, model output statistics

1 Introduction

Climate is a crucial factor in agricultural production and food security (Anhuf 1989; Herbers 1999; Mall et al. 2006; McCarthy et al. 2001). This is particularly true in the developing countries where investments in agriculture are low and vulnerability of the social systems is high (Burton and Lim 2005). A dramatic example for this vulnerability has been given by the severe Sahel drought during the second half of the 20th century (Nicholson 2001) which also prevailed in the more humid Guinean Coast region (Le Barbé et al. 2002): deficient precipitation amount over many years has led to considerable economic loss, hunger, civil war and migration (Benson and Clay 1998; Findley 1994; Richter 2000). It is likely that food security represents a problem which will not be overcome in the near future. On the one hand, population growth and urbanization trends are still enormous in most African countries (Gaebe 1994; Schulz 2001). On the other hand, climate models predict a deterioration of climate conditions in tropi-

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cal Africa (Houghton et al. 2001). Achenbach (1994) pointed out that rainfall variability has the highest risk potential for food security in the tropics and subtropics, although the problem is generally more complex, including factors like demography, soil fertility, world market conditions, cash crops, land degradation as well as socio-economic, historical and religious aspects. Therefore, this study is dedicated to the assessment of future climate changes in Africa and related anomalies in crop yield in order to provide a scientific basis for adaptation strategies in food production systems. The practical relevance of this issue is obvious: knowledge of the vulnerability of various alimentary crops may lead to an appropriate selection of crops in order to improve or maintain food security in the light of global warming and increasing population.

The following section summarizes previous works on African climate and food security. Section 3 introduces the region of interest. The observational and model data as well as the model output statistics (MOS, Glahn and Lowry 1972) used in this study are described in section 4. The results of the climatological analysis and the MOS are considered in section 5. The results are summarized and discussed in section 6.

2 Scientific background

Several studies have dealt with the effect of increasing greenhouse-gas (GHG) concentrations on African climate. There are still large discrepancies between different climate model predictions: some models tend to simulate negative precipitation trends in the Sahel Zone and inner Sahara but more humid conditions in the southernmost Guinean Coast region (Houghton et al. 2001; Hulme et al. 2001; Paeth and Hense 2004). Other model experiments indicate a northward shift of the rain band into the Sahel Zone with drier climate near the Guinean Coast and more abundant precipitation in the north (Coppola and Giorgi 2005; Hoerling et al. 2006; Kamga et al. 2005). African rainfall is also embedded in a complex system of tropical teleconnections, for instance with the El Niño-Southern Oscillation phenomenon in the tropical Pacific (Saravanan and Chang 2000). Thus, remote effects may also arise from climate changes in other regions of the globe.

However, the impact of human activity on the Earth's climate is not confined to the emission of greenhouse gases. Land cover changes also play an important role by altering the energy balance at the surface, the turbulent exchanges in the atmospheric boundary layer and the hydrological cycle via transpiration and interception from vegetation (Feddema et al. 2005; Pielke et al. 2002). Bounoua et al. (2000) have demonstrated the warming effect of reduced vegetation cover in the low latitudes. Deforestation may result in more arid climate conditions in most of tropical Africa (Semazzi and Song 2001; Werth and Avissar 2005). The same holds for the Sahel Zone where excessive land use in the form of pasture and irrigated agriculture may increase the drought risk (Wang and Eltahir 2000). Along the Guinean Coast region near-surface warming over land may cause enhanced moisture advection during the West African summer monsoon season and, hence, a compensation of the general drying effect of reduced vegetation cover (Clark et al. 2001). Soil degradation is a further process which is related to deforestation and excessive land use. It may contribute to the drought tendency in sub-Saharan Africa (Douville et al. 2001; Feddema and Freire 2001). In addition, biomass burning is accompanied by the emission of aerosols which have been found to compensate the GHG-induced heating but to aggravate the weakening of the hydrological cycle over Africa, as inferred from idealized climate model experiments (Paeth and Feichter 2006). Finally, local feedbacks with vegetation cover, albedo and soil moisture may also represent a source of internal variability in Africa by enhancing the amplitude and prolonging the persistence of climate anomalies once initiated by changes in the large-scale circulation or in the ocean (Long et al. 2000; Nicholson 2001).

The discussion of these previous findings demonstrates that a realistic assessment of future climate change in Africa has to account for both the effect of increasing GHG concentrations and ongoing land-use changes (Douville et al. 2000). So far, both effects have only be combined in coarse-grid global climate model simulations (Feddema et al. 2005; Maynard and Royer 2004) which do not usually meet the spatial requirements of decision makers in policy and agriculture at the national and regional scale. Given these practical aspects and the fact that African climate is characterized by a prominent scale interaction between the large-scale monsoon circulation and meso-scale processes like squall lines and convective systems (Weischet and Endlicher 2000; Saha and Saha 2002), the use of high-resolution regional climate models is required (Jenkins et al. 2002). In the present study, we derive the future pathway of African climate from a number of time-slice experiments with the regional climate model REMO (JACOB 2001). Based on several sensitivity studies with this high-resolution model (PAETH 2004), fairly realistic scenarios of the human impact on African climate have been developed, including GHG emissions, deforestation, desertification and soil degradation (PAETH and THAMM 2007). It is assumed that these climate predictions provide reasonable insight into the future agricultural risks and potentials in tropical Africa. Thus, our study basically comprises two improvements with respect to previous attempts: a high-resolution regional climate model is considered and more realistic scenarios for future climate change are taken into account.

There has also been a number of studies dedicated to the relationships between climate and agriculture all around the globe (ANHUF 1989; MCCARTHY et al. 2001). It appears that food production systems in the low latitudes are more affected by climate variations than in the mid-latitudes (ACHENBACH 1994). On the one hand, this arises from the low economic potential for irrigation, fertilization or other compensatory measurements in the developing countries (BURTON and LIM 2005). On the other hand, tropical and subtropical plants seem to be more sensitive to temperature fluctuations: a warming of 2 °C to 3 °C may be tolerable for plants in the extra-tropics but may lead to remarkable crop failure in the low latitudes (EASTERLING and APPS 2005). ZHAO et al. (2005) have shown that especially the cultivation of grain may be struck by a relatively low warming rate, while even more disastrous consequences may arise from an enhanced frequency of extreme events. Beside water quantity the quality is also a key component which is affected by human activity (HERBERS 1999).

