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Adaptation strategies to climate change using cotton (*Gossypium hirsutum* L.) ideotypes in rainfed tropical cropping systems in Sub-Saharan Africa. A modeling approach

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ABSTRACT

Developing cultivars with adaptive traits to improve sustainability in the face of climate change is an important option for climate smart agriculture. The CROPGRO-cotton model was calibrated and evaluated at two locations in Cameroon over a period of two years using two planting dates and four contrasted cultivars. The model was used to assess yield gains by modifying plant traits such as specific leaf area, photosynthetic capacity and crop phenology. The ideotype was tested in conventional and conservation agriculture systems and under baseline and future climate conditions. The results revealed that, compared to existing cultivars, the ideotype requires longer to reach maturity and has thicker leaves with good photosynthetic capacity. In 2050 in North Cameroon, climate change will shorten time to maturity and cause a shift in the rainy season but neither change will have an effect on yields. Simulations with an ensemble of climate models revealed that models that assume higher rainfall predicted lower yields, suggesting that N leaching is a more important constraint than drought in North Cameroon. Our results will help cotton breeders select promising new traits to introduce in their cultivars for adaptation to climate changes in Cameroon and to similar sub-Saharan soil, cropping systems and climatic conditions.

1. Introduction

Cotton is a major crop in West and Central Africa. Considered as a regional entity, the sub-continent is the world's third or fourth largest exporter of cotton depending on the year (ICAC, 2016). In small farming systems in Africa, cotton is an important source of income and contributes to the food security of millions of farmers (Tschirley et al., 2009). In North Cameroon, cotton is the main cash crop, covering 30% of the agricultural landscape (Mbétid-Bessane et al., 2006) as well as the main source of income. Like for most rainfed cropping systems in the region, climate is an important factor, especially the onset and the length of the rainy season, both of which affect the seasonal water resources available for the crop and explain a significant part of the spatial and temporal variability of crop productivity in North Cameroon (Blanc et al., 2008; Sultan et al., 2010).

In Africa, water resources are subject to high hydro-climatic variability in space and over time, and are a key constraint to the continent's continued economic development (Kabat et al., 2003). Strategies that integrate risk reduction in a framework of emerging climate change risks would bolster resilient development in the face of the projected impacts of climate change (Niang et al., 2014). Although the effects of climate change on crop yield in sub-Saharan Africa are expected to be mostly negative (Roudier et al., 2011; Schlenker and Lobell, 2010), some positive effects on growth and yield are expected, especially for C3 crops like rice and cotton (Gérardeaux et al., 2012, 2013; Tingem et al., 2008). However, the uncertainty in climate projections in the region and in the effects of climate change on cotton production remain high. According to the fifth assessment report of the intergovernmental panel on climate change, in Cameroon in 2080, the average temperatures are projected to increase by between 2.5 °C and 3.5 °C compared to the baseline scenario (1961–1990), and between 3.1 °C and 4.4 °C depending on the global circulation model (GCM) used (Niang et al., 2014). Precipitation is expected to increase or decrease also depending on the model used (Tingem et al., 2009).

The other factors that affect yields in North Cameroon are pests, poor soils, low fertilizer use, and erratic rainfall. In 2011, Cao et al.

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highlighted the importance of late planting dates, a shift in the rainy season and the need to adapt cultivar cycles to new season lengths (Cao et al., 2011). In addition to these constraints, the climate changes projected in the region will adversely impact cotton yields. Changes in rainfall coupled with an increase in temperatures may reduce or modify the growing season. Therefore, re-matching the crop cycle with season onset and length appears to be especially important for cotton yield stability. A very efficient way to adapt to climate change is to use optimum cultivars (Boote, 2004; Challinor et al., 2014). This is especially true in regions like sub-Saharan Africa where farmers have reduced capacity for adaptation. They may change their cultivars more easily than other cropping system components that would require financial investment. The breeding of new cultivars with higher yields under future climate is thus an important adaptation option in the region. The basis on which any new cultivars are developed will depend on the nature and extent of climate change in any given region or cropping system. Crop models that include the dynamics of crop, soil and weather interactions and integrate crop resource capture principles can assist plant breeders in evaluating the impact of specific traits on yield across a range of climates, soil types and seasons (Asseng et al., 2002). Models have good potential for hypothesizing possible improvement in yield by improving combinations of genetic traits (Boote et al., 2001; Singh et al., 2017). Some authors conducted such analyses using variations in traits to mimic physiological processes, natural feedback like water, N and C requirements, and pleiotropic effects like compromise between leaf thickness and photosynthetic capacity (Aggarwal et al., 1997; Boote and Tollenaar, 1994; Kropff et al., 1995). To our knowledge, only one such analysis has been conducted on cotton in African rainfed conditions (Loison et al., 2017). These authors concluded that ideotypes with an earlier anthesis date, a longer reproductive period, and an increase in the maximum photosynthetic rate were more resilient under climate change projections.

