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Does climate opportunity facilitate smallholder farmers' adaptive capacity in the Sahel?

Richard Lalou[1], Benjamin Sultan[2], Bertrand Muller[3] & Alphousseyni Ndonky[4]

ABSTRACT In Africa, adaptation will be crucial to offset expected negative climate change impacts on food security and agriculture development. In this study, we combine meteorological data from 18 local stations, field surveys on agricultural practices and agronomic information on the growth of millet to demonstrate the crop suitability to the present climate and the ability of Senegalese farmers to adapt their practices to climate variability, and to disseminate them. From data collected in both 665 villages and 1061 farmers, our study provides quantitative evidence of the responsive adaptation of farmers in the Sahel where the recent resumption of rainfall has provided new agricultural opportunities. Statistical models and cropping simulations show that these farmers innovate by reintroducing and disseminating a long cycle millet cultivar—more suitable for wet environments. We note that although this adaptation is a clear response to recent changes in quantity and distribution of rainfall, its adoption remains limited (50% of the villages visited and 25% of the surveyed agricultural producers have cultivated the new millet variety) and varies strongly within the same climatic context and by characteristics of farmers (willing and capacity), indicating different agricultural strategies (diversification, market exchanges). If land access and development of cash crops are hindrances to the adoption of sanio, poverty is clearly not a barrier and adaptation is not a lever for wealth creation. Such adaptative capacities, together with government incentives for farmers to sustainably adapt to climate change, can be important in reducing climate risks in the coming years.

[1] MERIT, Université de Paris, IRD, F-75006 Paris, France. [2] ESPACE-DEV, Univ Montpellier, IRD, Univ Guyane, Univ Réunion, Univ Antilles, Univ Avignon, 500 rue Jean-François Breton, F-34093 Montpellier Cedex, France. [3] UMR AGAP, CIRAD/INRA/SupAgro, 34398 Montpellier, France. [4] LPED, Aix-Marseille Université, IRD, Campus International UCAD/IRD, Dakar, Senegal. Correspondence and requests for materials should be addressed to R.L. (email: richard.lalou@ird.fr)

Introduction

Some evidence show that agriculture will be more affected by climate change in Africa than in other regions of the world (Sultan and Gaetani, 2016; Knox et al., 2012; Roudier et al., 2011, Rippke et al., 2016). Smallholder agriculture, the most widespread across Africa, has long been characterised by adaptive and flexible strategies to reduce vulnerability to climate natural variability and soil depletion (Adger et al., 2003, Tschakert, 2007; Eriksen et al., 2008; Thomas et al., 2007). African farmers, particularly in dry land areas, have developed both on- and off-farm adaptation strategies in response to these risks. These are based on four principles: (i) diversification (crops and farming/non-farming activities); (ii) association (different crops on the same field, mixed crop-livestock farming, cultivated/natural spaces); (iii) intensification (labour resources and soil fertility); and (iv) species selection (based on natural conditions and population needs) (Agrawal, 2010). These adaptive strategies have aimed to offset the negative impacts of natural climatic variations and shocks, including droughts, and sustain the agroecosystem, whenever possible, without changing its fundamental attributes (Malik et al., 2010; Parry et al., 2007; Fankhauser et al., 1999).

In the context of climate change in Sahel, these adaptations often had limited impacts and mostly amounted to survival strategies for farmers with no possibility of increased agricultural production. When facing climate-related shocks, resource-poor farmers adopt erosive coping strategies for agriculture, whose long-term impacts are negative on household productivity (Kates et al., 2012; Rickards and Howden, 2012), and/or develop migration strategies (Suhrke, 1994; Findley, 1994; Henry et al., 2004; Lalou and Delaunay, 2017). Thus, if climate shocks require agricultural adaptation strategies from African smallholder farmers, they hinder these adaptations rather than favour them. Climate change can also create agricultural opportunities and farmers can develop strategies to take advantage of them (IPCC, 2014). Unlike shocks, climatic opportunities, such as a rise in rainfall, are likely to increase available natural resources without diminishing household economic capacities. Hence, the question raised in this study is to determine whether climate opportunity is likely to facilitate adaptation of vulnerable agrarian societies.

Just as the relationship between rainfall quantity and crop growth cannot be reduced to a simple causal association (Adejuwon, 2005), climate opportunity and adaptation are linked by interactive and mediatized mechanisms through many factors that drive the adaptive strategy (Mertz et al., 2009; Berrang-Ford et al., 2011; Huq and Reid, 2004; Smit and Wandel, 2006; Kristjanson et al., 2012). Farmers' adaptation to climate opportunity results from the combination of necessary conditions, ancestral know-how, and economic and bioecological utilities. We aimed at establishing the causal link between a climatic factor (the increase in rainfall) and the recurrence of a variety of long-cycle millet (adaptation strategy), describing the spread of long-cycle millet cropping and understanding the determinants of this strategy. To this end, we analysed meteorological, agronomic and socioeconomic databases, collected at different multidecadal timeframes (1950–2015; 1997–2015) in 665 villages and 1061 farms in West Africa across scales (across individuals, farms and villages).

We focused on the old groundnut basin area in Senegal that is characterised by a recent increase in annual rainfall and the reappearance of a long-cycle millet. The study zone (yellow in Fig. 1a) is situated 135 km east of Dakar, lying mainly in the department of Fatick (the Fatick region) and extending into the regions of Thies in the West and Diourbel in the North. It also includes the Niakhar Health and Demographic Surveillance System (HDSS-Niakhar) (green in Fig. 1a), a long-running health and demography surveillance system, which is made up of 30 villages in large majority sereer across 203 square kilometres within the continental Sahel-Sudan climate zone.

The objective of this study is to determine whether a climate opportunity can help farmers to adapt and pave the way for agriculture transformation. We use four databases—meteorological, agronomic, geographic and socio-behavioural—for the various analyses described in the Method section (spatial and temporal correlation models, event coincidence analysis, agronomic simulation and logistic regression). Regarding the results, we show first that decade-long trend of rainfall is very well perceived by farmers, who quickly responded using some adaptive strategies. Second, based on statistical analyses and crop modelling studies, we demonstrate that some farmers are better able to adapt by reintroducing a long-cycle cultivar of millet (sanio), that was abandoned because of the lengthy drought in the 1980s and which is suitable to current weather conditions. Finally, we discuss the determinants of this adaptation strategy and its ability to transform agriculture into the region.

Methods

Data collection. All the databases used in the analyses presented in the previous sections are described in Table 1. Overall, the data used, are of two types:

- Time series of data collected in routine (meteorological data, agronomic data and population data of HDSS-Niakhar). They are generally exhaustive for the covered geographical area and they describe a pluri-decadal evolution.
- Declarative and retrospective agricultural survey data (data on agricultural practices and on the spatial distribution of villages cultivating the sanio). These databases are sometimes exhaustive, sometimes representative (random sample).

