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Scenario-based simulations of the impacts of rainfall variability and management options on maize production in Benin

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Many studies have dealt with crop production under climate change projections in sub-Saharan Africa, focusing on average long term trends over time-windows of five to twenty years. The efforts undertaken in this study rather combine effective farm management/abiotic factors (e.g., soil tillage, sowing date, fertilizer use, soil fertility status) with variabilities in rainfall conditions at decadal scale to simulate rainfed maize yield in Benin (West Africa). To achieve this goal, the model system Environmental Policy Integrated Climate (EPIC) was used. Management options such as fertilizer use and sowing date scenarios were considered. Variability in rainfall conditions were considered to account for extremes in yield production. Changes in plant growth limiting factors such as water stress and nitrogen stress were conjointly analyzed to account for not only the effects of climate changes, but also soil fertility status and various pressures on the land resources. Excluding catastrophic factors such as floods and pests the results indicate yield production ranges of about 500 to 1400 (±250) kg ha^{-1} a^{-1} in the North and 1100 to 2300 (±300) kg ha^{-1} a^{-1} in the South of the investigated region. The impacts of sowing date on the production were within comparable magnitudes of that of climate changes/ rainfall variability (up to -50% of the yield in the North). Higher yield production was globally associated with earlier sowing date referring to the period 2000 to 2009, while associated with later sowing dates referring to period 2010-2050. Moreover, higher water stress is associated with earlier sowing dates, while higher nitrogen stress is associated with later sowing dates referring to the period 2010 to 2050. Shifting towards late sowing dates corresponding to a cumulated rainfall of 180 mm may reduce water stress and make efficient use of fertilizers in future (2010 to 2050), regardless high or low annual rainfall.

Key words: Maize yield, sowing date, fertilizer use, rainfall variability, climate change impacts.

INTRODUCTION

Benin is not classified at the same vulnerability level as the sahelian countries, but is highly dependent on the agricultural sector, which determines the economic development of the country (Kuhn et al., 2010). Up to a recent past a stable yield production in Benin is mainly the results of shifting agriculture based on fallow

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systems, without the use of fertilizers. The country is characterized by harsh climatic conditions, high rainfall intensities, prolonged dry seasons, extensive drought periods, high population growth, and the excessive use of resources (Heldmann and Dovenspeck, 2008; Hiepe, 2008; Gaiser et al., 2011; Bossa et al., 2012b, Bossa and Diekkrüger, 2012). Compared to temperate regions, the decline in food productivity since the 70s is drastic due to the climate condition, low soil fertility, and the poor quality of the subsoil and unstable soil properties (Hiepe, 2008; Bossa et al., 2012b). Some regional climate models predict a decrease in annual rainfall up to 30% by 2050 with a significant within-region differences (Paeth et al., 2008). This change will decrease yield production already challenged by low knowledge of efficient agricultural management. Although it is well known that yield reduction could be compensated by fertilizer availability and use, without exact knowledge of the reduction mechanism, adaptation and resilience measures are less efficient.

Variability in food availability may be seen as the results of complex interactions between a large number of process factors (Diepen and van der Wall, 1996) and different sources of climate variability (IPCC, 2001): (1) abiotic factors, such as soil moisture, soil fertility, weather; (2) farm management factors, such as soil tillage, sowing date, fertilizer use, irrigation; (3) socioeconomic factors, such as population pressure, education levels; (4) catastrophic factors, such as droughts, floods, and pests; and (5) changes in the mean annual rainfall or/and spatial/intra-seasonal patterns. Climate change increases the variability of rainfall in many parts of the world. This will be a critical concern for Benin, whose food security is essentially based on rainfed agriculture. Rainfall variability and mean effects of climate changes are already shown as the highest potential risk for food security in Benin (Paeth et al., 2008; Speth et al., 2010; Agbossou et al., 2012), but this still needs to be regionally nuanced due to combined effects of large variability in the intra-seasonal rainfall pattern, large variability in the abiotic factors (soil fertility status), uncertainties concerning the onset of the rainy seasons (sowing date), and variability in fertilizer use as well as tillage techniques. A clear consideration of all these aspects in the simulation models may be seen as relevant assets to support specified adaptation and resilience measures under different conditions at the regional scale.

Lacatusu and Lacatusu (2011) combined field and laboratory description of abiotic factors to suggest a complex indicator for assessing soil fertility using two groups of potentiating and penalty indicators. They included in the first category climatic indicators (mean precipitation and temperature), the nutritive spaces, water and air regime (edaphic volume, and gleization level), physical indicators (texture, bulk density), chemical indicators (pH, humus content and the content of macro elements). The second category includes levels of salinization, alkalization, carbonation, pollution and artifacts content. It was a successful approach that may be associated with the simulation efforts to account for the prediction uncertainties and the significance of soil fertility effects while attempting to quantify the impacts of climate changes on yield production. Many studies have shown the importance of planting date for agricultural management (Stern et al., 1981; Mandal et al., 2005; Baldwin and Cossar, 2009; Egli and Cornelius, 2009). The sowing date determines moisture availability through the growing season as well as the schedule of management practices such as tillage and fertilizer use. Planting too early might lead to crop failure and planting too late might reduce valuable growing time and crop yield, but there is still no consensus in literature about the question of how much rain over which period defines the onset of the rainy season for agro-climatological impact studies (Laux et al., 2010). Inter-annual variable and spatially distributed planting dates may be developed on the basis that wet season starts when, for the first time after March 1st, 25 mm of rain falls within 2 consecutive days, and no dry period of 10 or more days occur in the following 30 days (Stern et al., 1981; Kiniveton et al., 2009; Laux et al., 2008, 2010). Ati et al. (2002) as well as Ndomba (2010) mentioned that such criteria are rather useful for retrospective analysis but not for guiding farmers in a particular year. Ilesanmi (1972) successfully used cumulated percentage mean rainfall (7 to 8%) to derive the onset of the rainy season. It is a commonly used approach, mathematically elegant, efficient, free of assumptions, and relying only on rainfall data rather than the mere inferential methods (Olaniran, 1983; Odekunle et al. 2005; Odekunle, 2006; Ndomba, 2010). For Burkina Faso, Waongo et al. (2014) showed that a Fuzzy Rule based approach is helpful for determining optimal sowing date and that yield may increase by 20%. For their regional scale study, the General Large-Area Model for Annual Crops was used.

This study rather used early and late sowing dates derived from cumulated rainfall amount of 100 and 180 mm counting from the first day of the year, to better discuss the impacts of scenario-based rainfall conditions on maize production.

The study analyzed at a regional scale the spatial limitations of maize production under different conditions of climate changes, agricultural management, soil fertility status and planting dates. The aim of the study was to use the agro-ecosystem model Environmental Policy Integrated Climate (EPIC) to answer the following questions: (1) are there any regional differentiations in maize production in Benin? (2) How significant are the influences of management practice and fertilizer use on maize yield? (3) What are the changes in maize production under climate change up to 2050? (4) Under climate change conditions are water and nitrogen stress the limiting factors for maize production? Are there any

