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Effects of climate variability and climate change on crop production in southern Mali

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ABSTRACT

In West Africa predictions of future changes in climate and especially rainfall are highly uncertain, and up to now no long-term analyses are available of the effects of climate on crop production. This study analyses long-term trends in climate variability at N'Tarla and Sikasso in southern Mali using a weather dataset from 1965 to 2005. Climatic variables and crop productivity were analysed using data from an experiment conducted from 1965 to 1993 at N'Tarla and from a crop yield database from ten cotton growing districts of southern Mali. Minimum daily air temperature increased on average by 0.05 °C per year during the period from 1965 to 2005 while maximum daily air temperature remained constant. Seasonal rainfall showed large inter-annual variability with no significant change over the 1965–2005 period. However, the total number of dry days within the growing season increased significantly at N'Tarla, indicating a change in rainfall distribution. Yields of cotton, sorghum and groundnut at the N'Tarla experiment varied (30%) without any clear trend over the years. There was a negative effect of maximum temperature, number of dry days and total seasonal rainfall on cotton yield. The variation in cotton yields was related to the rainfall distribution within the rainfall season, with dry spells and seasonal dry days being key determinants of crop yield. In the driest districts, maize yields were positively correlated with rainfall. Our study shows that cotton production in southern Mali is affected by climate change, in particular through changes in the rainfall distribution.

1. Introduction

Since the early 1990s the Intergovernmental Panel for Climate Change (IPCC) has provided evidence of accelerated global warming and climate change. The last IPCC report concludes that the global average temperature in the last 100–150 years has increased by 0.76 °C (0.57–0.95 °C) (IPCC, 2007). Finding evidence of global trends in rainfall is complex because of large regional differences, gaps in spatial coverage and temporal shortfalls in the data. Rainfall generally increased over the 20th century in eastern parts of North and South America, northern Europe and northern and central Asia. Drying has been observed in the Sahel, the Mediterranean region, southern Africa and parts of southern Asia (IPCC, 2007). Furthermore, there is evidence for increases in the frequency of both severe droughts and heavy rains in many regions of the world. Climate change due to greenhouse gas emissions is expected to further increase temperature and alter precipitation patterns. All 21 General Circulation Models (GCMs) used by IPCC predict a temperature increase in sub-Saharan Africa in the order of 3.3 °C by the end of the 21st century. With regard to predicted changes in rainfall amounts in sub-Saharan Africa, the uncertainty is considerably greater and in many instances models do not agree on whether changes in rainfall will be positive or negative (Cooper et al., 2008).

Rainfed agriculture produces nearly 90% of sub-Saharan Africa's food and feed (Rosegrant et al., 2002), and is major livelihood activity for 70% of the population (FAO, 2003). This agricultural sector is negatively affected by climate variability, particularly through heat waves, droughts, floods, and other extreme weather events. Overall, the success or failure of crop production under rainfed conditions in Sudano-Sahelian West Africa is strongly linked to rainfall patterns (Graef and Haigis, 2001).

In West Africa, a combination of external and internal forces makes the climate of the region one of the most erratic in the world (Zeng, 2003). Annual cycles of rainfall are strongly determined by the position of the inter-tropical convergence zone (WCRP, 1999).

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Many studies have characterized the rainy season in West Africa; most of them were based on decadal, monthly or total annual rainfall analysis (Ati et al., 2002; Nicholson, 1980; Sivakumar et al., 1984), while others studies described the start and end of rainy season (Diop, 1996; Dodd and Jolliffe, 2001; Omotosho et al., 2000; Stern and Coe, 1982). A good understanding of seasonal variability patterns is of critical importance because of the highly unstable onset of the rainy season and the high frequency of dry spells. The last century's climate in Sudano-Sahelian West Africa was marked by high spatial and temporal variability and by alternations between dry and wet seasons (Servat et al., 1998). A review by Traoré et al. (2007) of current knowledge on the regional climate in Sudano-Sahelian West Africa revealed that rainfall remains unpredictable. This rainfall unpredictability is a major constraint for farmers who have to plan the start of the cropping season (Piéri, 1989). The first rains are not always followed by the full start of the monsoon (Sultan and Janicot, 2003), dry spells can occur afterwards, i.e. during the early stages of the crop growth so that seeds may not germinate properly or germinated plants may die off. However, if sowing is delayed, the land may be too wet to till.

Southern Mali occupies 13.5% (approximately 160.825 km^2) of the Malian territory. It represents 50% of the cultivable lands of the country and holds 40% of the Malian population. In southern Mali agricultural activities play an essential role in supplying food to the country; they represent 45% of the country's income (Deveze, 2006). Most people in the region are likely to be vulnerable to climate variability (Sivakumar et al., 2005). Hence, it is imperative to better quantify climate variability and change and their effects on crop production. Several studies analysing long-term relationships between climate and crop yields have been published recently (Kucharik and Serbin, 2008; Lobell and Burke, 2008; Lobell et al., 2008; Lobell and Field, 2007), but none of these focused on West Africa.

We analysed long-time series of weather data recorded in southern Mali, and crop yield data from an experiment at the Research Station of the Institut de l'Economie Rurale at N'Tarla and from farmers' fields in ten districts in southern Mali. The objectives of this study are therefore: (i) to quantify possible changes in climate and crop production over 30 years in southern Mali and (ii) to quantify the effect of annual climate variability and change on crop production.

2. Methods

2.1. Study area and source of data

The climate in southern Mali is typical of the Sudano-Sahelian zone. Average long-term annual rainfall is 846 ± 163 mm at N'Tarla (12°35′N, 5°42′W 302 m.a.s.l.) and 1073 ± 187 mm at Sikasso (11°35′N, 5°68′W 374 m.a.s.l.). The rainy season extends from May to October and the seasonal average temperature is 29 °C. During the dry season (November–April) the temperature and saturation vapour deficit increase and crop production is impossible without irrigation (Sivakumar, 1988).

The most common farming systems in the region are extensive mixed agrosylvo-pastoral systems, focused around cotton (*Gossypium hirsutum* L.) – the main cash crop – in rotation with cereals – sorghum (*Sorghum bicolor* (L.) Moench), pearl millet (*Pennisetum glaucum* (L.) R.Br.), maize (*Zea mays* L.) – and legumes – groundnut (*Arachis hypogaea* L.) and cowpea (*Vigna unguiculata* (L.) Walp.). Cotton and to a lesser extent maize, receive nutrient inputs in the form of organic manure and/or chemical fertilizer, as well as pesticides. Other cereal crops seldom receive any fertilizer. As a result, soils are often mined and soil organic matter contents are declining (Piéri, 1989). Cattle, goats and sheep are the main livestock species. Agro-pastoralists generally practice sedentary farming, although due to large herd sizes and the lack of feed resources, transhumance is practiced in the dry season.

2.2. Climate data

The meteorological data used for the climate analysis in this study were recorded at the meteorological stations of N'Tarla (12°35′N, 5°42′W 302 m.a.s.l.) and Sikasso (11°35′N, 5°68′W 374 m.a.s.l). The database contained long-term (from 1965 to 2005) records of daily rainfall and minimum and maximum temperatures. Daily minimum and maximum temperature were averaged over the rainy season to represent the seasonal temperatures. For the districts, we used the annual rainfall data as they were recorded at the different districts with rain gauges.

2.3. Long-term crop experiment

An experiment was conducted from 1965 to 1993 at the N'Tarla agricultural research station (12°35′N, 5°42′W 302 m.a.s.l.) to determine the long-term impact of cotton-based cropping systems on soil fertility (IRCT, 1969). The trial was set up according to a Fisher block design with three crops (cotton, sorghum, groundnut) as part of a rotation, four fertilization treatments and four replications. Initially, a 3-year crop rotation cotton–sorghum–groundnut was used, from 1968 the crop rotation was cotton–sorghum–groundnut–sorghum and in 1976 returned to the 3-year rotation cotton–sorghum–groundnut. At the start of the experiment, the four fertilization treatments were: an unfertilized control, application of manure, application of mineral fertilizer and the combined application of manure and mineral fertilizer. The fertilizer treatments were modified over time, with the aim to limit soil fertility decline. In the first phase (1965–1979) of the experiment, mineral fertilizer and manure (9 t DM ha^{-1}) were applied only to cotton. From 1980 onwards, mineral fertilizer was allocated to the three crops and manure to cotton (6 t DM ha^{-1}) and sorghum (3 t DM ha^{-1}). Mineral fertiliser was then also applied in the control treatment. Weed and pest control were carried out on all treatments according to the standards recommended by the local agricultural research institute (IER/CMDT/OHVN, 1998).

