IMPACT OF CLIMATE CHANGE ON AGRICULTURAL PRODUCTION IN THE SAHEL – PART 1. METHODOLOGICAL APPROACH AND CASE STUDY FOR MILLET IN NIGER

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Abstract. In the last 30 years the climate of the West African Sahel has shown various changes, especially in terms of rainfall, of which inter-annual variability is very high. This has significant consequences for the poor-resource farmers, whose incomes depend mainly on rainfed agriculture. The West African Sahel is already known as an area characterized by important interaction between climate variability and key socio-economic sectors such as agriculture and water resources. More than 80% of the 55 million population of West African Sahel is rural, involved in agriculture and stock-farming, the two sectors contributing almost 35% of the countries' GDPs. It is therefore obvious that climate change seriously affects the economies of these countries. Adding to this situation the high rate of population increase (∼3%), leading to progressive pressure upon ecosystems, and poor sanitary facilities, one comes to the conclusion that Sahelian countries, Niger amongst them, will be highly vulnerable to climate change. This paper investigates the impact of current climate variability and future climate change on millet production for three major millet-producing regions in Niger. Statistical models have been used to predict the effects of climate change on future production on the basis of thirteen available predictors. Based on the analysis of the past 30-years of rainfall and production data, the most significant predictors of the model are (i) sea surface temperature anomalies, (ii) the amount of rainfall in July, August and September, (iii) the number of rainy days and (iv) the wind erosion factor. In 2025, production of millet is estimated to be about 13% lower as a consequence of climate change, translated into a reduction of the total amount of rainfall for July, August and September, combined with an increase in temperature while maintaining other significant predictors at a constant level. Subsequently, various potential strategies to compensate this loss are evaluated, including those to increase water use efficiency and to cultivate varieties that are adapted to such circumstances.

1. Introduction

The West African Sahel (17° W–23° E/13° N–17° N), hereafter referred to as the Sahel, is already known to be an area characterized by important interactions between climate variability and key socio-economic sectors such as agriculture and water resources. Annual rainfall ranges in general from 350 to 800 mm on a north–south transect. Inter-annual and spatial variability is very large, leading to a wide

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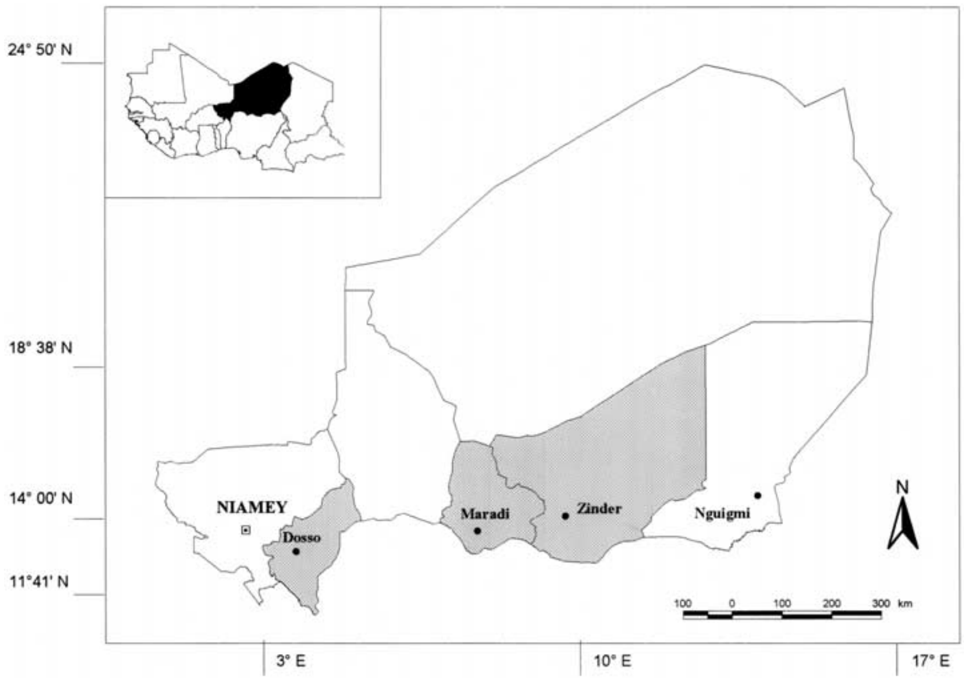

Figure 1. Map of Niger and its location in West Africa, and the three regions of study.

range of crops and cropping systems. Annual rainfall less than long-term averages can occur during a period of 10 to 20 years (Sivakumar, 1989; Sivakumar et al., 1993). More than 80% of the 55 million population in the Sahel is rural, involved in agriculture and stock-farming, the two sectors contributing almost 35% of the countries' GDPs. Adding to this situation the high population increase rate, leading to progressive pressure upon ecosystems, and poor sanitary facilities, one can state that Sahelian countries, Niger amongst them, already have serious challenges in producing sufficient food.

Niger is located between latitudes 11°37′ and 23°33′ N and between longitudes 0° and 15° E, with a territory of 1,267,000 km^2 of which around two-thirds is desert and sub-desert (FAO, 1993). It is a land-locked country with seven regions, i.e., administrative areas (Figure 1). In general, one can distinguish four rainfall zones in Niger: (i) the Sahara zone with annual rainfall of 0–200 mm, covering 67% of the country, (ii) the Sahel–Sahara zone with 200–350 mm (20%), (iii) the Sahel with 350–600 mm (10%), and (iv) the Sudanian zone with more than 600 mm rainfall (3%). Only about 25% of the total area is suitable for cultivation, i.e., south of the 350 mm isohyet (MAG/EL, 1997), of which only about 150,000 km^2 is suitable for agriculture.