To understand the dynamics of the reappearance and distribution of sanio in the study zone we questioned rural populations in all of the villages listed in the territory (usually including the village chief) using a questionnaire with approximately fifteen questions. The questions covered: (i) the use of sanio in the 2015 rainy season; (ii) the year this grain reappeared in the village; (iii) the advantages and drawbacks of growing sanio and (iv) the presence and number of farmers who had never stopped growing this variety. The geographic coordinates of the village centre were taken using GPS. This light survey was conducted between April and August 2015 and gathered information on sanio growing practices from 665 villages in our study zone.

To learn more about the social and agricultural rationales and motivations behind Sereer farmers' decisions whether or not to plant sanio, we conducted a survey in 30 villages in the HDSS-Niakhar and in 1061 family farms (32% of the households in these villages). Two questionnaires were administered at each farm. One was a "household" questionnaire, administered to the head of household, which revealed the crop system used during the 2013 rainy season and included over 45 questions about sanio and souna millet cultivation. A "farmer" questionnaire was then administered to a randomly selected farmer in the household, which covered which crops were intended for sale, such as peanuts and watermelon, or for livestock fattening. Other questions addressed perceptions of the climate today and in the past, and on knowledge of climate change. The survey was conducted from December 2013 to March 2014.

Finally, questionnaire-based surveys were supplemented by several focus groups and individual interviews. These helped further our understanding of the decision-making processes and motivations both for and against planting sanio. The focus groups
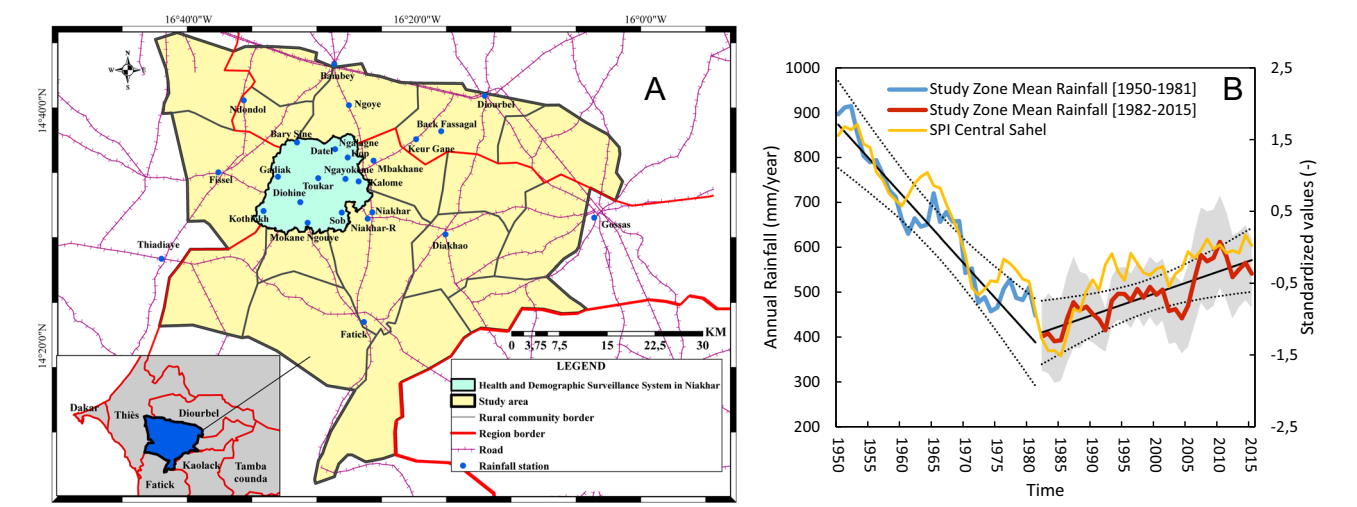
Fig. 1 Map of the study zone (**a**) and Annual rainfall evolution (**b**). Average annual rainfall from 1950 to 2015 in the study zone (blue and red lines). Due to data availability, the time series is based on an average of two stations (Bambey and Fatick) from 1950 to 1981 (blue line) and an average of 18 stations from 1982 to 2015 (red line). The location of the stations is shown on the left map. The black line shows the linear trend over the two-time periods with a 95% confidence interval. The grey shaded area represents values included within 1 standard deviation of the mean of the 18 stations between 1982 and 2015. The yellow time series on the right axis represents the standard precipitation index computed from 43 stations in Central Sahel published by Panthou et al. (2014). A five-year moving average has been applied to all time series to remove high-frequency variability

Table 1 Description of the databases used in the study

Characteristics	Databases			
Data type	**Weather data**	**Agronomic data**	**Spatial distribution data on sanio**	**Farming pratice data**
Responsible services	● ANACIM (Senegal) ● CIRAD (France) ● IRD (France)	● CIRAD (France)	● CIRAD (France) ● IRD (France)	● IRD (France)
Subject/Description	Time series of rainfall (annual cumulation)	Crop model simulations of biomass and yields of souna and sanio millet (kg/ha)	Declarative data on the cultivation of sanio in the villages-History of the cultivation of sanio (16 questions) in the community.	● Routine data from the Health and Demographic Surveillance System (HDSS-Niakhar) ● Survey data on the functioning of farms and on the cropping system
Collection Number of observations	20 collection points followed up for 65 years	Annual yields and biomass from 1950 to 2015	665 villages surveyed, of which 346 had cultivated sanio before 2015	1061 surveyed farmers
Representativeness	Completeness	The simulation is representative at the plot scale at the Bambey station but similar patterns were found using the data of the Diourbel meteorological station.	Completeness	Simple random draw, proportional to village size (survey rate: 1061/ 3265, 32.5%)
Method	Daily reports of precipitation from meteorological and synoptic stations (Diourbel and Bambey) and rain gauges (18 other sites)	Simulations of crop yields and above-ground biomass of souna and sanio millet were performed using the SARRA-H crop model at the Bambey location.	Key informant survey, face-to-face	Survey of farmers, face-to-face
Methods of analysis	Trend (Fig. 1b), correlation (Fig. 3) and Event coincidence (Fig. 4) analyses	Trend and correlation analyses (Fig. 5)	Analysis of the spatial diffusion of sanio crop (Fig. 2a, b)	Analysis of the factors associated with the cultivation of sanio by logistic regression model 2013–2014
Time coverage Space coverage	1950–2015 20 collection stations spread over the Fatick region and in the frontier areas with the Diourbel and Thiès regions. (See Fig. 1a)	1950–2015 At the plot scale at Bambey location	1997–2015 All villages in the study area (See Fig. 1a)	All 30 villages of HDSS-Niakhar (See Fig. 1a)

were also an opportunity to collect information on the history of sanio cultivation in the villages, whether it continued to be planted during the dry season, and how common it was among the rural Sereer population and across this territory. The main focus groups took place in the villages of Sob (March 2012), Ngayokhem (November 2013 and October 2014), and Keur Ngane (November 2013).

