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Review

Spatial and temporal analysis of maize (*Zea mays*) crop yields in Benin from 1987 to 2007

Arcadius Y.J. Akossou[a,*], Eloi Y. Attakpa[b], Noël H. Fonton[c], Brice Sinsin[d], Roel H. Bosma[e]

[a] Département d'Aménagement et de Gestion des Ressources Naturelles, Faculté d'Agronomie, Université de Parakou, BP 123, Parakou, Benin
[b] Département de Production Animale, Faculté d'Agronomie, Université de Parakou, BP 123, Parakou, Benin
[c] Laboratory of Study and Research in Applied Statistics and Biometrics, University of Abomey-Calavi, BP 526, Cotonou, Benin
[d] Laboratoire d'Ecologie Appliquée, Faculté des Sciences Agronomiques, Université d'Abomey-Calavi, BP 526, Cotonou, Benin
[e] Animal Sciences Group, Wageningen University, P.O. Box 338, 6700 AH, The Netherlands

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ABSTRACT

Maize represents the main food crop and grows in all agro-ecological zones in Benin. Various technologies were introduced to increase its yield; the impact of these technologies can be assessed through a spatio-temporal analysis of the yields. Thereto, the record of yields from 1987 to 2007 of 77 agriculture districts was collected. The spatial analysis showed that there is a variation among the yields of the eight different agro-ecological zones of Benin. In most zones, the yields show an increasing annual trend fitting to an exponential smoothing model. However, yields are relatively low and highly variable due to several factors. Climatic factors, in particular the quantity of rain during the periods of full vegetative growth (May in the south, and July and August in the north), explained 15–77% of the interannual yield variations. The effect of rainfall was highest in the most northern and the south-west zones having a monomodel and bimodal rainy season, respectively, and where maize is not the main crop. In the central cotton-growing zones the effect of the preceding year on the maize yield was strong due to manuring of the cotton. In general, the increase of yields is due in particular to the adoption of new agricultural practices (application of organic matter, fertilizers, number and period of weeding). Estimations of crop yields and impact of climate change on crop yields, as well as the analysis of adaptations in response of climate changes, should consider the spatio-temporal variations and the impact of new technologies.

Contents

* Corresponding author.
E-mail addresses: sakos90@hotmail.com (A.Y.J. Akossou), attakpayae@yahoo.fr (E.Y. Attakpa), hnfonton@gmail.com (N.H. Fonton), brice.sinsin@uac.bj (B. Sinsin), roel.bosma@wur.nl (R.H. Bosma).

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1. Introduction

Economic growth of most countries in Sub-Sahara Africa (SSA) has relied on agricultural production and has remained as the main source of wealth for its residents. West African agricultural production has recorded a remarkable increase in the last twenty-five years (Soulé and Gansari, 2010; FARM,[1] 2008). The volume of so-called cash-crops (cocoa, cotton, coffee, pineapple, cashew nuts, and palm oil) increased from 19 million tons in 1980 to 38 million tons in 2006, representing a 100% increase. The volume of all food crops (cereals, roots and tubers, pulses and vegetable) increased with a factor 3.5 from 59 million tons in 1980 to 212 million tons in 2006. The volume of cereals increased with a factor 3, from 16 million tons in 1980 to 49 million tons in 2006, and reached the threshold of 52 million tons in 2009 (CILSS,[2] 2009).

In Benin, the agricultural sector earns about 35% of GDP, provides 75% of export income, and employs 70% of the workforce (PAM,[3] 2014). About 3.2 million people, consisting of 51% women, are involved in agriculture. Almost every farmer practices mixed farming, although many mono-crop plantations can be found in the southern agro-ecological zones of Benin (Fig. 1). Exports are dominated by cotton whose future is threatened by the price reductions on the international market, while food crops are dominated by cereals. To ensure food security and reduce poverty, researchers have developed new technologies to improve the productivity of the crops. These technologies concern fertilizer application, crop improvement and disease control. The use of mineral fertilizer to rehabilitate and maintain soil fertility was recommended. However, RAMR[4] (1989) noted that mineral fertilizer would be economically viable only when it is combined with the techniques on organic amendment, and proposed a technology using less mineral fertilizer. Thus, alley cropping of *Leucaena leucocephala* and *Gliricidia* sp., and fallows of *Mucuna utilis* and *Acacia auriculiformis* were introduced. Along with fertilizer application trials, several improved varieties of maize have been tested since 1986. Overall, field research on resistance to diseases and pests showed that local varieties are more resistant to pests than improved varieties (Fanou, 1990; Abadassi, 2001; Agbaka et al., 2005). Similarly, in 1989–1998, the Sasakawa Global 2000 project introduced new technological packages to improve yield of maize production. These packages included the introduction of (1) the maize-streak-virus resistant open-pollinated variety, (2) sowing on line with higher density, (3) a timetable for weeding and use of 150 kg/ha of fertilizer. In addition, complementary technologies have been introduced to protect soil and restore fertility, particularly in southern Benin. The latter technologies involve the use of leguminous plants in the cropping plan, like the use of velvet bean to fight infestations of *Imperata cilindrica* and restore soil fertility.

The objective of this study is to analyze the spatio-temporal changes of maize yields and measure the impact of these technologies between 1987 and 2007. Maize is the main food crop and a staple food of the Beninese population. Maize production has grown remarkably over the last twenty years. The volume of production surpassed the 800,000 tons in 2008 and reached to one million tons in 2009 (CILLS, 2009). Long confined to the southern areas, the production of this cereal has extended to areas producing cotton, particularly in northern regions. However, this increasing trend might be stopped or reversed by climate change. Maize is the only cereal that provides the country a surplus for export to neighboring countries such as Niger (PRESAO,[5] 2011). Its role in the nutrition of the people of West Africa in general and Benin in particular, has increased significantly over the past four decades (CILLS, 2009). Accordingly, research to improve yield potential plays an important role in agricultural programs; one of the major advances has been the development of early and extra early varieties of maize, together with the associated agronomic practices. The availability of these varieties has not only helped open new frontiers for the production of maize but also helped reduce lean periods in the savannah. The rate of adoption of improved early and extra early varieties of maize in the savannah zone is beyond expectations and these varieties have revolutionized the production of maize in West and Central Africa (Hartmann, 2005).

In Benin, most studies on maize focused on assessment of genetic potential, doses of fertilizers, adaptability to tropical conditions (characterized by deficiencies in certain minerals), biological pesticides, and so on (e.g. Abadassi, 2001; Fanou, 1990; Galiba, 1994; Igue et al., 2013; PRESAO, 2011; RAMR, 1989), but none analyzed the spatio-temporal information throughout Benin. Analysis of this spatio-temporal knowledge on the changing crop yield may provide information which the producers and the policy makers can use for their decision-making. Knowledge on the spatial and temporal variation in yields is important also for researchers in predicting impact from climate change or in addressing the need for adaptation. With the goal to improve the model used to predict the future yield, this paper analyses the fit of models simulating the past yields, and presents and discusses the trends in the spatio-temporal variation of maize yield in Benin.

2. Materials and methods

2.1. General information on Benin

The Republic of Benin extends over an area of 114,763 km^2 of which 63% is arable land. About 70% of the population is engaged in agricultural and related activities. Administratively, Benin has twelve departments divided into 77 districts, including three cities with special status (Cotonou, Porto-Novo and Parakou).