The population of Niger was estimated to be about 9 million in 1999 and has one of the highest population growth rates in Africa (i.e., 3.3% compared to 1% in the 1940s; MDS, 1994). Eighty-five percent live in the rural areas and predom-

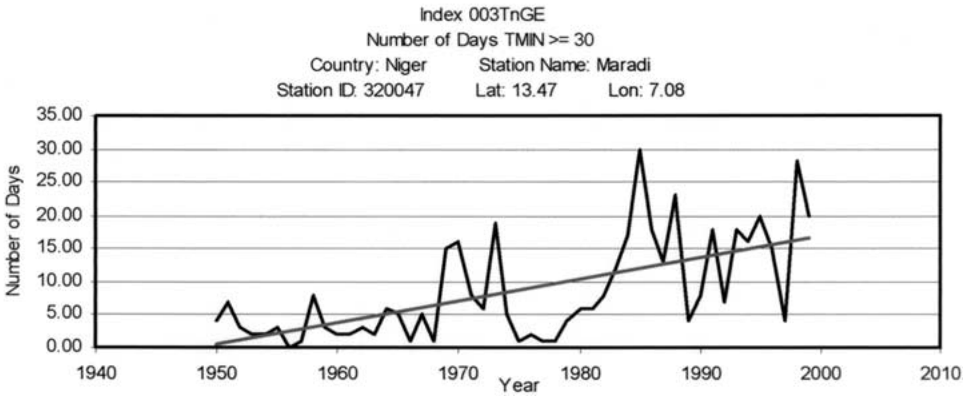

Figure 2. Evolution of number of days with annual mean minimum temperature greater than 30 °C between 1950 and 1998 for Maradi.

inantly depend on rainfed agriculture, due to limited surface water resources. The main objective of the population is to increase production to attain self-sufficiency, but the natural resource base is being degraded more and more, partly caused by climatic conditions of the Sahel coupled with the occurrence of pests and diseases. Dominant crops in the larger part of Niger are millet and cowpea, and in the southern part, sorghum and groundnut. Other food crops (rice and maize), and cash crops (cotton) are also cultivated. The traditional cereals, millet and sorghum represent about 85% of total food production in Niger, and cover 80–90% of the energy requirements of the population. It is stressed that crop production is thus highly correlated with climatic conditions. Although a few technical options for improving water use efficiency have been developed that can be applied without major financial input (Amadou et al., 1999), it is clear that a change in climate could severely affect agricultural production in Niger.

Climate change is usually associated with an increase in mean global surface temperature. Based on available temperature data for Niger since 1925, one can clearly distinguish a trend towards an increased number of days with annual minimum temperature greater than 30 °C for the Maradi site, as shown in Figure 2.

This paper investigates the impact of climate variability and change on crop production, with a particular focus on pearl millet, while a subsequent paper will focus on groundnut and cowpea (van Duivenbooden et al., 2002). Despite its importance in the southern part of Niger, sorghum has not been included as it is of less importance in the selected departments and the crop responds to climate change more or less like millet. Moreover, when the climate becomes drier and warmer farmers are forced to switch from sorghum to millet, because millet has lower water requirements and is more heat tolerant.

Table I

Yield, cropped area, and production of millet in Niger and its neighboring countries for different periods (ICRISAT and FAO, 1996; www.fao.org)

Period	Burkina Faso	Mali	Niger	Nigeria
Yield (kg ha^{-1})				
1979–81	490	720	440	1040
1989–91	540	690	340	1040
1992–94	640	600	380	890
2000	720	829	424	1063
Area (million ha)				
1979–81	0.80	0.64	3.01	2.40
1989–91	1.21	1.19	4.19	4.50
1992–94	1.24	1.20	4.87	5.20
2000	1.25	1.15	5.30	5.60
Production ('000 t)				
1979–81	390	460	1310	2500
1989–91	650	820	1410	4670
1992–94	793	732	1858	4620
2000	900	953	2250	5960

1.1. MILLET IN WEST AFRICA AND NIGER

Among the different millet species, pearl millet (*Pennisetum typhoides* (Burm.), Stapf and Hubb) is the most important one from the point of view of cultivated area, production and food security. With an estimated world production of millet of about 28 million tons, pearl millet accounts for 54%. Pearl millet makes up 5% of the world cereal crops cultivated area, but only 1.5% of world cereal crops production (ICRISAT and FAO, 1996). Nearly 37% of the world's millet area is found in West Africa, producing 79% of the total African millet production. The main millet producing countries in West Africa in 2000 were Nigeria (54%), Niger (20%), Mali (9%), Burkina Faso (8%) and Senegal (5%), although their relative importance varies from one year to another, as illustrated in Table I. In Niger, pearl millet, the main staple food, is dominant in the production systems and contributes about 75% of national cereal production (Amadou et al., 1999).

Millet is widely cultivated, especially on marginal lands in areas where annual rainfall is as low as 250 to 800 mm. These areas are further characterized by variable and irregular rainfall, a short rainy season and a high evaporative demand (high

Table II
Non-climatic factors that contribute to low crop yields in Niger

Type	Descriptor	Details
Bio-physical	Soils	Low water holding capacity; low to very low soil fertility; highly susceptible to water and wind erosion; occasional occurrence of a thin surface crust; marginal soils being cultivated
	Carrying capacity	Exceeded to reduced access to rangelands
	Pests and diseases	
Socio-economic	Population	High population growth rate (3.4%); movement to marginal areas; low education level
	Extension and research	Non-existent or poor extension services; reduction of research activities
	Inputs	Low to very low level for chemical fertilizer; improved varieties, organic manure, biocides, and pesticides
	Credit	National Agricultural Credit disappeared in 1986
	Market	Only for onion (Ivory Coast) and millet (Nigeria); remainder internal/home consumption
	Land tenure	Non-ownership leading to over-exploitation

temperatures and radiation). In addition, rainfall can be very intense, especially in short rainstorms with observed maximum intensities of 386 mm h^{-1} (Hoogmoed, 1986). The soils have a low water holding capacity and are therefore subject to deep drainage beyond the rooting depth in years of adequate rainfall. In addition, evaporation from the soil is a major component of the water balance, due to low planting densities (sparse canopy). Sivakumar (1992) discusses in detail the effects of water shortage per month of the growing season on millet's growth. Finally, the soils are acidic with low mineral fertility (particularly low in phosphorus) and organic matter content. For all of these reasons, millet is considered to be a traditional crop of drier areas and is generally reserved for areas where sorghum and maize fail because of low rainfall and adverse soil factors. In addition to climatic factors, yield is determined by bio-physical and socio-economic constraints (Table II), which cause yields to be lower than in neighboring countries Burkina Faso and Nigeria (Table I). The sum of all these constraints makes modern agriculture in Niger a rather risky enterprise.

2. Methodology

Although millet is grown in the entire country, the focus of this study is on a major producing area. It accounts for more than 55% of the production within the annual rainfall zone of 350–600 mm, and consists of the Dosso, Maradi and Zinder regions (Figure 1). Daily and annual rainfall for the period 1951–1966, and production data (1967–1998) are used to analyze the rainfall variability. Rainfall data were obtained from the National Meteorological Service and statistical data on millet production from the Ministry of Agriculture and Livestock. Both data sets were standardized before use in this study. Standardization (normalization) generally means computing of the quantity often called the anomaly index (or simply index), obtained as follows (Kraus, 1977). Due to the absence of a sufficient dense matrix of rainfall gauges within a region, we base our analysis on the data of the main meteorological station of the region, which we consider to be representative.