Agronomic simulation

Crop model description. We used the process-based crop model SARRA-H Version 32 developed by CIRAD which is particularly suited for the analysis of climate impacts on cereal growth and yield in dry tropical environments (Sultan et al., 2013; Sultan et al., 2014; Dingkuhn et al., 2003; Baron et al., 2005; Sultan et al., 2005). The crop model simulates yield attainable under water-limited conditions by simulating the soil water balance, potential and actual evapotranspiration, phenology, potential and water-limited assimilation, and biomass partitioning (Kouressy et al., 2008 for a detailed review of model concepts). The inputs to the model are daily weather data, latitude, soil depth, soil water content capacity, mulches if any, sowing density and depth, and a series of crop parameters. The water balance simulates runoff using a rain event empirical threshold of 20 mm (Mishra et al., 2008), soil evaporation, storage, deep drainage, transpiration and soil surface evaporation. The soil is divided into a 200 mm top layer used to simulate evaporation and a layer of variable thickness representing the wetted zone. Water holding capacity of the soil between wilting point (pF = 4.2) and field capacity (pF = 3.0) is calibrated from available soil data and is set to 100 mm m^{-1} for this study to represent a sandy soil, which is typical of the major millet-producing soils in West Africa (Bationo et al., 2005). The root front, which descends at empirical rates depending on the growth stage, follows the wetting front but is also limited by it. The maximum root depth is fixed at 1800 mm. Water extraction from the soil consists of two additive components, surface evaporation and extraction from the root zone through transpiration. Potential carbon assimilation rates are obtained by multiplying intercepted photosynthetically active radiation, calculated according to the Beer-Lambert law, with an empirical conversion efficiency coefficient that is analogous to radiation use efficiency (Sinclair and Muchow, 2000) but based on assimilation before subtracting respiration losses. After subtraction of a temperature and biomass dependent maintenance respiration (Penning de Vries et al., 1989), biomass is partitioned during the vegetative stage among roots, stems and leaves according to empirical allometric rules. Leaf biomass is converted to leaf area index (LAI) from dynamically simulated specific leaf area (SLA) (Penning de Vries et al., 1989). Grain filling is simulated to capture the influence of the environment on harvest index by determining sink capacity during pre-floral stages and inducing leaf senescence after flowering when sink capacity exceeds current assimilation rates by decreasing leaves and stem biomass. The phenology is based on simplified concepts of successive phases: basic vegetative phase, photoperiod-sensitive phase (PSP), reproductive phase, flowering and grain filling phase and maturation phase which ends with grain maturity. PSP depends on both temperature and astronomic day length and the other phases have constant (genotypic) thermal duration (Dingkuhn et al., 2008). Daily observed minimum and maximum temperatures are used for the calculation of thermal time depending on temperature thresholds (Dingkuhn and Miezan, 1995).

Crop model calibration and validation. Trials were used to calibrate the model to farmers' varieties (souna 3 and sanio) by adjusting model parameters such as phenological stages, sums of temperature, photoperiod sensitivity coefficients, biomass partitioning coefficients and potential grain yields. These trials were carried out at the Bambey research station of ISRA (Senegal Agricultural Research Institute) in 2008 (Kouakou et al., 2013). Independent data from trials conducted in the same site (1996–1999 for souna 3, 2012 for sanio; see Kouakou et al., 2013) were used to validate the model. These experiments included different plots under varying levels of water supply, but under constantly high nutrient supply and no significant biotic stresses. The performances of the model were assessed using the two following indicators applied to yield estimates at harvest as follows:

Relative Root Mean Square Error : RRMSE
$$= \left(\sum_{i=1}^{n} (Pi - Oi)^2 / n \right)^{1/2} / \overline{O} \qquad (1)$$

Index of Agreement : IA
$$= 1 - \left(\sum_{i=n}^{n} (Pi - Oi)^2 / \sum_{i=n}^{n} \left(|Pi - \overline{O}| + |Oi - \overline{O}| \right)^2 \right) \qquad (2)$$

where Pi = predicted value, Oi = actual value, $\overline{O}$ = average of the actual values, n = number of cases considered (Willmott, 1982). As the performance of a model increases, RRMSE and IA tend respectively towards 0% and 1. After calibration of souna 3 variety, the values of RRMSE (Eq. 1) and IA (Eq. 2) were 36% and 0.76, respectively. RRMSE and IA reach 19% and 0.63, respectively, after the calibration of sanio. More details on these calibration and validation steps can be found in Kouakou et al. (2013).

In this study, we used SARRA-H to simulate crop yields of both souna 3 and sanio over the 1950–2015 period. The simulation was done at the Bambey location, which was the only site in our surveyed area with all the necessary daily weather data to force the crop model (rainfall, global radiation, surface wind speed, humidity, and minimum, maximum and mean temperature).

Statistical analysis.

Rainfall trends were evaluated using data from rainfall measurement stations and from three meteorological stations set up by ANACIM (National Meterology Agency), ISRA (Senegal Institute for Agronomic Research) and IRD (French Research Institute for Development). Our study zone was covered by a total of 26 sites measuring rainfall, including 18 in the HDSS-Niakhar. Geostatistical analyses and mapping representations were produced using ArcGIS Esri^{TM} 10.5.

- The rainfall measurements come from the Bambey and Diourbel meteorology stations and from average total rainfall data from 18 stations in the HDSS-Niakhar (See Table 1).
- The density surface area of villages that had started growing sanio again was obtained from a raster grid that combined the point density at each pixel with nearby points. We combined three methods to statistically limit the geographic sanio zones by the degree of village sanio cultivation—standard deviational ellipse, point density, and hierarchical neighbourhood clusters—and thus defined three distinct areas in the study zone: one with a high concentration in the centre, one with a very low presence of long-cycle millet in the north, and one with a fairly low presence of the grain in the south.

The study of the dynamic interdependencies between different observational time series is made by the traditional correlation analysis and by the event coincidence analysis, which takes the timings of events of two series into account (Donges et al., 2016; Rammig et al., 2015; Sigmund et al., 2016a and 2016b).