Among the regional studies in the low latitudes, food production systems in India have been analysed with respect to internal variability, such as El Niño-Southern Oscillation (SELVARAJU 2003) and anthropogenic climate change (MALL et al. 2006). These works highlight the strong relationship between climate and agriculture at different time scales. The same is true for sub-Saharan Africa: the most recent global climate model simulations of the 4th assessment of the IPCC indicate a severe "agricultural drought" due to the drying of soils in Africa (WANG 2005). In Mali, BUTT et al. (2005) have reported on a decrease in crop yield in the amount of up to 17%. They predicted that the share of the population threatened by hunger may rise from 34% nowadays to 72% up to 2040. As this dramatic development is mainly related to radiative heating, the authors recommend the cultivation of more heat-resistant crops in the future.

3 Study area

For several reasons, the present study is focused on Benin in tropical West Africa: (1) Long-term time series of agricultural production are available for various crops. (2) Population growth is still at a high level (3.25% p. a.) and, hence, the demands with respect to the natural system are supposed to be quite high. (3) The region is located in the so-called Dahomey gap, a region with lower precipitation amount than in the surrounding regions at the same latitude (SAHA and SAHA 2001). This may cause a higher vulnerability in terms of the expected climate change. (4) Precipitation and heat stress are subject to a prominent seasonal cycle embedded in the large-scale monsoon circulation (BOKO 1992). Climate models are supposed to reproduce this large-scale phenomenon in a realistic

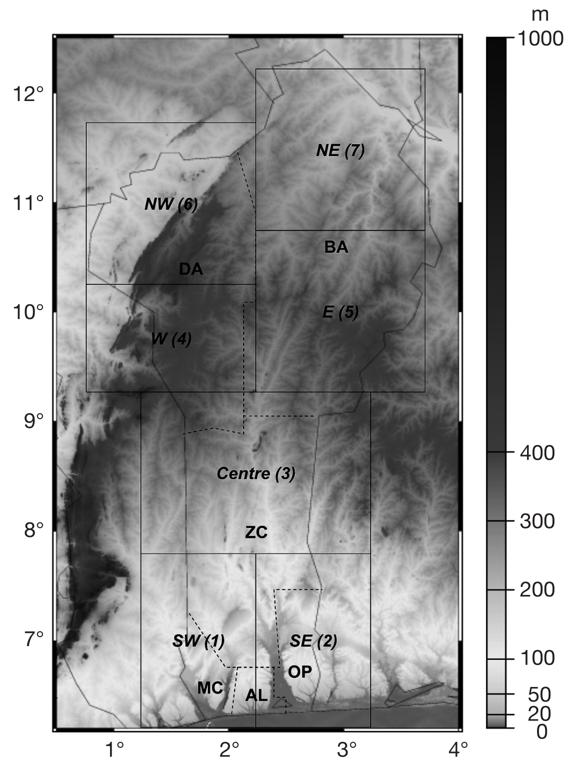

Fig. 1: Map of Benin with topography in m above sea level. The black rectangles (solid lines) denote the boundaries of the idealized agro-climatological units, the numbers in brackets indicating the respective reference number (italic characters). The dashed lines mark the department structure for which time series of crop yield are available (for abbreviations see Tab. 1).

way (Paeth et al. 2005). (5) A previous study has revealed the dramatic response of maize production in Benin to global warming (Agbossou and Akponipé 1999).

Benin is located along the Guinean Coast region in tropical West Africa (aspects of regional geography from Adam and Boko 1993). The country covers an area of 112,622 km^2 and extends roughly from 1°E to 4°E and from the coastline at 6.5°N to 12.5°N (Fig. 1). The topography is dominated by the mountain range of the Atacora in the northwest with altitudes of up to 700 m above sea level and a smooth ascent from the Atlantic coast in the south and the Niger basin in the northeast towards the centre of Benin with altitudes between 250 and 300 m. This rather smooth topography does not lead to pronounced windward and lee effects in the distribution of rainfall, except for the Atacora region. In most of the country (82%) ferruginous soils with favourable agricultural potential prevail. Less fertile conditions are found in the barely developed mineral soils of the Atacora region and in the sandy soils along the coast. In contrast to other countries along the Guinean Coast, the natural vegetation in Benin is not dominated by dense evergreen woodlands but by woody savanna. From south to north, according to the gradient of precipitation amount, there is a typical sequence of ecosystems with decreasing water demand, density and biodiversity: the coastal zone with littoral forests, the Guinean-Congolian zone with rainforests, the southern and northern Guinean zone with woody savanna, as well as the southern and northern Sudanian zone with predominating grass savanna. Meanwhile, most natural ecosystems are superimposed by agricultural activity and pasture. From a hydrological point of view Benin is subdivided into three major river catchments: the Pendjari basin in the ultimate northwest, the Niger basin in the northeast and the Ouémé catchment, which drains most of the country. The Ouémé River rises in the Atacora Mountains and traverses the central and southern parts of the country before flowing into the Atlantic Ocean. It represents the most important freshwater reservoir of Benin with mainly unused irrigative potential in regions with relatively high soil fertility.

The most striking climatic feature in sub-Saharan Africa is the distinct gradient in precipitation amount from south to north (Saha and Saha 2001). While the Guinean Coast region receives more than 1,200 mm p.a., this amount gradually decreases towards the central Sahel Zone with less than 400 mm p.a. and even less than 100 mm p.a. in the transition zone between Sahel and Sahara. In addition, precipitation is subject to a clear seasonal cycle (Boko 1992). The patterns of observed seasonal rainfall in figure 2 have been derived from the CRU data set (New et al. 2000). This data set is a merged product of all available station data over the continents between 1901 and 1998 interpolated to a regular grid with 0.5 ° resolution. Poccard et al. (2000) have shown that the CRU precipitation data provide a reliable estimate of rainfall amount and variability in tropical Africa. During the winter monsoon season (January to March, JFM) regular rain events only occur near the coast, whereas arid conditions prevail in the northern half of Benin under the influence of the dry northeasterly Harmattan wind (Fig. 2). Subsequently, the moist southwesterly summer monsoon penetrates into the continent with a first rainfall peak in April to June (AMJ) in the southern part of the country. During the July to September period (JAS) precipitation amount is highest in the central and northern part of Benin while a relative dry period is observed along the coastal region. In autumn (OND) the southwest monsoon retires towards the Atlantic Ocean, causing a secondary rainfall peak near the Guinean Coast. As a consequence, the mean distribution of monthly precipitation is bimodal in southern Benin while one single peak is observed in central and northern Benin (Adam and Boko 1993; Boko 1992).