The rainfall varies between 850 and 1300 mm. The extreme north and southwest are areas where the mean annual rainfall is less abundant (850–900 mm). The coastal regions benefit from a bimodal rainfall pattern (rainy seasons in March–July and September–November), while the northern regions have a monomodal rainfall pattern (single rain season from May to October). From November to February a dry wind from the north (harmattan), sometimes carrying dust blows over the country; the harmattan is felt in particular in the northern parts of the country.

[1] FARM, Fondation pour l'agriculture et la Ruralité dans le Monde.
[2] CILSS, Comité Permanent Inter-Etats de Lutte contre la Sécheresse dans le Sahel.
[3] PAM, Programme Mondial pour l'Alimentation.
[4] RAMR, Recherche Appliquée en Milieu Réel.
[5] PRESAO, Programme de Renforcement et de Recherche sur la Sécurité Alimentaire en Afrique de l'Ouest.

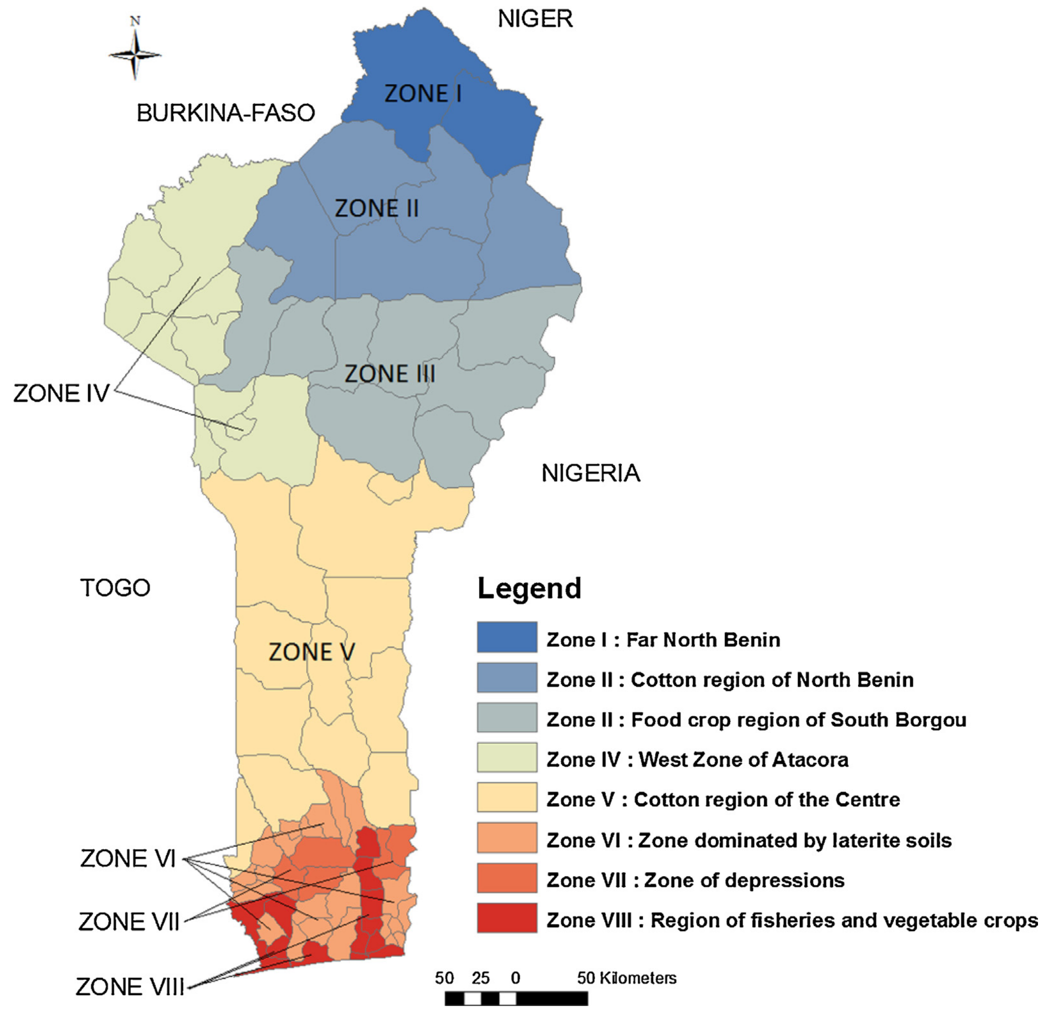

Fig. 1. The distribution of the agro-ecological zones of Benin.

Adapted from SIG – DPP/MAEP (2001).

Based upon climatic factors, soil type, elevation, hydrology and different crops grown, the MDR[6] in Benin (1998) defined eight agro-ecological zones (Fig. 1; Table 1). The main soil types are: coastal sandy soils, occupied mostly by coconut trees; lateritic soils in the south frequently covered with oil palms associated with maize, cassava, groundnuts, cowpeas and others; gray and leached ferruginous soils, in central and northern parts of the country, which are well suited to e.g. maize, cassava, groundnuts, vouandzou, sorghum, millet and cowpea.

2.2. Data collection

Agronomic data were obtained from annual reports published by the Ministry of Agriculture, Livestock and Fisheries. These data cover the crop years from 1987 to 2007 for all 77 districts of Benin. The yield per year in each district was calculated by dividing the total production by the total cultivated area. Originally the total production mentioned in the reports was obtained by multiplying the number of ha cultivated by the average of yields measured in a sample of fields of known size. This yield represents an average yield of all cultivars of maize in Benin. As for the yield of each agro-ecological zone, it is obtained by averaging the yields of the included districts (Table 1).

The monthly weather data for the period were acquired from the Agency for the Safety of Air Navigation. These data come from the six synoptic stations of Benin (located in the districts of Cotonou, Bohicon, Kandi, Natitingou, Parakou and Savè) and from the Central Station of Agricultural Research on Perennial Plants. The monthly data included 8 variables: rainfall, average temperature, minimum temperature, maximum temperature, average humidity, minimum humidity, maximum humidity and evapotranspiration. Meteorological data for each district and each agro-ecological zone were determined by using data from weather stations in this zone. In contrast, if the area does not have weather station, an estimate was made by using either the data from the nearest meteorological station, or by calculating by year and by month, for each climate parameter, the average of the data obtained in the closest weather stations. For example, data from zone I were estimated by using those from zone II, while those from zone VI were estimated from the average of data from the Cotonou and Bohicon stations.

2.3. Statistical analysis

The spatial distribution of yields was analyzed by making a map of yield trends for each district by five years. The trends noted

[6] MDR, Ministère du Développement Rural.

Table 1
Administrative coverage, main crops and main ecological characteristics of the agro-ecological zones of Benin.