- The correlation between the amount of annual rainfall and the renewed cultivation of sanio is based on the estimate of rainfall within each of the three defined areas. Using raster-format files generated by spatial interpolation of the observed data (standard kriging), the average annual rainfall was estimated for every year from 1998 to 2015 and in the three vector-format polygonal areas that represent the degree of sanio cultivation. Once the three rainfall measurement series were obtained, we looked for the best fractional polynomial of annual rain accumulation to define the polynomial function that fits the incidence level of villages adopting sanio with annual rainfall. This function is:

$$f(x) = \sum_{i=1}^{k} \gamma x^{Pi} + \varepsilon \qquad (3)$$

The degrees of the polynomial function (Eq. 3) were tested at all strengths using the group $P = \{-2, -1, -0.5, 0, 1, 2, 3, 4\}$, where p^0 becomes $ln(p)$. More generally, third degree equations were adequate to obtain a good fit. The model that best fit the data was selected using the AIC criterion. All calculations were performed using STATA® 13.1 (2014; Stata Corporation, College station, Texas, USA).

- The event coincidence analysis (ECA) is a method to quantify the simultaneity of events contained in two series of observations, as lagged coincidence within a user-specific temporal tolerance window. The method is particularly effective in highlighting threshold effects, which can be produced by extreme events. Thus, the two time series of data on rainfall (event A) and on the adoptive villages of the sanio crop (event B) have been defined with a binary structure (event/no event) and in relation to a threshold beyond which event A triggers the event B, in proportions that strongly deviate from the average (e.g.: 65th percentile). As part of this study, we analysed the trigger coincidence rates, calculated from the CoinCalc package, an open-source software package written in the programming language R by J. Sigmund (Sigmund et al., 2017). The trigger coincidence rate is:

$$r_t(\Delta T, \tau) = \frac{1}{N_A} \sum_{i=1}^{N_A} \theta \left[\sum_{j=1}^{N_B} 1_{[0, \Delta t]} \left(\left(t_i^A - \tau \right) - t_j^B \right) \right] \qquad (4)$$

where $r_t(\Delta T, \tau)$ measures the fraction of B type events that are followed by at least one A-type event (Donges et al., 2016). The statistical significance of trigger coincidence rate is based on the calculation of event coincidence analysis for a large number of randomly shuffled time series having the same number of events like the original time series ("shuffle.surrogate").

The ECA approach is appropriate for a naive conception of causality, in the sense given to it by physics: the cause precedes the effect, but is not appropriate to causality considered predictive (in the sense of C. Granger).

The explanatory model of sanio cultivation was constructed using data from the questionnaire survey together with information collected on a routine basis at the HDSS-Niakhar. To show that increased rainfall is a necessary but not sufficient condition for growing sanio in the region, we evaluated the effects of farmer and farming practice characteristics on the use of this grain. The individual and household variables incorporated into the model were: farmer's gender, farmers' perception of the climate today, previous practices of sanio cultivation by the farmer's father, the average amount of time spent in seasonal migration by males in the household, the dominant caste of the household, household monetary poverty, and the number of members of the household of working age. The farm-related variables we selected were: available manpower, the amount of arable land owned, borrowed land, commercial agricultural activities (growing watermelons

and livestock fattening), and the number of active household members with non-agricultural income. This model was tested using binary logistic regression on the STATA® 13.1 software.

The sample created for the ESCAPE survey was designed to be representative for all of the 30 villages of the HDSS-Niakhar. To increase the sensitivity of the prediction model, we cleared the model (analysis of residuals), eliminating values that differed significantly from others (outliers) and those that excessively affected the model (leverage points and influencers). The overall adjusted and cleared model was shown to be quite robust (Hosmer-Lemeshow test) and had greater sensitivity, which increased to 77% after the sample was adjusted.

Results

Recovery of rainfall. Rainfall time series in the study zone (see Fig. 1a) show two distinct periods in rainfall evolution since the 1950s (See Fig. 1b). From 1950 to 1981, a rapid decrease in rainfall (−15.64 mm/year) was observed. In contrast, the recent period has seen a partial recovery of rainfall with a positive linear trend ranging between +5.0 mm/year and +7.8 mm/year depending on the rainfall station. Consequently, a 39% increase in rainfall was observed from 1982 to 2015 in the study zone. Following two dry years, 2006 and 2007, the trend of increased rainfall has risen even more sharply since 2008, with precipitation up by an average of 4% per year between the 1998–2007 and 2008–2015 periods (average accumulation of 420 mm and 590 mm per year, respectively). Similar rainfall regimes (levels and trends) have been observed throughout the Fatick department.

Such changes in rainfall are not an isolated feature of this location of Senegal but belongs to a large-scale recent change in rainfall observed in Senegal and in several Sahelian countries (Panthou et al., 2014; Salack et al., 2011). Using 83 rainfall station data, Salack et al. (2011) depicted a similar positive trend in rainfall amount in Senegal associated with some changes in the frequency and intensity of rainy events. In addition, this observed rainfall variability in Senegal fits very well with the decades-long evolution and rainfall trends in Central Sahel as depicted by Panthou et al. (2014), which computed the Standardised Precipitation Index (SPI) with data from 43 rainfall stations in Benin, Burkina Faso and Niger (See Fig. 1b). The correlation between the SPI in Central Sahel and the study zone rainfall time series from 1950 to 2015 is $R = 0.94$.

To assess climate perceptions, individual questionnaire-based surveys were administered in 2014 to 1061 randomly selected farmers in the 30 villages of the HDSS-Niakhar. The questions covered climate characteristics both at the time of the survey and 20 years previously (in the mid-1990s). The responses from the rural populations in this area about recent rainfall trends revealed a close correlation between perceptions and observed rainfall. More than 96% of those surveyed were aware of the recent rainfall increase. The populations surveyed in Senegal clearly perceived the transition observed between a dry period 20 years ago and the present wet period (See Fig. S1). The drought—a major environmental problem two decades earlier for 65% of the population surveyed—has now become just a minor concern, with less than 3% considering it to be a problem affecting their area. The questions that support these results were: *In your opinion, what are the main climate and environmental issues that most affect the area where you live now? In your opinion, what were the main climate and environmental issues that most affected the area where you live 20 years ago?*