The seasonal cycle of near-surface temperature is less pronounced as inferred from the CRU observational data (Fig. 2). It is generally inverse with respect to the seasonal cycle of precipitation due to the effect of cloudiness: in JFM temperature is rather uniform over the entirity of Benin, ranging between 28 °C and 29 °C. After the onset of the summer monsoon (AMJ) the highest temperatures are observed in northern Benin with up to 32 °C in the seasonal mean. The lowest temperatures are related to the peak phase of the summer monsoon in JAS. In the post-monsoonal period rather uniform conditions re-establish. The prominent seasonality of rainfall in sub-Saharan Africa implies a clear limitation of the vegetation period and, hence, of agricultural activity in most parts of Benin, except for the southernmost region.

The estimated population of Benin amounts to about 7 million people (INSAE 2003). The mean population density is quite low (~63 inhabitants per km^2) but high concentrations exist in southern Benin: for instance the small AL region (Atlantique-Littoral, see Fig. 1) is home to 12% of the entire population. The population growth rate is 3.25% which leads to an estimated population of 17 million people by 2027. This is more than a doubling within 20 years. Thus, it can be expected that the demand for food and land will increase considerably in the near future, raising the question of food security under changing climate conditions and increased land degradation. The economic system of Benin is one of the least developed on Earth, with the largest portion of people working in agriculture (54%), mainly on the basis of subsistence. The gross income amounts to 368 $ per capita (PNUD 2003). This demonstrates the low economic potential for investments in agriculture, for instance in the form of irrigation techniques and fertilization.

4 Data and methods

4.1 Agricultural data

The data on agricultural production in Benin have been collected and documented by the Ministry of Rural Development (MDR 2004). The data availability is summarized in table 1. Nineteen different crops are listed, which mainly serve as alimentary products for the population of Benin. Cotton is primarily cultivated for export but has suffered from the recent slump on the world market. The crop yield data refer to six major regions in Benin which largely correspond to the department structure. The spatial extent of these regions is displayed by the thin dotted lines in figure 1. It is obvious that the time series in table 1 have a different spatial representation. The agricultural data have been recorded since 1970 and are available up to 2003. The time series have been corrected, homogenized and quality-controlled by MDR (2004). However, there are still many gaps in the data set. This arises partly from missing data and partly from the fact that some crops are not cultivated in all regions of Benin (for instance Sorghum in southern Benin). In order to rely on robust time series, only crops with complete data coverage are considered for the statistical analysis. At least, it was required that the regional mean over Benin can be computed for the entire 1970–2003 period. This holds for peanuts, cotton, beans, yams, maize, manioc, rice and sorghum. Thus, a total of 56 predictand time series is given: 8 crops times 7 regions (6 sub-regions plus the overall Benin average).

The related time series of crop yield per hectare observed since 1970 are displayed in figure 3. Each time series refers to the Benin average. For some

Table 1: Available data periods of annual crop yield for 19 different crops in the six regions marked in figure 1 (dotted lines)

	Mono-Couffo (MC)	Atlantique-Littoral (AL)	Ouémé-Plateau (OP)	Zou-Collines (ZC)	Donga-Atacora (DA)	Borgou-Alibori (BA)
Peanuts	1970–2003	1970–2003	1970–2003	1970–2003	1970–2003	1970–2003
Cotton	1970–2003	1999–2003	1970–2003	1970–2003	1970–2003	1970–2003
Gumbo	1981–2003	1981–2003	1981–2003	1981–2003	1981–2003	1985–2003
Beans	1970–2003	1970–2003	1970–2003	1970–2003	1970–2003	1970–2003
Yams	1970–2003	–	1970–2003	1970–2003	1970–2003	1970–2003
Maize	1970–2003	1970–2003	1970–2003	1970–2003	1970–2003	1970–2003
Manioc	1970–2003	1970–2003	1970–2003	1970–2003	1970–2003	1970–2003
Millet	–	–	–	1987–2003	1970–2003	1985–2003
Batatas	1988–2003	1988–2003	1988–2003	1988–2003	1981–2003	1989–2003
Pimento	1981–2003	1981–2003	1981–2003	1981–2003	1981–2003	1985–2003
Peas	1991–2003	–	1991–2003	1991–2003	–	–
Rice	1970–2003	1998–2003	1994–2003	1970–2003	1970–2003	1970–2003
Sesame	–	–	1981–2003	1990–2003	1990–2003	1992–2003
Soy Beans	1993–2003	–	1993–2003	1993–2003	1993–2003	1993–2003
Sorghum	–	–	–	1970–2003	1970–2003	1970–2003
Tobacco	1970–1977	–	1970–1977	1988–2003	1973–2003	–
Taro	1988–1992	–	1996–2003	1988–2003	1988–2003	–
Tomato	1981–2003	1981–2003	1981–2003	1981–2003	1981–2003	1985–2003
Bambara Peas	–	–	1996–2003	1988–2003	1981–2003	1993–2003

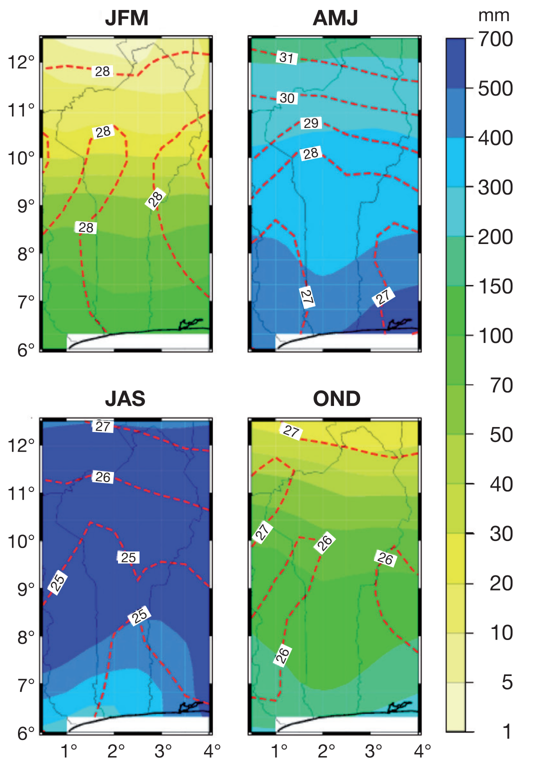

Fig. 2: Observed seasonal sums of total precipitation in mm (colour shading) and seasonal-mean near-surface temperature in °C (isolines) in Benin averaged over the 1970–1998 period, CRU data set.