Zone	Districts covered	Major speculation	Rain pattern	Soil type	Climate	Vegetation
Zone I: Far North Benin	Karimama and Malanville	Millet, sorghum, cotton, maize, rice, onion, potato and vegetable crops along the Niger River	Mono-modal	Ferruginous soils on crystalline basement, very fertile alluvial soils of the River Niger, clayey, loamy black shallows and fertile swamps	Sudano-Sahelian	Shrub savannah (baobab, locust bean, shea butter), galleries forestry; high vegetation degradation due to bush fires
Zone II: Cotton region of North Benin	Sègbana, Gogounou, Banikoara, Kandi, Kérou	Sorghum, maize, yams, cotton	Mono-modal	Ferruginous soils on crystalline basement	Sudano-Sahelian	Shrub savannah
Zone III: Food crop region of South Borgou	N'Dali, Nikki, Kalalé, Sinendé, Pèrèrè, Pehunco, Bembèrèkè and Kouandé	Yam, cotton, maize and cashew	Mono-modal	Ferruginous soils on crystalline basement	Sudanian	Shrub savannah with a dominance of Butyrospermum paradoxa (shea-butter) species
Zone IV: West Zone of Atacora	Cobly, Ouaké, Boukombé, Tanguiéta, Matéri, Natitingou, Djougou, Toucountouna and Copargo	Cereals in the north of the zone and yam in the southern part	Mono-modal	Ferro sol with a deep base and poor water reserve	Sudanian and tends toward the dry savannah with an irregular and fluctuating rainfall pattern	Savannah, bushland, or grassland threatened by degradation of bush fires and population pressure
Zone V: Cotton region of the Centre	Bassila, Parakou, Tchaourou, Ouessè, Bantè, Savè, Savalou, Glazoué, Kétou, Djidja, Dassa and Aplahoué	Cereals, tubers, pulses and cotton	Mono-modal	Ferruginous tropical soils; more or less leached soils concretions; sandy soil, sandy clay soil; and hydromorphic black soils in the valleys	Guinea savannah with a high rainfall pattern (1100–1400 mm per year)	Reserved forests threatened by man, teak and cashew trees plantations, shrub savannah, gallery forest; Advanced degradation of vegetation
Zone VI: Zone dominated by laterite soils	Abomey-Calavi, Allada, Kpomassè, Tori-Bossito, Zè, Djakotomé, Dogbo, Klouékanmey, Houéyogbé, Toviklin, Adjarra, Ifangni, Avrankou, Porto-Novo, Akpro-Missrété, Sakété, Abomey, Agbangnizoun, Bohicon, Covè, Zakpota and Zagnanado	Maize head rotation, cassava, cowpea and groundnut	Bi-modal	The soil is hard pan profoundly degraded and easy to work on	Tropical guinean	Relics of forest
Zone VII: Zone of depressions	Adja-Ouèrè, Pobè, Toffo, Lalo and Zogbodomey	Maize associated with cassava, cowpea, tomato, pepper, etc.	Bi-modal	Humid and deep clayey soil is fertile but often hydromorphic and difficult to work on	Tropical guinean	Relics of forest
Zone VIII: Region of fisheries and vegetables.	Athiémé, Grand-Popo, Bopa, Comé, Lokossa, Ouidah, So-Ava, Sèmè-Kpodji, Aguégués, Dangbo, Adjohoun, Bonou, Ouinhi and Cotonou	Mainly fisheries and maize rotation with cassava and cowpea	Bi-modal	Alluvial soil is very fertile, the sandy soil of the Littoral is marginally fertile.	Tropical guinean	Vegetation consists of grassland, grassland and swamp formations, mangroves and gallery forests.

were studied by establishing empirical models. The approach is described as follows. Suppose that the general yields model is defined by the relation:

$$y_t = f_1(t) + f_2(m) + e_t$$

In which y_t is the yield at year t, $f_1(t)$ is the component related to the general trend, $f_2(m)$ is the component related to weather and ε_t the random component.

The first approach that was used to determine the general trend $f_1(t)$ of yield, was to fit the data to a single equation for the whole series by classical linear regression: $y_t = y_0 + bt$ (in which y_0 and b were constants). The data for the dependent variables y_t were transformed by using the Box–Cox transformation (Box and Cox, 1964) in order to find the best model. In Box–Cox procedure, the original variable y_t is transformed to y_t^{λ}. The Lambda value (λ) indicates the power to which all data should be raised. In order to do this, the Box–Cox transformation searches from $\lambda = -2$ to $\lambda = +2$ until the best value is found.

The second approach is based on time series methods: the exponential smoothing and the autoregressive integrated moving average (ARIMA) (Box and Jenkins, 1976). An ARIMA model is noted as ARIMA (p, d, q), in which p is the number of autoregressive terms, d is the number of differentiations, and q the number of moving average terms.

The technique of exponential smoothing is a special case associated with ARIMA forecasts. The methods used are simple exponential smoothing, double exponential smoothing of Holt (1957) and double exponential smoothing of Brown (1956). The difference between Holt's and Brown's approach is that the latter uses only one smoothing constant and that the estimated trend values are very sensitive to random influences. Unlike Brown's technique, more flexibility is given by Holt's technique in selecting the smoothing constant rates (Makridakis et al., 1998).

Given a time series y_t, $t = 1, 2, \ldots, T$, the additive smoothing model is of the form:

$$y_t = \mu_t + \gamma_t t + S_{t,p} + a_t$$

where μ_t represents the time-varying mean (level) term, γ_t represents the time-varying slope term (called "trend" term by exponential smoothers), $S_{t,p}$ denotes the time-varying seasonal term for the p seasons ($p = 1, 2, \ldots, P$) in the year, and a_t is a residual error term (in previous model it is equivalent to $a_t = f_2(m) + e_t$. For smoothing models without trend, we used and $\gamma_t = 0$ for all t, and for smoothing models without seasonal effects, which is the case of the present study, $S_{t,p} = 0$ for all p. At each time period t, each of the above time-varying components (μ_t, γ_t, $S_{t,p}$) are estimated by means of so-called smoothing equations. By way of notation, let L_t be the smoothed level that estimates μ_t, T_t be the smoothed slope that estimates γ_t, and the smoothed seasonal factor S_t estimates the seasonal effect $S_{t,p}$, at time t.

A simple exponential smoothing model should be used when the time series data has no trend and no seasonality. The simple exponential smoothing model is given by the model equation:

$$y_t = \mu_t + a_t$$

The smoothing equation is $L_t = \alpha y_t + (1 - \alpha)L_{t-1}$, where L_t is the forecast value of yield for next period at time t; L_{t-1} is theactual yield at time $t - 1$; α is the smoothing constant ($0 < \alpha < 1$). Values of α close to one have less of a smoothing effect and give greater weight to recent changes in the data, while values of α closer to zero have a greater smoothing effect and are less responsive to recent changes. For each series of yields the value of α was used, which gave the model with a minimum mean square error (MSE). The h-step-ahead prediction equation is $\hat{y}_{t+h} = L_t$, $h = 1, 2, \ldots$ i.e., y at h-steps ahead will be forecast by using the last available estimated (smoothed) level state. The ARIMA model equivalent to the simple exponential smoothing model is the ARIMA (0,1,1) model: $(1 - B)y_t = (1 - \theta B)a_t$, where $\theta = (1 - \alpha)$, and B represents the backshift operator such that for any given time series $x_t : B^r x_t = x_{t-r}$.

A double exponential smoothing model should be used when the time series data have a trend but no seasonality. The Double exponential smoothing model of Brown is given by the model equation: $y_t = \mu_t + \gamma_t t + a_t$. The actual smoothing equation is:

$$L_t = \alpha y_t + (1 - \alpha)L_{t-1}$$

$$L'_t = L'_{t-1} + \alpha(L_t - L'_{t-1})$$

$$C_t = L_t + (L_t - L'_{t-1})$$

$$T_t = \left[\frac{(1 - \alpha)}{\alpha}\right](L_t - L'_{t-1})$$

$$\hat{y}_{t+h} = C_t + hT_t$$

where L_t is the single exponential smoothing series at time t; α is the smoothing constant ($0 < \alpha < 1$); y_t is the actual yield at time t; L'_t is the double exponential smoothing series at time t; C_t is the intercept of the L' forecast series at time t; T_t is the slope of the L' forecast series at time t; $\hat{y}_{t+h}$ is the forecast yield at time $t + h$; h is the number of time periods ahead (Brown, 1956).