If r_i is the annual rainfall, $\bar{r}$ is the mean annual rainfall over a certain period, σ the corresponding standard deviation, then the annual rainfall index I_{ri} is computed as:

$$I_{ri} = (r_i - \bar{r})/\sigma \, .$$

2.1. ANALYSIS OF RAINFALL

The time series of annual rainfall data (1951–1998) have been analyzed for their simple random character through various statistical tests (cf. Snyers, 1975), according to which time series are considered random if they are not persistent, give no tendency, and present a stability of dispersion around the mean.

2.2. ANALYSIS OF IMPACT OF CLIMATE CHANGE

2.2.1. *Regression, Construction and Evaluation of Models*

In Niger, rainfall is a dominant climatic factor with variability characteristics as mentioned above. Since 85% of the annual rainfall is received during July, August and September (Sivakumar et al., 1993), and the total rainfall of these three months is much better correlated with the sea surface temperatures (SST) than the annual rainfall (WMO, 1998), only the total of the months of July, August and September (JAS) is considered.

To various degrees, rainfall influences other climatic parameters, such as evaporation, temperature, solar radiation, wind and humidity. Unlike humid areas, dry areas are characterized by high temperatures, rather violent winds with dust, high evaporation and low air moisture and therefore by a high evaporative demand. The effect of high air and soil temperatures makes the establishment of crops very difficult at the beginning of the season. At sowing, maximum air temperatures may exceed 40 °C, while soil temperatures often easily reach 50 °C, as observed in the sandy soils at ICRISAT's experimental station near Niamey (Sivakumar, 1989).

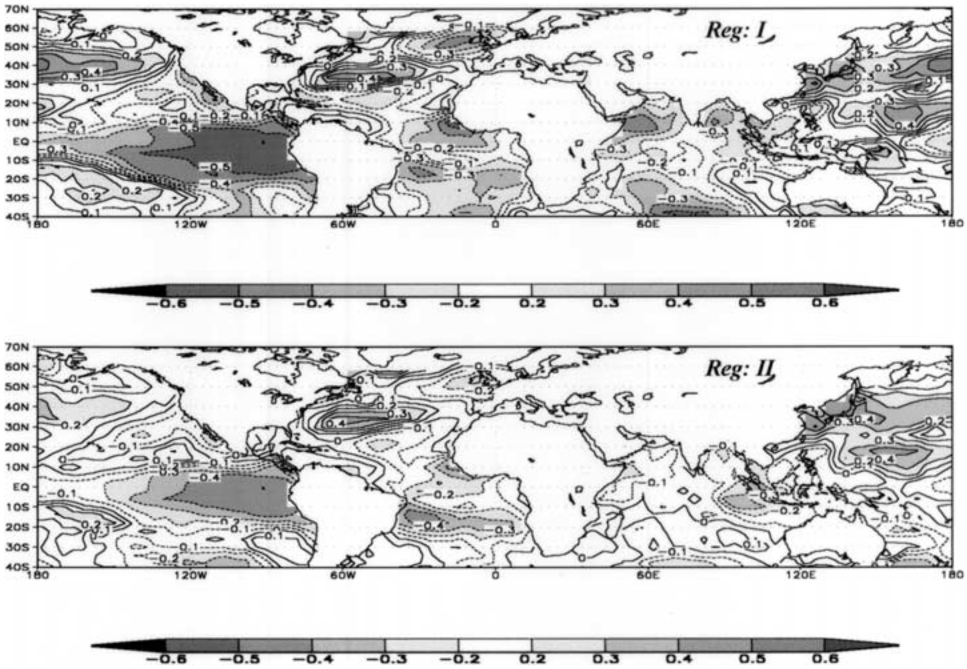

Figure 3. Correlation between JAS rainfall for Region I (0°–6° E) and Region II (6°–12° E) of Niger and SST anomalies.

Wind is another climatic factor influencing crop growth and yield. Under the influence of high-speed winds, the process of wind erosion takes huge quantities of sand from the bare soils, carries them away and deposits them on young millet seedlings. The combined effect of the weight of this deposition and the high soil temperature seriously affects the establishment of crops, leading to several re-sowings in a year. Wind speeds exceeding 100 km h^{-1} have been observed in Niger (Sivakumar et al., 1993).

The assessment of the impact of climate variability and change is based on statistical modeling in which crop yield (or production) is estimated on the basis of agro-climatic parameters (predictors). This procedure is similar to the one adopted two years ago by the African Centre of Meteorological Applications for Development (ACMAD) in collaboration with the National Meteorological Services in West Africa (WMO, 1998) for West African seasonal rainfall prediction, as illustrated by Figure 3.

Thirteen predictors are considered in the present study. These are: sea surface temperature anomaly of the Indian Ocean (SSTA-Ind); sea surface temperature anomaly of third principal component of the global ocean (SSTA-EOF3); sea surface temperature anomaly of the Equatorial Atlantic Ocean (SSTA-EA); Total rainfall in July, August, and September (R-JAS); number of rainy days (NRD); daily amount of rainfall (DAR); dry spell (DS); maximum air temperature in the hottest month April (Ta); minimum air temperature in the coldest month January (Tj); ratio of area cultivated with millet and groundnut (RMG) and ratio of area cultivated with millet and cowpea (RMA).

Included is also the length of rainy season (LRS); i.e., the difference between the dates of the beginning and the end of the season. The beginning of the growing period is defined as being when the amount of rainfall recorded in three consecutive days is at least 25 mm and no dry spell of more than seven days duration occurs in the following 30 days. The end of the rainy season is that rainy day after which rain recorded during 20 days is less than 5 mm (Sivakumar, 1990). Mean values of LRS over the time period 1951–1997 for Dosso, Maradi and Zinder are 102, 99 and 84 days respectively.

Finally, dry season (October–May) wind erosion is included in the analysis because of the quasi-permanent presence of terrigenous dust in the atmosphere (Ben Mohamed, 1998). Furthermore, initial assumptions about possible climatic implications of increased atmospheric dust concentrations in the Sahel (Ben Mohamed, 1985) are now being confirmed with respect to drought aggravation by dust in the wind (Rosenfeld et al., 2001). A wind erosion factor (WEF) is thus defined as the number of days during the dry season when horizontal visibility is less then 5 km, traducing hence the possible effect on the energy budget in the boundary layer, and consequently on the convection development and influence on rainfall. The second consequence is impoverishment of soils that are subject to these winds. Finally, an important aspect of this study is that SST's appear to be a key parameter for assessment of impact of climate on agricultural production in the Sahel.