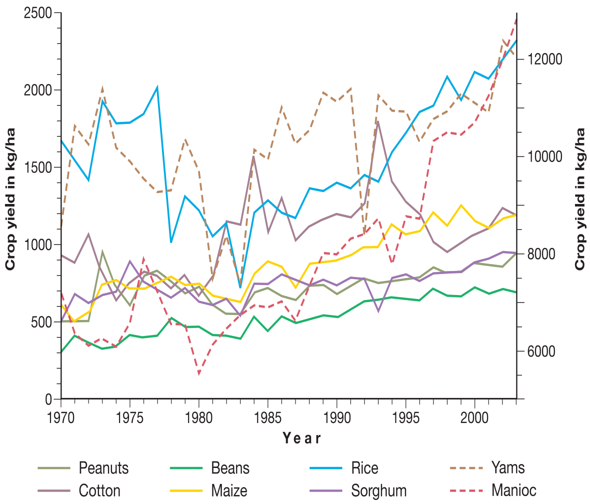

Fig. 3: Observed time series of annual yield in kg per hectare, averaged over Benin, for the crops for which complete regional-mean time series over Benin are available. The solid lines refer to the left scale, the dashed lines to the right scale of the ordinate.

crops the regional time series differ considerably (not shown). Most crops are characterized by a positive trend of annual yield. The increased efficiency of the food production systems in Benin can be explained by some biotechnological progress in the form of improved crops, fertilization, irrigation, use of pesticides and transfer of knowledge by foreign relief organizations (SERAGELDIN 1999). The yield per hectare of yams and manioc is one order of magnitude higher than for most other crops. The strongest increase in production has been reached for Manioc: more than 50% within 34 years. Indeed, yams and manioc represent basic alimentary crops in Benin with obvious potential of enhanced productivity. Superimposed on the general positive trend is a remarkable interannual variability. For some crops the year-to-year fluctuations are in the same order as the long-term changes (e.g. yams, rice, sorghum). Given the fact that investments in the agriculture of Benin are low and that the latter is barely orientated towards the world market, it can be assumed that these shorter-term fluctuations are at least partly governed by climatic conditions. This is the basic hypothesis of our study. It will be evaluated by means of the MOS approach (subsection 5.2).

The data set provided by MDR (2004) also contains estimates on the spatial extent of agricultural area for each crop. This area has clearly increased during the last decades (not shown). However, we do not consider this variable for two reasons: (1) The spatial extension of agricultural activity is assumed to arise from the enhanced food demand due to population growth. Thus, it reflects a demographic rather than a climatic process. (2) The extension of agriculture is limited in space due to the political boundaries and natural resources of Benin. Actually, there are some indications that agriculture converges towards a maximum extent. Beyond this threshold no variability occurs regardless of any climate variations.

4.2 Climate model data

Climatic information for the 20th and 21st century is taken from the regional climate model REMO. It is a hydrostatic nonlinear limited-area model which is based on the primitive equations with surface pressure, temperature, horizontal wind components, water vapour and cloud water content as prognostic variables (JACOB 2001). REMO is designed for processes at the meso-α, synoptic and larger scales. In the present version, it is run with 0.5 ° grid point-spacing and 20 terrain-following atmospheric levels (Paeth et al. 2005). The time step of the discretized model equations is 5 minutes. The model domain covers entire tropical and northern Africa, the Mediterranean region and the Arabian Peninsula within the sector 30°W to 60°E and 15°S to 45°N. Here, the model is driven in the uncoupled mode, i.e. it is once initiated by a global data set and then, the lateral atmospheric and lower oceanic boundary conditions are prescribed every 6 hours. Land surface conditions are usually taken from satellite data.

For our purpose, two different forcing data sets are used: (1) The hindcast period 1979 to 2003 has been driven with re-analysis data from the ECMWF (European Centre for Medium-range Weather Forecast). The re-analyses incorporate all available observations from ground-based and satellite measurements and represent a quasi-observational data set without any spatial and temporal gaps. The hindcast simulation with REMO is dedicated to train the MOS (see subsection 4.3), provided that REMO is able to reproduce the interannual variability of the real climate system and, hence, the relationship with agricultural production.

(2) Future African climate change is derived from 5 time-slice experiments between 2005 and 2025, each 5 years apart from each other. The time-slices are subject to various simultaneous forcings: the lateral atmospheric and lower oceanic boundary conditions are taken from the coupled global climate model ECHAM4/HOPE which was forced by increasing GHG concentrations according to the moderate IPCC emission scenario B2 (Houghton et al. 2001). Thus, the global model introduces changes in the large-scale atmospheric circulation and sea-surface temperature fields. The GHG increase according to the B2 scenario is also implemented in REMO. In addition, a fairly realistic spatial pattern of expected land-use changes is described, accounting for processes like shifting cultivation, urbanization and desertification in sub-Saharan Africa. The amount of land degradation increases steadily from 2005 to 2025 according to estimates by the FAO (Food and Agriculture Organization). These estimates are based on the observed demographic development extrapolated into the future. Finally, soil degradation is implemented in REMO by modifying the soil parameters which govern the ratio between infiltration on the one hand and drainage as well as surface runoff on the other hand. A more detailed description of the experimental design, including scenarios and background assumptions, can be found in Paeth and Thamm (2007).