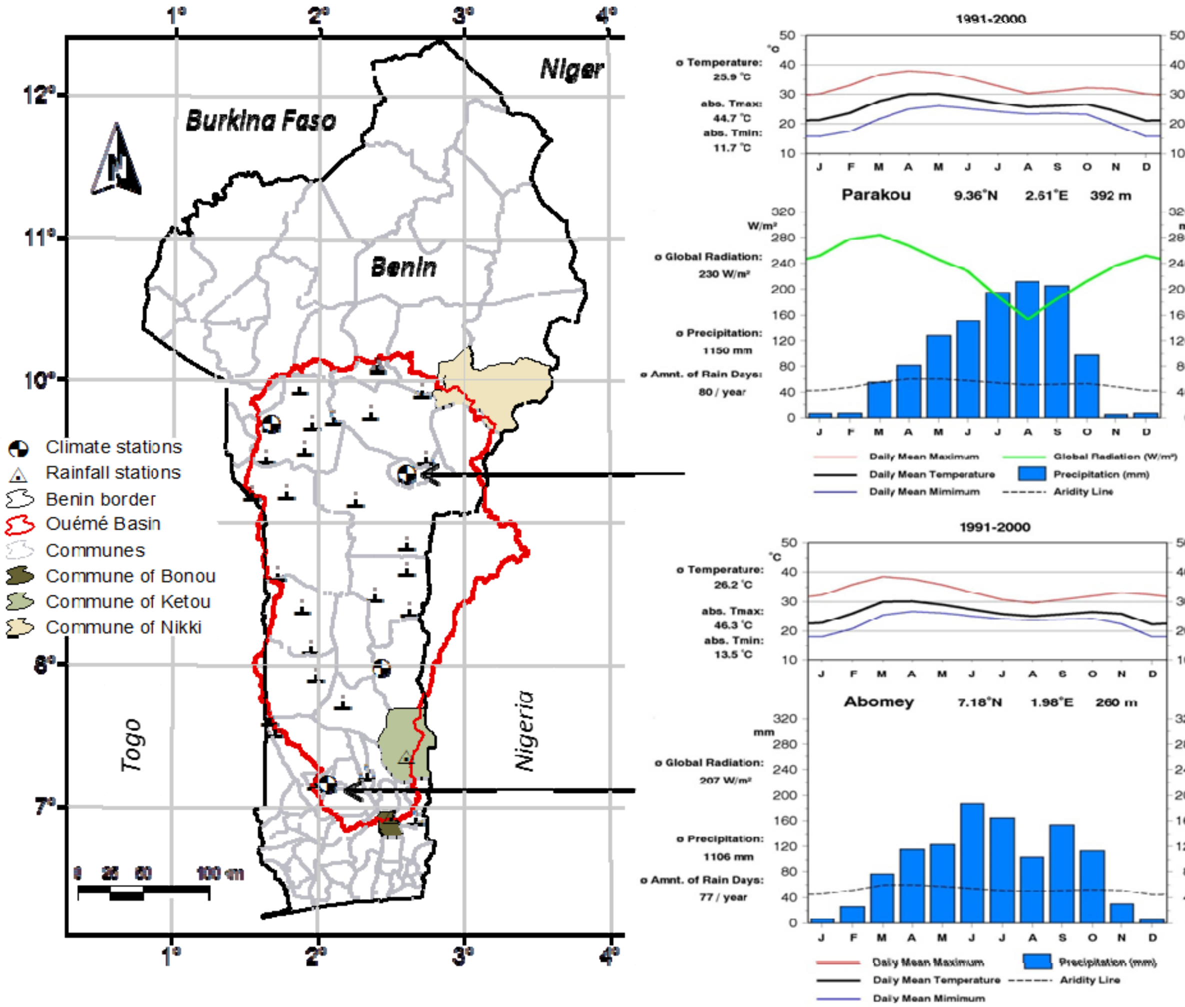

Figure 1. Study area and location of the three communes. Climate diagrams of the North (Soudanian climate) and South (Guinean coast) of the Ouémé catchment (after Speth et al., 2010).

regional differentiations? (5) Are there any potential management responses to constrain the effects of climate change on maize production?

MATERIALS AND METHODS

Study area

Benin is located in the West of Africa, between Togo and Nigeria (Figure 1) with an economic situation entirely based on agriculture, forestry and fisheries (Kuhn et al., 2010c). Compared to other countries located at the same geographical latitudes Benin records up to 400 mm less precipitations, because of the Dahomey gap anomaly. During the year the region is successively influenced by the humid monsoon air and the dry and hot harmattan. Situated in the wet (Guinean coast) and the dry (Soudanian zone) tropical climate, the Ouémé catchment (as considered in this work) (Figure 1) records annual mean temperatures of 26 to 30°C, annual mean rainfalls of 1,280 mm (from 1950 to 1969) and 1150 mm (from 1970 to 2004) at the climatic station of Parakou (cf. Figure 1) (Speth et al., 2010). As shown in Figure 1, the Soudanian zone has a unimodal rainfall season that starts in April and peaks in August whereas the Guinean zone exhibits a bimodal rainfall season that starts in March and peaks in June and October (Fink et al., 2010). A complex rainfall pattern is observed within the study region. Indeed, it was shown that the daily rainfall accumulation at one location may surpass 150 mm (corresponding to roughly 8% of mean yearly accumulation), with 80 mm falling within two hours, while slight or no rainfall may occur at a point only 20 km away from that location (Diederich and Simmer, 2008). At regional scale, predominant soils are fersialitic soils (ferruginous tropical soils), characterized by clay translocation and iron segregation (ferruginous tropical soils with concretions), which lead to a clear horizon differentiation (Faure and Volkhoff, 1998; Gaiser et al., 2010a; Bossa, 2012). A local scale description has shown a typical catena with soils formed on the slopes, leached ferruginous tropical soils (Orthidystri-Epi- or Endoskeletic Acrisols/Haplic Lixisols or Typic Kandi-ustults/Typic Kandiustalfs) (Busche et al., 2005; Junge, 2004; Sintondji, 2005; Hiepe, 2008; Gaiser et al., 2010a; Bossa et al., 2012a,b). Leached and indurated ferruginous tropical soils (Hyperalbi-Petric Plinthosols/Plinthic Petraquepts) are developed at lower parts of the slopes. Hydromorphic soils (Humic Gleysols/Typic Epiaquepts) are found in the inland valleys. In the riverbeds, poorly evolved soils are distributed (Arenic Fluvisols/Typic Ustifluvents) (Junge, 2004;

Sintondji, 2005; Hiepe, 2008; Gaiser et al., 2010a; Bossa et al., 2012a,b).

Different types of savannahs and agricultural lands dominate the landscape in Benin. Whereas the South of the country is already stamped by agriculture, the remaining natural vegetation in the Northern regions is converted step by step to agriculture (Wezel and Böcker, 2000). Maize constitutes the most important crop and one of the main staple foods. Despite the increasing maize production in central- and Northern Benin, the South still accounts up to 60% of total maize production in Benin (van den Akker, 2000). Usually shifting agriculture with fallow systems is used to regenerate soil fertility. Due to very low degree of mechanization, tillage is only possible with traditional hand tools and man power. Irrigation and fertilizer use are still weak in Benin. Furthermore, the amounts of fertilizer usually applied are under strict policies (Kuhn and Gruber, 2010). This study concentrates on three communes/localities indicated in light-brown, light-green and dark-green within the Ouémé catchment (Figure 1): (1) Nikki (light-brown), North of the Ouémé catchment; (2) Ketou (light-green) in the South; and (3) Bonou (dark-green), also in the South of the catchment.

Modeling approach

The EPIC (Williams et al., 1989) is an agro-ecosystem model able to calculate crop growth under different environmental conditions. It takes into account all relevant processes required for simulating maize production and has already been successfully applied in Benin (Gaiser et al., 2010b). In addition it allows the evaluation of crop growth stress factors including water stress, nitrogen stress, temperature stress which are very important for discussing the limitations of the production at a specific location. Besides maize, EPIC is suitable for many other crops. EPIC is a field scale model using a daily time step and allows long term simulation up to hundreds years. Although there is already an update version, in this study the version 3060 is used due to technical consideration concerning manual fertilizer application. To represent the important processes for crop growth, EPIC contain eight sub-models accounting among others for weather, soil and hydrological processes (Williams 1995; Williams et al., 2006). The crop growth is calculated through the leaf area development, the light interception and the conversion into biomass. Biomass is therefore estimated with the Monteith´s approach (Monteith, 1977) which is indicated through Equation (1).

$$\Delta B_{p,i} = 0.01 \times WA \times PAR_i \quad (1)$$

Where, $\Delta B_{p,i}$ is the potential increase in biomass in kg ha^{-1} in day *i*, WA is the Biomass-energy ratio describes the conversion of energy to biomass in (kg ha^{-1})(MJ m^{-2})$^{-1}$, *PARi* is the photosynthetic active radiation in MJ m^{-2}d^{-1}.

Only maize yield is simulated in this study as amount of economic dry yield (kg ha^{-1}), estimated in EPIC through the harvest index Equation (2):

$$YLD = HIA \times B_{AG} \quad (2)$$

Where, YLD is the amount of dry and economic useful yield in kg ha^{-1}, HIA is the adjusted (water stress reduced) harvest index and B_{AG} is the cumulative above-ground biomass (kg m^{-2}) before senescence occurs.

The harvest index is calculated using Equation (3)(Williams et al., 1989):

$$HI_i A = HI_{i-1} A - HI\left(\frac{1}{1 + WSFY \times FHU_i (0.9 - WS_i)}\right) \quad (3)$$

Where, HI is the potential harvest index on the day of harvest and is defined as the ratio of harvestable yield to total aboveground biomass), *WSFY* is the crop parameter expressing the sensitivity of harvest index to drought, *FHU* is the crop growth stage factor, WS is the water stress factor, i and i-1 are the Julian days of the year.

Crop growth is limited through stress factors if their values are below 1. In EPIC five stress factors could constrain the daily increase in biomass production. These five factors include water stress, temperature stress, nitrogen stress, phosphor stress and aeration stress. For our work only water and nitrogen stress are interesting. Water stress is calculated through supply and demand, occurring when demand is higher than supply controlled by available water in the soil Equation (4):

$$WS_i = \frac{\sum_{l=1}^{M} u_{il}}{Ep_i} \quad (4)$$

Where, *WS* is the water stress, *u* is the water use in horizon *ℓ*, *Ep* is the potential water use of plant on day *i*.

Nitrogen stress is calculated similarly to water stress, considering also supply and demand. The accumulated nitrogen content of the plant is compared with optimal nitrogen content (Williams, 1995). All stress factors are indicated through stress days, without differentiation of stress intensity.