To build a statistical model with a maximum determinant coefficient for the prediction of the result for the different locations two steps were taken. First, annual rainfall data have been standardized (as defined above), which allows one to solve the problem of coefficients comparison. Second, the best informative predictors for each multiple regression estimated value, using the stepwise regression method, have been selected. In addition, the following options have been retained: (i) tolerance level close to 1, (ii) test of significance at 95%, and (iii) partial correlation coefficients $-0.3 < r > +0.30$. Multiple regressions (coefficient Rm) were run using different predictors in order to obtain a model which allows prediction of the production of millet. The backward method was chosen when running the statistical software package SYSTAT 8.0 (SPSS, 1998).

The accuracy of the model is estimated on the basis of the following parameters: (i) Fisher's test (F-Ratio), (ii) Skill, (iii) Hit Skill Score (HSS), (iv) Probability of coincidence (C%), (v) Probability Of Detection (POD): in our case, we used below normal, normal, and above normal (equal terciles), and (vi) False Alarm Rate (FAR).

The performance of a model is measured by (i) a high value of F-ratio and low p-value, (ii) a high skill, (iii) a high POD, (iv) a low FAR, (v) a high C%, and (vi) a high value of HSS. The model is also characterized by a quantity labeled %Var. It is the percentage of the variation of the estimated value explained by the significant predictors.

2.2.2. *Estimated Impact of Climate Change*

When looking at the few available predictions for the Sahel zone based on Global Climate Models (GCM), one notes substantial differences between results from the various models used as far as rainfall indices, annual cycles, daily and annual rainfall are concerned. Hence, one has to be particularly careful in considering these outputs until changes in precipitation patterns and river runoffs have been accurately simulated.

On the other hand, the coarse resolution of these models ($5° \times 5°$) make their use questionable for this area where a gradient of rainfall can develop over a very short distance, the anomaly not being caused by topography and not occurring in the same place in other years (Taylor et al., 1997). A striking example of this spatial variability is the measured annual rainfall at ICRISAT's 500 ha large research site in Niger in 1995, ranging from 450 to 554 mm (18 rain gauges; van Duivenbooden et al., 1996). In other words, the social consequences of such a situation are simply that whilst one village can have a good harvest, their neighbors suffer crop failure during the unique rainfall season of the year.

Therefore, although models will hardly be able to predict the development of climate parameters in a region year by year, there is a need for more research to improve the quality of outputs of GCM's, to have them at a scale of at least $1° \times 1°$. This highlights the need for Regional Climate Models in order to take into account the interaction of large-scale atmospheric circulations and meso-scale physical processes. This is also, from our point of view, an important point to keep in mind when using the available climate scenarios for the Sahel area.

The first step in our analysis was the selection of a model among those available. For the present study, the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) to estimate the impact of climate change in terms of rainfall and temperature (IPCC, 1995a) was available. This model uses the same input parameters (including SST) as those used by IPCC (1995b) and is linked to the software package SCENario GENerator (SCENGEN) which can be used under two scenarios: a reference and a policy scenario. However, due to the coarse resolution of this MAGICC model and in view of the above comment, outputs for the year 2025, for which horizon demographic projections are available for Niger (MDS, 1994), show small variations from both the Hadley Centre Unified Model 2 (HadCM2) and the Geophysical Fluid Dynamics Laboratory Model (GFDLLO), namely a decrease of only 4% in rainfall for the whole of Niger. When compared to observed coefficients of variation for rainfall (32% for Dosso, 2% for Maradi and 28% for Zinder), one should thus be careful in considering these outputs of both types of models.

The next step was to define a scenario to estimate the impact of climate change using the obtained statistical models. In order to take into account the observed local variability of climate parameters, we have defined two scenarios for the year 2025 with a reduction in rainfall of 10 and 20%, and an increase in temperature of 10 and 20% with respect to the average values of the reference period 1968–1998, respectively. The value of 10% was chosen in light of the changes recorded in the past 30 years, which can be expected to happen again. The 20% values are used to present a somewhat more dramatic, yet reasonable situation. The obtained new anomalies are simply plugged into the statistical model to assess the impacts of such changes, keeping the SSTA constant because of non availability of information on future evolution of SST's.

3. Results and Discussion

3.1. CLIMATE INDUCED CONSTRAINTS TO PRODUCTION

As far as agriculture is concerned in the Sahel, the most important climatic parameters to consider are rainfall, temperature, solar radiation and wind; all other agroclimatic variables can be derived from these fundamental parameters. On the other hand, most of the expected impacts of climate change reported in the literature concern primarily rainfall and temperature. This means that, although wind is very important with regard to wind erosion and survival of growing crops in this area (e.g., Ben Mohamed et al., 1998; Michels et al., 1995; Sterk, 1997), the discussion in this chapter will focus mainly on rainfall and temperature.

Rainfall is unimodal (one rainy season per year) and falls between the months of May/June and September/October with large spatial and temporal variability, and a slight tendency of decreasing over time (Figure 4a). Annual rainfall varies from 800–900 mm in the south-west to less than 100 mm in the north (Sivakumar et al., 1993), with an average rainfall decrease of 1 mm km^{-1} latitude. A similar phenomenon occurs from west to east, creating an isohyet curvature towards the southeast, such that between Zinder and Nguigmi rainfall decreases by 0.6 mm km^{-1} (Amadou et al., 1999).

Average monthly minimum and maximum temperatures (Figures 4b,c) vary considerably from one year to another, but variability is similar for the three sites. This demonstrates the predominance over the whole country of the same air masses at near surface level during the dry and humid seasons, namely the harmattan and monsoon trade winds.