The soils of the experimental site are highly weathered and classified as Lixisols (FAO, 2006). They have a sandy-loam texture (<10% clay) at the surface, but are richer in clay with depth (30% at 60 cm depth). Soil organic carbon content is low (0.3%), pH is around 6 and CEC is less than 3 cmol (+) kg^{-1}. They are typical soils for the region.

For the analysis of impacts of climate variability and change on crop production, we used only the crop yields of the treatment with the combined application of manure and mineral fertilizer. Since in this treatment there was no significant trend in soil carbon over time, we did not expect soil carbon or soil fertility in general, to have a strong influence on trends in crop yields. We, therefore, assumed that water was the main limiting factor. On the other hand, to evaluate the long-term effects of soil fertility on crop production, the crop yields in the control treatment were used.

2.4. Crop yields from farmers' fields

Crop yield data from ten cotton growing districts of southern Mali (Fig. 1) were obtained from the Malian cotton company (Compagnie Malienne pour le Développement des Textiles). From the available data, a database was developped with average yields at district level for cotton (1974–2005) and maize (1994–2005) together with the corresponding annual rainfall in the districts to evaluate yield-rainfall relationships. Yields from the database

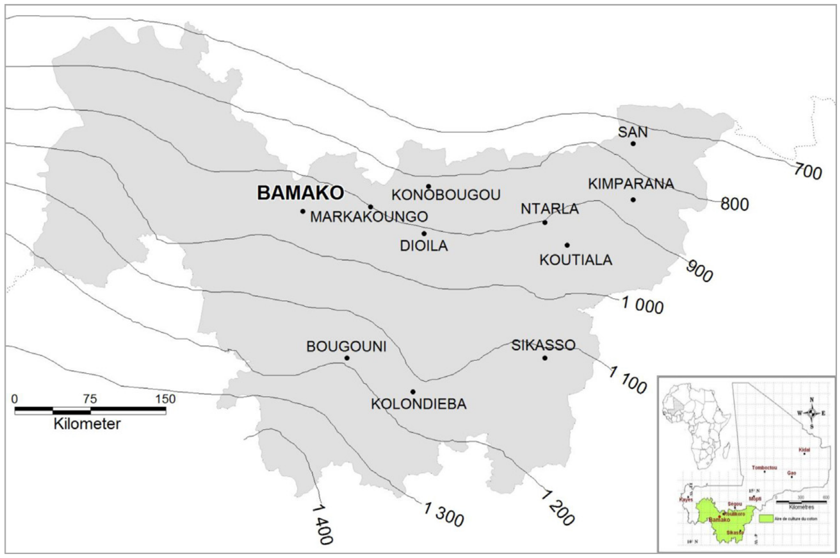

Fig. 1. Map of cotton districts in southern Mali with rainfall isotherms.

represent actual farmers' crop yields that were recorded by the cotton company in the villages of the respective districts.

2.5. Climate analysis

The 41 years of daily weather data were analysed for changes in pattern and variability. Trends were examined using linear regression models with the rainfall and temperature as the dependant variables and year as the independent variable. Correlations coefficients (r) were used to describe the relationships between the different variables. The variables included in the rainfall analysis were annual rainfall, number of rainy and dry days, date of start and end of the rains, the length of the rainy season and the distribution of dry spell periods of different lengths.

The start of the rainy season was defined as the moment when, counting from 1st May, cumulative rainfall for two consecutive days was larger than 20 mm and there was no dry period longer than 10 days with no rainfall within the following first 30 days after onset (Raman, 1974; Stern and Cooper, 2011; Stern et al., 1981). This period corresponds to land preparation and first sowing of crops. The end of the rainy season was defined as the moment when, starting from 15 September, there is a 10-day period without rain. In this period soil water is gradually depleted and the crops mature. Based on the annual values of the start and end date of the rainy season we calculated the length of the rainy season.

The occurrence of long dry spells during the growing season of a crop is a major agricultural hazard (Shaw, 1987; Stern and Coe, 1982); therefore we quantified the probabilities of the occurrence of dry spells of different lengths (Archer, 1981; Stern et al., 1981). A day was considered to be "dry" when daily rainfall was lower than 0.1 mm. The daily observations were represented as successive sequences of dry and wet periods and the total number of occurrences of 5, 7, 10, 15, 20 and 30 days dry spells across the years were calculated. The differences in probability of occurrence of certain dry spells between dry and wet years were analysed, and between years in which crop yield was high (>3 t/ha) and low (<1 t/ha) for cotton.

2.6. Correlating crop yields and climate

Crop yields from the N'Tarla long-term experiment were averaged per year across the different sequences in the rotation. The resulting yields of cotton, sorghum and groundnut were analysed for the 1965–1993 period by correlating them with meteorological variables using simple linear regression models. In addition, a statistical analysis was performed to determine relationships between differences (year-to-year changes) of crop yields and climatic variables such as temperature and annual rainfall (Lobell et al., 2005; Nicholls, 1997). Crop yield data from farmers' fields in ten cotton districts in southern Mali were correlated with annual rainfall over the period 1974–2005 for cotton and over the period 1994–2005 for maize using simple linear regression models.

3. Results

3.1. Observed climate trends

Seasonal minimum daily air temperature increased significantly ($P < 0.01$) over time (Fig. 2a) at N'Tarla and Sikasso with an average rise of 0.06 °C per year for the period 1965–2005. The increase in seasonal maximum daily air temperature at N'Tarla was also significant during the period 1965–2005 (0.02 °C per year) (Fig. 2b); the increase took place particularly between 1965 and 1993 (0.08 °C per year). In contrast, at Sikasso maximum air temperature decreased significantly by 0.01 °C per year over the period 1965–2005. The average seasonal minimum and maximum temperatures over the period 1965–2005 were respectively 23 °C and 35 °C at N'Tarla and 22 °C and 33 °C at Sikasso. The number of dry days (Fig. 2c) increased significantly between 1965 and 2005 at N'Tarla ($P < 0.05$) but not ($P > 0.05$) at Sikasso. Over the period 1965–2005, no significant trend in annual rainfall was observed at either sites (Fig. 2d), but rainfall decreased signficantly between 1965 and 1993 at N'Tarla.

3.2. Rainfall variability

Both the number of dry days and seasonal rainfall showed inter-annual variability with a coefficient of variation of respectively 7% and 20% at N'Tarla and 12% and 17% at Sikasso. The start date of the rainy season was the most important factor determining the length of the season at both sites (Fig. 3a); its relationship with the length of the season ($r = -0.81$ at N'Tarla, $r = -0.86$ at Sikasso, $P < 0.01$) was much stronger than that of the end of the rainy season. Start and end dates of the rainy season were not correlated and did not change over the period. The number of dry days and rainfall were significantly correlated ($r = 0.66$ both at N'Tarla and Sikasso, $P < 0.01$ Fig. 3b). The length of the rainy season was significantly