Model parameterization

To simulate the maize production with EPIC, many different types of information are necessary to obtain realistic yields. Among the most important data required are information about the geographical location (latitude, longitude, elevation, etc.), soil data, management data, weather data and hydrological information (Williams et al., 2006). Table 1 shows the nature, source, scales and types of parameters required for applying the EPIC model in the study area. Each soil type is described through many parameters including hydrological soil group (derived from internal drainage characteristics) (Gaiser et al., 2010), number of soil horizon, albedo, previous years of cultivation, minimum and maximum depth of groundwater and soil organic matter pool (Liu, 2009). EPIC can accept up to 20 parameters for up to 10 soil layers. Specific information on soil layers such as number and depth of soil layer (m), bulk density (t/m³), sand content, silk content, carbon and organic content (%), cation exchange capacity (cmol/kg), saturated hydraulic conductivity (mm/h) (Liu, 2009; Tan and Shibasaki, 2003). In total six different soil types including 2 from each investigated locality together with their associated parameters were considered for the simulations (cf. Table 2). These parameters are combined with other abiotic parameters such as the mean annual weather conditions to compute a complex indicator of fertility (CIF) to discuss the simulation issues. The CIF (Lacatusu and Lacatusu, 2011) is defined as the difference between the sum of potentiating indicators (x) and the sum of the penalty indicators (y) and is expressed for agricultural soils by the Equation (5):

$$CIF = \sum_{i=1}^{12} x_i - \sum_{i=1}^{5} y_i \quad (5)$$

Where the potentiating indicators x_1 = annual average precipitations (mm), x_2 = annual average temperature (°C), x_3 = level of gleization, x_4 = level of pseudo-gleization, x_5 = textural class, clay content of <2µ (%), x_6 = edaphic volume (%), x_7 = bulk density (g cm^{-3}), x_8 = reaction pH$_{H2O}$, x_9 = humus content (%), x_{10} = total nitrogen content

Table 1. General model input data used in this study. Soil and land use data are from IMPETUS (Christoph et al., 2008) and INRAB (Institut National de la Recherche Agricole du Bénin; Igue, 2005), Climate data are from IMPETUS, IRD (Institut de Recherche pour le Développement), and DMN (Direction de la Météorologie Nationale). Management information are obtained from the MAEP (Ministère de l'Agriculture, de l'élevage et de la Pêche) and the CeRPA (Centre Régional de Promotion Agricole).

Data (data sources)	Scale	Parameter and types of investigation
Topography (DEM SRTM)	90 m resolution	Elevation and slopes.
Soil (SOTER INRAB and IMPETUS)	1 : 200,000	Saturated conductivity, organic carbon, bulk density, Texture, soil erodibility factor, soil available water content, pH, OrgN, etc.
Management (CountryStat, MAEP, CeRPA)	Commune level	Tillages, crop systems, conservation measures, fertlization, etc.
Weather (DMN, IRD, IMPETUS)	1 per site	Daily wind speed, precipitation, temperature, solar radiation, etc.

Table 2. Investigated site soil types and soil properties as used in the simulations. Only mean values of the topsoil (depth < 0.4 m) are displayed in this table.

Types and soil properties	Luvic arenosol (Bonou)	Eutric Vertisol (Bonou)	Eutric Vertisols (Ketou)	Ferric Acrisols (Ketou)	Haplic Lixisol (Nikki)	Eutric Gleysol (Nikki)
Topsoil depth (M) (total profile depth)	0.38 (1.2)	0.3 (0.6)	0.35 (0.7)	0.25 (1.6)	0.38 (1.2)	0.28 (0.7)
Soil porosity (M/M)	0.39	0.49	0.50	0.38	0.33	0.40
Field Capacity - soil water (M/M)	0.20	0.44	0.25	0.11	0.12	0.22
Saturated conductivity (MM/H)	5.01	1.92	22.00	37.69	22.46	4.59
Sand content (%)	61.50	19.65	51.35	82.90	81.70	58.47
Silt content (%)	22.25	23.70	30.85	14.70	9.85	22.43
Clay content (%)	16.25	56.65	17.80	2.40	8.45	19.10
Rock fraction (%)	2.60	5.30	7.65	5.30	15.00	2.60
pH_{H2O}	5.80	5.95	6.60	6.10	5.65	5.80
Cationic exchange capacity (CMOL/KG)	9.30	34.50	10.80	37.40	5.80	8.63
Organic P (G/T)	46.50	189.50	218.00	76.00	45.50	67.00
Organic N (G/T)	370.00	1515.00	1740.00	610.00	360.00	536.67
Organic C (%)	0.37	1.52	1.74	0.61	0.36	0.54

(%) or the amount of nitrogen index (NI), x_{11} = mobile phosphorus content (mg kg^{-1}), x_{12} = mobile potassium content (mg kg^{-1}); and the indicators for penalty y_1 = level of salinity, y_2 = level of alkalization, y_3 = level of carbonation, y_4 = level of pollution, y_5 = level of artifacts (%). Additionally to all the above-described general parameters, the model was provided with literature-based (sensitive/experimental-based/calibrated) validated model parameters under regional conditions for maize production in Benin, mainly from Gaiser et al. (2010b).

He pointed out that the physiological parameter set for maize in the EPIC database was only slightly changed to

Table 3. Scenario-based annual rainfall [mm] at decadal scale from 2000 to 2050. D = dry condition, W = wet condition. A dry year (resp. wet year) is considered as a year recording the smallest (resp. highest) amount of rainfall.

Variables	2000-2009 [Reference]	2010-2019	2020-2029	2030-2039	2040-2049
Nikki W+A1B	1302	1436	1270	1454	1370
Nikki D+A1B	1041	801	752	816	792
Nikki W+B1	1302	1309	1468	1314	1337
Nikki D+B1	1041	768	781	760	792
Bonou W+A1B	1258	1489	1340	1323	1309
Bonou D+A1B	862	783	803	773	715
Bonou W+B1	1258	1472	1485	1465	1353
Bonou D+B1	862	760	828	813	813

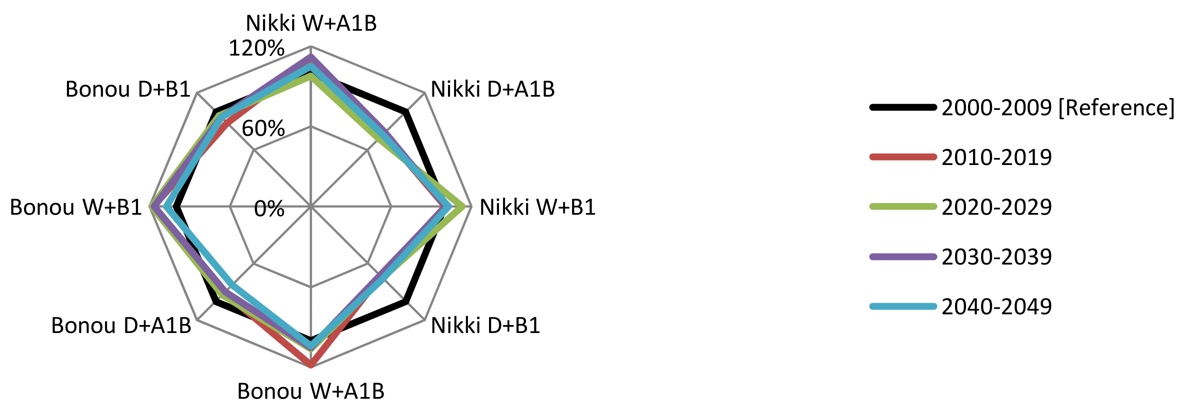

Figure 2. Relative changes in the scenario-based annual rainfall at decadal scale from 2000 to 2050. D = dry condition, W = wet condition. A dry year (resp. wet year) is considered as a year recording the smallest (resp. highest) annual amount of rainfall within a ten years period.

fit the conditions in Benin (Gaiser et al., 2010c). Nevertheless, it was found necessary to strike the values of the indicated most sensitive parameters by an uncertainty rate of ±20% to account for all potential uncertainties affecting the simulations. It is the case of 5 model parameters including the harvest index (HI = 0.35 [-]), the minimum harvest index (via WSYF = 0.01 [-]), the Aluminium tolerance index (ALT = 3 [-]), critical aeration factor [-] (CAF = 0.85) and previous years of cultivation (RTN = 50 years). Thus, a relatively large parameter matrix was created and used to evaluate maize yield at the three investigated locations, based on two different management scenarios associated with two sowing date scenarios and for a reference dry year (2001) and a reference wet year (2003) (cf. section 2.4 for detailed information on the different scenarios). A dry year is considered as a year recording the smallest amount of rainfall in a given decade, and a wet year recording the highest rainfall. The variability associated with the simulated yield was useful to estimate the possible production range at each location with the potential uncertainty. The results were finally used to validate the commune level observed yield, recorded by the Ministry of Agriculture and Livestock (MAEP) and published online (countrystat.org/ben).