Holt's two-parameter method is one kind of exponential smoothing technique frequently used to handle a linear trend. The trend and slope can be smoothed by this technique through using different smoothing constants for each. The smoothing equation is:

$$L_t = \alpha y_t + (1 - \alpha)[L_{t-1} + T_{t-1}]$$

$$T_t = \gamma[L_t - L_{t-1}] + (1 - \gamma)T_{t-1}$$

$$\hat{y}_{t+h} = L_t + hT_t$$

In which L_t is the new smoothed value; α is the smoothing constant for the data ($0 \le \alpha \le 1$); y_t is the new observation or actual value of series in period t; γ is the smoothing constant for estimating the trend ($0 \le \gamma \le 1$); T_t is the trend estimate in period t; h is the periods to be forecast; $\hat{y}_{t+h}$ is the forecast for h periods into the future (Holt, 1957).

The effects of agro-ecological zone and climatic conditions were evaluated by using the Analysis of Variance (ANOVA) to compare the average yields of different agro-ecological zones. The Newman–Keuls test (Student, 1927; Newman, 1939; Keuls, 1952) which is a stepwise multiple comparison procedure was used to identify sample means that are significantly different from each other. Stepwise regression was used to assess the effect of climate after eliminating the effect on the trend. The latter is done by modeling the quantity a_t according to climate data using: $a_t = f_2(m) + e_t$. Thereto the classical method of least squares with the stepwise selection method of variables is used. The selection of variables is based on the test F of Snedecor for significance of the regression coefficients. The same level of significance was used for the introduction and the exclusion of a variable in the model.

In order to coincide weather data with the period of maize culture, monthly data from March to November were used to measure the effects of climatic factors on yields.

2.4. Criteria for evaluating models

The best general trend models are those minimizing the normalized Bayesian information criterion (BIC normalized) (Schwarz, 1978):

$$\text{Normalized BIC} = \ln(\text{MSE}) + k\ln(n)/n$$

in which $\text{MSE} = \sum (y_t = \hat{y}_t)^2/(n - k)$ is the mean square error, k is the number of parameter estimated and n is the number of observations. This criterion has the advantage of penalizing models where the parameters are redundant compared to the Akaike criterion (AIC) (Akaike, 1973).

To test if the autocorrelations of residuals are different from zero, we used the Ljung–Box Q test (Ljung and Box, 1978), which can be defined as follows:

H0. the residuals from the model have no autocorrelation.

H1. The residuals are not independently distributed.

The test's statistical function is defined as:

$$Q = (n - d)(n - d + 2)\sum_{k=1}^{h} \frac{\hat{r}_k^2}{(n - d - k)}$$

where n is the total number of observation, d is number of differences, $\hat{r}_k$ is the autocorrelation of the residuals for the k^{th} lag, and h is the number of lags being tested. For significance level α, the critical region for rejection of the hypothesis of randomness is: $Q > \chi^2_{1-\alpha,h}$, where $\chi^2_{1-\alpha,h}$ is the α-quantile of the chi-squared distribution with h degrees of freedom.

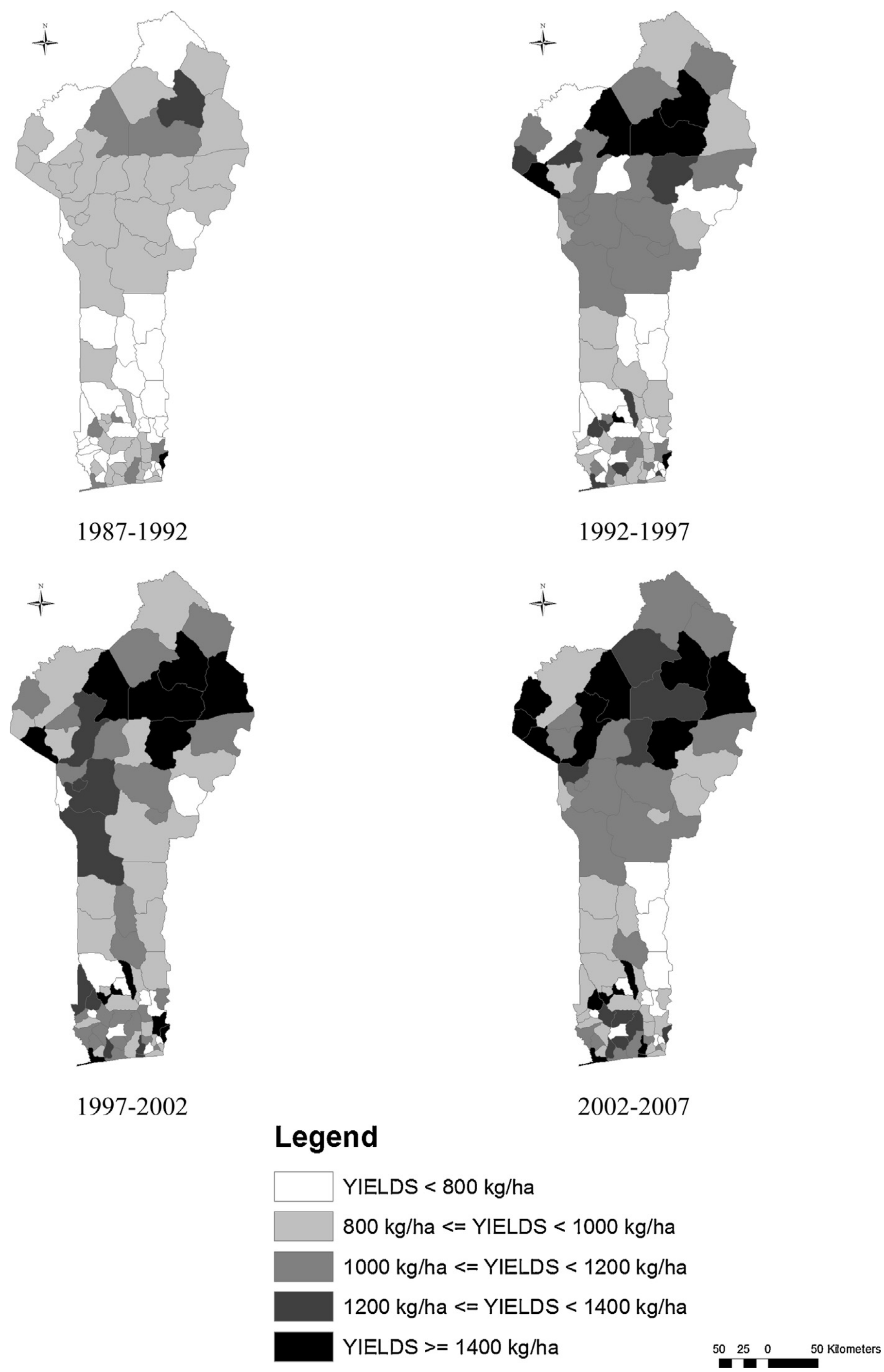

Fig. 2. The five year mean maize yield by districts.