Annual rainfall data were compared to the long-term average (1951–1998) and three sub-periods (SP) were distinguished. While the study by Daouda et al. (1998) for the period from 1950–1967 to 1968–1985, and by Sivakumar (1992) for the period 1969–1988 indicated the moving of isohyets only towards the south, Figure 5 shows that the isohyets are again moving towards the north during the last decade. The descent towards the south of the 400 and 500 mm isohyets between SP1 and SP2 are estimated at 183 and 166 km, and the rise towards the north at 68 and

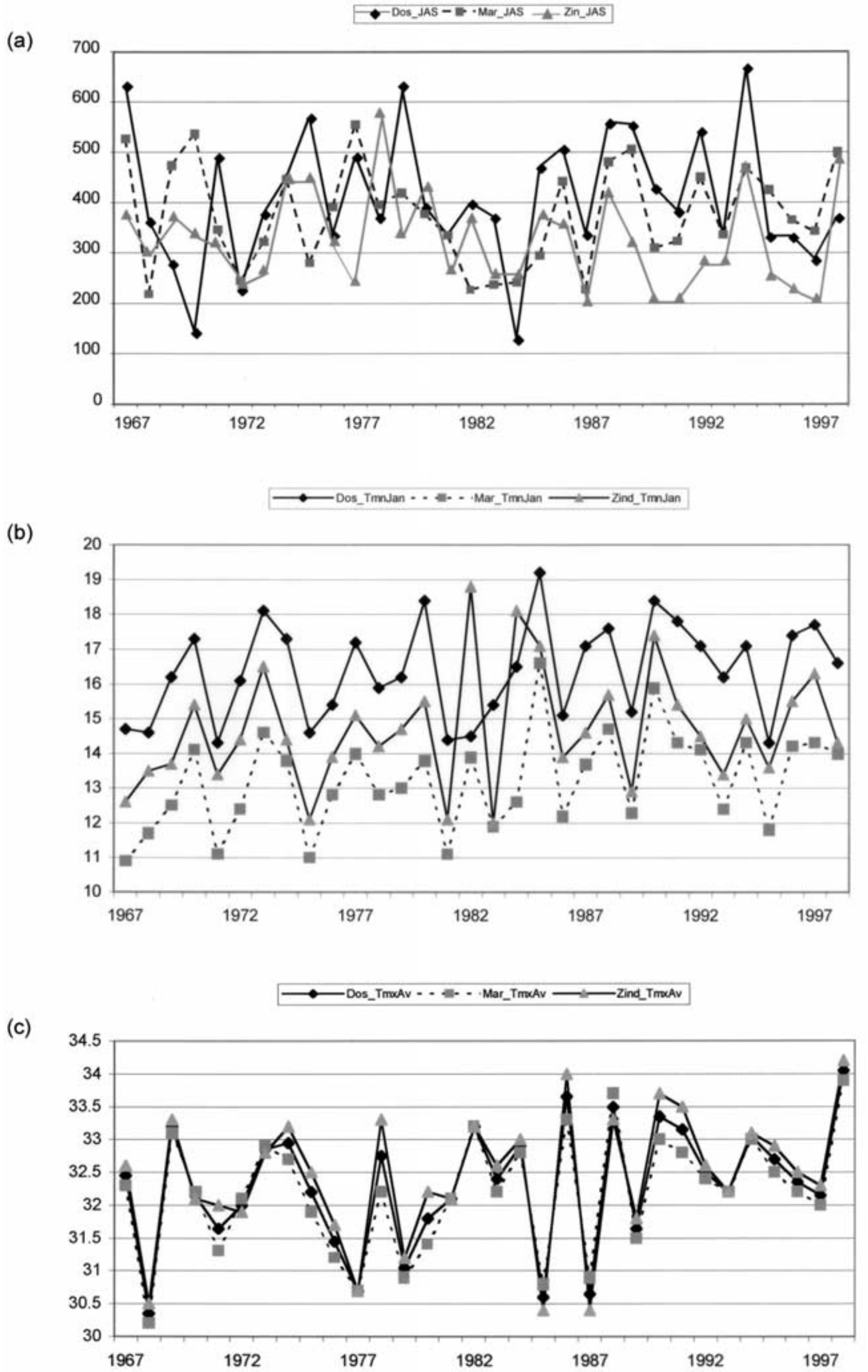

Figure 4. Evolution of (a) the total rainfall (mm) of the months July, August and September (JAS), (b) maximum temperature (°C; April–May) and (c) minimum temperature (°C; December–January) during the period 1966 to 1998 for the three sites in Niger. Dos: Dosso; Mar: Maradi and Zin: Zinder.

Table III

Results of the analysis for random character of annual rainfall in the three sites in Niger

Synoptic station	Persistence	Tendency	Dispersion	Fisher's stat.
Zinder (13°48′ N, 8°59′ E, 451 m)	1.75	–4.3	–0.2	26.7
Maradi (13°28′ N, 7°25′ E, 368 m)	3.4	–4.2	–1.1	39.7
Dosso (13°01′ N, 3°11′ E, 218 m)	2.4	–3.0	0.5	31.5

Table IV

Significant predictors of estimated millet production in the three locations in Niger and their combined % of variance

Region	Significant predictors								% var
	SSTA-Ind	SSTA-EOF3	R-JAS	NRD	DAR	DS	Ta	WEF	
Dosso	X		X	X					75.3
Maradi	X							X	82.4
Zinder		X	X	X	X	X	X	X	76.0

SSTA-Ind = Sea surface temperature anomaly of Indian Ocean; SSTA-EOF3 = Sea surface temperature anomaly of third component of the global Ocean; R-JAS = Rain in July, August, and September; NRD = number of rainy days; DAR = Daily amount of rainfall; DS = dry spell; Ta = maximum air temperature in April; WEF = wind erosion factor.

51 km, respectively. The northward move, however, seems promising but time will tell if this is a real improvement, or just a temporary improvement as occurred in the second half of '70s. The analysis has also been carried out for the three sites, and is presented in the following paper (van Duivenbooden et al., 2002) together with other detailed rainfall component data.

The test for the random character of rainfall carried out for the three locations shows that there is a significant tendency of annual rainfall decrease for all the studied locations, with a clear, persistent character and stability of dispersion from the mean (Table III). As a consequence, the historical rainfall data for the three locations do not have a simple random character.

3.2. IMPACT OF CLIMATE VARIABILITY ON PRODUCTION OF MILLET

It is now established (WMO, 1998) that the character of the West African rainy season for July, August and September (JAS) rainfall can be forecasted from sea surface temperature anomalies (SSTA). Table IV shows, however, that the three sites, although under the same influence of El Niño, are not correlated in the same way with the SSTA of the Equatorial Atlantic Ocean and the Indian Ocean.