4.3 Model output statistics

The statistical relationships between the simulated climatic predictors and the agricultural predictands are evaluated by means of a MOS approach (Glahn and Lowry 1972). The procedure is described in figure 4. For each predictand (one crop in one region) a stepwise multiple regression analysis is carried out during the overlapping period 1979–2003 between REMO and the agricultural data. Given the time series of crop yield $\vec{y}$ and the matrix X, with various climatic predictors arranged in columns, the multiple regression model is based on the equation

$$\vec{y} = X \cdot \vec{a} \qquad (1)$$

where $\vec{a}$ denotes the vector of multiple regression coefficients. According to the least-square fit the coefficients can be estimated by

$$\vec{a} = \left(X^T X\right)^{-1} X^T \vec{y} \qquad (2)$$

For each step the full set of 96 climatic predictors is considered. The stepwise analysis leads to an arrangement of the predictors in the order of their importance as measured by linear correlation with the predictand. As regression models are often subject to overfitting, a cross validation is included. For this purpose, the time series are split up into a dependent data set which is used to fit the regression model, and an independent data set which is used to evaluate the regression model. The list of predictors is cut off when the mean square error between these independent data and the estimated data from

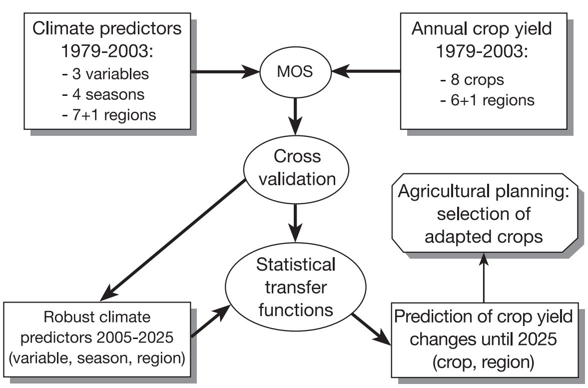

Fig. 4: Flowchart of the statistical approach in this study. Model output statistics (MOS) are based on a stepwise multiple linear regression analysis. The statistical transfer functions are filtered by cross validation which is also used to determine robust climate predictors. The aspect of agricultural planning is not part of this study but a crucial potential arising from this approach.

the regression model increases. This ensures that the relationship between climate and crop yield is not over-estimated. Thus, the cross validation leads to a limited set of robust predictors and the final statistical transfer functions between predictors and predictand. In addition, the entire regression model is tested for statistical significance in order to ensure the transferability of the statistical relationships from samples to population. It is assumed that these statistical transfer functions are stationary in time, i.e. simulated predictors from REMO for the time-slices 2005–2025 can be transferred to crop yield anomalies until 2025. A more detailed description of the MOS approach used here is given by Paeth and Hense (2003). The MOS approach is also related to a practical objective: the idea is to provide a scientific basis for agricultural planning by detecting crops which are less affected by the expected climate change in Africa.

The critical point of this method certainly is that stationarity of the statistical relationships is assumed. It is conceivable that in a warmer climate non-linearities occur which lead to modified thresholds and sensitivities in the light of climate variability. Note that this is not a peculiarity of this study but a general problem climate impact research is faced with. Therefore, it will be of major value to corroborate our findings with complex non-linear crop models which, however, require a large number of unknown or uncertain input parameters.

5 Results

5.1 Climate variability

Climate variability is illustrated in figures 5–7. It is assumed that the impact of climate on agriculture can be assessed with a small set of basic variables which themselves arise from a variety of thermodynamical processes in the atmosphere and ocean: near-surface temperature, precipitation amount and relative humidity. These variables are also supposed to respond more or less directly to human activity through changes in the radiation budget, energy balance, horizontal temperature gradients and large-scale atmospheric circulation (Houghton et al. 2001). According to the horizontal resolution of the gridded CRU data set, Benin is split up into 7 sub-regions as marked by the red rectangles in figure 1. For each sub-region the spatial-mean and seasonal values of temperature, precipitation and relative humidity are determined. In addition, the overall mean time series for entire Benin is computed. This makes a total of 96 climatic predictor time series: three atmospheric variables times 4 seasons times 8 regions. The idea is that agriculture is mainly affected by the regional climatic conditions in the direct vicinity, which themselves may be related to remote effects from all around the globe, particularly to teleconnections with the tropical oceans (Paeth and Hense 2003).

The green curves in figure 5 denote the observed variations of JFM and JAS precipitation averaged over Benin. The time series reflect the seasonality of rainfall during the dry winter and moist summer monsoon. The time window 1970 to 2003 masks the prominent negative trend in the decade before: JAS precipitation amount has been on a much lower level than during the 1950s and 1960s (Le Barbé et al. 2002; Nicholson 2001). Particularly the JAS season is characterized by considerable interannual fluctuations: in wet years total precipitation amounts to 200 mm more than during dry years which is equivalent to +50%. In northern winter, the anomalies are less pronounced. However, some years experience almost no rainfall during the winter monsoon season, as for instance in 1992. Comparing the time series in figures 3 and 5 with each other reveals some obvious relationships: the dry anomaly during the first half of the 1980s was accompanied by some crop failure, especially in terms of yams, rice and sorghum – some of the most important alimentary crops in Benin. The absence of winter precipitation in 1992 may have caused a negative anomaly in yams yield. The short wet period prior to 1975 coincides generally with high crop yield. In contrast, the productivity of manioc seems to be anti-correlated with precipitation amount. In subsection 5.2, it will be tested as to whether these obvious relationships can be confirmed statistically.

The red curves and dots in figure 5 refer to the simulations with the regional climate model REMO. It is obvious that REMO is in excellent agreement with the observed year-to-year variations of JFM and JAS precipitation. This means that the information of interannual and longer-term variability in tropical African climate is inherent in the lateral atmospheric and, particularly, lower oceanic boundary conditions (Palmer et al. 1992). The relationship between African precipitation and tropical sea-surface temperatures has also led to approaches of seasonal climate forecasting (Garric et al. 2002; Mo and Thiaw 2002; Paeth and Hense 2003). The fact that the observed and simulated rainfall time series

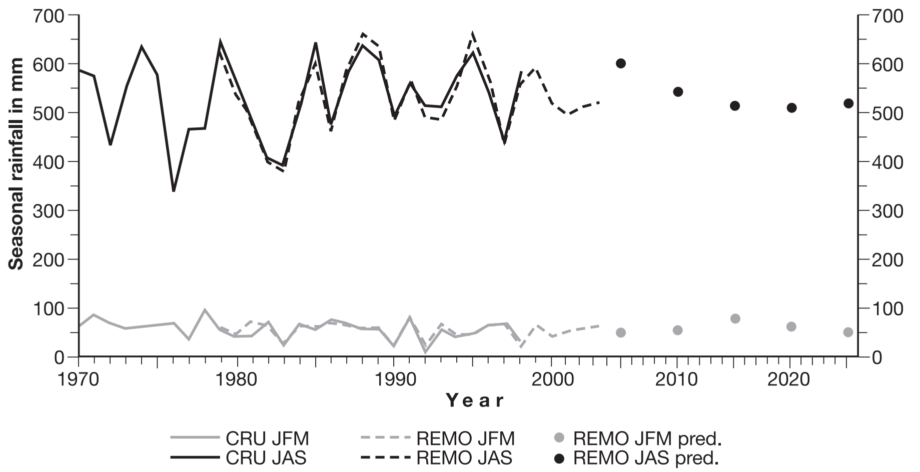

Fig. 5: Observed and simulated time series of JFM and JAS precipitation in mm, averaged over Benin. The circles denote the time slice experiments under enhanced greenhouse conditions and land degradation in the near future.