Table 2
Percentage of districts by agro-ecological zone belonging to the yield classes for the periods 1987–1992 and 2002–2005.

Period	Yield classes (kg/ha)	Zone I	Zone II	Zone III	Zone IV	Zone V	Zone VI	Zone VII	Zone VIII
	<800	50.0		12.5	22.2	66.7	40.9	60.0	35.7
	[800 1000]	50.0	40.0	87.5	77.8	33.3	36.4	40.0	50.0
1987–1992	[1000 1200]		40.0				18.2		07.1
	[1200 1400]		20.0						07.1
	>1400						04.6		
	<800		20.0	12.5	33.3	16.7	13.6	20.0	14.3
	[800 1000]	100.0	40.0	37.5	33.3	41.7	45.5	20.0	21.4
2002–2007	[1000 1200]		20.0	25.0	22.2	16.7	18.2	20.0	50.0
	[1200 1400]		20.0	25.0		08.3	13.6	20.0	07.1
	>1400				11.1	16.7	09.1	20.0	07.1

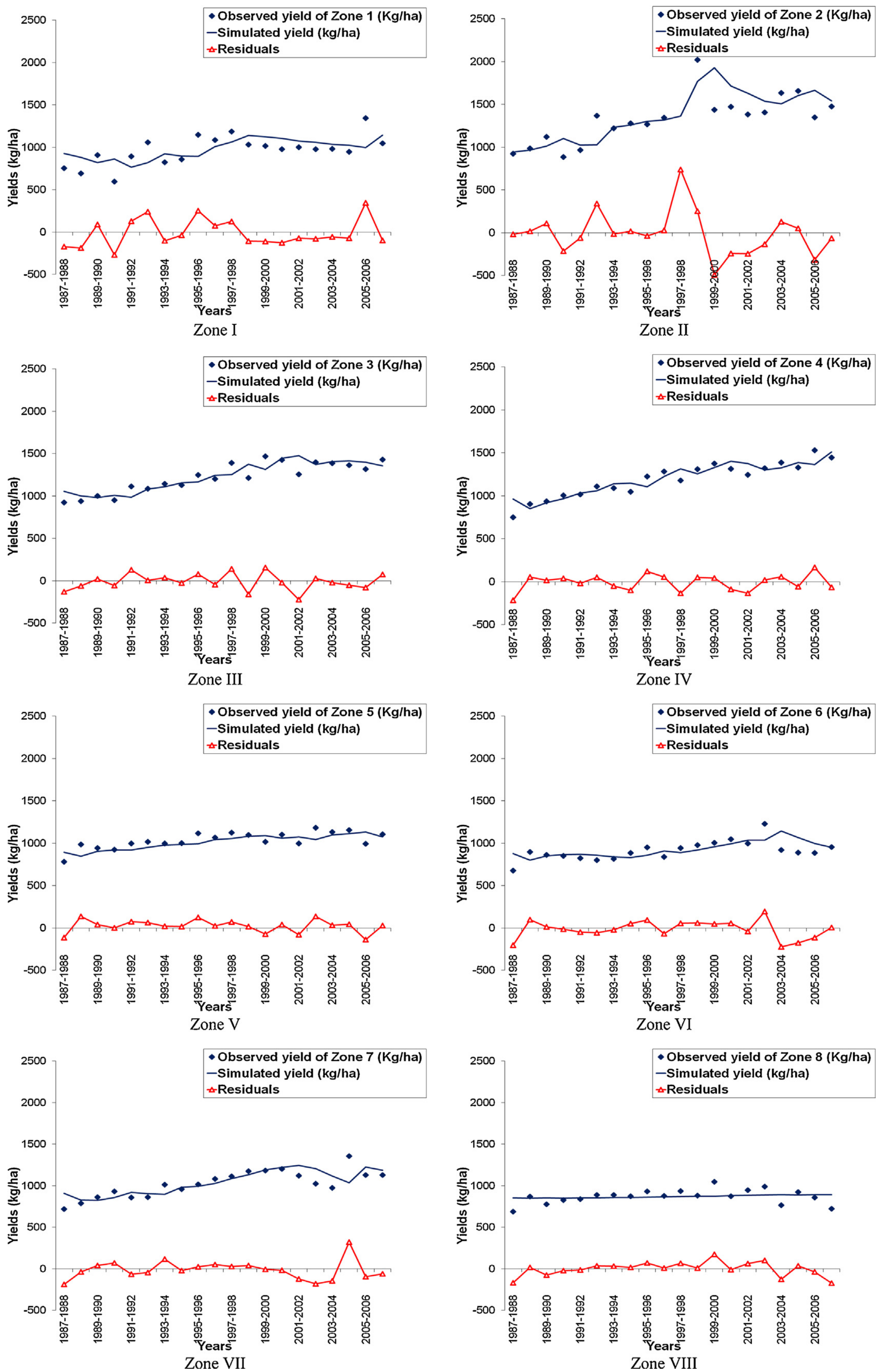

Fig. 3. Graphs of the observed yields, the fitted model, and the residuals of the observed and simulated yields from 1987 to 2007 for the eight agro-ecological zone.

Table 3
Average yield comparison, standard error, minimum and maximum maize yields in the period 1987–2007 by agro-ecological zone.

Zone	Average yield (kg/ha)[a]	Standard error (kg/ha)	Minimum yield (kg/ha)	Maximum yield (kg/ha)
Zone I: Far North Benin	967[cd]	38	596	1021
Zone II: Cotton region of North Benin	1366[a]	72	885	2104
Zone III: Food crop region of South Borgou	1220[b]	40	926	1470
Zone IV: West Zone of Atacora	1190[b]	45	751	1531
Zone V: Cotton region of the Centre	1037[c]	21	780	1182
Zone VI: Zone dominated by laterite soils	913[c]	25	676	1230
Zone VII: Zone of depressions	1025[cd]	36	719	1359
Zone VIII: Region of fisheries and vegetable crops.	871[d]	19	689	1049

[a] Average yields followed by the same alphabetical letters are not significantly different at the 5% level with Newman–Keuls' test.

For linear regression Durbin–Watson test statistic was used. This statistic tests the null hypothesis that the residuals from an ordinary least-squares regression are not autocorrelated.

The test statistic is:

$$\mathrm{DW} = \frac{\sum_{t=2}^{n}(e_t - e_{t-1})^2}{\sum_{t=1}^{n} e_t^2}$$

where $e_t = y_t - \hat{y}_t$ and y_t and $\hat{y}_t$ are, respectively, the observed and predicted values of the response variable for individual t. DW becomes smaller as the serial correlations increase.

To draw a conclusion of the test, we compare the statistics observed at lower and upper bounds in Durbin–Watson table in which critical values were tabulate. If DW is greater than the upper limit, there is no correlation. If DW is less than the lower limit, there is a positive correlation. Finally, if DW is between both bounds, the test was not conclusive.

3. Results

3.1. Spatial analysis

As the average yield in the districts increased over the period, the number of districts in the higher yield classes gradually increased (Fig. 2). In most agro-ecological zones, most districts obtained yields below 1000 kg/ha during the period 1987–1992, but in the period 2002–2007 the percentage of districts within the yield classes <1000 kg was almost halved in most zones (Table 2). The latter shift reflects the increased yields in these districts. The zones III–V and VII presented the highest increases. In contrast, zones VI and VIII showed low and zones I and II, very low increases.