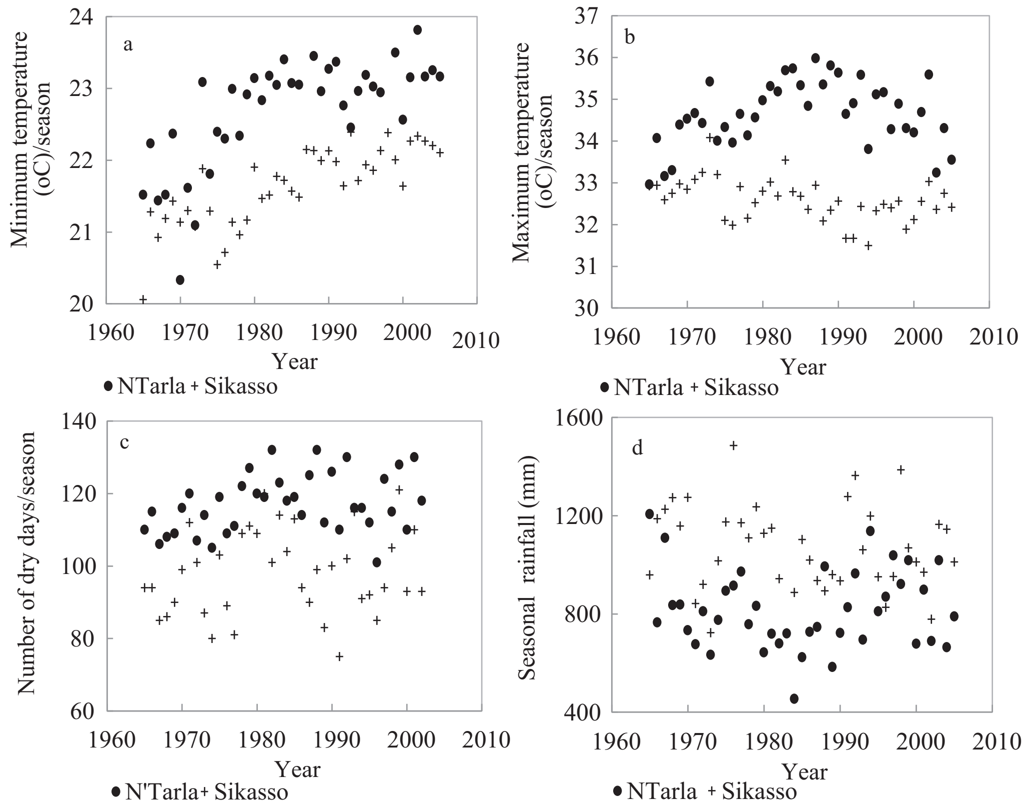

Fig. 2. Variation in climatic variables between 1965 and 2005 at N'Tarla, and Sikasso in southern Mali. (a) Regression of seasonal minimum temperature and year for N'Tarla: $Y = 0.05x - 68.34$ ($r = 0.70^{***}$, $n = 41$) and Sikasso: $Y = 0.04x - 50.12$ ($r = 0.79^{***}$, $n = 41$). (b) Regression of seasonal maximum temperature and year for N'Tarla: $Y = 0.014x - 6.26$ ($r = 0.20$, $n = 41$) and at Sikasso: $Y = -0.018x + 69.29$ ($r = -0.44^{**}$, $n = 41$). (c) Regression of seasonal dry days over the period 1965–2005 at N'Tarla: $Y = 0.2x - 350$ ($r = 0.33^{*}$, $n = 41$) and at Sikasso: $Y = 0.2x - 211$ ($r = 0.15$, $n = 41$). (d) Regression of seasonal rainfall and year for N'Tarla: $Y = -0.12x + 1045.3\ 8$ ($r = -0.13$, $n = 41$) and at Sikasso: $Y = -1.97x + 4967.8$ ($r = -0.13$).

($r = 0.47$, $P < 0.01$) correlated to the seasonal rainfall (Fig. 3c) at both sites.

3.3. Impact of climate on crop yields

Before studying the relationship between crop yields and climate variables, we analysed the crop yield trends over the 30 years of experimentation at N'Tarla. Yields of cotton, sorghum and groundnut from the experimental treatment with combined application of mineral fertilizer and manure at the N'Tarla research station were highly variable from year to year with no clear trend over time (Fig. 4). The coefficients of variation were respectively 27%, 45% and 40% for cotton, sorghum and groundnut.

Correlating changes in sorghum and groundnut yields with changes in climate variables revealed no significant ($P > 0.10$) relationship (Figs. 5 and 6) while cotton yield was significantly ($P < 0.05$) related to seasonal maximum temperature, rainfall and number of dry days (Fig. 7). An increase of 0.08 °C of maximum temperature during the rainy season corresponds to a yield loss of 24 kg/ha of cotton whereas the effect of the minimum temperature increase was insignificant. A wide range of cotton yields were observed for similar amounts of rainfall (Fig. 7c), and the relationship between rainfall and cotton yield resembles more a so-called step-function, represented by the dashed line in Fig. 7c. An important factor explaining this yield variation in the 'step' of the step-function is the rainfall distribution within a rainy season. Rainfall resulting in high yields (Fig. 7c, e.g. 1990) had a regular distribution during the early part of the growing season for cotton, whereas rainfall resulting in low yields (Fig. 7c, e.g. 1993) had an irregular distribution (Fig. 8). Within the period June–July there were 32 dry days in 1990 against 37 dry days in 1993. The effect of dry days during the rainy season on cotton yield was significant ($P < 0.01$): an increase of one dry day during the rainy season lead to a yield loss of 41 kg/ha. Within the growing season, the increase of the number of dry days was significantly related to the number of 5-day and 7-day period dry spells (Fig. 9). It therefore seems that length of the dry spell is a good indicator for the quality of the rainfall distribution within a growing season. Multiple linear regressions indicated a significant effect of rainfall on cotton yield: on average 1 mm of rain is converted into 2 kg of cotton (Table 1). The estimated impact of the decline in seasonal rainfall between 1965 and 1993 on cotton was -17 kg ha^{-1} year^{-1}, -4 kg ha^{-1} year^{-1} for minimum temperature, and 4 kg ha^{-1} year^{-1} for maximum temperature (Table 2).

Table 1
Multiple linear regression analysis of cotton yield and climatic variables in the long-term experiment conducted from 1965 to 1993 at N'Tarla agricultural research station, southern Mali.

Variable	Estimate	SE	*t*-Value	*P*
Intercept (kg/ha)	256	7430	0.03	0.97
Yield effect of				
Seasonal rain (kg/ha/mm)	2.1	0.95	2.18	0.04
Seasonal T_{min} (kg/ha/°C)	−66	202	−0.33	0.75
Seasonal T_{max} (kg/ha/°C)	53	267	0.2	0.84

Multiple $R^2 = 0.31$, $P = 0.05$.

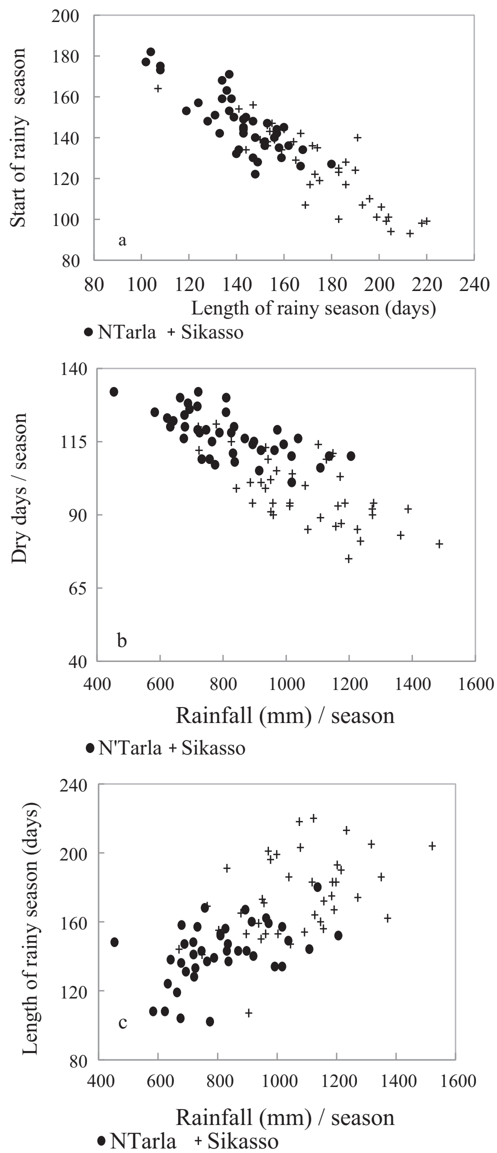

Fig. 3. Relationships between climatic variables from 1965 to 2005 at N'Tarla and Sikasso in southern Mali. (a) Regression of length of rainy season and onset date for N'Tarla: $Y = -0.70x + 246.46$ ($r = 0.81^{***}$, $n = 41$) and Sikasso: $Y = -0.64x + 236.97$ ($r = 0.86^{***}$, $n = 41$). (b) Regression of seasonal dry days and seasonal rainfall for N'Tarla: $Y = -0.03x + 143.38$ ($r = 0.66^{***}$, $n = 41$) and Sikasso: $y = -0.04x + 140.94$ ($r = 64^{***}$, $n = 41$). (c) Regression of length of rainy season and seasonal rainfall for N'Tarla: $Y = 0.05x + 100.87$ ($r = 0.47^{**}$, $n = 41$) and Sikasso: $Y = 0.07x + 100.79$ ($r = 51^{**}$, $n = 41$).