Some cultural practices already exist or are being introduced to cope with climate change. For example, direct mulch cropping (Naudin et al., 2010), agroforestry, water retention pits or walls are adaptation strategies to climate change related to water and soil management.

To our knowledge, few studies combining cotton phenotypic diversity, cropping systems and their interactions with climate variability and changes have been conducted in Africa. Therefore, this paper aims to:

- Compare cycle length, leaf area and dry matter production dynamics in a set of cultivars with different phenotypic traits as measured during field experiments and to explain the results using crop models.
- Identify the optimum combinations of different cultivar parameters used in the CSM-CROPGRO-Cotton model under current and future weather conditions.

2. Materials and methods

2.1. Study location and genetic material

Four experiments were conducted. In 2010, we conducted one experiment at Sanguere research station near Garoua (9.246 °N; 13.471 °E; 250 m above sea level) and another one at Kodeck research station near Maroua (10.652 °N; 14.410 °E; 380 m above sea level). In 2011, the same trials were repeated. Weed and pest control were maximized. Plots were 32 m^2, spacing 0.8 × 0.4 m (31,250 plants ha − 1), with three replications. Soils are common ferruginous tropical soils. The experiments compared four cultivars (L484, L457, IAN338 and Ogosta) and two planting dates (early: June 10 to 20 and late: July 10 to 20). These cultivars were chosen for their diversity in phenology and leaf dynamics. L484 and L457 are reference cultivars that were grown by farmers in North Cameroon from 2008 to 2017. They are tall and vegetative with thin leaves. They are appreciated by local farmers for their productivity. They also have a high percentage of fiber (42–43%) and a very good quality fiber. A description of similar African cultivars can be found in Cao et al. (2011). IAN338 is a cross between Chaco South American cultivars and variety called ISA 205 selected in Cote d'Ivoire. IAN338 is early maturing, productive and robust and of moderate height. It was designed to be harvested either manually or mechanically. It has a moderate fiber percentage (41%). The leaves are thick and dark green, the bolls are of medium size. Ogosta is of Bulgarian origin and has a low fiber percentage (36%). It is a very early flowering and maturing cultivar with small bolls and seeds. It was chosen to cope with situations with a short cycle such as late planting and a short rainy season. Yield, phenology, leaf area index, and dry matter content, number of shells and seeds, threshing percentage and oil and protein contents were recorded for all the cultivars.

2.2. Climate data

Two synoptic weather stations located in Maroua and Garoua run by the AGRHYMET Regional Center were used as local ground truth. These stations record rainfall and other meteorological parameters including solar radiation, insolation, surface wind speed, humidity and temperature at a height of 2 m from the ground. Daily data are available from 1979 to 2012. The Maroua experimental site has a Sahelo-Sudanian climate with a rainy season lasting from June to September (850 mm mean annual rainfall), whereas the Garoua experimental site has a Sudanian climate with a rainy season from mid-May to mid-October (1150 mm mean annual rainfall). The weather data used for our simulations were rainfall (mm d^{-1}), minimum and maximum air temperature (°C), solar radiation (MJ m^2) and duration of insolation (h d^{-1}). The duration of insolation was used occasionally to calculate radiation to replace one month of missing radiation data in Maroua. The experimental plots were located at a distance of nearly 5000 m from the weather station. We generated a climatic variability of 40 different samples for each year using SIMMETEO (Soltani and Hoogenboom, 2007).