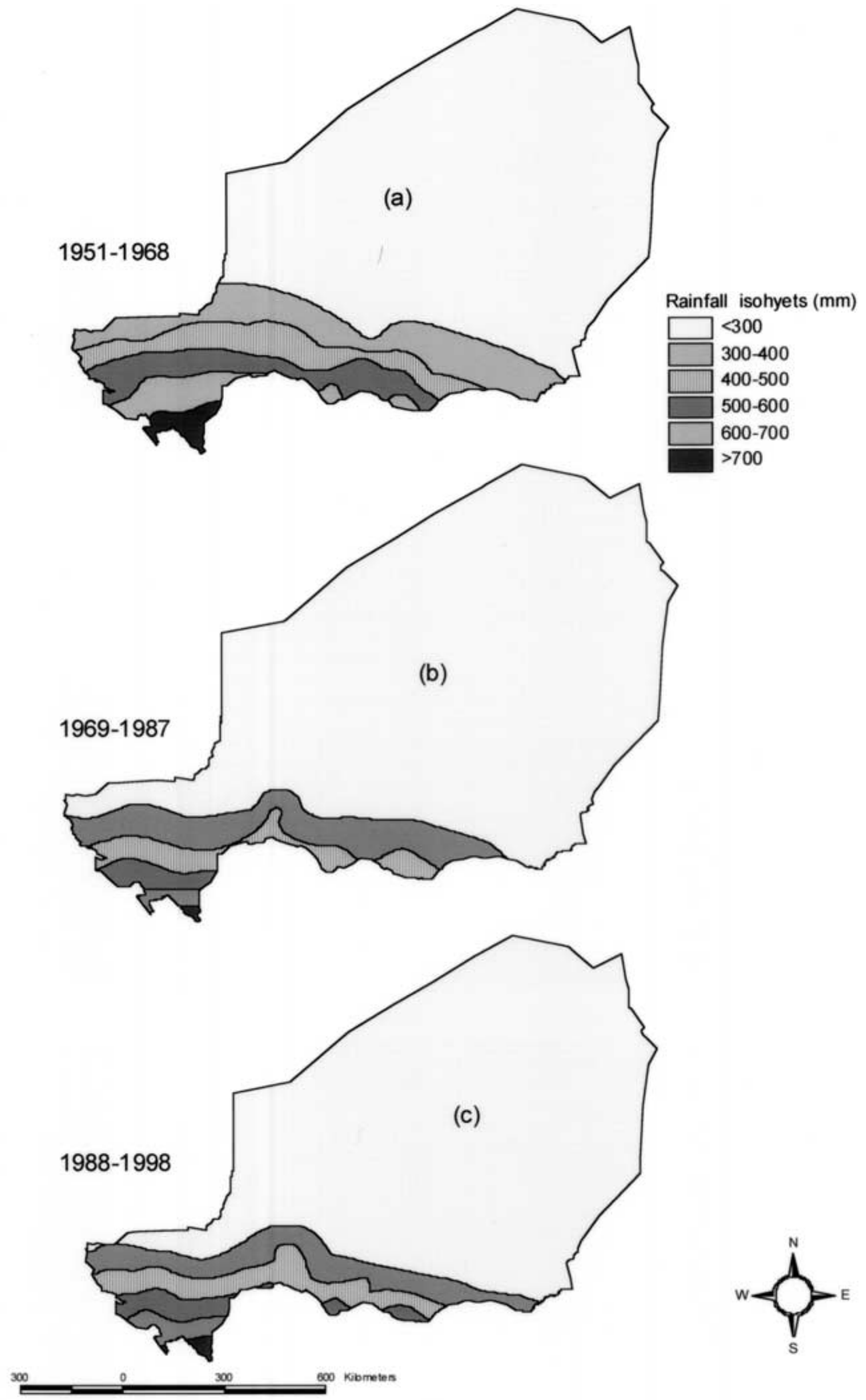

Figure 5. Map of Niger showing the change in location of isohyets in the period (a) of 1951–1968, (b) 1969–1987, and (c) 1988–1998.

Table IV also presents the significant predictors as well as the percentage of the variation of the estimated value explained by those significant predictors. Among the significant predictors four parameters clearly stand out. They include SSTA of the Indian Ocean, the amount of rainfall in the three months, the number of rainy days and wind erosion factor.

Table V presents the summary of the ANOVA results and the model's performances. According to what was mentioned above about statistical model performance, the obtained models show probabilities of detection of the production categories well above 60% and a very low false alarm rate. In view of the obtained skills, one can stress the usefulness of this approach in this area of marked climate variability as a realistic step towards assessment of vulnerability to long-term climate change.

Figure 6 shows the evolution of yield and the production of millet between 1967 and 1998 for the three sites. Yield had a tendency to decline, whereas the production increased for all three sites. This implies that more and more land is being cultivated, as was already illustrated in Table I. This constitutes the paradox of agriculture in the Sahel, a region experiencing chronical food deficit because of climate and prevailing agricultural practices. It is worth mentioning the limited use of fertilizer by local farmers in order to improve yields.

3.3. POTENTIAL IMPACTS OF FUTURE CLIMATE CHANGE ON MILLET PRODUCTION

Using this statistical approach we highlight the importance of crop sensitivity to current climate variability as an important step towards assessment of impact of climate change. At the same time, however, the dependence on SSTs of the statistical models makes them difficult to apply, simply because projections for SSTs are not easily available. Alternative calculation of future yields using dynamic crop simulation models also seems not feasible at this moment in time, because there are, to our knowledge, no such models available that are validated for the varieties grown and the Nigerian conditions (poor sandy soils with large spatial heterogeneity in both rainfall and low soil fertility, especially nitrogen and phosphorus). Moreover, for the regions being discussed, detailed (daily) data are scarce, if existing at all. As a consequence, we used this statistical approach and kept SSTA constant in the present analysis.

Figure 7 shows the results of the modeling of millet production in the Dosso, Maradi and Zinder regions for the past 31 years. This is presented as a temporal evolution of parameters observed and estimated.

Production is used instead of yield for two reasons. First, production data are the raw data collected by official agricultural services in the villages after harvest, and yields are derived from often imprecise field areas estimated by farmers themselves. Second, production better compares with the population's food requirements. For example, assuming a per head average annual consumption of

Table V

Summary of ANOVA results and the model's performance for millet production in the three regions in Niger

Location	ANOVA			Model performance			Category: < normal		Category: > normal	
	R	F-ratio	P	Skill	HSS %	C %	POD %	FAR %	POD %	FAR %
Dosso	0.88	12.03	0	0.78	52	68	80	0	78	0
Maradi	0.91	16.85	0	0.85	41	61	64	0	78	10
Zinder	0.90	7.43	0	0.70	25	50	70	9	67	15

Fisher's test (F-Ratio): gives the ratio of the independent value estimated by the regression and it's variance residue, and its p-value.
Skill: the correlation between observed values of the predictor and those obtained by the cross-validation, which gives the performance of the forecast model.
Hit Skill Score (HSS): the value added by the model to the one calculated by chance; if HSS equals one then 100% equals a perfect model, while 0 indicates a chance model.
Probability of coincidence (C%): the ratio of the percentage of the categories predicted correctly by the model and the time series used to develop the model.
Probability Of Detection (POD): the capacity of the model to (detect) predict accurately in a category previously fixed. In our case, we used below normal, normal, and above normal (equal terciles).
False Alarm Rate (FAR): the number of the prediction category where the opposite was observed, divided by the total number of this category.