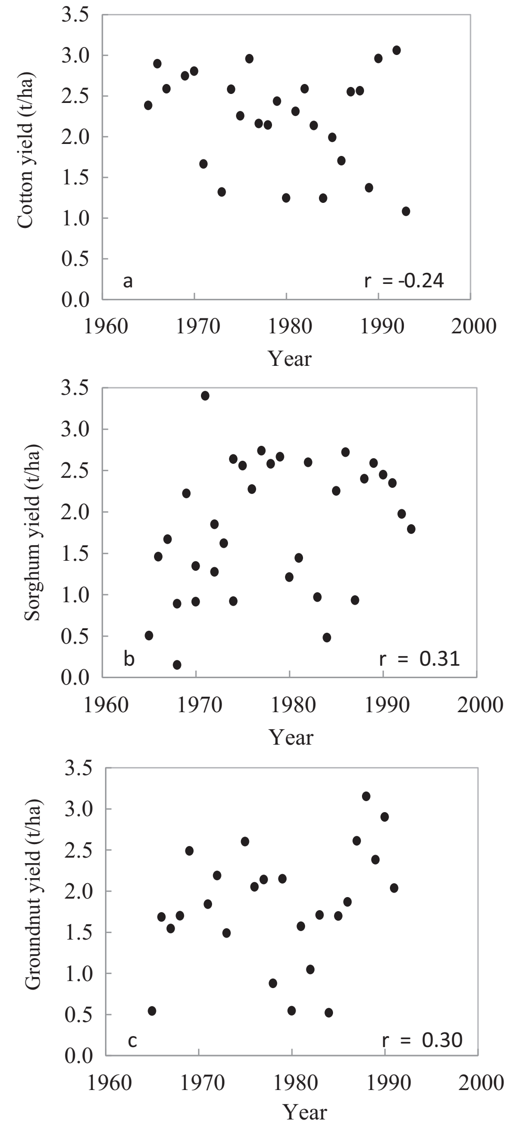

Fig. 4. Yields of cotton, sorghum and groundnut (t/ha) in the treatment with combined application of mineral fertilizer and manure in the long-term experiment conducted from 1965 to 1993 at N'Tarla agricultural research station, southern Mali. (Regressions are not significant for a, b and c.)

The correlation of the average farmers' cotton yields in ten districts of southern Mali with annual rainfall indicated no significant ($P > 0.10$) relationship. There was a tendency towards a negative correlation in the wettest districts (Sikasso, Konlondieba and Bougouni) (Table 3). On the contrary, average maize yields on farmers' fields showed a significant positive correlation with rainfall in the driest districts (San, Diola, Marakakoungo and Konobougou).

Table 2
Trends of climatic variables and impact on cotton yields in the long-term experiment conducted from 1965 to 1993 at N'Tarla agricultural research station, southern Mali.

	Rainfall	T_{min}	T_{max}
Change/season	−7.5	0.07	0.08
Estimated impact (kg/ha/season)	−15.47	−4.29	4.24

4. Discussion

4.1. Climate trends

Observed climate trends at two meteorological stations in southern Mali, N'Tarla and Sikasso, were similar. The increase in the annual minimum temperature of 0.5 °C per decade observed at both stations is higher than the forecast rise of 0.3 °C per decade on a global scale in the next century (Abrol and Ingram, 1997). In the Sahara region and West Africa warming is projected to occur more rapidly than the global average (GIEC, 2007).

There was a significant decrease in rainfall between 1965 and 1993 at N'Tarla, and a significant increase in the number of dry days. From the previous analysis at the scale of West Africa, Nicholson et al. (2000) concluded that a decrease in rainfall occurred during 1968–1997 with annual rainfall on average some 15–40% less in 1968–1997 than during the period 1931–1960. The period between 1965 and 2005 was especially marked by droughts during 1972–1973 and 1983–1984 with respectively 640 mm and 482 mm of rainfall at N'Tarla while at Sikasso it was 765 mm and 671 mm.

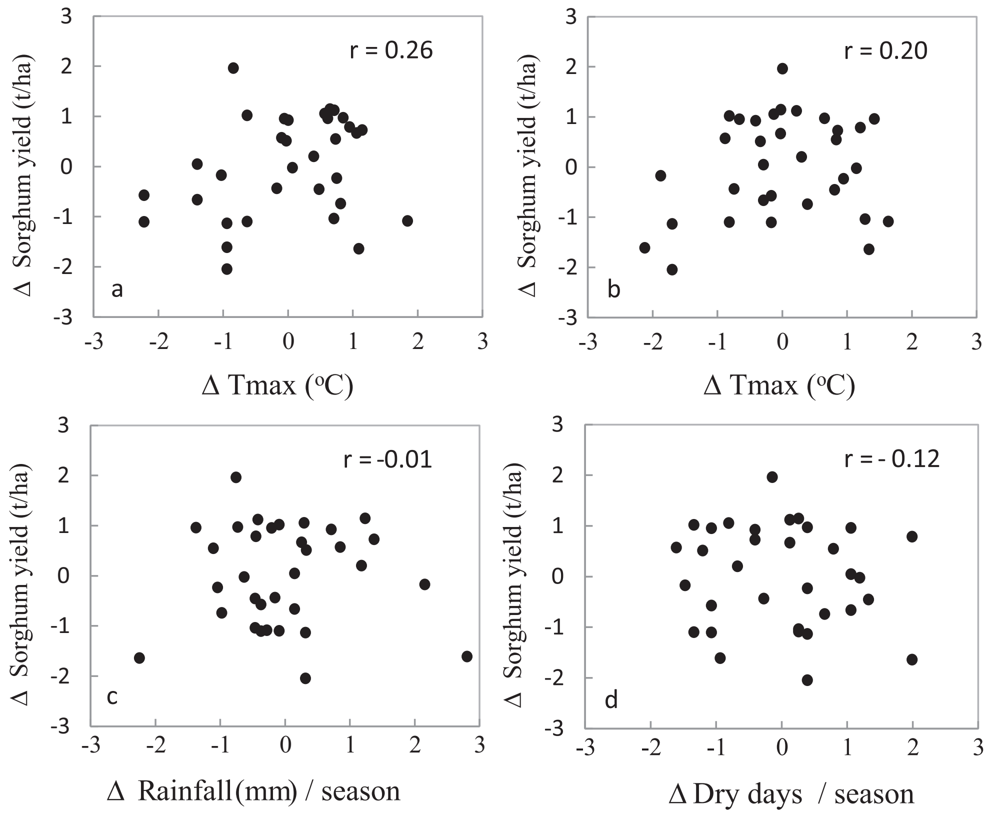

Fig. 5. Changes in mean yields of sorghum (t/ha) against change in seasonal minimum temperature, seasonal maximum temperature, seasonal rainfall and number of dry days in the long-term experiment conducted from 1965 to 1993 at N'Tarla agricultural research station in southern Mali. (Regressions are not significant for a, b, c and d.)

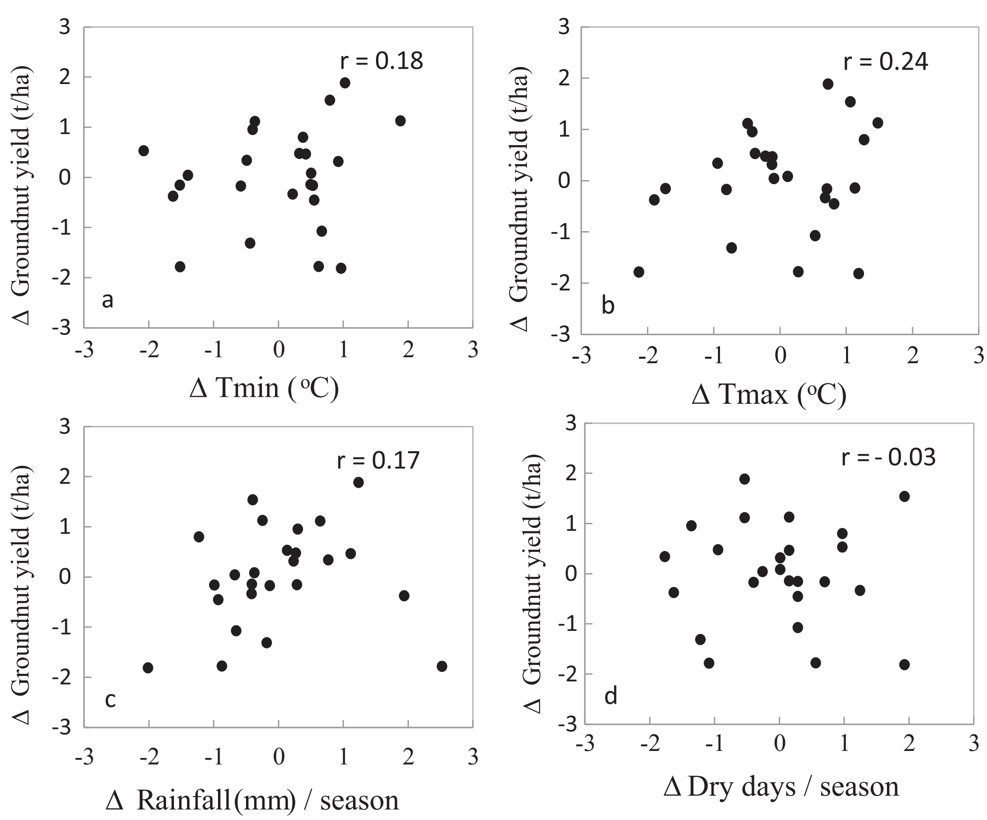

Fig. 6. Changes in mean yields of groundnut (t/ha) against change in minimum temperature, maximum temperature, annual rainfall and number of dry days in the long-term experiment conducted from 1965 to 1993 at N'Tarla agricultural research station in southern Mali. (Regressions are not significant for a, b, c and d.)