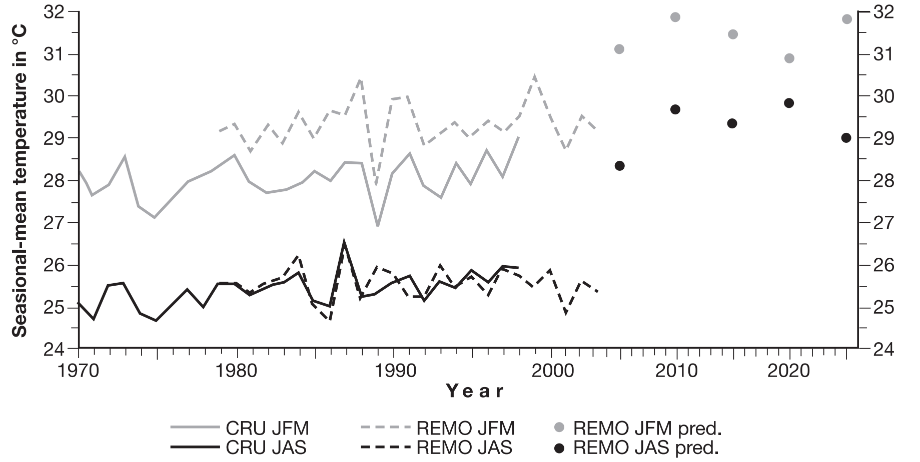

Fig. 6: Same as Fig. 5 but for near-surface temperature in °C.

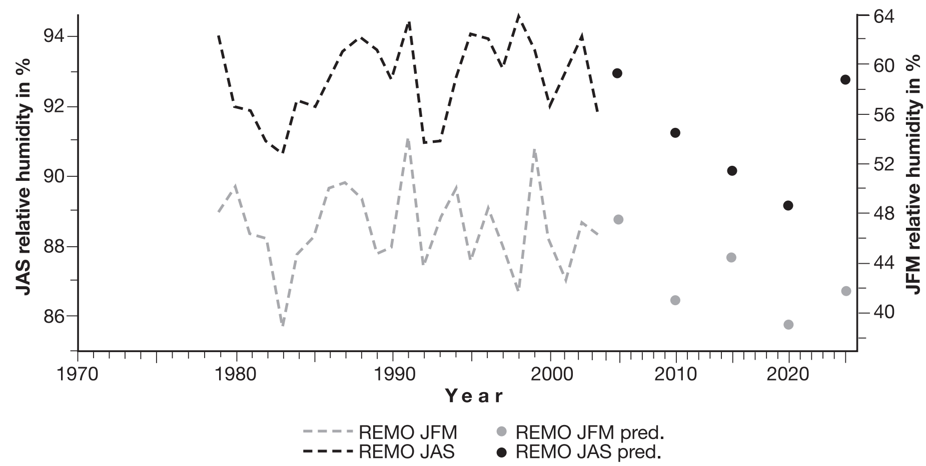

Fig. 7: Same as Fig. 5 but for relative humidity in %. Observational data are not available for this variable.

also agree in a quantitative way arises from the fact that REMO produces a systematic bias which can be corrected by a simple regression analysis.

The dots in figure 5 indicate the predicted changes in seasonal rainfall due to enhanced greenhouse conditions and ongoing land and soil degradation. Although the 2005 time-slice starts on a relatively high level, the combined forcing scenario leads to a general reduction of summer monsoon rainfall. However, this drying trend is still in the range of the observed variability during the last three decades. During the winter monsoon season, no systematic change is simulated. From our physical understanding, reduced vegetation cover and soil moisture should cause a distinct weakening of the hydrological cycle. This is exactly what REMO predicts in the Sahel Zone and Congo Basin (Paeth and Thamm 2007). Along the Guinean Coast and, hence in Benin, this effect is compensated by a strengthening of moisture convergence (Clark et al. 2001; Maynard and Royer 2004). Therefore, the minor response of rainfall over Benin is not astonishing. Note that the time-slice experiments have also been corrected in the same way as the hindcast period 1979-2003. This ensures that the changes between the time slices (red dots) and the hindcast simulation (red lines) arise from the various forcings mentioned above instead of from systematic differences between corrected and uncorrected model data. The model versions are identical for the hindcast and time slice experiments. This is also a basic requirement when applying the MOS to both, the model period 1979–2003 and the future time slices until 2025.

The observed and simulated time series of near-surface temperature are displayed in figure 6. The observations during the late 20th century may be indicative of a slight warming trend which is superimposed by strong interannual variability. Again, REMO reproduces the observed year-to-year fluctuations in a realistic way. However, in JAS a systematic bias towards higher mean temperatures exists. This bias does not affect the statistical relationship between the simulated climate and crop yield because it is a property of the MOS to correct all kinds of systematic model biases (Glahn and Lowry 1972). Greenhouse forcing and land degradation induce a remarkable warming by 2 °C in JFM and almost 4 °C in JAS. This near-surface heating is comparable to the effect of increasing GHG concentrations alone until the year 2100 (Coppola and Giorgi 2005). Thus, land degradation appears to accelerate the warming trend considerably, as suggested by Feddema et al. (2005). The physical explanation is that reduced vegetation cover and soil moisture cause a shift from latent to sensible heat fluxes. Furthermore, decreasing surface roughness weakens the turbulent exchanges within the atmospheric boundary layer, such that the heating is captured near the land surface. The abrupt warming between 2003 and 2005 arises from the fact that no land-cover change is allowed for until 2003 but it is abruptly switched on during the first time-slice experiment for 2005. The dots also demonstrate that the time-slice experiments are subject to some interannual variations imposed by the lateral and lower boundary conditions from the global climate model: for instance the heating anomaly in JAS 2025 is lower than in the time slices before. This has to be taken into account when interpreting the changes in crop yield in subsection 5.3.