The climate observation in Benin is based on a national rain-gauge network (under DMN authority, 'Direction Nationale de la Météorologie') counting roughly 100 measurement sites by 2005 (Diederich and Simmer, 2010). As already reported by Bossa et al. (2012) and documented in more detail by Speth et al. (2010), the climate scenarios used were provided by Paeth et al. (2009) for the Africa continent between -15°S and 45°N latitude, using the regional climate model REMO driven by the IPCC SRES scenarios A1B and B1. REMO is a regional climate model that is nested in the global circulation model ECHAM5/MPI-OM (Paeth et al., 2008). Considering REMO initial runs, the rainfall amount and variability were systematically underestimated over West Africa with a shift in its pattern towards more weak events and fewer extremes (Paeth and Diederich, 2010). This has led to the application of MOS (Model Output Statistics) to adjust the rainfall data (monthly bias correction) using other near-surface parameters such as temperature, sea level pressure and wind components from the model. Since the regional-mean spatial patterns of daily rainfall events strongly differed from the observed a conversion of the MOS-corrected regional-mean data derived from REMO to local rainfall event patterns has been done. As reported by Gaiser et al. (2011), a weather generator (WEGE) was applied, producing virtual station data, matching the rainfall stations in Benin, which was finally adjusted to the statistical characteristics of observed daily precipitation at the rainfall stations by probability matching (Paeth and Diederich, 2010). Table 3 and Figure 2 show the scenario-based highest/lowest annual rainfall amounts at decadal scale from 2010 to 2050. It can be seen that rainfall amounts in the wet years will likely increase of up to 20% at all investigated locations, while decreasing in the dry years of up to 25% mainly occurs in the locality of Nikki.

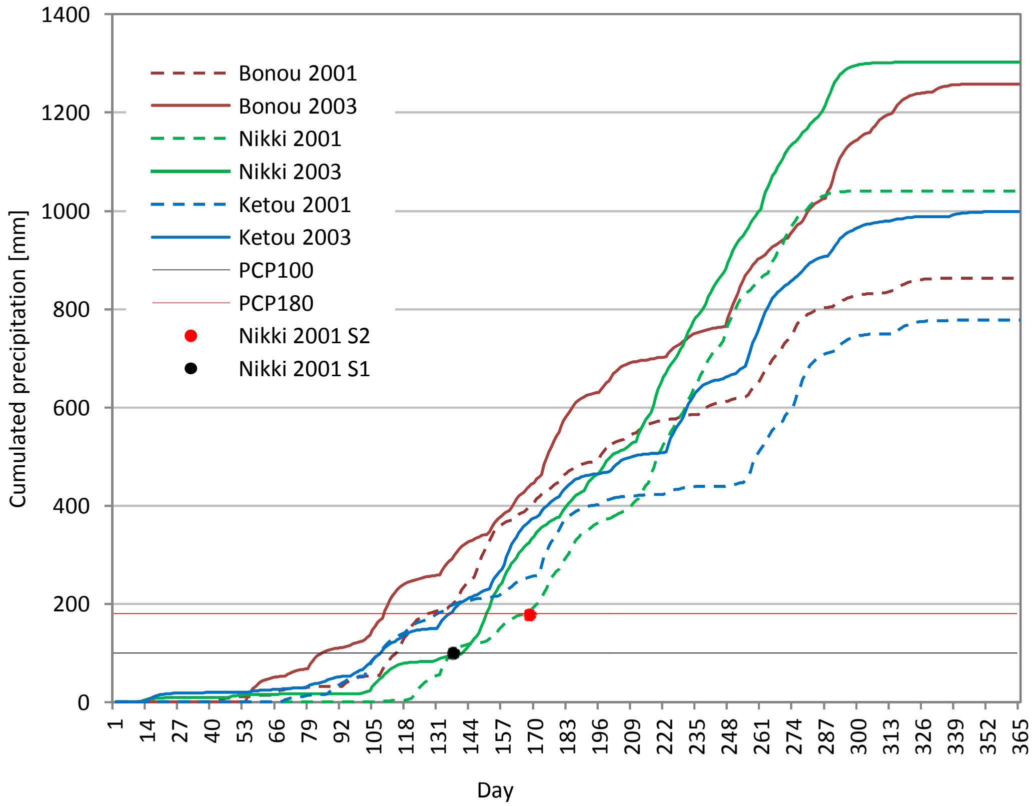

Figure 3. Rainfall distribution in 2001 and 2003 for the three communes Nikki, Ketou and Bonou. 100 and 180 mm cumulated rainfall are indicated by the black and red lines while the dots are examples indicating two different sowing dates in the dry year 2001 for the locality of Nikki.

Management scenarios

The most commonly used tools in the study area are the hoe and the machete (Bossa, 2012). Thus field preparation starts with cutting shrubs and bushes with machete, burning of trees and cleaning up with hoes depending on the season. Maize is grown with or without ridges and a spacing of 0.80 m is generally practiced for the ridges. From experience, the farmer often choose the best ridge orientation in order to significantly reduce losses of soil and nutrients and allow good water drainage of soils. Motor tractors are still rarely used by the farmers. Shifting cultivation is practiced (subsistence farming), consisting of cultivating the fields for a few years and leaving them for fallows in order to restore soil fertility. Agricultural inputs such as NPK and urea are currently at very low level but increasingly used for maize, cotton and rice. Mixed cropping practiced in the study area include yam-maize-okra, maize-cassava, maize-groundnut, maize-sorghum, or maize-cowpeas. Crop rotations are not very common in the cultural practices of farmers, since there is still enough potential cultivation spaces (due to relatively low population density in most parts of the Ouémé catchment). In this study crop associations and rotations are not considered.

EPIC requires a detailed description of management practices (Tan and Shibasaki, 2003). As common in Benin, the fertilizers NPK and Urea were specified in this study for maize production. Other variables were also specified: (1) the N and P element fractions of the total fertilizer applied to the soil surface, (2) the heat unit fraction for management operations, (3) tillage depth, (4) the mixing efficiency, etc. Heat unit may be defined as the accumulated number of daily temperature degrees above a certain threshold base temperature (needed to reach plant maturity), which varies among crop species. The mixing efficiency of the tillage implement defines the fraction of the residue, nutrients, and bacteria pool in each soil layer that is redistributed through the depth of soil that is mixed by the implement (Bossa et al., 2012). The scenarios used in this study were based on the current management practices to give a realistic representation of the current situation. Two management scenarios essentially based on tillage and fertilizer use were considered. In both scenarios soil plowing is made with the hoe once at 25 cm depth following by two consecutive maintenance tillages to 10 cm depth. These are respectively assigned in the model with mixing efficiencies of 0.5 and 0.25. The first scenario describes the most widespread situation based on tillage schedule without fertilizer use, while the second scenario took in addition the use of fertilizer NPK and urea with annual rates of 80 kg ha^{-1} (NKP) and 40 kg ha^{-1} (urea) at all simulated locations. These amounts of fertilizer were taken from Kuhn et al. (2010a).

To set the cultivation period, two different scenarios of sowing dates (PCP100 and PCP180) were derived from the dates for cumulated amounts of mean annual rainfall amounts accounting for percentages of 7 to 15%, relying on the literature (Ilesanmi, 1972). An earlier sowing date was fixed to the day after the rainfall event that resulted in a cumulative rainfall of 100 mm, counting from the first day of the year (Figure 3), whereas the later sowing was set to the day after a threshold of 180 mm.

To take into account the effects of the climate conditions and to highlight the high rainfall variability within the region, the established management scenarios as well as the sowing date

Table 4. Abiotic factors and soil fertility status for the simulated sites.

	Indicators	Soil type					
		Haplic Lixisol (Nikki)	**Eutric Gleysol (Nikki)**	**Eutric Vertisols (Ketou)**	**Ferric Acrisols (Ketou)**	**Luvic arenosol (Bonou)**	**Eutric Vertisol (Bonou)**
Potentiation factors	x_1= annual average precipitation (mm)	1	1	1	1	1	1
	x_2 = annual average temperature (°C)	1	1	1	1	1	1
	x_3 = level of gleization	0	2	5	0	5	5
	x_4 = level of pseudo-gleization	0	2	0	0	0	0
	x_5 = textural class, clay content of <2µm (%)	4	2	1	4	4	4
	x_6 = edaphic volume (%)	4	2	5	4	5	5
	x_7 = bulk density (g cm^{-3})	3	3	2	3	2	5
	x_8 = reaction pH_{H2O}	3	3	3	4	2	3
	x_9 = humus content (%)	2	2	2	2	2	1
	x_{10} = total nitrogen content (%)	4	5	5	5	5	5
	x_{11} = mobile phosphorus content (mg kg^{-1})	1	1	5	5	5	5
	x_{12} = mobile potassium content (mg kg^{-1})	4	4	3	3	3	3
Penality factors	y_1 = level of salinity	1	1	2	2	2	2
	y_2 = level of alkalization	0	0	1	1	1	1
	y_3 = level of carbonation	1	1	2	2	2	4
	y_4 = level of pollution	1	1	2	2	2	2
CIF		24	25	26	25	28	29
Fertility level		medium	medium	medium	medium	medium	medium

scenarios were combined with different soil conditions to simulate maize yield for the years with the highest/lowest annual rainfall amount observed for the period 2000 to 2009: (1) 2001 represents the reference dry year, and (2) 2003 the reference wet year. Figure 3 shows the rainfall distribution (cumulated amounts) for the reference years 2001 (dry) and 2003 (wet) for the three different locations investigated (Nikki, Ketou and Bonou).