The average temperatures (maximum and minimum) from planting to harvest do not differ significantly between years and locations. The average temperature is in the range of 27.5 °C +/− 0.5 in both years and at both locations. Radiation is almost the same for years but different for locations. Maroua receives more sunlight than Garoua (average radiation received from June to October: 17.1 MJ m^{-2} d^{-1} vs. 15.5 MJ m^{-2} d^{-1} respectively). Table 1 summarizes the rainfall amounts in 2010 and 2011 in Garoua and Maroua. The rainfall pattern in 2010 can be considered as providing good growing conditions for cotton as there was no dry spell and there was sufficient rainfall in October for the crop to reach maturity. On the other hand, 2011 was a dry year but for different reasons at the two sites. In Garoua, total rainfall was very low (681 mm). In Maroua, the rainfall pattern differed during the months of June and October. Low rainfall in June meant late planting for the farmers and low rainfall in October meant that the crop was water stressed before reaching maturity.

2.3. Cultivar experiments

The average yield of our four experiments was 1433 kg ha^{-1},

Table 1
Rainfall amounts (mm) in Garoua and Maroua during the June to October cropping season.

Year	Location	June	July	August	September	October	total
2010	Garoua	213	143	184	169	95	805
2010	Maroua	180	153	240	155	114	842
2011	Garoua	118	121	234	134	73	681
2011	Maroua	71	300	277	175	29	854

Table 2
Seed cotton yields and yield components in experiments crossing cultivar and planting dates conducted in Garoua and Maroua in 2010 and 2011. Variance analysis and estimated means.

Variance analysis

Source	DF	Boll weight (g)	N° of bolls m^{-2}	Seed cotton yield (kg ha^{-1})
Cultivar	3	ns	ns	ns
Planting date	1	ns	***	**
Year	1	***	***	ns
Location	1	***	**	**
Cultivar*planting date	3	ns	ns	*
Location*planting date	1	ns	***	***

Estimated means

Source	Boll weight (g)	N° of bolls m^{-2}	Seed cotton yield (kg ha^{-1})
Cultivar-IAN338	4.44	35.9	1545
Cultivar-L457	4.54	33.0	1420
Cultivar-L484	4.60	33.0	1460
Cultivar-Ogosta	4.35	31.4	1309
Year-2010	**4.42**	**34.3**	1370
Year-2011	**4.55**	**32.5**	1497
Location-gar	**4.40**	**40.1**	**1677**
Location-mar	**4.56**	**26.6**	**1189**
Planting date-early	4.59	38.1	**1719**
Planting date-LATE	4.38	28.5	**1147**
Location-gar*planting date-early	4.51	**41.5**	**1803**
Location-gar*planting date-late	4.28	**38.8**	**1550**
Location-mar*planting date-early	4.66	**34.9**	**1635**
Location-mar*planting date-late	4.47	**18.3**	**744**
Cultivar-IAN338*planting date-early	4.62	40.9	**1870**
Cultivar-IAN338*planting date-late	4.27	30.9	**1206**
Cultivar-L457*planting date-early	4.63	39.0	**1762**
Cultivar-L457*planting date-late	4.44	27.1	**898**
Cultivar-L484*planting date-early	4.73	38.5	**1822**
Cultivar-L484*planting date-late	4.46	27.6	**1014**
Cultivar-Ogosta*planting date-early	4.36	34.4	**1392**
Cultivar-Ogosta*planting date-late	4.33	28.4	**1222**

In the variance analysis, only significant interactions are shown. Significance (*** Pr < 0.001; ** Pr < 0.01; * Pr < 0.05;. Pr < 0.1; ns (not significant): Pr > 0.1).