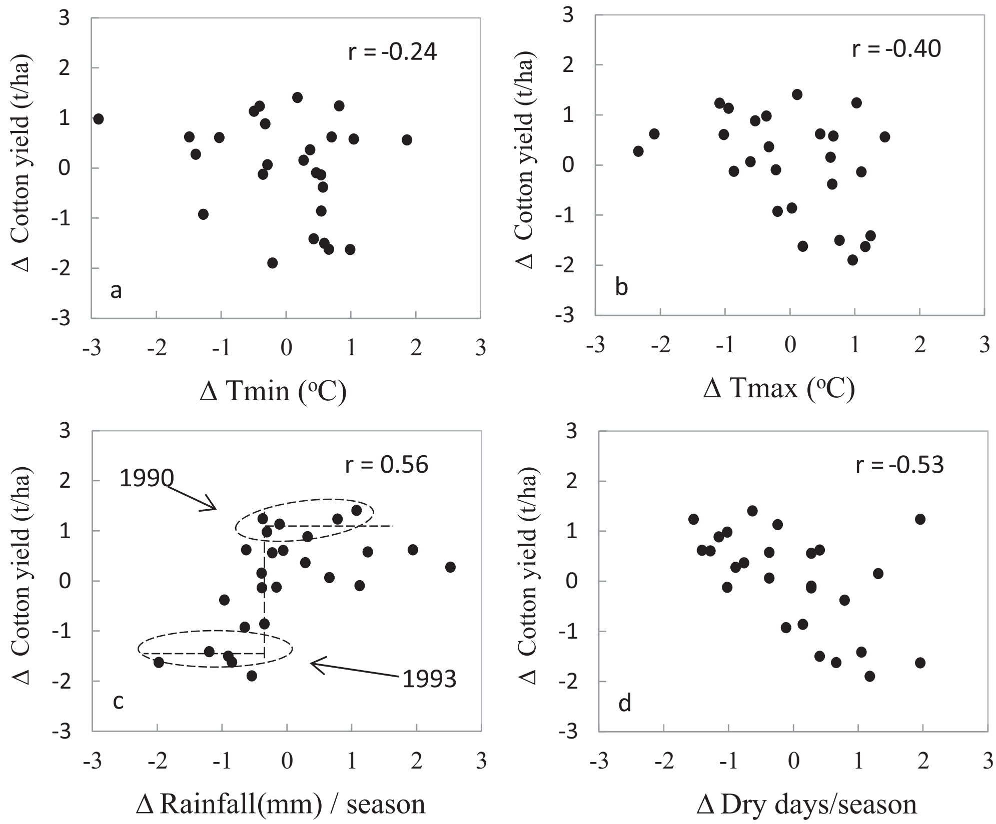

Fig. 7. Changes in mean yields of cotton (t/ha) against change in minimum temperature, maximum temperature, annual rainfall and number of dry days in the long-term experiment conducted from 1965 to 1993 at N'Tarla agricultural research station in southern Mali. Regressions are not significant for a but significant for b, c and d ($P < 0.05$).

Our analysis showed that in terms of rainfall amount and distribution, there is a clear indication that the Sikasso area is currently like what N'Tarla was 40 years ago, and that climate bands are shifting in the region.

There is considerable uncertainty about future rainfall patterns in West Africa (IPCC, 2007). The clearest signal is the large proportional increase in rainfall from June to August in the Sahara where absolute amounts of rainfall are extremely small (Washington and Harrison, 2004). Overall, it is expected that more year to year variation in rainfall will occur in the majority of the zones where an increase in rainfall is projected (FAO, 2008).

4.2. Rainfall variability and associated risk for crop production

The rainfall analysis revealed sequences of dry spells which affect cotton yields. The occurrence of dry spell of 5, 7, 10, 15 and 20 days was highest in May and October (results not shown). This point out the uncertainty of the regularity of rainfall in May which represents the land preparation period, which consequently may delay the planting date and reduce rainy season length. It also indicates the magnitude of the risk of planting in May. In the case of late planting, the grain filling period of varieties of maize such as Sotubaka with a growing cycle of 115–120 days extends until October which also corresponds to a period of high probability of dry spells. Frequent dry spell with high evapotranspiration demand may lead to a decrease in yield of up to 40% because of insufficient water supply during grain filling stage (Barron et al., 2003). Consequently, the significant increase of the number of dry days during the rainy season and its impact on yield makes it one of the most important characteristic of climate change in southern of Mali.

The start date of the rainy season was demonstrated to be the key variable to which all other seasonal rainfall variables are

Table 3
Simple linear regression coefficients between cotton and maize yields against total annual rainfall in 10 cotton districts of southern Mali.

Cotton district	Cotton				Maize				Average rainfall (mm)
	R^2	Slope	Estimate	Prob.	R^2	Slope	Estimate	Prob.	
Koutiala	0.0	0.007	1128	0.965	0.09	0.481	1375	0.258	859
Mpessoba	0.07	0.132	1057	0.55	0.04	0.542	1169	0.49	887
Sikasso	0.03	−0.176	1507	0.333	0.03	0.202	2100	0.467	1114
Bougouni	0.06	−0.201	1322	0.169	0.04	0.326	1564	0.451	1126
Konlondieba	0.09	−0.419	1580	0.123	0.14	0.787	880	0.313	1078
Kimparana	0.07	−0.336	1157	0.212	0.00	0.12	1306	0.865	748
San	0.05	0.472	478	0.281	0.44	1.143	355	0.013	658
Diola	0.03	−0.233	1362	0.353	0.2	0.783	1218	0.091	798
Marakakoungo	0.0	0.017	1113	0.941	0.24	0.922	930	0.059	787
Konobougou	0.0	0.038	956	0.909	0.23	0.865	1015	0.086	719
All districts	0.06	0.2724	855	0.001	0.32	0.988	871	0.001	862

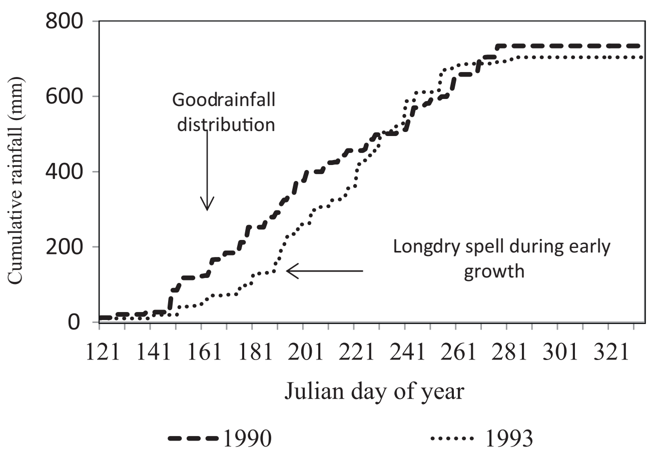

Fig. 8. An example of dry spell analysis for two contrasting years (1990 and 1993) that received similar cumulative rainfall at N'Tarla agricultural research station in southern Mali. The number of dry days was 132 in 1990 and 126 in 1993.

related. Many farmers are aware that rainy seasons with early onset are generally better for crop production than those with late onset (Sivakumar, 1990; Stewart, 1991). The lack of a clear relationship between the start and the end of the rainy season refutes the popular belief that late beginnings of the rainy season are compensated by late ending of rainy season or that rainy seasons become shorter because of a late onset and early end. In the south of the West African Sahel the rainy season starts earlier and ends later than in the north (Traoré et al., 2000, 2007). These characteristics of the Sudano-Sahélien climate are due to the north–south movement of the intertropical front (Diarra et al., 1987; Diop, 1996; Oladipo and Kyari, 1993; Sivakumar, 1988). An early start of the rainy season presents some risks as a long dry spell after planting may result in crop failure. Conversely, a late end of the rainy season will make short-cycle cultivars prone to insect attack and bird damage (Stewart, 1991).