RESULTS AND DISCUSSION

Variability of abiotic factors and fertility status for all investigated locations

As mentioned in model parameterization, soil parameters are combined with other abiotic factors such as the mean annual weather conditions to compute a complex indicator of fertility (CIF) (Lacatusu and Lacatusu, 2011), defined as the difference between the sum of potentiating indicators and the sum of the penalty indicators (Table 4). Fertility status was found medium at all investigated locations with slightly higher values for the South, mainly for the commune of Bonou showing a CIF of up to 28-29 against 24-25 for the North (Commune of Nikki). The fertility status in the commune of Ketou was found similar to that of Nikki with a very small advantage (CIF of 25-26). This already suggests a decreasing gradient in yield production from the South to the North. To answer the research questions we split the modeling results into four parts: (1) Combined effects of management options – sowing date scenarios – variable abiotic factors on maize yield production; (2) Water and nitrogen stress under dry and wet conditions for the reference period (2000 to 2009); (3) Impacts of scenario-based rainfall conditions on maize yield production under sowing date sensitivity; and (4) Water and nitrogen stress under scenario-based dry and wet conditions at decadal scale from 2010 to 2050.

Combined effects of management options – sowing date scenarios – variable abiotic factors on maize production under different rainfall conditions for the reference period 2000 – 2009

Figure 4 shows the combined effects of management options – sowing date scenarios – variable abiotic factors on maize yield production with associated uncertainty ranges. Significant differences of up to 800 kg ha^{-1} a^{-1} of

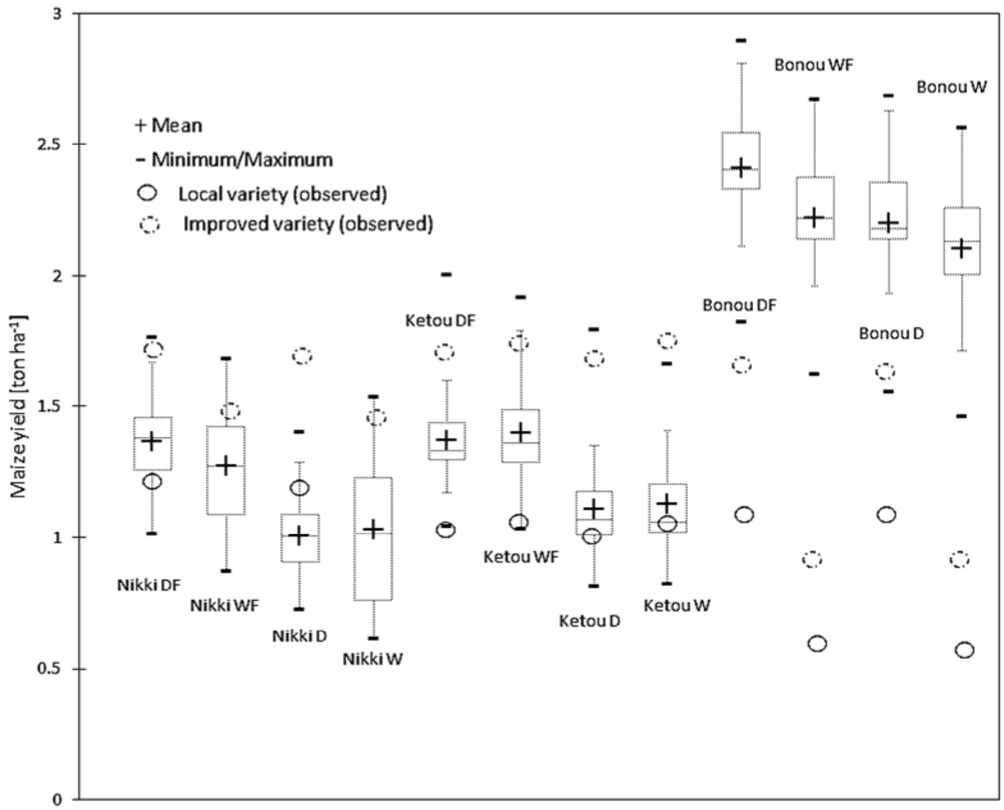

Figure 4. Box-wisker plots of the combined effects of management options – sowing date scenarios – variable abiotic factors on maize yield production under different rainfall conditions for all investigated communes (for the reference years 2001 and 2003). DF = dry condition + fertilizer, WF = wet condition + fertilizer, D = dry condition, W = wet condition. Local variety means a variety of maize grain traditionally cultivated in a given area. Improved variety means a maize grain variety that is experimentally selected to better fit to specific climate and soil conditions.

yield between the South (Bonou) and the North (Nikki) of the study area are indicated. Beyond catastrophic factors such as floods and pests the extreme yield productions are likely of about 500 to 1400 (±250) kg ha^{-1} a^{-1} in the North (Nikki) and 1100 to 2300 (±300) kg ha^{-1} a^{-1} in the South (Bonou). This is consistent with the soil fertility status, which is gradually higher in the South compared to the North. It is well known that the cultivation of maize is only possible by sufficient water availability (Zech and Hintermaier-Erhard, 2002). Given the fact that the simulations in Bonou included a Luvic Arenosol with also relatively high yield, it could be stated that moisture availability over the growing season as well as soil fertility were good in this region compared to the North. It can be seen from Table 4 that soil nitrogen and phosphorus indicators (x_{10} and x_{11}) are weak in the North (Nikki) compared to the South (Bonou) and this is critical for the most widespread soil type Haplic Lixisol (Table 4), which is already shown in many study as significantly affected by soil erosion (Bossa and Diekkrüger, 2012). This soil condition in the North does not allow optimal maize production. Similarly, it is not even the best soil condition for maize production in the locality of Bonou, since Vertisol was found to be not suitable for maize cultivation in the tropics (Zech and Hintermaier-Erhard, 2002). As also shown in Figure 4, the observed yields for the local as well as the improved maize variety are within the simulated ranges for Nikki and Ketou, but are much lower than simulated for Bonou. This is in contrast to the fertility status in the locality of Bonou and is due to the fact that most of the agricultural lands in this commune are located in the Deltaic flooding zone of the Ouémé River. Two different negative scenarios are often observed: (1) the growing processes are significantly inhibited by high water saturation of the soils leading to reduction of the harvested yield; and (2) the growing processes are perfect until crop maturity, but finally destroyed before the harvest. The farmers usually avoid the second scenario by arbitrarily anticipating the harvesting activities. This completely escapes the control of the competent services of the Ministry of Agriculture (MAEP) and reports are only based on the normal harvesting time. MAEP usually provide statistics only for mean seasonal yields at commune level, hiding high disparities/spatial variations.

The EPIC model is unfortunately unable to simulate this inhibition of the growing processes, since it is a field scale model that is not dynamically linked to upland hydrology. Although the simulated results for Bonou could not be directly validated by the observations, it could be at least explained.

Contrary to the finding of Kuhn et al. (2010), no correlation was found between the annual rainfall precipitation and the simulated yield. This is rather consistent with the statement of Gruber et al. (2009), who emphasize that the annual precipitation is not meaningful for evaluating the influence of rainfall on maize production. This can also be explained by the fact that the minimum amount of annual rainfall for maize of 500 mm (Lafitte, 2000) is reached in all simulation years and locations. Even the total amount of rainfall during the growing period was not correlated with the yield. Higher rainfall amount in the dry year (2001) is found for Nikki compared to the wet year 2003. Additionally, the intra-seasonal rainfall patterns over the growing season (June – July – August) in Nikki is characterized by an additional monthly rainfall amount of roughly 40 mm compared to the South (an example is shown in Figure 1). During the growing period Nikki recorded in mean about 270 mm more rainfall than Bonou, nevertheless the yield is higher in Bonou (calculations were based on the reference years 2001 and 2003). The arising question is whether this particular rainfall pattern (good water availability within the growing period) is negatively affecting the maize yield production at this location (Nikki). But this situation at least explained the higher variability in the yield obtained in Nikki compared to the others locations (Ketou and Bonou) (as shown in Figure 4). For analyzing crop production's dependence on available water, the investigation of the agronomic water availability is useful. It is an outcome of the meteorological water availability but also considers evapotranspiration, the groundwater table, as well as the water demand of plants (Dikau and Weichselgartner, 2005). Although the calculation is not simple, the EPIC model as used in this work was parameterized to account for that, even the modeled yield at this location (Nikki) are well validated by the observations as discussed in the previous paragraph and presented in Figure 4. From analyzing the management scenarios it can be concluded that even though the fertilizer amount used in the simulations are relatively low they resulted in higher yields in all communes (Figure 4). This is consistent with Kormawa et al. (2003). The amount of fertilizer was set equal for the three communes even if in the South the currently used amount is almost zero in many small farming systems. The use of fertilizer could help overcoming the problem of increasing land scarcity due to population growth and be an incentive for intensification instead of shifting agriculture (Kuhn et al., 2010a). "Higher productivity on existing farmland will reduce cultivation extension into forest or savannahs" (Angelsen and Kaimowitz, 2001). It could be assumed that as long as there is still new land available and fertilizer remains expensive, farmer would never invest in fertilizer use. This is already expressed with the theory of Boserup (1965).