ranging from 744 to 1855 kg ha^{-1}. The average yield and range are close to the yields obtained by local farmers with the mean cotton yield from 1978 to 2007 ranging from 900 to 1450 kg ha^{-1} (Naudin et al., 2010). Variance analysis revealed no effect of the cultivar or of the year on yield (see Table 2). The planting date affected both yield and the number of bolls. The location affected all the variables (boll weight, number of bolls and yield). The cotton grown in 2010 produced more bolls than in 2011 (34.3 vs. 32.8 respectively) but the bolls were lighter (4.42 g vs. 4.52 g respectively) resulting in similar yields. The average yield in Garoua was higher than that in Maroua, which is a common result observed in the cotton company Sodecoton statistics and is probably due to the longer rainy season in Garoua (see Table 1, rainfall amounts in June and October 2011-Maroua) and better soil fertility in the Garoua experimental station. The interaction between location and planting date had a very significant effect ($p < 0.001$) on yields and on the number of bolls. This is mainly due to the yields in Maroua that are very dependent on the length of the rainy season. Yields in Maroua are high (1635 kg ha^{-1}) if the cotton is sown early and very low (744 kg ha^{-1}) if the cotton is sown late, whereas no such decrease is observed between late and early planting in Garoua. An interaction between cultivars and planting date was also observed with an effect on yields. Ogosta produces the lowest yields compared to other cultivars if planted early but produces more cotton than local cultivars (L457 and L484) if planted late (Table 2). IAN338 produces more cotton than the other cultivars at both early and late planting dates.

2.4. The cropping system model

The cropping system model used in the study was the Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003). DSSAT is a mechanistic, complex simulation model that has been regularly improved to increase the biophysical representation of soil water, organic matter and nutrient dynamics of cropping systems. For instance, the CENTURY soil organic matter model (Parton, 1996) was incorporated into DSSAT by (Gijsman et al., 2002) to improve simulations of long-term soil carbon and nitrogen dynamics. Further modifications of DSSAT were made more recently to simulate the effects of crop residues left on the surface on soil water and organic matter dynamics of cropping systems (Jones et al., 2010). As a result of these improvements to the model, DSSAT has increasingly been used as a tool to compare different crop management practices under diverse soil and climate conditions, under the hypothesis of a comprehensive accuracy of the model (Jagtap and Abamu, 2003; Saseendran et al., 2007).

DSSAT has already been used to study potential effects of climate projections on different crops in different tropical areas: including rice in Madagascar (Gérardeaux et al., 2012), cotton in Cameroon (Gérardeaux et al., 2013) and maize and sorghum in Botswana (Chipanshi et al., 2003). In addition, DSSAT incorporates two weather generators (Pickering et al., 1994).

2.5. Model calibration and evaluation

The dataset for calibration came from experiments conducted in 2010 and 2011. Some of the data collected were randomly selected for evaluation of the crop simulation. Data from Maroua 2010 and Garoua 2011 were used for calibration and Garoua 2010 and Maroua 2011 for evaluation.

2.6. Calibration of the cultivars

In our calibration procedure, we varied the parameter values to minimize the RMSE. We used a manual iterative approach according to Godwin et al. (1989) and based on our own experience. The initial values for the cultivar are listed in Table 3.

- The preliminary step was to change the threshing percentage (THRSH), the fraction of oil (SDLIP) and protein (SDPRO) according to our measurements and analysis.
- The first step of calibration was to fit flowering and maturity dates using the parameters that represent the phenology: the time between plant emergence and flower appearance (EM-FL), the time between the first flower and the first boll (FL-SH), the time between the first flower and the first seed (FL-SD) and the time between the first seed and physiological maturity (SD-PM).
- The second step was to fit observed and simulated leaf area index using specific leaf area (SLAVR) and maximum leaf size (SIZLF) and the maximum fraction of assimilates that goes to the fruits (XFRT). The fit was a compromise between maximum leaf area index and leaf area dynamics.
- The third step was to fit the aboveground biomass (Top Weight) using the photosynthesis parameter LFMAX.
- The last step was to fit harvested seed cotton yield with XFRT, average seed per boll (SDPDV), the time required for the cultivar to reach final boll load (PODUR) and seed filling duration for boll cohort (SFDUR).
- Iterations were made from step 2 to the last step until the seed

Table 3
Initial cultivar characteristics used to define the simulation parameters.