Modeling the trend of yields showed that the yields of 25 districts did not present a significant trend. Yields of 19 districts fit to simple exponential smoothing and yields of 33 districts had a tendency fitting double-exponential smoothing of Brown. Values of χ^2 and p showed that the fit of the models is generally satisfactory (results are not further specified in the paper for reasons of brevity).

The comparison of the average yields obtained during the study period (1987–2007) between the agro-ecological zones showed that the best maize yields were obtained in the agro-ecological zones II and III (Table 3). The lowest yields were obtained in zone VIII. The Student–Newman–Keuls test (Student, 1927; Newman, 1939; Keuls, 1952) showed that according to yields, the eight zones can be grouped into four categories. In the first category, zone II, the average yield is estimated at 1366 kg/ha. Zone II, located in the central part of northern Benin is the main cotton growing area of Benin (see Table 2 for details). Here, farmers adopted mechanization and the use of fertilizers and pesticides for cotton mainly; next to cotton and maize, they cultivate sorghum and yam. The second category encompasses zones III and IV with an average yield estimated at 1205 kg/ha. Zone III covers the southern districts of northern Benin where farmers focus more on food crops (yam, cereals and cashew) than on cotton. In zone IV, the western part of northern Benin, the soils are poor and farmers crop cereals and in its meridional zones yams. The third category includes zones V and VII with an average yield estimated at 1031 kg/ha. In the septentrional part of zone V farmers tend to focus on cotton, while both zones in the center of Benin have a bimodal rain pattern allowing to farm other crops (tubers, pulses, cereals including maize) twice during the year. In zone VII, the fertile depression, maize and cassava are associated with cowpea, tomato and pepper. The fourth category is the fisheries zone (VIII), where maize, yielding on average 871 kg/ha, is cultivated as main crop in rotations with cassava, cowpeas, vegetable and fruits The yields of zone I and VI are not significantly different from those of categories 3 and 4, and these zones could be classified in either of these two categories depending on the year (see Section 4).

3.2. General trend

The average maize yields measured from 1987 to 2007 fitted an exponential smoothing model in the majority of the districts. The percentage of variance of the dependent variable transformed by Box and Cox's transformation showed that classical linear regression models explained the highest proportions (Table 4). However, the use of classical linear regression assumes that the regression residuals are independent, while the data in this study were correlated. Indeed, the residuals autocorrelation test of Durbin–Watson shows that in most cases the observed value of DW statistic is less than the critical value of the lower bound (1.201) read in the table of Durbin–Watson for a sample size equal to 20 and one explanatory variable at the 5% level. Thereby indicating that the errors are positively autocorrelated. In other words, yields of a given year are related to the yields obtained in previous years. Exponential smoothing models are appropriate for the analysis of such data. For a given zone, the values of the BIC criterion obtained for the different exponential smoothing models were not very different from one another. In addition to the BIC criterion, comparison of the models' percentage of variance and the significance of the alpha values, showed that the yields of five agro-ecological zones (I, III–V and VIII) fitted the double exponential smoothing model of Brown and three zones (II, VI and VII) fitted the simple exponential smoothing model (Table 4). The coefficients α of the simple and Brown models for all zones were significantly different from zero. Overall, the parameters of the residuals of Ljung–Box (χ^2 and p values) showed that the simple and Brown models were satisfactory except for zones IV and V, which showed values of the χ^2 statistic that were significant. However, overall results showed that the Brown exponential smoothing models remained the ones simulating best the trends of zones IV and V. Fig. 3 shows the curve of the observed data, the curve determined by Brown's exponential smoothing fitting the trend (zones I, III–V and VII), the curve determined by simple exponential smoothing fitting the trend (zones II, VI and VIII) and the curve of the residuals obtained after the

Table 4
The parameters of the models adjusted for the general trend per agro-ecological zone.

Type of model		Model parameters		Agro ecological zone							
				ZoneI	Zone II	Zone III	Zone IV	Zone V	Zone VI	Zone VII	Zone VIII
Exponential smoothing	Simple	Parameters estimated	Alpha	0.35	0.64	0.56	0.78	0.40	0.41	0.53	0.34
			p-Value	0.05	0.01	0.01	0.00	0.02	0.03	0.01	0.08
		Model fit statistics	BIC standardized	10.25	11.31	9.34	9.24	8.91	9.38	9.56	9.01
		Ljung–Box statistic	Chi square	21.07	14.43	10.93	33.62	29.31	15.69	15.13	20.52
			p-Value	0.22	0.64	0.86	0.01	0.03	0.55	0.59	0.25
		Percentage of variance explained by the model: %*Sm*		9	35	66	74	25	15	45	1
		Percentage of variance explained by the residuals: %*Se*		89	65	34	26	75	85	55	99
	Brown	Parameters estimated	Alpha (level and trend)	0.21	0.30	0.34	0.40	0.25	0.23	0.31	0.02
			p-Value	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.00
		Model fit statistics	BIC standardized	10.34	11.46	9.34	9.25	9.04	9.50	9.65	9.05
		Ljung–Box statistic	Chi square	21.18	13.08	11.91	39.00	32.37	17.29	21.01	21.38
			p-Value	0.22	0.73	0.81	0.00	0.01	0.44	0.23	0.21
		Percentage of variance explained by the model: %*Sm*		10	23	69	78	30	10	47	1
		Percentage of variance explained by the residuals: %*Se*		90	77	31	22	70	90	53	99
	Holt	Parameters estimated	Alpha (level)	0.10	0.50	0.10	0.10	0.10	0.10	0.10	0.19
			p-Value	0.48	0.03	0.48	0.43	0.23	0.50	0.39	0.10
			Gamma (trend)	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00
			p-Value	1.00	1.00	1.00	1.00	0.26	1.00	1.00	0.20
		Model fit statistics	BIC standardized	10.23	11.48	9.20	8.89	8.83	9.47	9.52	9.03
		Ljung–Box statistic	Chi square	18.04	13.26	12.35	20.50	24.70	14.88	12.50	25.43
			p-Value	0.32	0.65	0.72	0.20	0.08	0.53	0.70	0.06
		Percentage of variance explained by the model: %*Sm*		7	25	67	72	20	8	40	1
		Percentage of variance explained by the residuals: %*Se*		93	75	33	28	80	92	60	99
Classical regression	Lambda value of Box–Cox transformation			0.93	−0.87	0.69	1.91	2	−0.59	0.30	1.96
	Intercept: y_0			481	0.0024	116	361,711	847,248	0.0201	7.57	524,210
	Regression coefficient: b			10.4	−0.00005	2.12	36,545	22,591	−0.00014	0.053	4617
	Percentage of variance explained by the model: %*Sm*			36.4	49.7	78.2	88.6	46.2	34.7	64.1	1.1
	Percentage of variance explained by the residuals: %*Se*			63.6	50.3	21.8	11.4	53.8	65.3	35.9	98.9
	Durbin Watson test statistic			1.42	0.82	1.06	1.17	1.38	1.46	1.13	1.34

Table 5
Climate variables significantly affecting the yield by agro-ecological zone (within parenthesis the sign of the regression coefficient).

