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Characterizing and modeling the diversity of cropping situations under climatic constraints in West Africa

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Abstract

The Sahel region is known for the high vulnerability of its agriculture to climate variability. Early warning systems that make use of agrometerological forecasts are one of the coping strategies developed by policy makers. However, the predictive quality of the tools and methods used needs improvement. In order to address some of these challenges, we conducted agronomic trials and on-farm surveys to adapt the SARRAH (Système d'Analyse Régionale des Risques Agroclimatiques, version H) crop simulation model, and also evaluated it in farmers' field conditions. The farmers' practices such as sowing dates and densities, fertilizer use and yields potentials of the millet and sorghum crops were characterized under different climatic conditions. Copyright © 2010 Royal Meteorological Society

Keywords: **climate impact; agriculture West Africa; farmer practices; sorghum; millet**

1. Introduction

The Sahel region of West Africa is known for the high vulnerability of its agriculture to climate variability (Mishra *et al*., 2008). The unprecedented droughts of the early 1970s, both in terms of physical dimensions (duration and spatial extent) and human impacts (thousands to millions of inhabitants affected), prompted the creation of early warning systems in the region, among which is the CILSS/AGRHYMET (French acronym for Permanent Inter-state Committee for Drought Control in the Sahel/Regional Center for training and applications in operational AGRicultural METeorology and HYdrology), which uses agrometeorological information to warn stakeholders on the possibility of food crops failure. For that purpose, a crop water balance simulation model, DHC (Diagnostic Hydrique des Cultures), was developed in the early 1990s and put into operational use in all CILSS member countries. Throughout the years, some deficiencies of the model were underlined, namely that its results were valid only for the sole millet crop and that it underestimated crop yields in the more humid Sudanian zones. The main objective of this study was to adapt and evaluate a new crop model, SARRAH (Système d'Analyse Régionale des Risques Agroclimatiques, version H), of the main food crop varieties and farming situations of the area in order to incorporate it into the crop forecasting system and improve its performance. The main issues related to this objective were the high variability of crop yields among farmer plots within the same village, among villages not very far away from each other and from one year to another. Of course, rainfall variability, both in time and space, plays a major role in this, but some previous studies (Traoré *et al*., 2000; Kouressy *et al*., 2008a) pointed out that farmer practices and coping strategies should be taken into consideration in explaining this yield variability. They consist mostly in using local photoperiod-sensitive sorghum and millet varieties and low-input practices (low fertilizer use, low planting densities, no irrigation, etc.). The second objective of this study was to assess the possibility of coupling the crop model with weather and climate forecasts in order to make yield predictions based on weather and/or climate scenarios (Baron *et al*., 2005; Mishra *et al*., 2008).

2. Materials and methods

2.1. Characterizing farmers' crop varieties and agricultural practices

Local crop varieties grown by farmers have relatively low yield potentials (around 3000 kg ha^{-1}) compared with the 'improved' ones. However, given the current conditions of high climate variability, low input levels and lack of irrigation, the improved varieties with high yield potentials have the same, if not lower performances as the local ones that are adapted to the variability of the season duration and more resistant to pest and diseases. These considerations lead us to focus on the characterization of the most widely used varieties for the purpose of modeling their growth and development and forecasting their yields.

As the cycle duration and yield potential of local crop varieties grown by farmers are poorly documented, we selected some pilot sites where we collected the seeds of the most widely used crop varieties in order to characterize them on experimental plots. Eight regions in Senegal, Mali, Burkina Faso and Niger (Figure 1), contrasting in their respective agroclimatic characteristics (annual rainfall from 450 to 900 mm) and agricultural practices, were chosen not only for seed collection but also for on-farm phenological monitoring and yields measurements.

The on-station trials consisted of (1) assessing the temperature–crop development relationships and the degree of photoperiod sensitivity of the studied varieties and (2) determining the various biomass partitioning coefficients and the corresponding allometric relationships. Photoperiod sensitivity is evaluated by sowing the seeds collected at survey sites at different dates, usually mid-June, mid-July and mid-August (Traore *et al.*, 2000; Dingkuhn *et al.*, 2008), and then from the variation of the duration from sowing to flowering or flag leaf (about 10 days before flowering). As for biomass partitioning, it is assessed through destructive measurements at key phenological stages (Alhassane *et al.*, 2008) and determining the allometric coefficients (slope and intercept of the relationship between the ratio of the weight of leaves to that of total aboveground biomass (leaves + stems) and total biomass).