Resurgence of the cultivation of sanio millet. Evidence of responsive adaptation by farmers to the recent rainfall recovery they perceived was found with the re-emergence of the cultivation
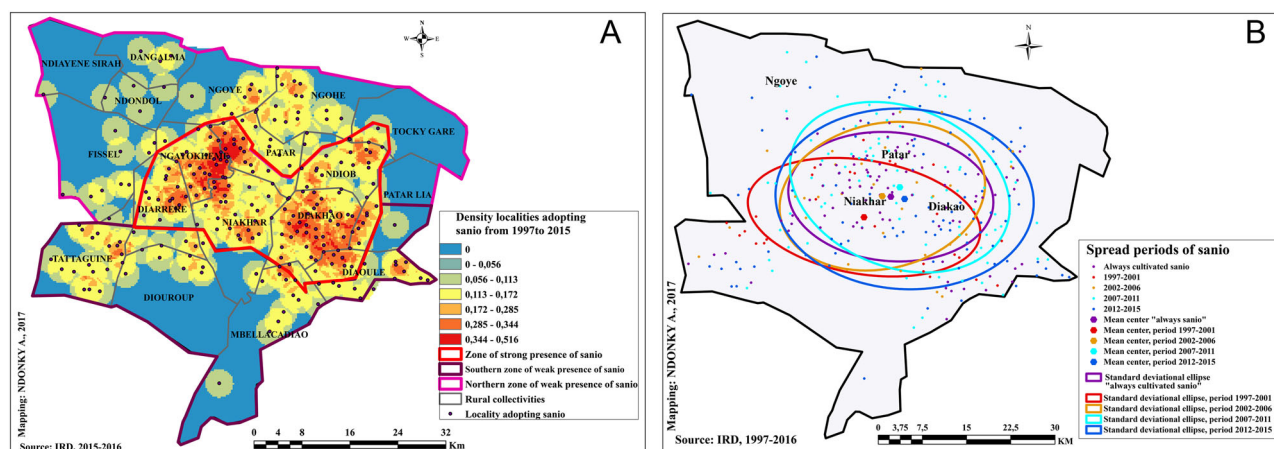
Fig. 2 Density of localities adopting sanio, 1997–2015 (**a**) and Spread of sanio (**b**). The density and diffusion estimate of the sanio are based on the 346 villages that cultivated sanio. In the study area, 319 other villages were surveyed, and no one said they had cultivated the sanio. The latter are not represented on both maps 2a and 2b. **a** evaluates the density surface area of villages that cultivated sanio over the recent 1997–2015 period, using data mapped in **b**. The density surface area of villages that had started growing sanio again was obtained from a raster grid that combined the point density at each pixel with nearby points. The three mains geographic sanio zones were identified by combining three methods: standard deviational ellipse, point density and hierarchical neighbourhood clusters. **b** is a map of the villages in the study zone by period of re-emergence of the cultivation of sanio millet. Villages that have never abandoned sanio cultivation in purple dots. The circles represent the standard deviational ellipses per sanio spread period and the points indicate the mean centres of these dissemination ellipses at different periods

of sanio millet in the study zone (See Fig. 2a). This type of pearl millet has higher water requirements and longer crop duration than the dominant cultivated crop, souna millet—a short cycle (80-day) variety better adapted to drought (Dancette, 1983). Focus groups, interviews and surveys with farmers revealed that while sanio millet was grown in the 1950s, it was abandoned by most farmers in the early 1980s, doubtless because of a succession of poor crops during the 1970s. The water deficit is the main reason cited by farmers for abandoning the cultivation of sanio millet (mentioned by 40% of the people surveyed; see Fig. S2), although other reasons were evoked by farmers that were not necessarily linked with drier conditions (insect and bird damage, soil fertility, lack of seeds).

In 2015, we found that 50.4% of the 665 villages surveyed grew sanio millet. This cultivation primarily reappeared after 1997, and especially in the years since 2008 (180 of 244 villages had resumed planting sanio) although farmers in 91 villages (14%) claimed not to have ever abandoned sanio cultivation. This resurgence was unevenly distributed across the territory surveyed. As Fig. 2b shows, this grain was mainly planted in the central area of the study zone (around two nodes), where 64% of villages reported having resumed growing sanio and 26% reporting they had never discontinued planting it (See Fig. 2b). In those areas, farmers justified the reintroduction of this millet by the better quality of its grain (better taste, more easily digested, more filling) and its stalks for forage, roofing and fences compared to souna millet (See Fig. S2). Conversely, only a minority of villages in both the northern and southern areas had resumed planting sanio (17% in the north and 39% in the south), and very few had never stopped (4% in the north and 12% in the south).

The spreading of sanio remained low for the decades between 1997 and 2015. For each five-year periods, the centre of the elliptical area cultivated in sanio, as schematized in Fig. 2b, extended on average from 2 to 6 km compared to the previous period. Despite a small expansion of the sanio culture to the north between 2007 and 2011, the cultivation of this cereal spread mainly to the west (first period) and south-east (last period).

In the HDSS-Niakhar where we conducted individual surveys, sanio was grown in 27 of the 30 villages (90%) in 2013. However, this practice was not common to all farmers, as only 25.4% of the

1061 surveyed had planted the grain that year. Furthermore, the cultivation of sanio millet is far from supplanting the cultivation of souna millet. In the HDSS-Niakhar, only 89 (14%) of the 630 fields cultivated with sanio millet were sown with sanio alone. The majority were planted with a combination of souna and sanio with fewer rows of sanio, generally at a ratio of one row of sanio to five rows of souna. In total, sanio only represented 3% of all planted fields and 7.3% of the grain fields in the 30 villages in the HDSS-Niakhar (See Fig. S3) (Muller et al., 2015). This indicates that even though farmers prefer sanio millet and have perceived that the climate is now favourable for its cultivation, they are aware of the risk of only cultivating a more water-intensive crop under a variable climate environment and that planting several varieties of millet can shield them from the risks of an unstable rainy season.

A link between rainfall and the re-emergence of sanio millet. Clearly, the re-emergence of sanio millet is linked with rainfall variability (See Fig. 3a). We found that the incidence rate of villages adopting sanio millet is slightly correlated to past year rainfall throughout the study zone ($R^2 = 0.36$). But we also found that the increase in annual rainfall accumulation strongly affects the resumption of sanio cultivation from north to south in this region. In the central area of the study zone, the annual incidence of villages adopting sanio increased 2.4 times more quickly than in the south and 4.2 times more quickly than in the north (calculated from adjusted regression coefficients). Annual rainfall better explains the expansion of sanio cultivation—albeit quite small—in the north ($R^2 = 0.76$) than in the south ($R^2 = 0.53$) or even in the centre ($R^2 = 0.56$), where sanio has spread more extensively.