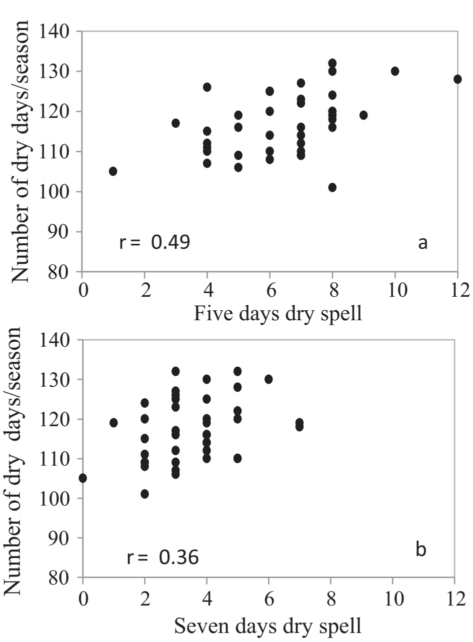

Fig. 9. Regression between dry spells/season and number of five days dry spell (a) and seven days dry (b) periods in a year over the period 1965–2005 at N'Tarla agricultural research station in southern Mali. (a) $Y = 1.9176x + 104.74^{***}$, (b) $Y = 1.9186x + 104.43^{*}$.

4.3. *Increased temperature and associated risk for crop production*

We observed no clear effects of changes in seasonal temperature on production of sorghum and groundnut. A detailed examination of the temperature records of N'Tarla and Sikasso shows that maximum daily temperatures do not exceed 36 °C, while minimum temperatures are above below 20 °C, which seems not to be a limiting factor for sorghum and groundnut production in southern Mali. However, there was a negative effect of increase in seasonal maximum temperature on cotton yield even though reported values in the literature of critical maximum temperatures are around 40 °C (Reddy et al., 1992). Similar effects of temperature increases on rice yields were reported (Peng et al., 2004). Overall, the sensitivity of crops to a temperature increase varies among cultivars because plants have adapted to a relative wide range of thermal environments (Hartwell et al., 1997). C4 cereals such as sorghum respond better to increased temperature than C3 plants such as cotton (Sombroek and Gommes, 1997). Moreover, most of the sorghum and maize varieties grown in southern Mali are local types which may provide more flexibility for adaptation (Clement and Leblanc, 1980; Kouressy, 2002).

High temperatures or heat waves usually occur in conjunction with other environmental stresses such as drought and high light intensity (Rahman, 2006) which might lead to increased crop water requirements and therefore cause scalding in cereals (Burke, 1990), disturb flowering and strongly reduce crop yield (Fisher et al., 1997; Mackill and Coffman, 1982; Zheng and Mackill, 1982). A recent meta-analysis of fully fertilized maize experiments in southern and eastern Africa showed that an increase in the temperature during the growing season can lead to a significant decrease of 3% in maize grain production (Lobell et al., 2011). For cotton, it is observed that the phase of boll formation is most sensitive to high temperatures (Reddy et al., 1992).

4.4. *Climate change, rainfall and crop production*

Analysis of data from the long-term cropping experiment at N'Tarla revealed that cotton is more affected by increase in maximum temperature than sorghum or groundnut. Annual variability in rainfall amounts, rainfall onset, number of dry days during the rainy season and rainfall distribution was large, and determined variations in yield of cotton. Our analysis showed that the number of dry days is a good indicator of the quality of the rainfall distribution for cotton production, and was strongly related to cotton yield. It is clear from this analysis that the number of dry days is as important as seasonal rainfall. Under farmers conditions no clear impact of rainfall on cotton yields was observed, probably because other factors such as low soil fertility and insect attacks which are limiting yields (Kanté, 2001; Lançon et al., 2007), as suggested by the fact that lower yields were observed on farmers' fields than at the experimental site at N'Tarla. It should also be noted that in the wettest districts such as Sikasso, Bougouni and Konlondieba relatively high rainfall amounts might reduce cotton yields as a result of increased air humidity that support development of harmful insects which can cause rot of fruit bolls (Rahman, 2006).

Effects of declining soil fertility on the cotton yield of the control treatment of the N'Tarla experiment (Fig. 10) were more important than effects of climate change during the period 1965 to 1980. Interestingly, after full fertiliser application in 1980, average yields increased but also showed more year-to-year variability. This is possibly related to the fact that after fertilisation, nutrient limitation became less important than water availability for crop yields, thereby resulting in strong links between variations in growing season weather conditions and yield. In sub-Saharan Africa the issues of soil fertility management have dominated the debate

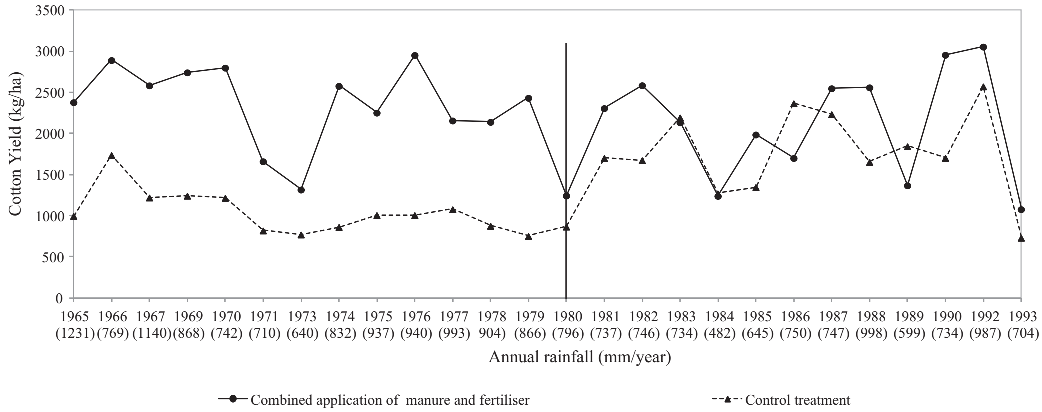

Fig. 10. Cotton yield trend per year under two rates of fertility management from 1965 to 1993 at N'Tarla agricultural research station, southern Mali. The vertical line indicates the start of using 163 kg ha^{-1} of N in both treatments. Values in parentheses represent annual rainfall.

on sustainability of farming for a long time (Breman, 2002; Piéri, 1989). Our findings stress that, effects of declining soil fertility are certainly as important as those of climate effects (rainfall variability and number of dry days) at field level. However, disentangling effects of climate and soil fertility is not straightforward, and results depend on the spatial scale of analysis. Spatial variability of climate is an important factor affecting regional crop productivity in the arid and semi-arid regions (Sivakumar and Hatfield, 1990), a scale at which small-scale variations in soil fertility are averaged out and where long term trends in soil fertility decline are difficult to detect. Extrapolating our results to large scales is difficult because of a large spatial variability in soil fertility within distances as short as a few meters (Brouwer et al., 1993; Buerkert and Lamers, 1999; Manu et al., 1996), diversity in farm types and agricultural management practices (Soumaré et al., 2004; Traoré et al., 2005). All of these factors affect the relative importance of changes in the driving variables of crop production, and it is therefore essential that studies make clear at which integration level there results hold: field, farm, landscape or regional level. A possible solution for this issue could be the use of dynamic crop growth simulation models directly linked to spatial databases containing detail information on soil properties, and management practices. Then the importance of the different factors could be unraveled at different integration levels. However, these databases do not exist at the moment.

The important characteristic determining the relationship between rainfall and crop production was the rainfall distribution which is related to the number of dry days during the rainy season. Better distribution of rainfall changes substantially the relationship between average seasonal rainfall and crop production (Lobell and Burke, 2008). This means that an average total amount of annual rainfall in Sahelian regions is not necessarily synonymous with good rainy season or with good crop production.

4.5. Adaptive crop management strategies

Traditionally, farmers cope with climate variability through risk-averse management practices such as the distribution of early and late crop maturity types throughout the landscape and spreading of sowing dates (Ouattara et al., 1998). This approach indicates that there is a great demand by farmers for climatic information at an intra-seasonal time scale. Accurate seasonal weather forecast information would help farmers to optimize their immediate decisions and tactical planning of crop management. Currently the predictably of seasonal rainfall is highly variable across Africa (Cooper et al., 2008).