Regardless the use of fertilizer the planting date is one of the most important factors influencing the maize production. As previously mentioned the sowing date determines the moisture availability through the growing season as well as the schedule of management practices such as tillage and fertilizer use. The sowing date scenarios contributed to the variability in the yield as displayed in Figure 4. This contribution can be better observed in Figure 5. The highest sensitivity is pointed out for Nikki. Higher yield production was in general associated with earlier sowing date and this was significantly pronounced in the wet years. It can be clearly seen from Figure 5 that sowing date influence maize yield by ± 500 kg ha^{-1} in Nikki, but only ± 100 kg ha^{-1} in Ketou and Bonou.

Water and nitrogen stress under dry and wet conditions for the reference period (2000 to 2009)

As indicated before, changes in plant growth limiting factors such as water stress and nitrogen stress were conjointly analyzed under different management options to account for not only the effects of rainfall variability, but also soil fertility status and pressure status on the land resources. The increasing gradient in the yield production from the South to the North can be once more explained with Figure 6 presenting water and nitrogen stress days and fraction of the total limiting factors.

It appears that nitrogen stress is clearly significantly higher than water stress by more than 50% over all regions. It can be assumed that the medium soil fertility pointed out all over the region is the main explanation. Specifically, high nitrogen stress is observed for Nikki and may be associated with the most widespread soil type Lixisols in the North. This is consistent with Table 4, showing a weak nitrogen indicator (xi_{10}) for Nikki compared to Ketou and Bonou. As mentioned before, there are studies (Bossa and Diekkrüger, 2012) that have clearly shown a strong link of soil erosion with this soil type. Even the use of fertilizer NPK and urea only reduce the stress by about 5% (Figure 6). It should be noticed that although the required total annual rainfall amount is met all over the study region (Lafitte, 2000), water stress was shown as the dominant limiting factor in the South, due to better soil fertility status (commune of Bonou) and the intra-seasonal rainfall pattern characterized by a relatively low rainfall amount over the growing period. This is not the case of the North (commune of Nikki) characterized by sever nitrogen stress, due to high sensitivity of soil resources to constant pressures leading to poorer soil fertility status with time. This is also due to intra-seasonal rainfall patterns characterized by an

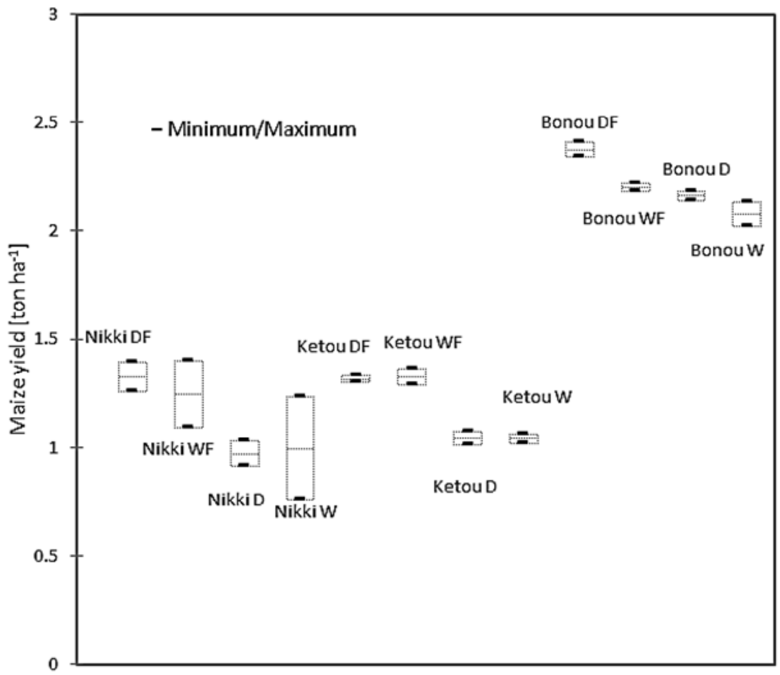

Figure 5. Sensitivity of the maize yield to sowing date in the three communes under different management scenarios (for the reference years 2001 and 2003). DF = dry condition + fertilizer, WF = wet condition + fertilizer, D = dry condition, W = wet condition.

additional monthly rainfall amount of roughly 40 mm compared to the South. It becomes clear that the heterogeneity in natural conditions (variability in the abiotic factors) influenced the yield all over the investigated communes and the use of fertilizer is more efficient in the North, due to higher nitrogen stress.

Impacts of scenario-based rainfall variability on maize yield production under sowing date sensitivity

The impacts of climate change on maize production until 2050 are presented in the Tables 5, 6 and 7 as well as Figure 7. Due to the contrasting differences up to here shown between the North and the South, only Bonou and Nikki were considered for the analysis. The figures show relative changes (in reference to the period 2000 to 2009) in the maize yield under rainfall variability (dry and wet years at decadal scale, based on the IPCC scenario-based A1B and B1) and different management options as well as different sowing date scenarios. An overall decreasing trend reaching -50% is indicated for maize production by 2050 due to climate changes. Two majors issues are pointed out in Nikki under the climate scenario A1B (Figure 7a): (1) combined effects of dry conditions in the scenario A1B and the early sowing date scenario PCP100 have resulted in a reduction of yield close to -50%, while (2) the combined effects of dry conditions in the same climate scenario A1B, fertilizer use and the late sowing date scenario PCP180 have resulted in a stable production level compared to the reference period 2000 to 2009. These are very contrasting results since it was clear on one hand that fertilizer has a positive effect on the production, and on the other hand that the early sowing date scenario PCP100 has also a positive effect on the production computed for the observed period 2000 to 2009. This is simply indicating an inversion of the situation for the future decades, where a rather late sowing date combined with fertilizer use should be the potential alternative to a stable production level. For climate scenario B1, two majors issues are pointed out in Nikki (Figure 7b): (1) combined effects of wet conditions in the scenario B1 and the early sowing date scenario PCP100 have resulted in a reduction of less than -30% and close to -50%, while (2) the combined effects of wet conditions in the same scenario B1, fertilizer use and the late sowing date scenario PCP180 have resulted in a stable production level (even more) as computed for the reference period 2000 to 2009. These are also very contrasting results that may have the same understanding as explained above in the case of the scenario A1B for the same location Nikki. It could be concluded from these analyses that with respect to the climate scenarios used (from 2010 to 2050), extremely low maize yields may be avoided if optimal sowing dates are chosen after an accumulated rainfall significantly

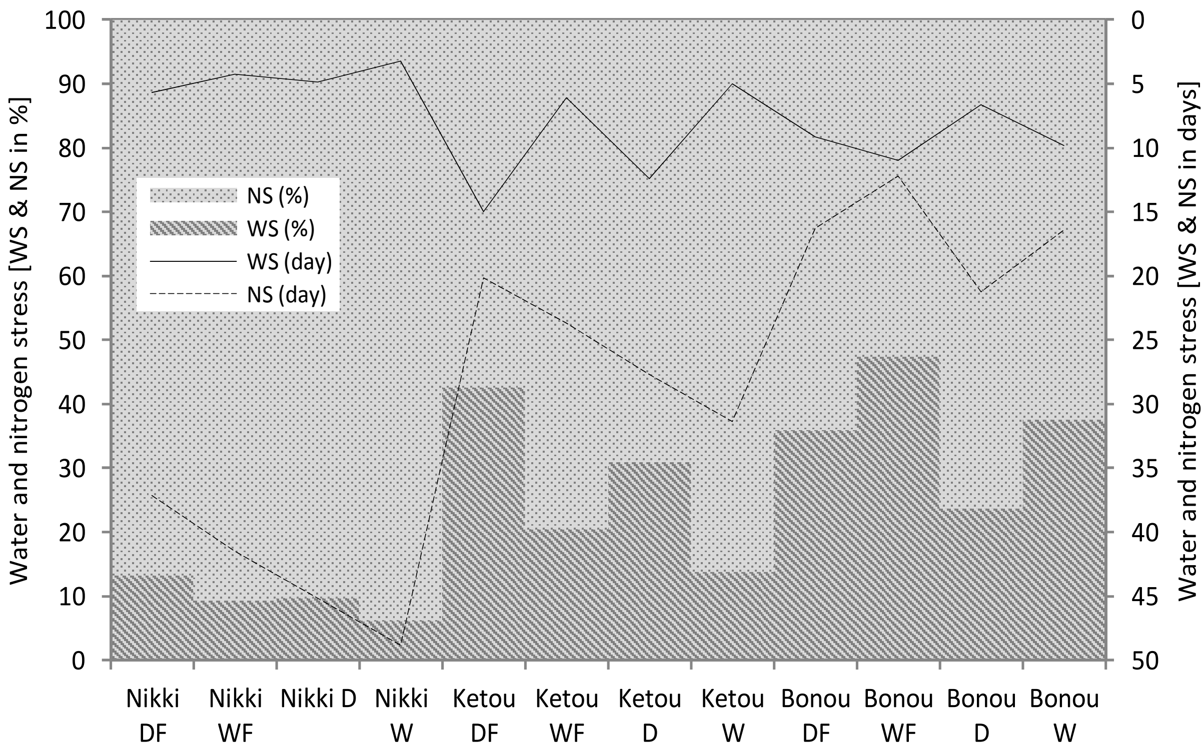

Figure 6. Water and nitrogen stress as percentages of total stress occurrences for all investigated communes under different management scenarios and different rainfall conditions (for the reference years 2001 and 2003). DF = dry condition + fertilizer.

more than 100 mm, regardless dry or wet conditions.