Across the entire study zone, more than 6.3 new villages adopt sanio millet per year when the average rainfall is around 415 mm by growing season and exceeds 25.6 villages per year when the rainfall averages between 580 and 620 mm by growing season (See Fig. 3a). The incidence of villages adopting sanio millet increases when there is more than 530 mm of annual rainfall in the centre of the study zone and more than 600 mm in the south (See Fig. 3b).
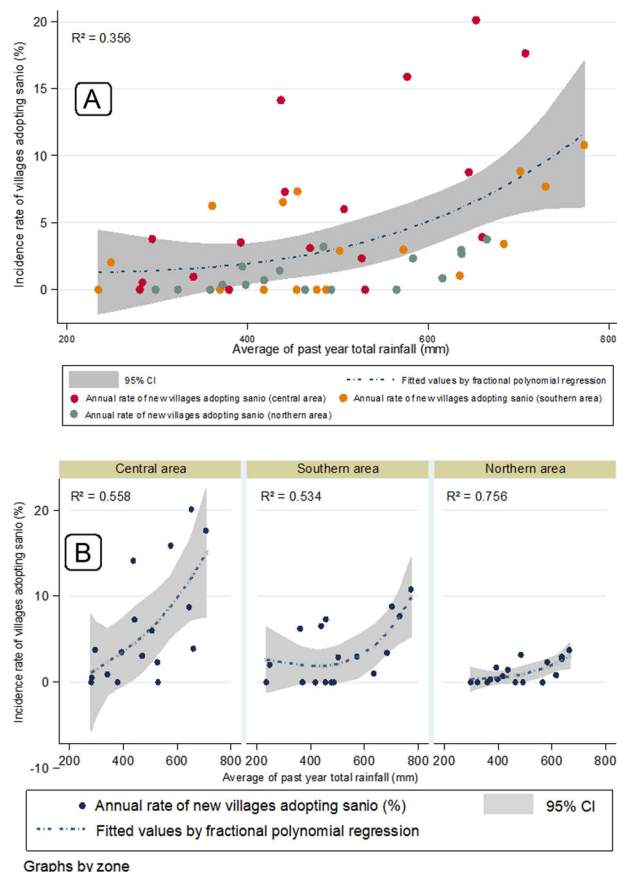
Fig. 3 Correlation between rainfall and sanio–**a** for the entire study zone and (**b**) by area. Figure 3 shows non-linear fitting between the incidence rate of villages adopting sanio millet and the average of past year total rainfall. The incidence rate indicates the number of new villages adopting sanio relative to the number of villages that have not adopted sanio millet (including the new villages). The average of past year total rainfall is the rainfall observed the year before the adoption of sanio millet. The fitted curve is calculated using a fractional polynomial regression with Stata 13.0®. **a** shows the fitted curve for the entire study zone. **b** shows the fitted curve by geographic sanio zone

In order to investigate more deeply the quasi-simultaneity of two events (annual rainfall and the adoption of millet by villages), we apply event coincidence analysis (ECA) (Donges et al., 2016; Siegmund et al., 2017), a novel yet conceptually simple statistical method. For this, we consider: the years according to whether or not they exceeded a certain threshold of cumulative rainfall and the years when the proportion of village adopting millet culture were greater (or not) than the 65th percentile of the distribution of villages adopting millet, for a given territory. It is assumed that the first event will trigger the second, if the latter occurs within two years after an annual rainfall above the defined threshold. The percentage of years which, having exceeded the annual rainfall threshold, triggers in the next two years a strong conversion of villages to the cultivation of millet, sets the trigger rate.

Figure 4 shows the evolution of the trigger rate of a high adoption of sanio millet culture by the villages, according to different rainfall thresholds and for each area studied. Overall, the culture of sanio millet has spread more rapidly and more strongly (in absolute numbers) in the central part of the study area compared to the northern and southern villages (See Fig. 3b). However, the same rainfall amount is related to a comparable village trigger rate of sanio millet diffusion (See Fig. 4). Beyond

500 mm of annual rain, the sanio culture is adopted, in nearly 75% of the rainy years, by a substantial proportion (above the 65th percentile) of villages. With more than 600 mm of annual rainfall, it is almost 100% of the very rainy years that trigger this same level of adoption of the Sanio among the late village adopters. In-below of 500 mm, trigger coincidence rates are more dispersed between zones, but are also overall less reliable at the 5% error threshold.

Simulations of crop yield (See Fig. 5a) and above-ground biomass (See Fig. 5b) of souna and sanio millet were performed using the SARRA-H crop model at the Bambey location. Crop yield simulations confirmed that even modest yields of sanio millet could not have been obtained during the 1970s and 1980s and most of the 1990s (See Fig. 5a). The synchronicity between the time series of crop yields and the evolution of the adoption rate of sanio by farmers is shown in Fig. 4a. The cultivation of this crop only became truly feasible again at the beginning of the 2000s, which corresponds roughly to the time it was re-adopted by farmers (See bars in Fig. 5a). In contrast, souna millet cultivation remained possible, but, of course, experienced several very bad years during the severe droughts of the 1980s. This can be explained by the different response of the crops to rainfall fluctuations in the crop model. The simulated crop yield of sanio millet is highly correlated to annual rainfall ($R = 0.80$) while souna millet is less responsive, with a correlation of $R = 0.56$ between crop yield and rainfall (See Fig. 5c). Souna millet is less sensitive to drought with higher yield than sanio millet when rainfall is below 600 mm per cycle.

Although the simulated crop yield of sanio millet clearly increases from the end of the 1990s, it is still more variable than that of the souna variety. The standard deviation of sanio millet yield is 986 kg/ha between 1995 and 2015 and only 663 kg/ha for souna. This high variability might explain why most farmers continue to grow the two crops together instead of investing everything in a single risky cultivation.

In contrast, we found in our simulations that it has always been possible to achieve good straw production with sanio millet (See Fig. 5b). This biomass production is usually greater than that of souna under the same management conditions because the crop is taller, and its cycle is about one month longer. This might explain why a significant number of farmers never abandoned the sanio cultivation (See Fig. 2b).

Discussion

This study confirms the observations already made by many researchers: smallholder farmers in the Sahel have adapted to changing climatic conditions over the period 1997–2015. They are well aware of the impacts of climate change on their agricultural production and they adapt their practices to try to reduce the negative effects or seize the opportunities of climate change (Altieri and Nicholls, 2017; Conway, 2011; Barbier et al., 2009; Mertz et al., 2010; West et al., 2008). The studied response to a favourable climate change—just like it would be to a climate-related shock—is responsive in nature, on the initiative of farmers and rooted in village community traditions (Crane et al., 2011). Finally, it is a strategy of risk reduction through crop diversification, a prevalent practice in Africa (Agrawal, 2010; Burnham and Ma, 2016).