Zone	Minimum humidity	Maximum humidity	Average humidity	Rainfall	ETP	Minimum temperature	Maximum temperature	Average temperature	R_a^2
Zone I	Jl (−)		Jl (+)	Jl (+) S (−)			Ma (−)	Au (+)	83.7
Zone II	Ma (−)	Ma (+) S (+)		Ma (−) Jn (−) Au (+)		O (+)			83.1
Zone III	Jn (−)		S (+) O (+)		Ma (−) Au (+) S (+)	Ma (−) Au (−)			92.0
Zone IV	O (+)			Ma (−) Au (+) O (−)		S (−)		Au (−)	69.0
Zone V			O (+)	Jn (+) Au (−)			S (−)		59.0
Zone VI	Ma (−)		Mr (+)	Ap (−) S (−)		Ma (−)		N (+)	77.4
Zone VII		Mr (−) O (+)		Ma (+) Jl (+)	O (+)			S (+)	90.8
Zone VIII	Ma (−)		Jn (−)	Ma (+)		Mr (+) Ap (−)	N (+)		78.1

Mr, March, Ap, April, Ma, May, Jn, June Jl, July, Au, August, S, September, O, October, N, November.

Table 6
Percentage of variance of the yields of each agro-ecological zone explained by three component of theoretical model: general trend, component related to weather and the random component.

Zone	*%Sm*	*%SW*	*%Se*
Zone I	10	75	15
Zone II	35	54	11
Zone III	69	29	2
Zone IV	78	15	7
Zone V	30	41	29
Zone VI	10	69	20
Zone VII	47	48	5
Zone VIII	1	77	22

Note: *%Sm* is the percentage of variance explained by the model *%SW* is the percentage of variance explained by the weather; *%Se* is the percentage of variance explained by the residuals.

extraction of the trend. These curves confirmed the findings presented above.

3.3. Effect of climatic factors

The climate variables having a significant effect on maize yields by agro-ecological zone according to the stepwise regression were: minimum humidity, rainfall and minimum temperature (Table 5). In most areas, the minimum relative humidity affected the yields negatively, while maximum humidity had no effect on yields except on the yields of zones II (cotton region) and VII (depression). Rain was the most determining factor in all areas. In the northern region where rain season is monomodal, rainfall in July and August had a positive effect on yields, while rainfall in May, September and October had a negative effect. In contrast, in the southern regions where the season is bimodal, rainfall in May, had a positive effect on yields. Overall, the minimum temperatures affected negatively the yields. The values of the adjusted R^2 (R_a^2) which express the percentage of the interannual yield variations, after eliminating trends explained by the models indicated that the models selected were satisfactory (Table 5).

3.4. Variability explained by climate and model

For each agro-ecological zone, the percentage of yield variability explained by the models showed that the simulations of zones III and IV fitted the data best (Table 6). This fit was moderate for zones II, V and VII. The trend of yields of zones I, VI and VIII fitted very weakly to the model; the fit was low in particular for zone VIII (Region of fisheries and vegetable crops) having the lowest average of yield (871 kg/ha). The percentages of yield variability explained by climatic factors was high for zones I, VI and VIII.

4. Discussion and conclusion

4.1. Data quality and model fit

In general, maize yields have increased over time in Benin. Trend analysis per agro-ecological zone showed that all yield trends fitted to the exponential smoothing model; the trends of five zones were simulated best with double exponential smoothing and three with simple exponential smoothing. The best predictor, for districts where yields had no trend, was the mean of the yield of the previous years. However, adjustments obtained by double exponential smoothing for the other districts implied the existence of a local trend; there the yield prediction was best performed by taking into account the local trend and the forecast made on yields in previous years. The exponential smoothing adjustments are special cases of ARIMA models: the simple exponential smoothing can be achieved by model ARIMA (0,1,1) without intercept, and the double exponential smoothing by model ARIMA (0,2,2). The analysis of the smoothing constant (α) in exponential smoothing models showed that the simple exponential smoothing models had relatively high coefficients significantly different from zero. This suggests that the forecasts obtained from the simple exponential smoothing models were strongly influenced by yields in more recent years, while the predictions based on the double exponential smoothing models (lower value of α) were influenced by the yields in a far past. Thus we conclude that in most of the districts, the yield in a specific year can be predicted by the yields of previous years. Future studies might use a principal component analysis or a cluster analysis to assess how the districts group together in terms of the space-time variations in maize yield. Rather, the approach used by the Ministry of Agriculture in predicting the future yields from the arithmetic average yield in the last five years in all districts can be improved. In view of our results, the method for forecasting yields should be based on exponential smoothing models, and must take into account the specificity of each agro-ecological zone.

4.2. Factors explaining spatial variation in the model fit

Several factors, relating to the production systems of the agro-ecological zones, may explain either the weak fit of the model or the strong effect of climate on the yields. Soulé and Gansari (2010) point out that the area under maize production increased significantly under the effect on the conquest of new areas of production in Benin. The new technological packages introduced by Sasakawa Global 2000 project had allowed an average yield of 3000 kg/ha on the plots using the technology package, against the 1000 kg/ha obtained on plots without the technology package, giving a net gain of 200% (Galiba, 1994). Thus, in districts with more farmers having adopted the technology, the innovations may have affected the trend more strongly. For example the farmer's capacity to use 150 kg/ha of nutrients is limited by their capital availability, particularly in zone IV (West Zone of Atacora) where soil fertility has become low. On other hand, introduction of soil protection and restoration of fertility in southern Benin and the nearby cities with bimodal rain pattern (zones VI, VII and VIII) provided more opportunities to finance fertilizer, thus improving yield while rainfall remained about the same. The production system is also an explanatory factor. In Benin, maize is often intercropped with cassava, sorghum, groundnuts, or cowpeas at very different densities. In some regions, maize is rotated with yam or rice. Groundnuts and beans are good predecessors for cropping maize because they fix nitrogen. The cropping rotations in zone VIII (Fisheries and vegetables) probably do not focus on maize which may explain the low yields. The highest yields are observed in cotton-growing areas (zone II with an average yield of 1366 kg/ha). In these areas, the maize benefits from both the multi-year effects of the application of organic matter (straw, manure, green manure, etc.) and fertilizers on the cotton crop, as confirmed in Benin by Soulé and Gansari (2010) and in the north of Ivory Coast by Akanvou (1995). Similar results were also noted by Segda (1995) on the rainfed crop systems in western Burkina Faso, and Teme et al. (1995) in southern Mali where maize yields increased from 2000 to 3000 kg/ha. This multi-year effect of manuring cotton explains that in zone II the yield obtained in year t is influenced by the yield of the previous years.

The introduction of animal traction and associated equipment for the cotton helped also to increase the area and to reduce working time, thus enabling more weeding. The effect of number and period of weeding on maize yields have been also highlighted by Sasakawa Global 2000 project. In Nigeria, an increase of 67% of yield with two weedings versus non-tilling of maize was recorded (Akobundu, 1993). In Philippines, Brazil, Gambia, Sierra Leone and Nigeria, 20–100% of yield losses for maize due to weeds were measured, and in Ethiopia from 30 to 56% (Palwal et al., 2002).

Maize yields obtained in Benin are relatively low when compared with the maize yields in other countries of the region. In the western part of Burkina Faso, Wey (1995) reported an average yield of 4049 kg/ha in cotton provinces of Houndé and Bama, and an average yield of 2569 kg/ha in food-producing provinces of Sidéradougou and Tiéfora. The last author also found yields of 4964 kg/ha for farms using motorized equipment, 3765 kg/ha for the farms using animal traction and 2773 kg/ha for the non-mechanized farms. However, some of these plots produced very low yields (less than 500 kg/ha). In Guinea, Camara (1995) reported that yields vary depending on whether the maize is associated with rice or with leguminous crops (600–800 kg/ha), or on intensified pure culture (1500–2000 kg/ha).