The on-farm surveys consisted of describing the farmer plot (soil type, type and amount of fertilizer used, sowing date and planting density) and delimiting sub-plots in which the phenological stages and the crop status (pest and diseases, drought, etc.) were monitored every 10 days from emergence to harvest. The sub-plots were fully harvested in order to estimate the grain and total biomass yields of the farmer plot. As an example, in the squared degree area (about 10 000 km^2) around Niamey (13.48N, 2.17 W) where millet is the dominant crop, 30 farmer plots were monitored each year in ten villages and in each plot, crop yield was estimated in three 10×10 m^2 sub-plots.

2.2. Crop model adaptation

SARRAH (Dingkuhn *et al.*, 2003; Baron *et al.*, 2005; Sultan *et al.*, 2005) is a simple, deterministic crop model operating at daily time steps and implemented on the Ecotrop platform of CIRAD (International Cooperation Center in Agricultural Research for Development, Montpellier, France). It simulates attainable yields at the plant population scale according to climate conditions. The soil is divided into a top layer which is used to simulate evaporation and a layer of variable thickness representing the wetted zone. The water not running off and not evaporating from the soil surface is partitioned among storage, deep drainage and transpiration. The rooting front progresses at empirical rates depending on the growth stage and is limited by the wetting front. Potential carbon assimilation rates are obtained by multiplying intercepted photosynthetically active radiation (PAR), calculated according to the Beer–Lambert law, with an empirical conversion coefficient (Epsilon B). This coefficient, similar to the radiation use efficiency (RUE), describes carbon assimilation before the subtraction of respiration losses. After subtraction of a

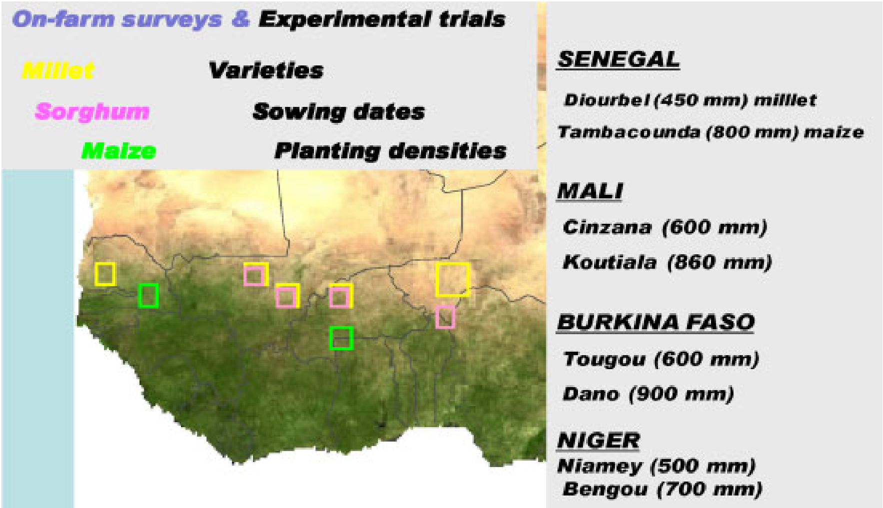

Figure 1. On-farm survey and seed collection sites for the characterization of the farmers' crop varieties and agricultural practices in West Africa.