Analyses of various databases show that the cultivation of sanio, a long-cycle millet, which had nearly disappeared from the Fatick region for nearly a quarter of a century, has once again spread throughout the study zone (in the centre of the Fatick department). The resumption of sanio cultivation is clearly associated with increased rainfall, including the crossing of the 550–600 mm/year threshold starting from 2008. These
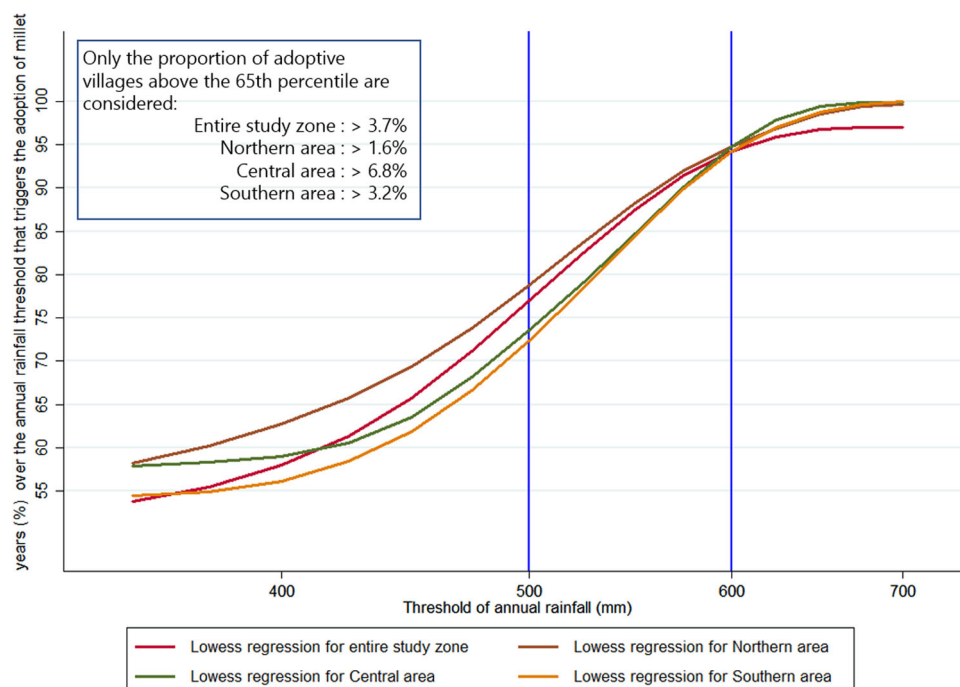
Fig. 4 Percentage of years over the annual rainfall threshold that triggers the adoption of millet by area for the 1997–2015 period. The indicator in the graph was calculated using the event coincidence analysis (Package CoinCalc) under R. The smoothed curve was calculated by local regression (lowess). This indicator represents the trigger coincidence rate for the adoption of millet by the villages, according to an annual rainfall threshold. For each area, a rainy year is considered a stimulus that triggers the adoption of millet, if the proportion of new villages adopting the cereal, in one of the following two years, exceeds the 65th percentile of the distribution of millet-growing villages. For example, about 95% (trigger rate) of years (t) exceeding 600 mm of annual rainfall triggered the adoption of millet by at least 6.8% of new villages in the central area, at year $t+1$ or $t+2$. Starting from 500 mm of annual rainfall, all trigger rates are significant at the 5% threshold. Before this level of annual rainfall (500 mm), 46% (11/24) of the calculated rates are not significant
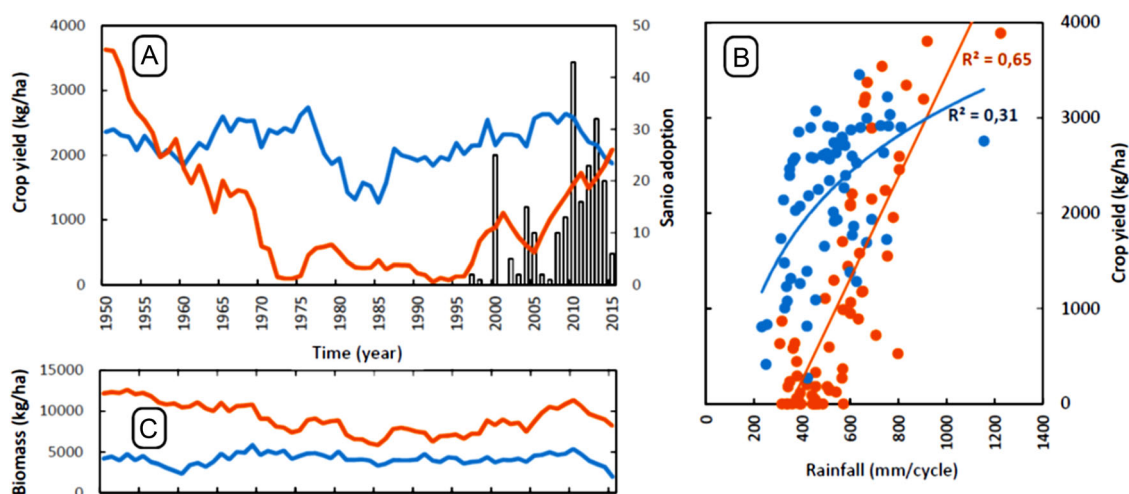

Fig. 5 Crop simulation of souna and sanio millet. **a** crop yield (kg/ha) and (**b**) above-ground biomass (kg/ha) of souna (blue line) and sanio (red line) millet simulated by the SARRA-H crop model at the Bambey location. A five-year moving average was applied to all time series. The bars represent the adoption rate of sanio by farmers, which is the number of new villages adopting sanio millet each year in the HDSS-Niakhar. **c** Relationship between crop yield (kg/ha) and annual rainfall (mm/year) at the Bambey location. A logarithmic fit has been applied for souna millet simulations (blue) and a linear fit has been applied for sanio millet simulations (red). The coefficient of determination (R^2) of those two fits is 0.3102 and 0.6449 for souna millet and sanio millet, respectively

observations are corroborated by our simulations and by the agronomic experiments conducted in 1976/1977 in our study area by C. Dancette et al. (1979, 1983), who estimated that the water requirements for 120-day millets (like sanio) were at least 562–657 mm.

The recovery of sanio culture is not a strictly opportunistic practice. It also falls within a strategy to reduce the risks and

increase cereal production. In the area covered by the HDSS-Niakhar, 2014 was a dry year, with a decrease of 200 mm of rain compared to 2013, and with a dry spell of 31 days between July and August (rainy season). This rain shortage led to a 34% reduction of the number of sanio producers. However, the great majority of growers continued to produce sanio, because this crop is better suited to late rainfall in the season, and that it was able to

partly compensate the poor harvest of the short-cycle millet (*souna*, in Wolof). Thirty-five percent of farmers felt that using sanio allowed them to diversify their crops and thus ensure better food security (See Fig. S2). Therefore,the double cereal crop (souna and sanio) over the growing season limited the risks associated with a high rainfall variability during the rainy season.