Meaning of the parameters	Values	Meaning of the parameters	Values
Critical short day length	23	Maximum size of full leaf (three leaflets) (cm2)	400.8
Slope of the relative response of development to photoperiod with time.	0.01	Maximum fraction of daily growth that is partitioned to seed + shell	0.60
Time between plant emergence and flower appearance	44.6	Maximum weight per seed (g)	0.160
Time between first flower and first boll	5.0	Seed filling duration for boll cohort at standard growth conditions	30.1
Time between first flower and first seed	11.1	Average seed per boll under standard growing conditions (#/boll)	30.40
Time between first seed and physiological maturity	24.9	Time required for cultivar to reach final pod load under optimal conditions	16.0
Time between first flower and end of leaf expansion	90.5	Threshing percentage. The maximum ratio of (seed/(seed + shell)) at maturity..	70.0
Maximum leaf photosynthesis rate	0.95	Protein fraction in seeds	0.180
Specific leaf area of cultivar	240	Oil fraction in seeds (g(oil)/g(seed))	0.166

cotton yield was properly simulated. We considered that it was properly simulated when the RMSE was below 25% of the seed cotton yield, the r^2 above 0.7.

Values for the parameters EM-FL, SD-PM, LFMAX, SLAVR and SIZLF were kept within the range of variability reported in other studies (Amin et al., 2017; Anapalli et al., 2016; Pathak et al., 2007; Wajid et al., 2014)

2.7. Virtual cultivars and experiments

2.7.1. Common features

The crop simulation model CROPGRO-Cotton coupled with the seasonal analysis tool available in DSSAT 4.6.1.0 was used to simulate cotton yields under baseline and climate change conditions. For each year and location, 40 simulations were run using generated weather data.

The model required the soil properties of different layers. The soil characteristics used were water holding capacity, saturated hydraulic conductivity, bulk density, nitrogen content, and organic carbon. After soil analysis, the surface layers were set according to the values shown in Table 4.

Row spacing and fertilization rate were set according to the local recommendations for conventional, no-till and conservation agriculture systems (see Table 5). In conservation agriculture (CA) system, we applied an extra 22 kg ha^{-1} of nitrogen in the CA system to compensate for the immobilization of nitrogen by microorganisms degrading the mulch.

2.7.2. First experiment (changes in crop physiology)

We decided to test different crop growth strategies commonly described in ecology (Wright et al., 2004), namely the conservative and the acquisitive strategies of plants based on leaf area dynamics and photosynthesis. To reproduce these strategies, we chose a set of virtual cultivars with different SLAVR and LFMAX values. Cultivars with high SLAVR had low LFMAX and vice versa. Values of SLA-LFMAX are as follows: V0: 240-0.95, V1: 230-1.02, V2: 220-1.09, V3:210-1.16, V4:200-1.23, V5:190-1.30, V6: 180-1.37 (the reasons for these values are revealed later, in the Section 4.2). We used the reference cultivar L457. We ran the simulations on seasonal mode for 40 years in Garoua with a planting date on June 20. This is the most common planting date and Garoua is the main cotton production region.

Table 4
Soil parameters and characteristics as inputs for DSSAT soil.

Soil parameters and characteristics	Values
Albedo	0.14
Soil fertility factor	0.9
pH	6.0
Drainage	0.25
Runoff coefficients	81
Water holding capacity (cm^{-3} cm^3)	0.073
Saturated hydraulic conductivity (cm h^{-1})	1.59
Bulk density (g cm^{-3})	1.48
Nitrogen content (g g^{-1})	0.05
Organic carbon (g g^{-1})	0.7
Texture and percentage stones	11% clay, 14.7% silt and 2% stones

Table 5
Management and initial cultivar characteristics used to define the simulation parameters.