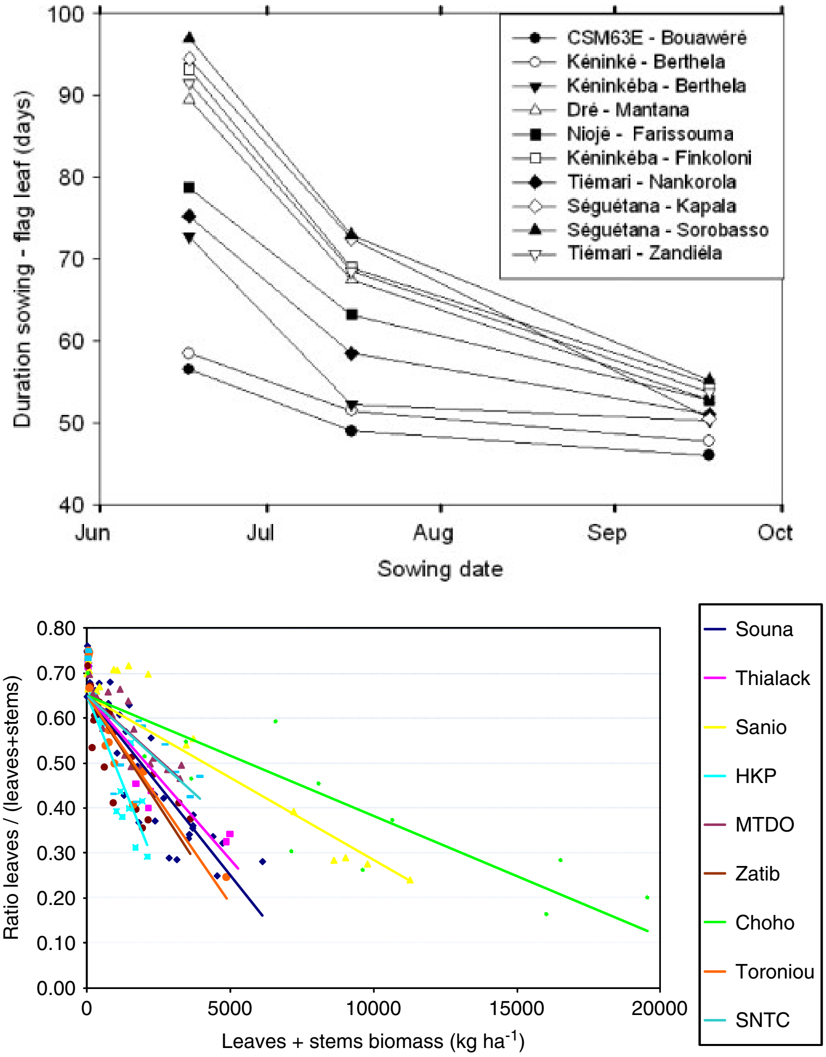

Figure 2. (a) Duration of the sowing to flag-leaf stage of local sorghum varieties collected from farmers in Mali. Because of their sensitivity to photoperiod, the cycle duration of all these varieties changes with sowing date. (b) Allometric relationships of local millet varieties collected from farmers in Senegal, Mali and Niger.

temperature- and biomass-dependent maintenance respiration term (Penning de Vries *et al*., 1989), biomass is partitioned during the vegetative stage among roots, stems and leaves according to empirical allometric rules. Grain filling is simulated with more detail to allow for a variable harvest index by determining sink capacity during pre-floral stages and inducing leaf senescence after flowering when sink capacity exceeds assimilation rate. The phenology is based on simplified concepts of successive phases: basic vegetative phase (BVP), photoperiod-sensitive phase (PSP), reproductive phase (RP) and maturation phase (MP). All these phases are considered to have constant (genotypic) thermal duration except PSP, which depends on both temperature and photoperiod.

In order to adapt the model to farmer varieties, measurements from the agronomic trials were used to readjust model parameters [phenological stages sums of temperatures (in degree-days), photoperiod sensitivity coefficients, biomass partitioning coefficients and potential grain yields; Figures 2 and 3]. The impact of soil fertility was taken into account by attributing correction coefficients according to soil fertility level (optimal, medium and low) to the Epsilon B parameter.

2.3. Crop model evaluation

For model evaluation with on-farm surveys data, we used the genetic coefficients estimated from experiments. Planting densities, sowing dates and soil types required by the model were those observed on farmers' plots. The daily rainfall and the other weather data were obtained from rain gauges installed in the villages and from the nearest weather stations. Simulation scenarios were determined for a given village and year, according to the sowing date and the crop variety. Sowing dates were determined either based on the observed date or, in case of 'dry sowing', the occurrence of a significant rainfall event (>10 mm) after the sowing. In fact, in Sahel, farmers usually sow millet either before or right after the first significant rainfall event (De Rouw, 2004). Also, in the same village, the majority of plots are sown within 5 days. Therefore, sowing dates spanning less than 10 days apart were put