Several factors explain the low maize yield and its spatio-temporal variability. One of the most important factors, next to soil quality, is the spatial and temporal variability of rainfall. Seasonal rainfall amount, intra-seasonal rainfall distribution and dates of onset/cessation of the rains, influence yields and cropping calendars of cereals such as maize (Sivakumar, 1988; Maracchi et al., 1993). This was confirmed by the results which showed the high percentage of yield variability explained by climatic factors in zones I and VIII (Table 5). These zones represent respectively the extreme north and southwest areas, representative for short growing seasons under either monomodal or bimodal rainfall. The classical distinction between regions with two rainy seasons (forest areas), and those with one rainy season (savannah areas) affects maize yields (CIRAD/FSA, 1995). In Benin, the most favorable climate zone for maize is the savannah with rainfall ranging from 800 to 1200 mm, where varieties with long-growing seasons can be used and the many sunny days/hours reduce parasitism. Further south in the forest zone, the reduced sunlight and related high pest pressure and the short rainy seasons, requiring the use of varieties with a short-growing season, reduce the potential productivity. Although maize with short-growing season produces less, farmers have no alternative for maize. In the northern zone I, farmers use alternative more drought resistant crops, but appreciate the maize for the shorter growing cycle providing food to bridge the period of shortage before the harvest of the other food crops.

In general, the deficiency of soil's water reserve in Benin is one of the main causes of poor crop yields when the rainfall pattern is irregular (Azontondé, 1991). In maize cultivation, water is a critical factor in yield as demonstrated by the results. When drought occurs during the development of culture, seedlings die, thereby reducing the number of plants (Palwal et al., 2002). Also, when water stress occurs at the critical period (20 days before and 10 days after flowering), yield losses can reach 60% (Semporé, 2008). It is estimated that during this period the plant absorbs 45% of its total water needs (CIMMYT, 1991). According to Shiferaw et al. (2012), climate change, higher temperatures and more frequent exposure to high temperature events are the major drivers of yield loss. Thus, Lobell et al. (2011) estimated that each degree day spent above 30 °C reduced the final crop yield by 1 percent under optimal rainfed conditions and by 1.7 percent under drought conditions.

The onset of the rainy season is also crucial (Ingram et al., 2002; Barbier et al., 2009) for agricultural management since it determines the planting period (Steward, 1991; Sivakumar, 1992; Omotosho et al., 2000). The strategy developed by farmers is sowing at the first rains. Thus, as shown by our results, in the northern area where rainy season is monomodal, rainfall in July and August has a positive effect on yields, while rainfall in May, September and October has a negative effect. In this part of Benin, the rainfall in July and August corresponds to the period of full vegetative growth, while that in May corresponds to the first rainfall of which discontinuation could lead to failures of seedlings or to a negative effect on plant growth, and therefore on the final yield. The rains in September and October are close to the end of the rainy season. These rains adversely affect the yield because they can have a negative effect on flowering or facilitate parasitic attacks (shoot borer, locusts' infestation). In contrast, in the southern regions where the season is bimodal, rainfall in May has a positive effect on yields. This period also corresponds to the period of full vegetative growth. Thus, plant water availability strongly depends on the onset, cessation and length of the rainy season (Laux et al., 2010). For sowing, it is important to know whether the rains are continuous and sufficient to ensure enough soil moisture during planting, and whether this level will be maintained or even increased during the growing period to avoid total crop failure (Walter, 1967). Planting too early might lead to crop failure, and in turn, planting too late might reduce valuable growing time and crop yield (Laux et al., 2010). In Niger, Marteau et al. (2011) analyzing the relationship between planting date, the rains and the yield of millet, noted that most farmers (73%) sow just after a wet period of two days with at least 10 mm of rain. Failure of seedlings was related to drought for at least 7 days after an initial period of 2 wet days with at least 10 mm of rain. The latter authors have also shown by simulations that the ideal planting date maximizing efficiency is on average about six days later than that observed. However, there is still no consensus in literature about the question of how much rain over which period defines the onset of the rainy season (ORS) for agro-climatological impact studies (Laux et al., 2010).

In the above models, the unexplained variability of the yields was relatively low (2–29%). This may be linked to, inter alia, types of soil found in the different zones. Indeed, the spatial and temporal variability of rainfall is exacerbated by poor soil fertility. To improve the fertility of their soil, farmers primarily use composted plant debris. These practices are done differently according to the zone. Igue et al. (2013) showed that the potential yields of the cultivar DMR-ESR-W are reached in south Benin when sowing was done in April (4 t/ha) and in central Benin when done in May (5 t/ha). The last cited authors also estimated that for the central and southern regions of Benin, the optimum nutrient needs for maize are 80–120 kg N/ha against 30–60 kg P/ha and 0–40 kg K/ha. These practices are done differently according to the zone (Igue et al., 2013).

4.3. Impact of the future availability of natural resources

Under specific conditions farmers can use most available methods to achieve optimum crop yields (Nhemachena et al., 2014). Most of these methods aim at increasing the efficiency on the use of natural resources such as water, land area, nutrients, solar radiation and atmospheric CO_2 (Awal et al., 2006). The reduced availability of land and water because of urbanization and industrialization are related to the global population increase. The local changes in the availability of water due to climate change are hard to predict but farmers have demonstrated their ability to respond. The intensity of solar radiation is expected to remain constant, while an increase in atmospheric CO_2 is predicted (Francesco and Frank, 2002; Francesco et al., 2007; Kant et al., 2012). The abundant radiation available over the tropics and subtropics, together with the increase of CO_2, represents an opportunity to increase crop production. Thus, Awal et al. (2006) showed that a maize/peanut intercropping would help to increase production through the efficient utilization of solar energy. Shiferaw et al. (2012) reported that there is no mechanistic basis for a direct effect of CO_2 on C4 photosynthesis and the weight of evidence indicates that in plants, such as maize, C4 photosynthesis is not directly stimulated by elevated CO_2. However, Shiferaw et al. (2012) mentioned also that growth and yield may benefit indirectly through a reduction in stomatal conductance. Moreover, through Free-Air CO_2 Enrichment (FACE) experiments, Leakey et al. (2009) demonstrated that elevated CO_2 improves C-4 plant's water relations and so indirectly enhances photosynthesis, growth, and yield by delaying and reducing drought stress.

4.4. Conclusion

This study carried out a retrospective analysis of maize yields in the 77 districts of Benin in order to assess the impact of introduced technologies. Yields varied widely from one year to the next and from one agro-ecological zone to another. The average maize yields fitted an exponential smoothing model in the majority of the districts. The increase of yields is due in particular to the adoption of new agricultural practices. Climatic factors in particular rain, largely explain the relatively low yields recorded during the period. However, there are specificities between districts and agro-ecological zones, e.g. regarding soil quality. Therefore, different approaches have to be adopted for different problems and different crops to define analogous zones to assure successful transfer of agricultural technology from one area to another. Estimations of crop yields and impact of climate change on crop yields, as well as the analysis of adaptations in response of climate changes, should consider the spatio-temporal variations and the impact of new technologies.

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