In Bonou, only the late sowing date scenario PCP180 was considered for investigating climate changes impacts on the yield production, since the sowing date impacts were previously found very weak. Generally, maize yield sensitivity to climate changes at this location is higher than found in Nikki. It could be seen that the yield production is almost insensitive to the type of climate scenarios (A1B and B1) as well as the fertilizer use option. Only dry and wet conditions have shown to impact the production either negatively or positively. This suggests that, with respect to the climate change scenarios, a stable or an increase yield compared to the period 2000 to 2009 can be reached in Bonou with increased moisture availability.

Water and nitrogen stress under scenario-based dry and wet conditions at decadal scale from 2010 -2050

Figure 8 presents the trend in the water and nitrogen stress for Bonou and Nikki under rainfall variability (climate change scenarios A1B and B1), sowing date scenarios (corresponding to cumulated rainfall more than 100 and 180 mm) and management scenarios (fertilizer use). This figure revealed an overall increase in water stress by 2050. This is critical for Bonou where more than 50% increase is shown, compared to Nikki (30%). Nitrogen stress in the North (resp. water stress in the South) is expected to reach 95 % (resp. 100%) of the total stress factors depending on the management options by 2050. High water stress is generally associated with the climate scenario A1B compared to the scenario B1. Moreover, higher water stress is associated with earlier sowing dates, while higher nitrogen stress is associated with the late sowing date (with respect to the climate scenarios over the period 2010 to 2050).

It could be seen that these results are consistent with the previous finding indicating that future sowing date should be shifted significantly towards a cumulated rainfall of 180 mm to avoid extremely low yield production, while reducing significantly water stress. It should be highlighted that this will offer a possibility to make efficient use of fertilizer. From field experiences, it is often observed that despite the use of high fertilizer amount the harvested yields are very low. These results clearly explained why. It is due to inadequate setting up (beginning) of the growing season. Under rainfall conditions (rainfed agriculture), inadequate beginning of the growing season may result in high water stress as dominant limiting factor, and this could not be unfortunately solved by putting high amount of fertilizer. Fertilizer can only lead to higher crop production when

Table 5. Simulated maize yields for Nikki (in tons ha^{-1}) under rainfall variability (climate change scenario A1B), sowing date scenarios (corresponding to cumulated rainfall of 100 mm and 180 mm) and management scenarios (fertilizer use). DF = dry condition + fertilizer, WF = wet condition + fertilizer, D = dry condition, W = wet condition.

Nikki [A1B]	2000-2009 [Reference]	2010-2019	2020-2029	2030-2039	2040-2049
W+PCP180+A1B	1.39	1.07	0.75	1.05	1.34
D+PCP100+A1B	1.40	1.18	1.25	1.10	1.06
W+F+PCP100+A1B	1.03	0.63	0.52	0.71	0.94
W+F+PCP180+A1B	1.23	0.76	0.77	0.67	0.72
W+F+PCP180+A1B	1.26	1.15	0.97	0.89	1.12
D+PCP100+A1B	1.09	1.11	1.08	1.13	1.04
D+F+PCP100+A1B	0.91	0.66	0.54	0.56	0.68
D+PCP180+A1B	0.76	0.65	0.64	0.63	0.62

Table 6. Simulated maize yields for Nikki (in ton ha^{-1}) under rainfall variability (climate change scenario B1), sowing date scenarios (corresponding to cumulated rainfall of 100 mm and 180 mm) and management scenarios (fertilizer use). DF = dry condition + fertilizer, WF = wet condition + fertilizer, D = dry condition, W = wet condition.

Nikki [B1]	2000-2009 [Reference]	2010-2019	2020-2029	2030-2039	2040-2049
D+PCP180+B1	1.39	1.39	1.12	0.90	0.97
D+PCP100+B1	1.40	1.31	1.22	1.17	1.14
D+F+PCP180+B1	1.03	0.91	0.69	0.63	0.63
D+F+PCP100+B1	1.23	0.88	0.68	0.81	0.67
W+PCP100+B1	1.26	1.21	1.21	0.99	1.08
W+F+PCP180+B1	1.09	1.08	1.04	1.00	1.22
W+PCP180+B1	0.91	0.69	0.75	0.61	0.67
W+F+PCP100+B1	0.76	0.67	0.60	0.61	0.63

Table 7. Simulated maize yields for Bonou (in ton ha^{-1}) under rainfall variability (climate change scenarios A1B and B1), sowing date corresponding to cumulated rainfall 180 mm and management scenarios (fertilizer use). DF = dry condition + fertilizer, WF = wet condition + fertilizer, D = dry condition, W = wet condition.

Bonou [A1B & B1]	2000-2009 [Reference]	2010-2019	2020-2029	2030-2039	2040-2049
D+PCP180+B1	2.34	1.22	1.46	1.41	1.30
D+PCP180+A1B	2.18	1.77	1.72	1.29	1.29
D+F+PCP180+B1	2.14	1.20	1.39	1.30	1.23
D+F+PCP180+A1B	2.02	1.64	1.55	1.29	1.22
W+PCP180+A1B	2.34	1.61	1.57	1.33	1.48
W+F+PCP180+B1	2.18	2.01	1.59	1.11	1.70
W+PCP180+B1	2.14	1.53	1.46	1.25	1.41
W+F+PCP180+A1B	2.02	1.67	1.50	1.07	1.53

soil fertility constrains the crop growth. Considering the fact that land resources are becoming scarce with significant reductions of shifting agriculture or fallow systems, efficient use of fertilizer (regardless the types) will be the potential alternatives for farmers in Benin to secure the food production in the future.

One can conclude by stating that with respect to the climate scenarios, possibilities are clearly offered to Benin to successfully deal with food security in the future (by 2050) by increasing or at least keeping stable the rainfed maize production. As a relatively low fertilizer amounts are currently used in the country (compared to rainfall of 100 mm towards sowing dates corresponding to 180 mm (cumulated rainfall) can be combined with increasing rate of fertilizer to enhance maize production.