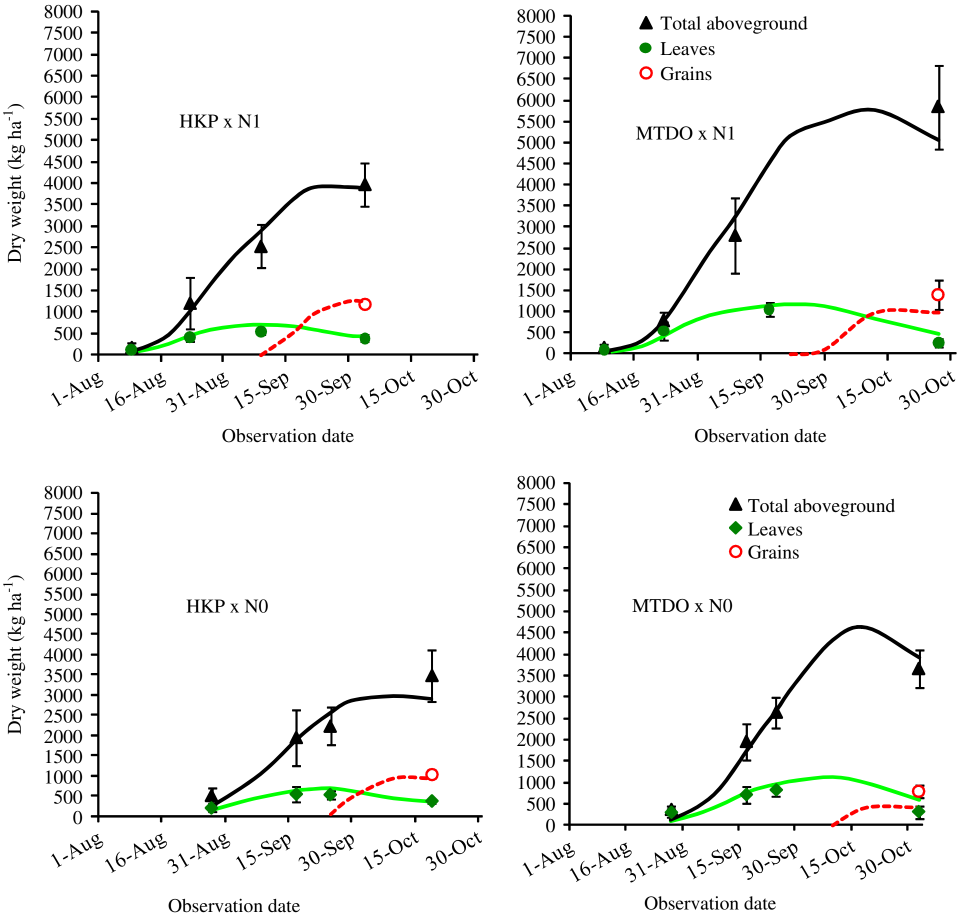

Figure 3. Simulated (lines) and observed (symbols) values of leaf, grains and total aboveground biomass of two millet varieties from Niger (HKP and MTDO) subjected to two levels of nitrogen fertilization (0 and 100 kg ha^{-1} N) (Alhassane, 2009).

together to get a single date. As a result, four simulation scenarios could cover all the cropping situations (sowing dates × varieties) in a village for a given year. Later, weighted averages of observed yields were calculated based on the number of plots per simulation scenario for the purpose of comparison of simulated and observed yields.

2.4. Coupling crop and climate models

Global circulation models (GCMs) are increasingly capable of making relevant predictions of seasonal and long-term climate variability, thus improving prospects of predicting impact on crop yields. However, translating GCM outputs into attainable yields has some challenges related to the larger spatial scale of GCM grid boxes relatively to the processes determining crop yields. As pointed out by Baron *et al.* (2005) and Berg *et al.* (2010), there is a bias in crop simulation when spatial and/or temporal scales of climate data are inappropriate, and that accounting for interannual variability and daily frequency of rainfall is essential in successfully simulating crop yields.