An improvement in the seasonal weather forecasting skills and effective agrometeorology extension services are crucial for agricultural communities to adjust to future climate variability. Farmers could use this seasonal climate information to plan crop management tactically, such as adjusting planting and fertilization dates. Our finding shows that the late start of the season determined the length of the season provides an opportunity for farmers to adjust their management by planting shorter-duration varieties when the rains start late. Longer-term information on the nature of climate variability and change may help farmers to design new cropping systems and/or management that is more adapted to the climate. As an example to cope with increased dry spells, land management using contour ridging (Gigou et al., 2006) improves water use efficiency as rainwater on the field is channelled between the ridges, where it filters into the soil and reduces runoff. For cotton systems an alternative management practice based on a high plant density and the use of a crop growth regulators was tested as a way to cope with climate variability and change (Barrabe et al., 2007; Rapidel et al., 2006). With this new practice the crop covers the ground earlier, the cycle of production is reduced by 10–20 days which induces an adaptive behavior to climate variability and change, with yield increases of about 30–40% (Rapidel et al., 2009; Traoré, 2011).

5. Conclusions

Observed climate trends at two meteorological stations in southern Mali, N'Tarla and Sikasso, were similar. The main variable that characterised the rainfall season was the date of start of the rainy season which determines the length of the cropping period. Indeed, the delayed start of the rainy season also causes planting delays and therefore increases the risk of low plant production.

Overall, the impact of seasonal rainfall and maximum temperature variability on cotton yield is greater than that of the long-term changes in climatic variables. The important characteristic between rainfall and crop production is the rainfall distribution which is related to the number of dry days during the rainy season. The significant increase of the number of dry days during the rainy season over the period 1965–1993 and its impact on yield makes it one of the most important characteristic of climate change in southern of Mali. An average total rainfall in Sahelian regions is not necessarily synonymous with good rainy season or with good crop production. In our study which is based on an analysis at field level, it appears that the effects of declining soil fertility are as important as those of climate variability and change. However, disentangling effects of climate and soil fertility is not straightforward, and results depend on the spatial scale of analysis.

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References

Abrol, Y.P., Ingram K.T., 1997. Les effets de la hausse des températures diurnes et nocturnes sur la croissance et les rendements de certaines plantes cultivées. In: FAO, POLYTECHNICA (Eds.), Changements du climat et production agricole, Agriculture mondiale: Horizon 2010. FAO/POLYTECHNICA, Rome, p. 472 (chapitre 6).

Archer, D.R., 1981. Rainfall sequences in northern Malawi. Weather 36, 2–9.

Ati, O.F., Stigter, C.J., Oladipo, E.O., 2002. A comparison of methods to determine the onset of the growing season in northern Nigeria. Int. J. Climatol. 22, 731–742.

Barrabe, A., Rapidel, B., Sissoko, F., Traore, B., Wery, J., 2007. Elaboration and test of a decision rule for the application of mepiquat chloride on cotton in Mali. Eur. J. Agron. 27, 197–204.

Barron, J., Rockström, J., Gichuki, F., Hatibu, N., Hughes, D., 2003. Dry spell analysis and maize yields for two semi-arid locations in east Africa. Agric. Forest Meteorol. 117, 23–37.

Breman, H., 2002. Soil fertility and farmers' revenue: keys to desertification control. In: Shimizu, H. (Ed.), Integration and Regional Researches to Combat Desertification. Present State and Future Prospect. The 16th Global Environment CGER/NIES. Tsukuba, pp. 26–41.

Brouwer, J., Fussel, L.K., Hermann, L., 1993. Soil and crop growth microvariability in the West African semi-arid tropics: a possible risk reducing factor for subsistence farmers. Agric. Ecosyst. Environ. 45, 229–238.

Buerkert, A., Lamers, J.P.A., 1999. Soil erosion and deposition effects on surface characteristics and pearl millet growth in the West African Sahel. Plant Soil, 239–253.

Burke, J.J., 1990. High temperature stress and adaptation in crops. In: Alscher, R.G., Cummings, J.R. (Eds.), Stress Response in Plants: Adaptation and Acclimation Mechanisms. Wiley–Liss, New York, pp. 295–309.

Clement, J.C., Leblanc, J.M., 1980. Prospection des mils pénicilaires, sorgho et graminées mineures en Afrique de l'Ouest. In: Campagne 1978. République du Mali. International Board for Plant Genetic Resources, Orstom, Paris.

Cooper, P.J.M., Dimes, J., Rao, K.P.C., Shapiro, B., Shiferaw, B., Twomlow, S., 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: an essential first step in adapting to future climate change? Agric. Ecosyst. Environ. 126, 24–35.

Deveze, J.C., 2006. Le devenir des agricultures cotonnières: Cas du Mali, Document de travail. AFD, Mali31.

Diarra, B., Lidon, B., Valet, S., Traoré, S.B., 1987. Zonage des potentialités agropédoclimatiques du Mali. In: ICRISAT (Ed.), Les cultures associées au Mali. ICRISAT, Bamako, pp. 17–28.

Diop, M., 1996. A propos de la durée de la saison des pluies au Sénégal. Sécheresse 7, 7–15.

Dodd, D.E.S., Jolliffe, I.T., 2001. Early detection of the start of the wet season in semiarid tropical climates of Western Africa. Int. J. Climatol. 21, 1251–1262.

FAO, 2003. Responding to Agricultural and Food Insecurity Challenges Mobilising Africa to Implement Nepad Programmes FAO. FAO, Maputo, Mozambique.

FAO, 2006. World reference base for soil resources 2006. In: A Framework for International Classification Correlation and Communication. FAO, Rome.

FAO, 2008. Climate and Climate Change: Atlas on Regional integration in West Africa. ECOWAS-SWAC/OECD. Abuja, Nigeria.

Fisher, G., Frouhberg, K., Parry, M.L., Rosenzweig, C., 1997. Les effets potentiels du changement de climat sur la production et la sécurité alimentaires mondiales. In: FAO, POLYTECHNICA (Eds.), Changements du climat et production agricole, Agriculture mondiale: Horizon 2010. FAO/POLYTECHNICA, Rome, p. 472.

GIEC, Bilan, 2007 des changements climatiques. Contribution des Groupes de travail I, II et III au quatrième Rapport d'évaluation du Groupe d'experts intergouvernemental sur l'évolution du climat, Genève, Suisse, 2007.

Gigou, J., Traoré, K., Giraudy, F., Coulibaly, H., Sogoba, B., Doumbia, M., 2006. Aménagement paysan des terres et réduction du ruissellement dans les savanes africaines. Cah. Agric. 15, 116–122.

Graef, F., Haigis, J., 2001. Spatial and temporal rainfall variability in the Sahel and its effects on farmers' management strategies. J. Arid Environ. 48, 221–231.

Hartwell, L., Allen, J.R., Baker, J.T., Boote, J.K., 1997. L'effet fertilisant du CO2: production et rétention accrues d'hydrates de carbone en termes de rendement en biomasse et en grain. In: FAO, POLYTECHNICA (Eds.), Changements du climat et production agricole, Agriculture mondiale: Horizon 2010. FAO/POLYTECHNICA, Rome, p. 472.

IER/CMDT/OHVN, 1998. Mémoire de réunion de concertation sur la baisse de rendement de la variété NTA 88-6 au cours de la campagne 97/98. Institut d'Economie Rurale, N'Tarla, Mali34.

IPCC, 2007. Summary for policymakers. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom/New York.

IRCT, 1969. Expérimentation régionale cotonnière. Station de N'Tarla, République du Mali41.

Kanté, S., 2001. Gestion de la fertilité des sols par classe d'exploitation au Mali-Sud. Documents sur la Gestion des Ressources Tropicales. Tropical Resource Management Papers. Wageningen University and Research Centre Departement of Plant Science, p. 225.

Kucharik, C.J., Serbin, S.P., 2008. Impacts of recent climate change on Wisconsin corn and soybean yield trend. Environ. Res. Lett 3.

Lançon, J., Wery, J., Rapidel, B., Angokaye, M., Gérardeaux, E., Gaborel, C., Ballo, D., Fadegnon, B., 2007. A methodology to design and assess integrated crop management systems: application to cotton in West Africa. Agron. Sustain. Dev. 27, 101–110.

Lobell, D.B., Burke, M.B., 2008. Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. Environ. Res. Lett. 3, 8.

Lobell, D.B., Field, C.B., 2007. Global scale climate–crop yield relationships and the impacts of recent warming. Environ. Res. Lett. 2, 7.