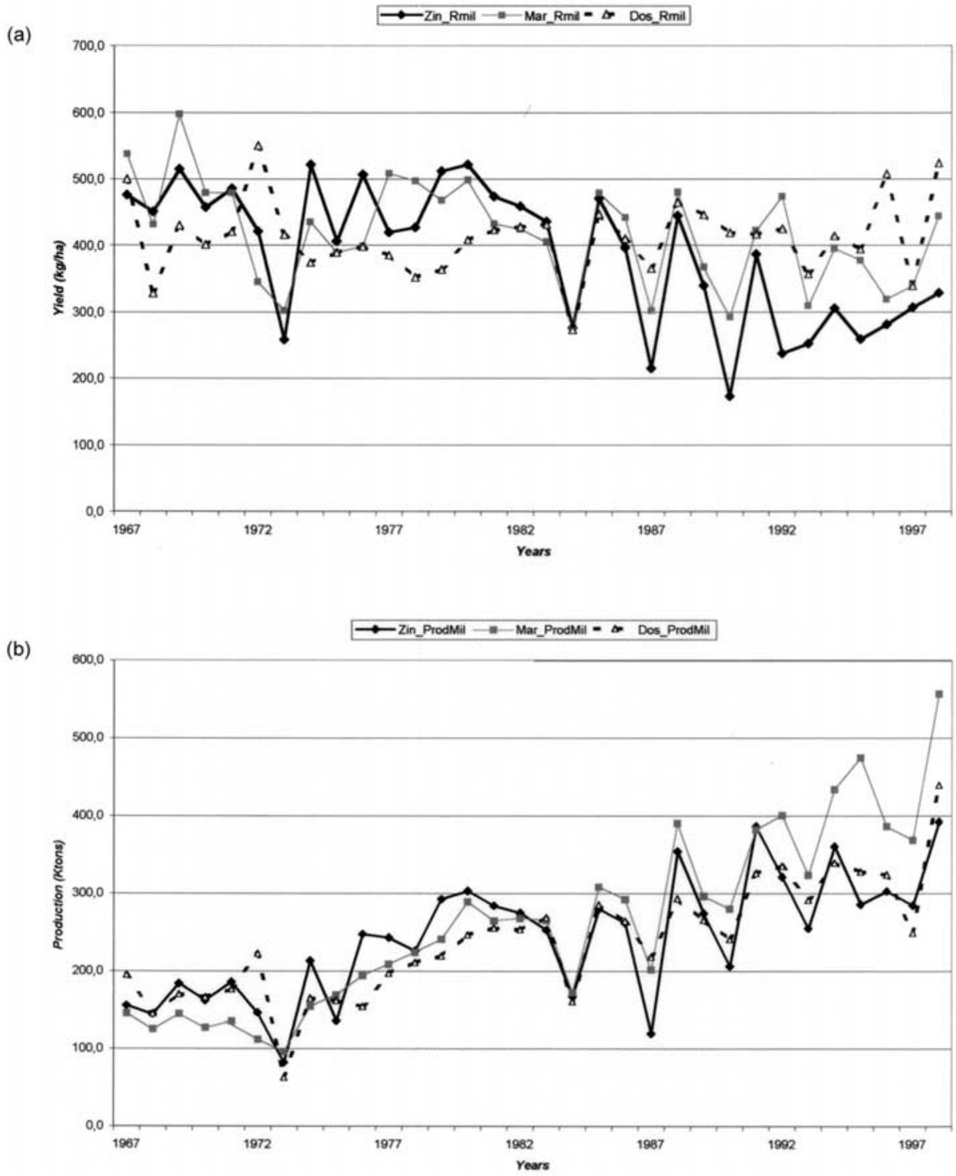

Figure 6. (a) Yield (kg ha^{-1}), and (b) total production ('000 t) of millet in the period 1953–1998 in the three sites in Niger. Dos: Dosso; Mar: Maradi and Zin: Zinder.

230 kg millet to cover energy requirements (cf. Mondot-Bernand, 1980), and using the forecasted population for Dosso, Maradi and Zinder regions, it is possible to anticipate food availability towards 2025 for these regions.

The simulations on agricultural production in 2025 should of course be considered with caution, as many non-climatic factors (e.g., CO_2 enrichment) may

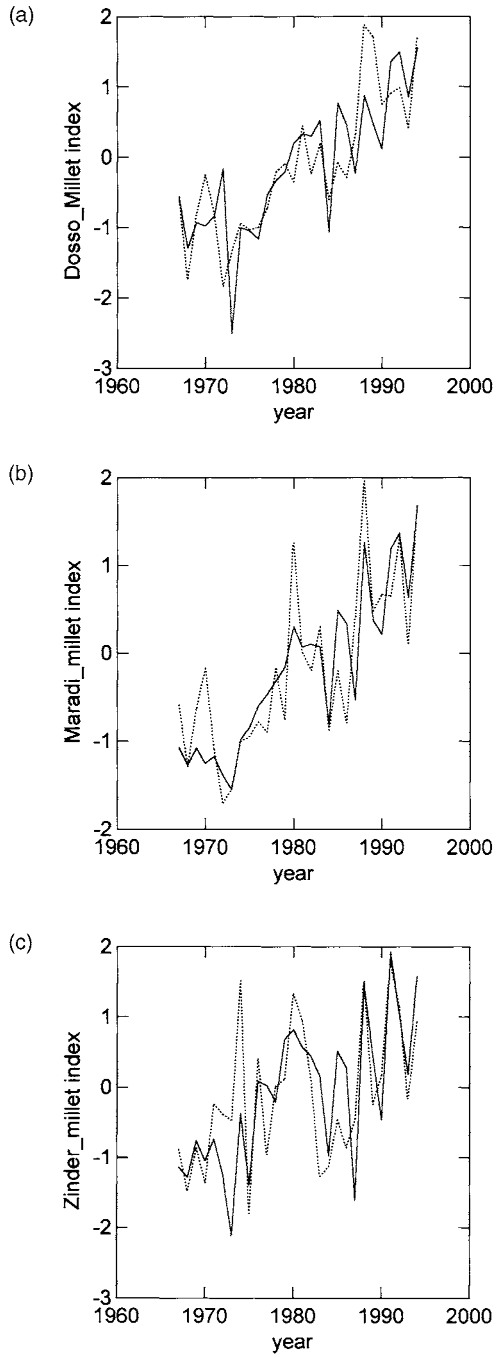

Figure 7. Indices for observed (line) and estimated (dotted line) millet production for the three sites in Niger: (a) Dosso, (b) Maradi, and (c) Zinder.

also influence production. In fact, soil related factors (fertility, soil moisture), the cycles of the varieties used, the cropping techniques and the type of production can significantly influence the outcome of growing seasons, and these factors are difficult to take into account in a modeling exercise at this scale.