Downscaling GCM outputs, especially rainfall, is therefore an important step to produce more appropriate climate inputs for crop models. The AMMA (African Monsoon Multidisciplinary Analyses project funded from 2004 to 2009 by EU under the 6th Framework programme (FP6). For more details, see www.amma-international.org) and ENSEMBLES (another EU FP6-funded project developed to quantify the uncertainty in long-term predictions of climate change) joint modeling initiative gave a unique opportunity to address this issue by evaluating the accuracy of several dynamical regional climate models (RCMs) in downscaling climate data. The ENSEMBLES-RT3 (RT3 was the ENSMEBLES Research Theme that had the responsibility to provide improved climate model tools developed in the context of regional models at 20-km spatial resolution for specified sub-regions. For more details, see http://ensemblesrt3.dmi.dk/) provided a set of 15-year runs of five RCMs: HIgh Resolution (HIRHAM, Christensen *et al.* 1996) outputs from the Danish Meteorological Institute (DMI) and Norwegian Meteorological Institute (METNO); Regional Atmospheric Climate Model (RACMO, Lenderink *et al.* 2003) outputs from the Royal Netherlands Meteorological Institute (KNMI); Rossby Centre Atmospheric regional climate model (RCA, Jones *et al.* 2004) outputs from the Swedish Meteorological and Hydrological Institute (SMHI) and PROgnostic Model at the MESoscale (PROMES, Castro *et al.* 1993) outputs from the University of Castilla – La Mancha, Spain (UCLM). All of these RCMs were forced by the ERA-Interim (1989–2005) data [European Centre for Medium range Weather Forecast (ECMWF) Re-Analysis is an 'interim' reanalysis observed weather data of the period from 1989 onwards in preparation for the next-generation extended reanalysis to replace ERA-40. For more details, see http://www.ecmwf.int/research/era/do/get/era-interim].

3. Results and discussion

3.1. Characterizing farmers' crop varieties and agricultural practices

The local varieties showed a much diversified pattern, both in terms of photoperiod sensitivity and biomass partitioning. Nevertheless, some groupings relative to the degree of photoperiod sensitivity and to biomass partitioning among organs could be made. Based on their degree of photoperiod sensitivity, the ten Malian local sorghum varieties could be classified into three main groups: very sensitive with about 40-day variation (Seguetana, Kéninkéba, Tiemari and Dre), moderately sensitive with about 20 days (Nodje, Timari and Keninkeba) and slightly sensitive with only 5 days (Keninke and CSM63-E) (Figure 2(a)). In the case of millet, all the 11 varieties collected from the same sites were photoperiod sensitive (not shown), and similar observations were made in Senegal, Niger and Burkina Faso. These results show that farmers in West Africa prefer to grow predominantly photoperiod-sensitive varieties, as pointed out by Traoré *et al.* (2000) and Kouressy *et al.* (2008b). As for biomass partitioning, Figure 2(b) shows that the slope of the allometric relationship of millet varieties collected in Mali, Niger and Senegal can vary from 2.43×10^{-5} to 16.87×10^{-5}.

3.2. Crop model adaptation

In order to determine a small number of parameters that take into account the intra-specific variability, we defined which parameters could be considered as invariant with species and which ones should be adapted by group of homogeneous varieties. The results of phenological observations as well as indications from literature (Dingkuhn *et al.*, 2008) led us to assume that most of the crop development stages can be considered as constant, except for PSP and BVP. With this assumption, we derived the BVP stage from observations of the latest sowing dates (mid-August or later), considering that photoperiod sensitivity is at its minimum at that date (Figure 2(a)). As for biomass partitioning, 17 local millet varieties from two sites in Mali could be distributed among four main groups (Choho, Sanio, Souna and HKP; Figure 2(b)).

3.3. Crop model evaluation

Figure 4(a) shows that for the 5-year period from 2004 to 2008 in the squared degree area of Niamey, the SARRAH model catches 34% of the on-farm yield variability. However, when analyzing year by year (Figure 4(b) and (c)), a very good correlation ($R^2 = 0.69$) is obtained for 2004 and 2005. However,