Lobell, D.B., Ortiz-Monasterio, J.I., Asner, G.P., Matson, P.A., Naylor, R.L., Falcon, W.P., 2005. Analysis of wheat yield and climatic trends in Mexico. Field Crops Research 94, 250–256.

Lobell, D.B., Schlenker, W., Costa-Roberts, J., 2011. Climate trends and global crop production since 1980. Sci. Exp. Rep., http://dx.doi.org/10.1126/science.1204531:1-9.

Mackill, D.J., Coffman, W.L.J.R., 1982. Pollen shedding and combining ability for high temperature tolerance in rice. Crop Sci. 20, 730–733.

Manu, A., Pfordresher, A.A., Geiger, S.C., Wilding, L.P., Hossner, L.R., 1996. Soil parameters related to crop growth variability in Western Niger, West Africa. Soil Sci. Soc. Am. J. 60, 283–288.

Nicholls, N., 1997. Increased australian wheat yield due to recent climate trends. Nature 387, 484–485.

Nicholson, S.E., 1980. The nature of rainfall fluctuations in subtropical West Africa. Mon. Wea. Rev. 108, 473–487.

Nicholson, S.E., Some, B., Kone, B., 2000. An analysis of recent rainfall conditions in West Africa, including the rainy seasons of the 1997 El Nino and the 1998 La Nina years'. J. Climate 13, 2628–2640.

Oladipo, E.O., Kyari, J.D., 1993. Fluctuations in the onset, termination and length of the growing season in northern Nigeria Theor. Appl. Climatol. 347, 241–250.

Omotosho, J.B., Balogun, A.A., Ogunjobi, K., 2000. Predicting monthly and seasonal rainfall, onset and cessation of the rainy season in West Africa using only surface data. Int. J. Climatol. 20, 865–880.

Ouattara, M., Vaksmann, M., Reyniers, F.N., Kouressy, M., Niangado, O., 1998. Variabilité phénologique des sorghos du Mali et adaptation à la diversité des agro-écosystèmes. In: Bacci, L., Reyniers, F.N. (Eds.), Le futur des céréales photopériodiques pour une production durable en Afrique tropicale semi-aride. CeSIA, Florence, Italy, pp. 123–137.

Peng, S., Huang, J., Sheehy, J.E., Laza, R.C., Visperas, R.M., Zhong, X., Centeno, G.S., Khush, G.S., Cassman, K.G., 2004. Rice yields decline with higher night temperature from global warming. PNAS 101, 9971–9975.

Piéri, C., 1989. Fertilité des terres de savanes. Bilan de trente ans de recherche et de développement agricoles au sud du Sahara, p. 443.

Rahman, H., 2006. Number and weight of cotton lint fibres: variation due to high temperatures in the field. Australian J. Agric. Res. 57, 83–590.

Raman, C.V.R., 1974. Analysis of commencement of Monsoon rains over Maharashtra State for agricultural planning. In: Scientific Report 216. Meteorological Department, Poona, India.

Rapidel, B., Defèche, C., Traoré, B., Lancon, J., Wery, J., 2006. In-field development of a conceptual crop functioning and management model: a case study on cotton in southern Mali. Eur. J. Agron. 24, 304–315.

Rapidel, B., Traoré, B., Sissoko, F., Lançon, J., Wery, J., 2009. Experiment-based prototyping to design and assess cotton management systems in West Africa. Agron. Sustain. Dev., http://dx.doi.org/10.1051/agro/2009016.

Reddy, K.R., Hodges, H.F., Reddy, V.R., 1992. Temperature eVects on cotton fruit retention. Agron. J. 84, 26–30.

Rosegrant, M.W., Cai, X., Cline, S.A., 2002. World water and food to 2025: dealing with scarcity. In: IFPRI-2020 Vision/International Water Management Book. IFPRI, Washington, DC.

Servat, E., Paturel, J.E., Kouame, B., Travaglio, M., Ouedraogo, M., Boyer, J.F., Lubes-Niel, H., Fristch, J.M., Masson, J.M., Marieu, B., 1998. Identification, caractérisation et conséquences d'une variabilité hydrologique en Afrique de l'Ouest et Centrale. In: Servat, E., et al. (Eds.), Water Resources Variability in Africa during the XXth Century. Abidjan, pp. 323–337.

Shaw, A.B., 1987. An analysis of the rainfall regimes on the coastal region of Guyana. Int. J. Climatol. 7, 291–302.

Sivakumar, M.V., Konaté, M., Virmani, S.M., 1984. Agroclimatologie de l'Afrique de l'Ouest: le Mali. In: Bulletin d'Information. ICRISAT, Patancheru.

Sivakumar, M.V.K., 1988. Predicting rainy season potential from the onset of rains in southern sahelian and sudanian climatic zones of West Africa. Agric. For. Meteorol. 42, 295–305.
Sivakumar, M.V.K., 1990. Exploiting rainy season potential from the onset of rains in the Sahelian zone of West Africa. Agric. For. Meteorol. 51, 321–332.
Sivakumar, M.V.K., Hatfield, J.L., 1990. Spatial variability of rainfall at an experimental station in Niger. West Africa Theor. Appl. Climatol. 42, 33–39.
Sivakumar, M.V.K., Das, H.P., Brunini, O., 2005. Impacts of present and future climate variability and change on agriculture and forestery in the arid and semi-arid tropics. Clim. Change 70, 31–72.
Sombroek, W.G., Gommes, R., 1997. L'énigme: Changement de climat - agriculture. In: FAO, POLYTECHNICA (Ed.), Changements du climat et production agricole, Agriculture mondiale. Horizon 2010, Rome, p. 472.
Soumaré, M., Bazile, D., Vaksmann, M., Kouressy, M., Diallo, K., Hamala Diakité, C.H., 2004. Diversité agroécosystémique et devenir des céréales traditionnelles au sud du Mali. Cah. Agric. 17, 79–85.
Stern, R.D., Coe, R., 1982. The use of rainfall models in agricultural planning. Agric. Meteorol. 26, 35–50.
Stern, R.D., Cooper, P.J.M., 2011. Assessing climate risk and cliamte change using rainfall data – a case study from zambia. Expl. Agric. 47, 241–266.
Stern, R.D., Dennett, M.D., Dale, I.C., 1981. Analysing daily rainfall measurements to give agronomically useful results. I. Direct methods. Expl. Agric. 18, 223–236.
Stewart, J.I., 1991. Principles and performance of response farming. In: Muchow, R.C., Bellamy, J.A. (Eds.), Proceedings of the international symposium on Climatic risk in crop production: Models and management for the semiarid tropics and subtropics, Brisbane, Australia, pp. 361–382.
Sultan, B., Janicot, S., 2003. The West African monsoon dynamics. Part II: the preonset and onset of the summer monsoon. J. Clim. 16, 3407–3427.
Traoré, B., 2011. Fiche technique de la culture du coton à forte densité et à croissance régulée au Mali, Programme Coton. IER, Bamako-Mali.
Traoré, B., Rapidel, B., Sissoko, F., Doucouré, C.T., 2005. Evolution des techniques culturales en zone cotonnière entre 1997 et 2002. Les Cahiers de l'Economie Rurale, 2ème trimestre 2, 21–28.
Traoré, P.C.S., Kouressy, M., Vaksmann, M., Tabo, R., Maikano, I., Traoré, S.B., Cooper, P., 2007. Climate prediction and agriculture: What Is different about Sudano-Sahelian West Africa? chapter 19. In: Sivakumar, M.V.K., Hansen, J. (Eds.), Climate Prediction and Agriculture: Advances and Challenges. Springer, USA, pp. 189–203.
Traoré, S.B., Reyniers, F.N., Vaksmaann, M., Koné, B., Sidibé, A., Yoroté, A., Yattara, K.M.K., 2000. Adaptation à la sécheresse des écotypes locaux de sécheresse. Sécheresse 11, 227–237.
Washington, R., Harrison, M., 2004. African Climate Report: A Report Commissioned by the UK Government to Review African Climate Science, Policy and Options for Action. Climatology Research Group, Oxford University Centre for the Environment, UK45.
WCRP, 1999. Climate Research for Africa. Informal Report No. 16/1999. World Climate Research Programme, International Clivar Project Office Publication Series No. 29. Southampton, United Kingdom.
Zeng, N., 2003. Drought in the Sahel. Science 302, 999–1000.
Zheng, K.L., Mackill, D.T., 1982. Effect of high temperature on anther dehiscence and pollination in rice. Sabrao J. 14, 61–66.