Conclusion

On the global scale, climate change will influence the

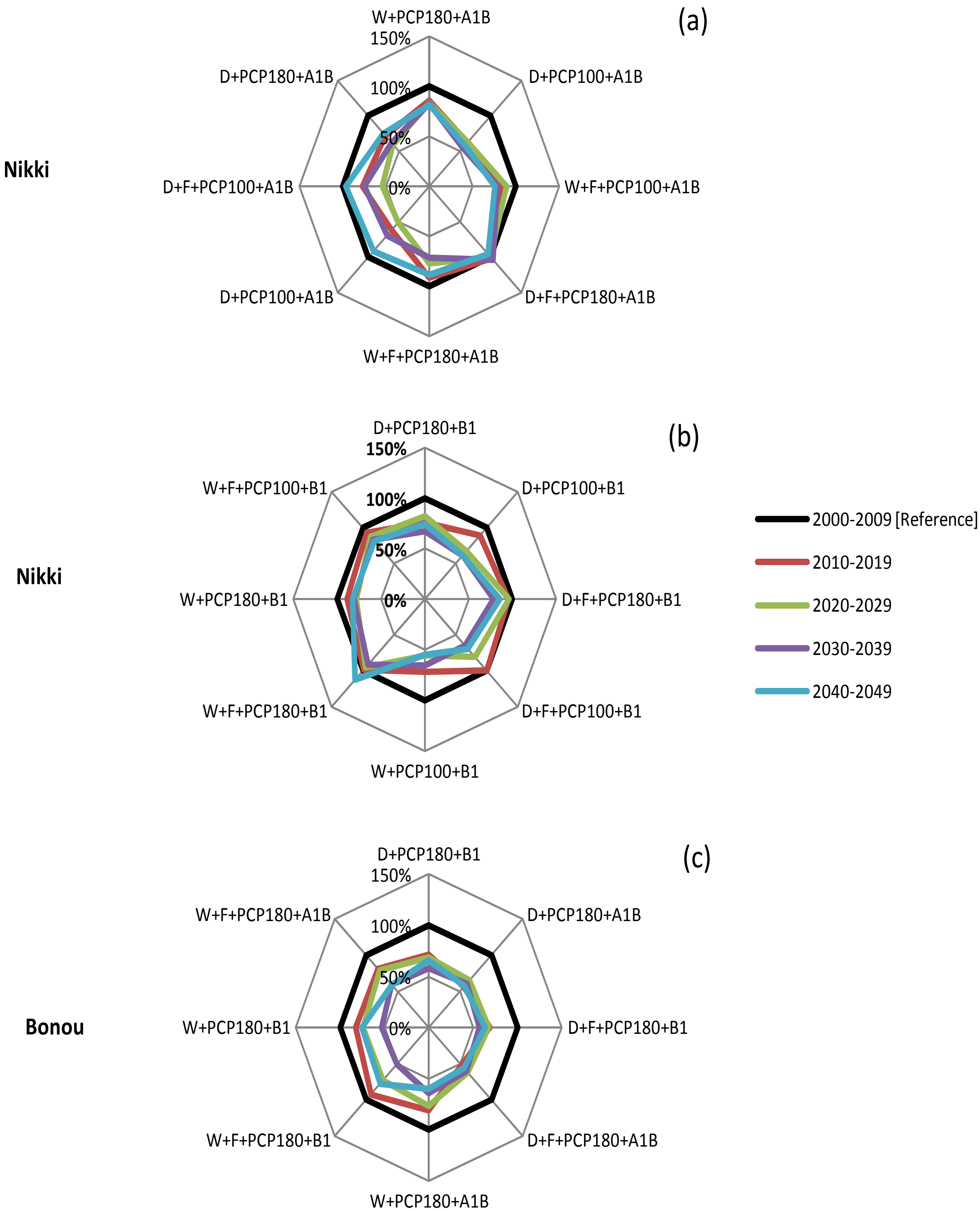

Figure 7. Simulated relative changes in maize yields for Bonou (referring to the period 2000 to 2009) under rainfall variability, sowing date corresponding to cumulated rainfall of 180 mm and management scenarios (fertilizer use). (a): climate change scenario A1B, (b): climate change scenario B1, (c): climate change scenario A1B and B1. DF = dry condition + fertilizer, WF = wet condition + fertilizer, D = dry condition, W = wet condition.

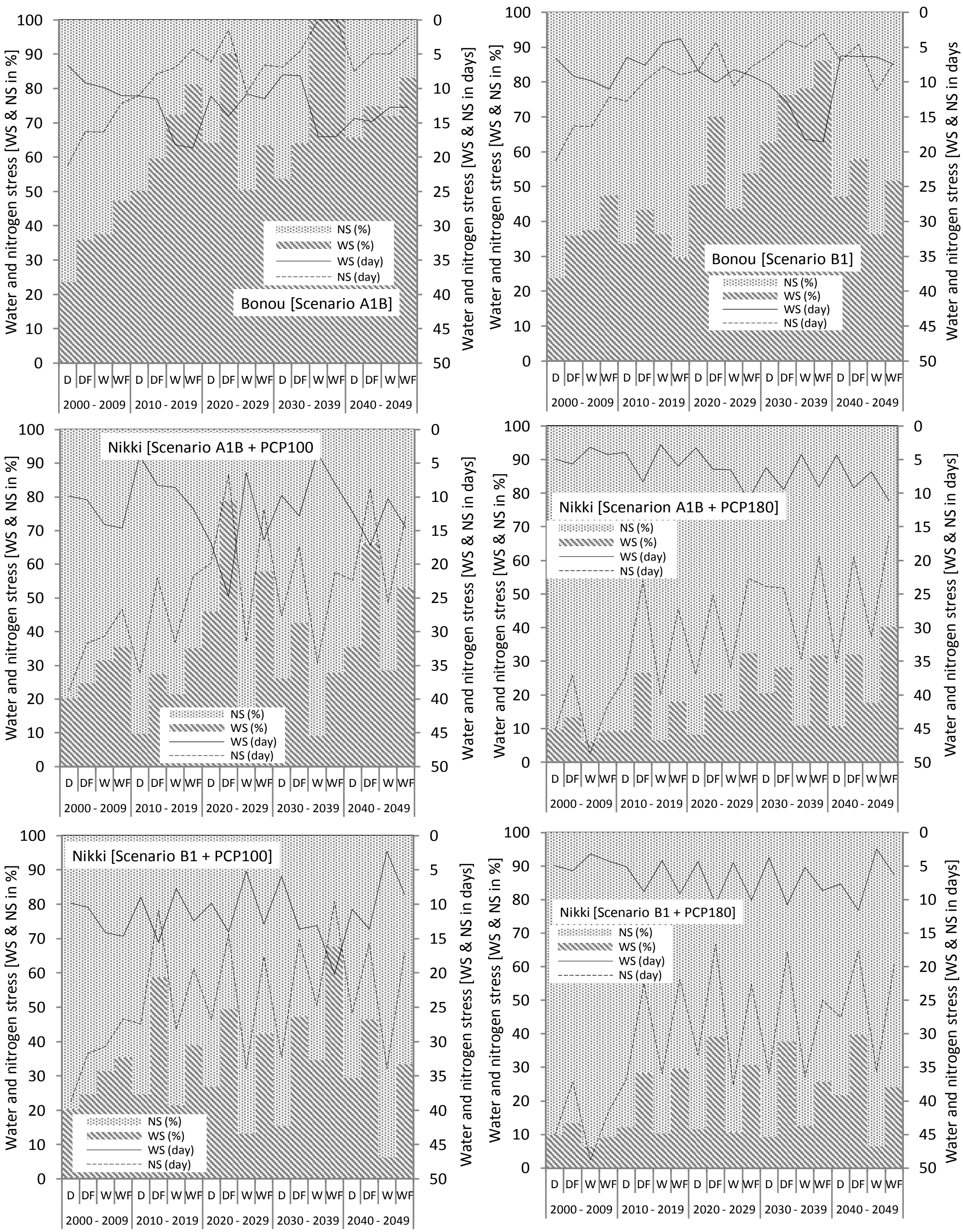

Figure 8. Water and nitrogen stress for Bonou and Nikki under rainfall variability (climate change scenarios A1B and B1), sowing date scenarios (corresponding to cumulated rainfall of 100 and 180 mm) and management scenarios (fertilizer use). DF = dry condition + fertilizer, WF = wet condition + fertilizer, D = dry condition, W = wet condition.

food situation (FAO, 2008; Kang et al., 2009). The high dependency of agricultural production on climate conditions has a negative effect on food production and increasing food prices lead to a more difficult access to other West African countries or Western countries), shifting the sowing dates corresponding to a cumulated food. West African countries including Benin are highly dependent on rainfed agriculture. Up to date a stable yield production at a low level is mainly the results of shifting agriculture based on fallow systems and inefficient fertilizer uses (Igué, 2000). Facing with increasing food demands as well as with increasing dry spells during the rainy season (Christoph et al., 2008), relevant issues are specific adaptation and resilience measures under different sub-regional conditions. This study successfully analyzed effects of different soil conditions, management options, different sowing dates and climate change conditions on maize production at different sub-regional scales in Benin. Occurrences of plant growth limiting factors such as water and nitrogen stress were successfully linked to spatial/intra-seasonal rainfall pattern and pressures on land resources.

The EPIC model (Williams et al., 1989) has been successfully applied at three different locations (from the South to the North of the Ouémé catchment, 50,000 km², Benin) with contrasting rainfall patterns, different edaphic conditions and fertility status. Contrary to the finding of Kuhn et al. (2010), no correlation was found between the annual rainfall precipitation and the simulated yield. This was found rather consistent with Gruber et al. (2009) as well as Lafitte (2000) pointing out a minimum annual rainfall of 500 mm for maize production, which is always met in the simulated years and locations considered in the study. Because the growing period in the North usually records in average 200 mm of rainfall more than the South, nitrogen stress is currently the limiting factor in the North in opposite to the South where water stress was revealed as the dominant limiting factor. This was in agreement with the significantly higher yields simulated for the South as response to favorable fertility conditions.

The impact of climate change on maize production under IPCC scenarios A1B and B1 specified for Benin (2010 to 2050) does not result in a dramatic or non-manageable situation. Higher yields were associated with the late sowing dates in opposite to the reference period (2000 to 2009) where higher yield were associated with the early sowing dates. An overall increase in the water stress of up to 50% was shown in all considered sub-regions. Higher water stress was associated with earlier sowing date, while higher nitrogen stress was associated with the late sowing date. Although a decrease of maize production of up to 50% may be caused by climate change, this study has indicated potential management options to keep stable or even increase the maize production. Therefore, shifting towards late sowing dates corresponding to a cumulated rainfall of 180 mm may reduce water stress and make efficient fertilizer use. It has to be mentioned that the impact of sowing dates on the maize yield were within the same magnitudes of that of climate changes. One can conclude that the current study has demonstrated the importance of having a differentiated regard on the various factors affecting maize production in Benin to specific adaptations and management strategies at regional scale.

Conflict of Interest

The authors have not declared any conflict of interest.

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