Figure 7 shows the simulated time series of relative humidity. For this variable, no observational data are available. Relative humidity is a function of atmospheric moisture content and air temperature. Thus, it is affected by thermal and hydrological changes and may be considered as a combined detection variable. The shorter-term fluctuations

Table 2: Results of the Model Output Statistics (MOS) applied to 9 crops for which complete regional-mean time series over Benin are available: explained variance derived from the dependent data, explained variance from cross validation, and characteristics of the most relevant predictor (variable: 1 = precipitation, 2 = temperature, 3 = relative humidity; season: 1 = JFM, 2 = AMJ, 3 = JAS, 4 = OND; region: 1–7 see reference numbers in Fig. 1, 8 = Benin average)

Crop	Explained Variance (dependent)	Explained Variance (independent)	Predictors Variable	Predictors Season	Predictors Region
Peanuts	79.2	47.2	3	3	7
Cotton	58.0	20.3	1	2	1
Beans	53.9	25.4	3	3	7
Yams	85.2	42.3	3	3	8
Maize	52.4	27.8	3	3	7
Manioc	72.5	30.2	1	1	7
Rice	73.4	53.3	3	3	7
Sorghum	72.9	43.6	3	3	7

are positively correlated with rainfall (e.g. the dry period in the early 1980s, Fig. 5). The long-term trend seems to be anti-correlated with temperature: the warmer the temperature, the lower the relative humidity according to the temperature-dependence of the air's water-holding capacity. The time-slice experiments are again characterized by pronounced interannual variations. In particular, the 2025 time-slice shows higher relative humidity in JAS than the time slices before. It will be shown in subsection 5.3 that this can also be traced in the resulting crop yield changes.

5.2 Statistical relationships between climate and agriculture

The results of the MOS for the eight crops considered averaged over entire Benin are listed in table 2. Note that all regression models have been found to be statistically significant at least at the 10% level. The explained variance of the regression analysis is once given for the dependent data and all predictors, and once for the independent data and the limited set of robust climatic predictors as inferred from cross validation. By definition the former value is larger than the latter one. The difference is partly considerable, implying that some predictors do not provide additional information on the independent data. This can be explained by colinearities between the climatic predictors: of course, the agro-climatological regions in Benin (cf. Fig. 1) are not independent of each other. The same is true for the three variables precipitation, temperature and relative humidity. Finally, there are also autocorrelations from season to season. The cross validation is able to account for these colinearities by removing predictors which are largely in phase with the predictors chosen before. Nonetheless, the remaining explained variance based on the independent data is still quite high. For rice yield, 53.4% of the interannual variations can be explained by climate anomalies. For peanuts, yams and sorghum it is still more than 40%. Cotton, beans and maize appear to be less governed by climate.

The most relevant predictor of the MOS is also indicated in table 2. It is obvious that relative humidity is a better indicator of crop yield than precipitation amount and temperature, except for cotton and manioc. Relative humidity arises from a combined temperature and humidity effect, which may result in an enhanced amplitude of a given climate anomaly. Among the different seasons JAS is the most relevant one. Thus, relative humidity during the main vegetation period in northern summer has the largest impact. However, manioc and cotton appear to be affected by rainfall amount in JFM and AMJ, respectively. This holds the prospect of seasonal forecasting (Garric et al. 2002; Mo and Thiaw 2002). In terms of the agro-climatological regions in Benin, the northeastern part usually is the best measure of crop yield. This region can be interpreted as an indicator of the strength and northward propagation of the moist summer monsoon flow. Again, cotton is an exception. Moreover, yams is best linked to the climatic predictors averaged over whole Benin.

When focusing on the crop yield in the subregions of Benin even stronger relationships with climate are found (Tab. 3). For each crop the subregion with the highest explained variance is listed. The values range between 40% and 63% based on the independent data. Again, relative humidity during JAS is the most prominent predictor. The relevant agro-climatological regions are more heterogeneous.

Table 3: Same as table 2 but for each crop the region with largest explained variance as derived from cross validation

Crop (Region)	Explained Variance (independent)	Predictors Variable	Season	Region
Peanuts (MC)	49.7	3	3	7
Cotton (DA)	44.5	1	1	3
Beans (MC)	54.0	3	3	5
Yams (BA)	56.1	3	3	7
Maize (MC)	48.9	3	3	7
Manioc (ZC)	40.6	3	1	2
Rice (BA)	63.0	1	2	3
Sorghum (ZC)	48.6	3	3	7