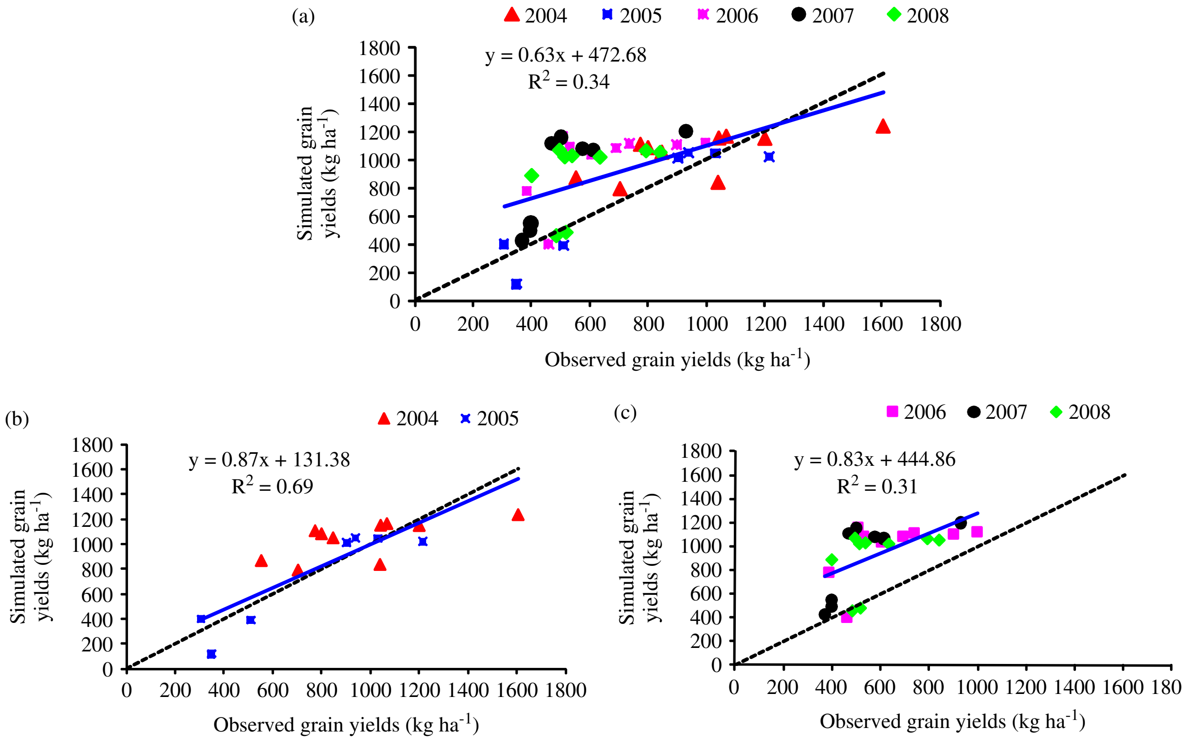

Figure 4. Relationship between observed and simulated millet yields from farmers' fields from 2004 to 2008 in the squared degree area of Niamey, Niger. for (a) the whole period 2004–2008, (b) 2004 and 2005 and (c) from 2006 to 2008.