For the year 2025, the scenarios with 10 and 20% reduction in rainfall, 10 and 20% increase in temperature, result in a reduction in the length of the rainy season (LRS) by 13 and 24%, or in a LRS of 97 or 85 days, respectively. This will certainly have consequences for the types of varieties that can be cultivated. The potential impact on millet production (assuming the same area being cultivated) in Dosso and Maradi in terms of reduction, without any adaptation to such harsher conditions, is for the first scenario 11% and for the second 26%, while for Zinder the reduction is 13% for both scenarios.

3.4. ADAPTATION STRATEGIES TO CLIMATE CHANGE

To mitigate the impacts of climate change on agriculture in Niger, various adaptation strategies can be envisaged. Some already exist and can be adapted to local conditions by farmers, while others need to be developed. These strategies include:

(i) to undertake specific impact and simulation studies on effects of climate change in certain agro-ecological zones in Niger for both food crops (e.g., millet, sorghum, cowpea and potatoes) and cash crops (such as groundnut, cotton, onions and sugarcane);
(ii) to determine the most appropriate sowing dates for the various crop varieties to optimize the available moisture in the soil and face the effect of eventual higher temperatures during the growing season;
(iii) to determine the varieties that are the most tolerant to drought for zones with recurring drought periods (cf. FAO, 1996; Ly et al., 1998);
(iv) use of irrigation or supplementary irrigation (cf. FAO, 1996; Amadou et al., 1999);
(v) to increase use of fertilizer, as its absorption increases the water use efficiency of the crop (e.g., Amadou et al., 1999) and
(vi) use of seasonal forecast by farmers in the planning of agricultural operation as well as a greater agro-meteorological assistance and a strengthening of early warning systems.

Given the predominantly poor socio-economic context of the farmers, an increased use of fertilizers will be difficult to realize despite various on-going efforts to show farmers the benefits (Ly et al., 1998). Irrigation also requires considerable investments that farmers are not able to pay, but the use of supplemental irrigation can be economically profitable (Sawadogo quoted by Anou et al., 1999). The use of mini-catchments using organic manure (to be constructed in the dry season) seems to help farmers to better guarantee their production potential. Efforts are being made by non-governmental organizations (NGOs) to help farmers, through

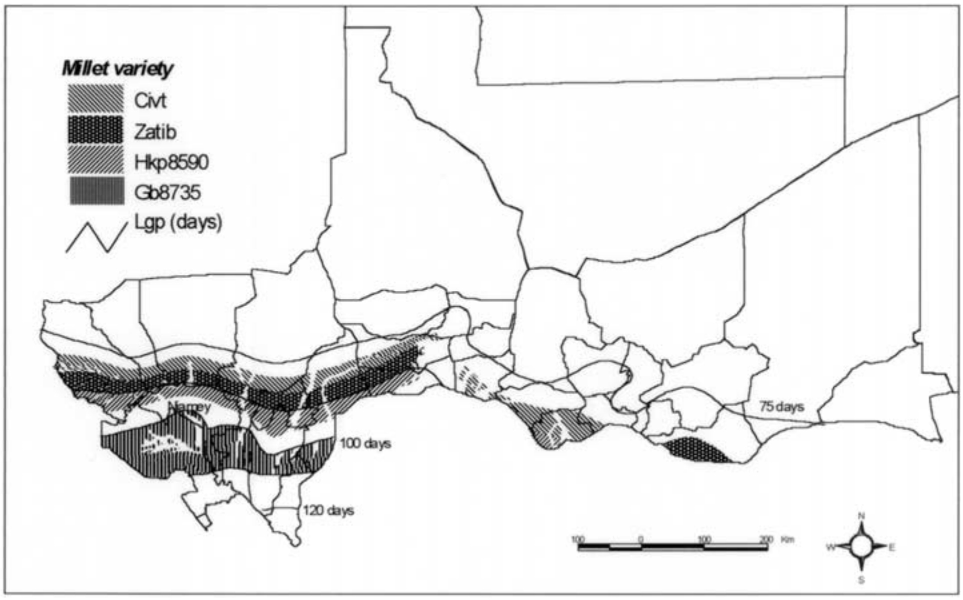

Figure 8. Example of target zoning for various millet varieties at national level in Niger using average length of growing period (LGP) and soil data in a GIS environment.

specific radio broadcasting, to optimise their agricultural operations. Furthermore, both the National Institute for Agricultural Research (INRAN) and ICRISAT are developing and testing, in close collaboration with NGOs and farmers, new varieties and other technologies (Ly et al., 1998). These technologies should be better adapted to the specific climatic conditions, give better yields, resist attacks by crop pests and diseases, and have growing cycles corresponding to the probable season length. Alternatively, target zones for a specific technology or a combination of technologies should be identified, as illustrated for four millet varieties in Figure 8.

4. Conclusion

The presented methodological approach stresses the use of statistical modeling to assess vulnerability to present climate variability as a first step towards assessing impact of potential climate change. Through a stepwise regression using the model and the past 30 years of rainfall data, the most significant predictors were identified. These are (i) sea surface temperature anomalies, (ii) the amount of rainfall in July, August, and September, (iii) the number of rainy days, and (iv) wind erosion factor. Regarding the latter, the need for measures to reduce degradation is striking. With the current tendency of cultivating marginal areas, in the case of rainfall failure an increased degradation will occur. Hence, farmers should be offered strategies or options for development to reduce risk of crop failure under more intensified cultivation of the cropped land while maintaining the productivity of the land (i.e., reduce further degradation).

Although this study shows that the isohyets have actually again moved towards the north during the last decade, the methodological approach assumes a further reduction in rainfall in the future, because of the substantial differences observed in the outputs of Global Circulation models with the coarse resolution used today. The estimated impact of climate change for the year 2025 seems considerable (minus 11 to 26%) on millet production in the already vulnerable semi-arid regions of Niger. Significant improvement of this methodological approach can be obtained through prediction of likely SSTs for the projected period, as these predictions appear to be very important.

To counteract these climate-induced reductions, management strategies become more important. Further related participatory research (e.g., for new varieties, and technologies to further optimize soil water use) by National Agricultural Research Systems, International Agricultural Research Centres and NGOs, and the development of improved rainfall forecasts are evident.

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