Although all the farmers living in the study zone's villages were subjected to the same climate conditions, and generally aware of the increase in annual rainfall (Kosmowski et al., 2015), not all of them resumed planting sanio millet, nor did they do it at the same degree. Sanio is only densely planted in the central area of our study zone (where 2 out of 3 villages resumed growing sanio). In the south, and to an even greater extent in the north, this grain remains much less common, grown in 1 out of 3 villages in the south and only 1 out of 5 villages in the north (See Fig. 2a). Thus, while the recovery of higher rainfalls explains why sanio was once again being planted, it does not explain its uneven adoption.

One reason for these geographic differences is that sanio farming is an expression of traditional practices for a variety of millet that is typical of the agricultural system and rural identity of the Sereer farmers in the Fatick region (Pelissier, 1966). In the villages of the central study zone where sanio cultivation is the densest, 27% of village key informants reported that some farmers in the village never stopped growing this long-cycle millet even during major droughts, as opposed to 12% in the south and 4% in the north. This rustic variety of millet has doubtless been preserved by a handful of farmers. A few of them reported that they had planted sanio in their compound yard plots, where the plants received runoff domestic water. So they were able to produce stalks and grains even in dry years. The farmers in the central study zone invested a lot in sanio production, some even before rainfall levels reached the 550 mm/year threshold (See Fig. 3b). Our survey data from farm operators further revealed that those whose fathers grew sanio in the past were nearly three times more likely to grow it in 2013 than those without this family tradition (OR = 2.72; $p = 0.000$, See Table S4) (Muller et al., 2015).

Sanio cultivation is an adaptation which seizes a climatic opportunity. It therefore does not seek to address a shortage, but to mitigate risks—those associated with intra-annual climate variability—and increase food productions. More rainfall at the end of the agricultural season allowed farmers to reduce somewhat their vulnerability and reconnect with an ancient cropping system. But due to the low financial and technical means of the vast majority of peasants, this climate opportunity has not led to a transformation of agriculture. The resurgence of rainfall has sometimes promoted commercial development of agriculture, but these market exchange adaptations (Agrawal, 2010) have remained insufficient to transform the regional economy. Watermelon in the Fatick and Kaolack regions, and rainfed rice and corn in the Kaolack region, are all agricultural products that thrive when rainfall increases, especially at the end of the rainy season. Unlike sanio millet, these crops generally require some investment (seed, fertiliser, phytosanitary products, equipment, etc.) as well as the mastery of cultivation techniques. Moreover, the cultivation of these commercial products has expanded in parallel with urban consumption and livestock feed factories and is supported by active farmer organisations and structured value chains.

In the HDSS-Niakhar study area, some high-income farming practices appear to limit the cultivation of sanio, such as cattle fattening (OR = 0.66; $p = 0.081$) and watermelon culture (OR = 0.57; $p = 0.079$), although statistical associations are significant to less than 10% (See Table S4). The opposite choice between sanio farming and commercial practices can also be assumed by the negative effect of the number of farmers managing plots per farm on sanio cultivation. Generally, apart from the

farm head, family members work on plots for their own benefit (sales of production). Therefore, the greater the number of farmers in the same farm, the less likely the farm will produce sanio (OR = 0.91; $p = 0.008$). Conversely, farmers are more likely to plant sanio as they had a large amount of farmland (OR = 1.14; $p = 0.000$) or if they borrowed land (OR = 2.08; $p < 0.001$) (See Table S4). The opposition between a market exchange adaptation, which requires a greater capital investment, and adaptation based on sanio farming is finally shown by the fact that households that are the poorest monetarily are those that grow sanio (OR = 2.03; $p = 0.000$). In 2014, the monetary poverty threshold was estimated at 479 FCFA (1 US$[1]) per day per adult, in the HDSS-Niakhar, and half of the population (52%) were poor. Thus, poverty is not a barrier to this diversification adaptation because no additional investment or technical expertise is needed to grow sanio. But this non-commercial food production is not a lever for wealth creation, contrary to what may have been observed from other adaptations (Ali and Erenstein, 2017).

Unlike climate shock, climate opportunity does not weaken farmers' adaptability. However, it does not increase it further. It is at most a positive stimulus that can (or not) promote adaptations (diversification, trade exchanges), depending on the initial socioeconomic status of farmers. Moreover, if specific climate conditions are necessary to trigger a process of transformation in the case of rainfed agriculture, it is the market that is often the most powerful driver to transform the local economy and improve economic and technical capital, and land tenure of farmers. The cultivation of a variety of long-cycle millet is not an innovation to transform the cultural system and the sereer agricultural economy. It is at best a non-erosive adaptation, accessible to the poorest farmers, well integrated into the traditional cultural sereer system and which improves the household's food security.

Conclusion

In West Africa, as elsewhere in the world, the adaptation of agriculture to climate change is not new. Mainly rainfed, small-scale African agriculture is highly subject to climate change and variability, compelling farmers and their families to implement adaptation strategies to maintain their standards of living and agricultural production, fodder, firewood and building materials. Even in the absence of economic and technical means, African farmers are therefore neither necessarily nor totally vulnerable to climate events. However, their answers must also deal with all the constraints, uncertainties and limitations that reduce their ways of acting. This results in minimal adaptations, sometimes ecologically sustainable and rarely transformational.

In Central Senegal, the combined cultures of short-and long-cycle millets improve the food security of some farmers and protect them against poor distribution of rainfall during the agricultural season. For example, the cultivation of watermelon, by other farmers allows trading exchanges, the modernisation of production techniques and reduction of economic vulnerability. The balanced association on the farm of staple and cash crops has long been a principle of the sereer agrosystem that participated in both the ecological maintenance of soil fertility and emergence of agricultural innovation. However, increased rainfall in this poor area may, while developing new opportunities, also deteriorate the traditional agro-system by upsetting the fragile balance between staple and cash crops.

This study illustrates the capacity of farmers in the Sahel to adapt to climate fluctuations. However, more research would be needed to fully understand the limits of such responsive adaptation to face radical climate changes. Indeed, warm and drought conditions in the west Sahel simulated by climate models with the increase in greenhouse gas emissions have no analogy with the

past we can draw on to make predictions for the future (Sultan et al., 2013). Farmers' spontaneous adaptations per se may not be enough to limit the negative effects of climate changes. Current practices may need to be combined with proactive, anticipatory adaptation (Hertel and Lobell, 2014). A positive adaptation strategy would incorporate new agricultural technologies to improve breeding more resilient crop varieties and innovating water harvesting techniques. Another important factor to enhance adaptation to climate change is related to institutional changes that affect markets and policies. The smallholder farmers from the Sahel should be able to access fertiliser subsidies, crop insurance, credits and weather and climate forecast services to reach their maximum potential to adapt to future climate conditions.

Data availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Notes

1 Exchange rate on 01/01/2014.

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Additional information

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