Management characteristics	values
Plant density	4 per m^2
Row spacing	0.8 m
Planting depth	5 cm
Nitrogen fertilization	
Conventional and no-till	22 kg N ha^{-1} repeated 10 and 60 days after planting
Conservation agriculture	22 kg N ha^{-1} at 10 days after planting and 44 kg N ha^{-1} at 60 days after planting

2.7.3. Second experiment (changes in crop phenology)

After calibration and evaluation of the four cultivars, we decided to explore the interest of different times to crop maturity. We used the reference cultivar L457. Next, six new versions of that cultivar with changed maturity timeframes were developed by changing EM-FL and SD-PM. These changes resulted in longer cycle lengths: +7, +14, +21, +28, +35 and +42 days to reach crop maturity. The recommended planting dates in North Cameroon range from June 1 to July 10. In our virtual experiments, we extended the planting dates to the end of July to see if the projected rise in temperature would allow very late planting. The planting window was set at June 1 to July 20. Seven planting dates were fixed at 156, 166, 176, 186, 196 and 206 Julian days. The climate change treatment was done by the delta method: adding 3.2 °C to the observed temperature and changing the CO2 concentration. We fixed the CO2 at 571 ppm as done by CMIP 3 and 5 (Sillmann et al., 2013) for the RCP 8.5 scenario. We ran the simulations on seasonal mode using 40 samples from the year 2010 in Garoua.

2.7.4. Third experiment (cropping system adaptation strategies)

Conservation agriculture with direct mulch cropping (DMC) and no tillage systems have been designed and tested in trials and in farmers' fields in North Cameroon. Conservation agriculture is defined by three factors: minimum mechanical soil disturbance, permanent organic mulch covering the soil, and diversified crop rotations. Both systems were designed to cope with drought, to allow early planting, and to reduce erosion. They are detailed in (Naudin et al., 2010). For the simulations, no tillage was parametrized with no plowing and CA also with no plowing, and with the addition of an organic amendment of 4000 kg ha^{-1} dry matter of *Brachiaria* banded on the soil surface (content 1% N). The preceding crop (maize, sorghum) residue was set at 1 T ha^{-1} of roots and 2 T ha^{-1} of unincorporated stems containing 0.5% N. The following simulation options were chosen: (i) Suleiman Ritchie for soil water balance, (ii) Priestley-Taylor/Ritchie for

Table 6
Climate models.

Acronyms	Climate models
DMI	HIRHAM model: Danmarks Meteorologiske Institut
GKSS	CLM model: Gesellschaft fur Kernenergieverwertung in Schiffbau und Schiffahrttrum
KNMI	RACMO model: Koninklijk Nederlands Meteorologisch Instituut
METNO	HIRHAM model: Meteorologisk institutt
SMHI	RCA model: Sveriges Meteorologiska och Hydrologiska Institut
UCLM	PROMES model: Universidad de Castilla–La Mancha

evapotranspiration, (iii) CROPGRO was run in the experimental mode and, (iv) CERES-Godwin for soil organic matter. The crop was planted after Julian day 156 when the soil moisture had reached 40% of extractable soil water in the top 40 cm soil layer for conventional tillage and in the top 20 cm soil layer for DMC and no tillage systems. To test the ability of each cropping system to cope with climate changes we crossed the cropping systems with climate projections (see below).

2.8. Climate simulations for the third virtual experiment

To obtain a more complex understanding of climate change and a range of variability of predictions, we used outputs from six climatic downscaled models (see Table 6).

A coherent multi-model experiment has been underway since the beginning of the ENSEMBLES project (2004–2009) (van der Linden and Mitchell, 2009). For our purpose, we used six regional configurations: the DMI, GKSS and KNMI regional configurations were forced by ECHAM5 A1B climate change scenario while METNO, UCLM and SMHI were forced by HadCM3, see (Gérardeaux et al., 2013) for more details on climate models. Regional climate outputs are freely available at a daily time scale at a 50 km resolution for the AMMA-region and were bilinearly interpolated to each of the two synoptic stations in North Cameroon. Since climate models have serious regional biases which may introduce errors in crop simulations (Ramarohetra et al., 2015), a bias correction method has been applied to climate projections. The transformation of cumulative distribution function method (Michelangeli et al., 2009) was applied to correct the statistical distributions of the regional climate model simulations and to make them as close as possible to those of the observations. This method aims to correct the cumulative distribution function (CDF) of a variable (temperature or precipitation, etc.) given at a relatively low resolution from a regional climate model simulation into the CDF of the equivalent variable at a much smaller scale. In the present study, the required cumulative distribution functions were non-parametrically estimated, but with a monthly discrimination. From May to November, a monthly correction was applied to each variable, by calibrating a monthly cumulative distribution function for the period 1979–2004. The cumulative distribution function was then applied to each regional climate output for the period 2005–2050. Corrected downscaled outputs were then used to drive the crop model described above. The outputs of theses climate models where formatted as daily climate files with rainfall, Tmax, Tmin and solar radiation and used as climate inputs for DSSAT-Cropgro in the third virtual experiment.