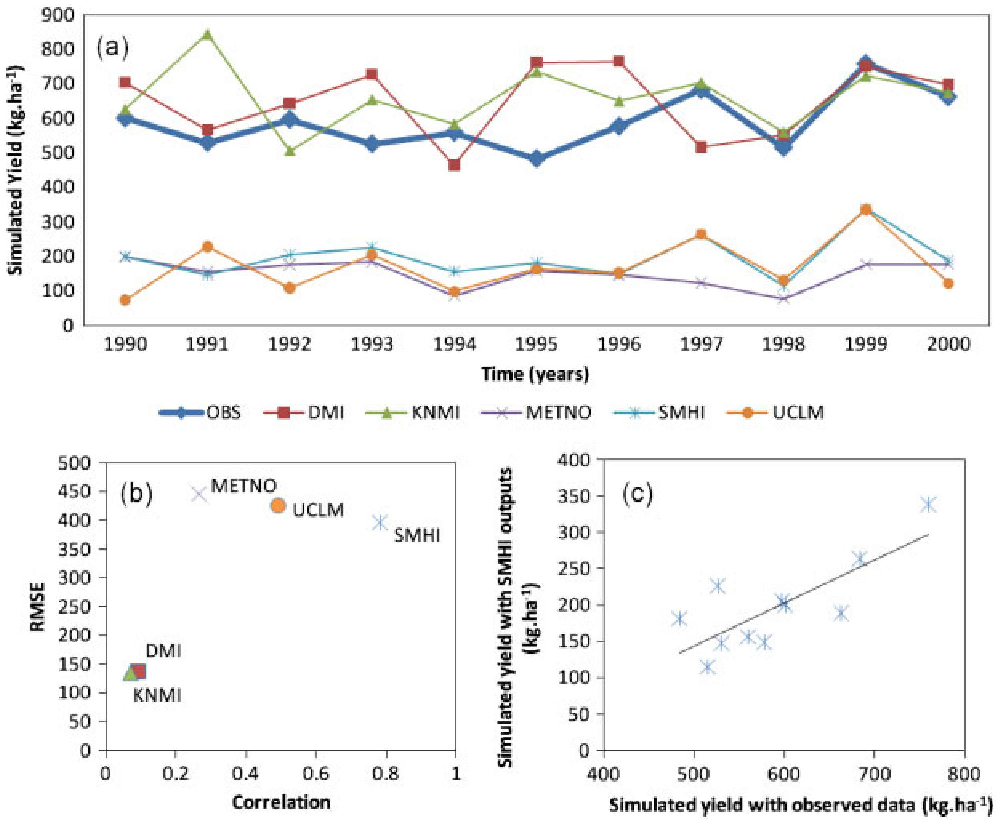

Figure 5. (a) Simulated yields of sorghum (kg ha^{-1}) in Senegal with observed weather data (12 stations from 1990 to 2000) and with RCM outputs. (b) Root mean square error (RMSE) and correlation between simulation with observations and those with RCM outputs. (c) Simulated yields with observed data and with SMHI outputs.

from 2006 onwards, the model performance decreases ($R^2 = 0.31$) and there is a systematic overestimation of millet yields. This could be explained by the relatively even distribution of rainfall throughout the season in 2004 and 2005, which was not the case in the following years, when very erratic rainfall patterns were observed (heavy downpours alternating with long dry spells or early cessation of rains). These discrepancies in the performance of the model could be explained by the poor assessment of the soil and crop water status during the reproductive and maturation phases. Yet, comparison with the DHC model results (Genesio *et al.*, 2011) indicates the same discrepancies and less accuracy of the latter ($R^2 = 0.12$ only). Also, sensitivity analysis showed that model responses are quite dependent on parameters such as runoff coefficients, soil water holding capacity and rooting depth, none of which were measured during our on-farm surveys. So, the discrepancies may have come from the assumed values of these parameters rather than from the model itself.

3.4. Coupling crop and climate models

Figure 5(a) compares the simulated yield of a local sorghum variety (type Seguetana in Figure 2(a)) in Senegal with observed weather data (12 stations over the 1990–2000 period) and with the five RCM outputs. Three RCMs (METNO, UCLM and SMHI) tend to largely underestimate simulated yields while the two others (KNMI and DMI) are able to capture the mean simulated yield. However, those two RCMs are not able to reproduce the interannual variability of the yields (Figure 5(b)). The yields obtained with SMHI outputs, despite a high root mean square error, show a good correlation ($R^2 = 0.79$) with those obtained with observed data (Figure 5(c)). Further work is needed to extend this validation to other regions and crops in West Africa, to identify which variable contribute to the biases in the crop simulations and therefore to apply appropriate bias correction in RCM outputs.

4. Conclusions and perspectives

The results reported in this paper show that it is possible, despite the high variability of yields at plot scale, to estimate average crop yields at the village level and relate them to climate when rainfall is well distributed. This spatial scale allows to define scenarios that include various farmer strategies depending on the social organization, economic constraints and environmental factors (vegetation, soil and climate). In particular, the long-standing farmers' strategy of using photoperiod sensitive varieties that are adapted to environmental variability was confirmed through the characterization of collected varieties.

This adaptation trait is expressed at different degrees depending on the origin of the varieties, usually following a North–South gradient similar to that of rainfall in West Africa. The results of field experiments and on-farm surveys allowed to adapt the SARRAH model, which is now able to simulate the growth and development of a large spectrum of local and improved crop varieties in contrasted agroclimatic conditions. We were also able to describe, with a small number of simulation scenarios, the main cropping practices used by farmers to cope with climate variability across a North–South gradient. Although more studies are needed to address some of the inconsistencies found between measured and simulated yields when heavy rainfall events or prolonged wet conditions were observed, significant progress was made relative to the currently used DHC model, the performance of which was lower in all circumstances. The coupling of SARRAH with climate models is now the new perspective for the improvement of crop yield forecasts for food security early warning in West Africa.

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