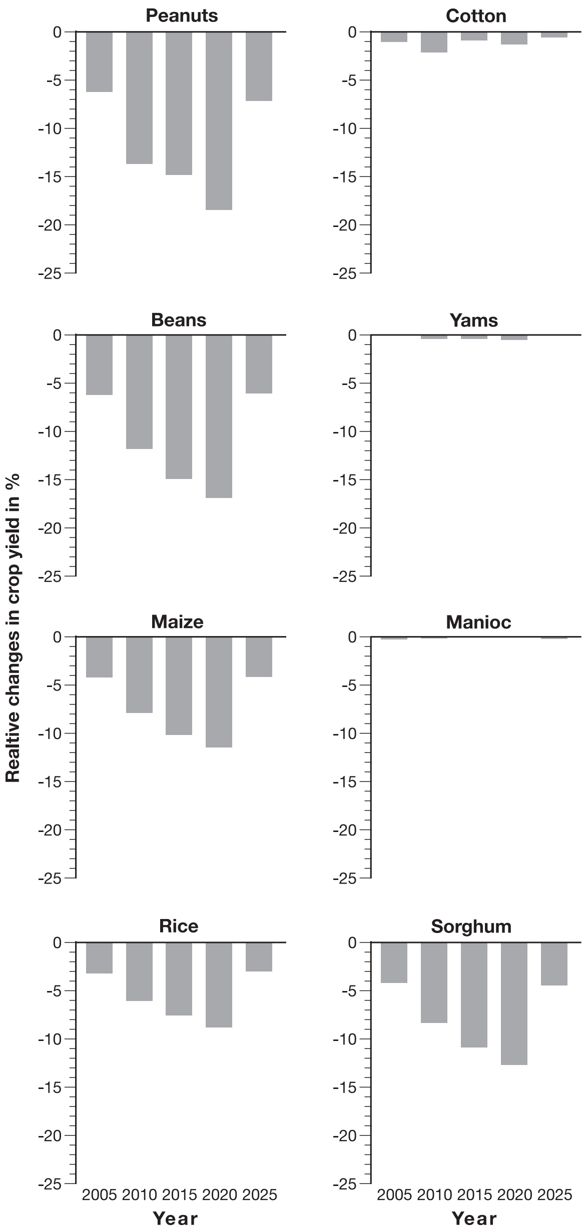

Fig. 8: Predicted changes in crop yield, averaged over Benin, until 2025 relative to the observed 1970–2003 mean. The values are computed by the MOS approach outlined in Fig. 4. The bars refer to the time slice experiments with the regional climate model REMO (cf. Figs. 5–7).

These results suggest that crop yield in Benin is largely governed by climate variations. The statistical relationships are based on robust climatic predictors and transfer functions derived from a regional climate model which is able to reproduce the observed year-to-year variability (cf. Figs. 5–7). The latter aspect is very important because it implies that the predictions from the same climate model can be used to assess the future risks and potentials of agricultural production in Benin.

5.3 Predicted agricultural development

The MOS in subsection 5.2 is trained with simulated climatic predictors during the 1979–2003 hindcast period. Assuming stationarity of the statistical transfer functions, the simulated time-slices until 2025 from the same climate model can be translated to a prediction of crop yield under changed climate conditions. The results are shown in figure 8 for the eight crops, averaged over Benin. The changes are scaled by the respective mean yield during the 1979–2003 period in order to allow for comparison between the various crops. It is obvious that the predicted climate changes over Benin may have negative implications for crop yield. Manioc is an exception, but the yield increase can be neglected (< 2‰) against the background of the large mean yield of about 10,000 kg per hectare (cf. Fig. 3). The sensitivity of the other crops is quite different: yams and cotton appear to be less affected by climate change than peanuts, beans, maize, rice and sorghum. Thus, most alimentary crops in Benin may experience a yield reduction by 15 to almost 25%. In the light of the expected population growth this development would be dramatic. The bars in figure 8 also reflect the effect of interannual variability between the time slices. For instance, the higher relative humidity in JAS during the 2025 time-slice (cf. Fig. 7) leads to a mitigation of crop yield decrease. This implies that under future anthropogenic climate change there are also some years with more favourable conditions for food production in Benin. However, the general tendency of crop yield draws a pessimistic picture for food security in Benin.

6 Discussion

The present study is dedicated to the relationship between climate change as simulated by a regional climate model, and food security in tropical West Africa. The seasonality of rainfall leads to a distinct vegetation period during the moist summer monsoon season and a limited time window for agricultural activity in large parts of Benin. Since 1970, productivity has increased for most crops, especially for manioc, maize and beans. However, there is also a very prominent variability at the interannual time scale. Assuming that this is not arising from world market conditions (except for cotton) and varying investments in agriculture, the effect of climate fluctuations may be an explanation. Indeed, the observed and simulated time series of seasonal precipitation, temperature and relative humidity over Benin reveal interannual and longer-term variations which are partly in phase with the time series of crop yield. Under enhanced greenhouse conditions, as well as ongoing land and soil degradation, the regional climate model projects a slightly drier and markedly warmer climate over tropical West Africa until 2025. The crop yield data and climate model simulations are related to each other by means of cross-validated model output statistics (MOS) in order to perform robust statistical transfer functions with a limited set of reliable predictors. The explained variance of the MOS amounts to more than 50% for various crops and regions in Benin, although the statistical relationships are derived from observed agricultural data and simulated climatic predictors. Among the large number of predictors, relative humidity in JAS over Northeast Benin appears to be the most important climate factor for crop yield in Benin. Under future climate conditions the efficiency of the food production systems in Benin may decrease considerably due to the drier and warmer summer monsoon season. This is particularly true for peanuts, beans, maize, rice and sorghum whereas cotton, yams and manioc appear to be less sensitive.

This study does not draw a very optimistic picture of future food security in Benin. On the one hand, our results are strictly related to the regional climate model REMO and the experimental set-up with prescribed GHG emissions and scenarios of land and soil degradation. On the other hand, the findings of this study are backed up by a number of previous works which confirm the negative implications of climate change for agricultural production (Agbossou and Akponipé 1999; Easterling and Apps 2005; Mall et al. 2006; McCarthy et al. 2001; Wang 2005; Zhao et al. 2005). A similar study for Mali has revealed crop failure in the same order of magnitude (down to -17% until 2040, Butt et al. 2005). The higher amplitude of crop yield decrease in our study (down to -23% until 2020) can be explained with the stronger – and probably more realistic – forcing scenario including land and soil degradation (cf. Douville et al. 2000, 2001; Pielke et al. 2002). It is likely that similar results could be found for most other countries in sub-Saharan Africa. The problem may even worsen into the Sahel Zone where rainfall reduction in JAS is more pronounced than along the Guinean Coast (Clark et al. 2001; Maynard and Royer 2004; Paeth and Thamm 2007) and where the natural potential is much lower.

The basic question is whether biotechnological progress and enhanced investments as suggested by Serageldin (1999) will be able to overcompensate for the simulated climate-induced crop yield reduction in Benin. Burton and Lim (2005) have pointed to the low adaptability of the food production systems in the low latitudes. However, there is one promising aspect in our study: manioc and yams as basic alimentary crops in Benin seem to be less affected by the projected climate change. Manioc may even profit from the predicted climate change. Butt et al. (2005) have concluded for Mali that more heat-resistant crops should be cultivated. For Benin, we suggest to rely on yams and manioc in order to maintain the food security in Benin under a warmer and drier climate.

In the following, the results of our study need to be confirmed by means of longer-term transient climate model simulations with adequate spatial resolution and anthropogenic forcings. Then, the aspect of long-term trends versus internal variations can be assessed in a more proper way, leading to more insight into the future agricultural risks and potentials in tropical West Africa. Such an approach is currently in preparation.

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