2.9. Statistical analysis

All statistical analyses were conducted with XLSTAT version 19.5, using ANOVAR when analyzing qualitative effects or ANCOVAR when the analysis involved a mixture of qualitative and quantitative effects. In the seasonal experiments, each sample of a year was considered as a replication.

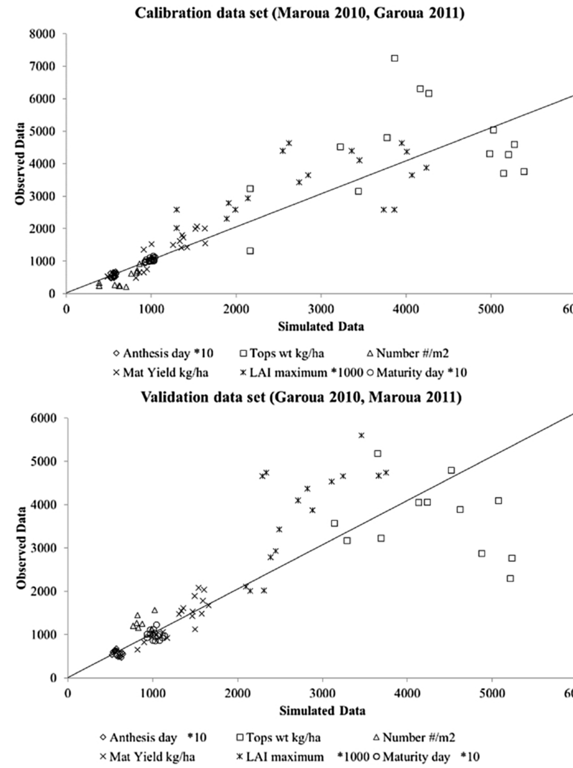

Fig. 1. Calibration and validation data set for the experiments conducted in 2010 and 2011 in 2 locations Garoua and Maroua with 4 cultivars. Observed and simulated anthesis and days to maturity, maximum leaf area index (LAI maximum), aboveground biomass (Tops wt), number of bolls (Number) and seed cotton yields (Mat Yield). Black line y = x.

3. Results

3.1. Calibration and evaluation

The two rainy seasons 2010 and 2011 and the two sites Garoua and Maroua gave us a good panel of environments for cotton. 2010 had a good rainy season at both sites while 2011 was a dryer year in Garoua and the rainy season was sorter in Maroua.

CROPGRO-cotton accurately simulated the average onset of flowering, maturity, leaf area, aboveground dry mass and yields in 2010 and 2011 (Fig. 1 and Table 7).

The yield was better simulated (RMSE: 256 kg, r^2: 0.74) than aboveground dry mass (RMSE: 1297 kg, r^2:0.08) and the number of seeds (RMSE 379, r^2: 0.04). This was previously observed (Harb et al., 2016) with Ceres and Cropgro, when the harvest index was not as well predicted as yields. The reason might be that there were fewer observations of aboveground dry mass and of the number of seeds than of

Table 7
Comparison between observed (Obs.) and simulated (Sim.) data in the validation data set (Garoua 2010 and Maroua 2011).

Variable Name	Mean (Obs.)	Mean (Sim.)	Mean (Ratio)	r-Square	RMSE	N° of Obs.
Anthesis day	57	58	1.04	0.21	8.8	16
Maturity day	99	102	1.04	0.02	12.3	16
Maximum LAI	3.83	2.73	0.75	0.51	1.39	16
Top weight (kg ha^{-1})	3666	4160	1.21	0.08	1297	12
Number of seeds (per m^2)	1256	934	0.76	0.04	379	8
Seed cotton yield (kg ha^{-1})	1444	1343	0.97	0.74	256	16

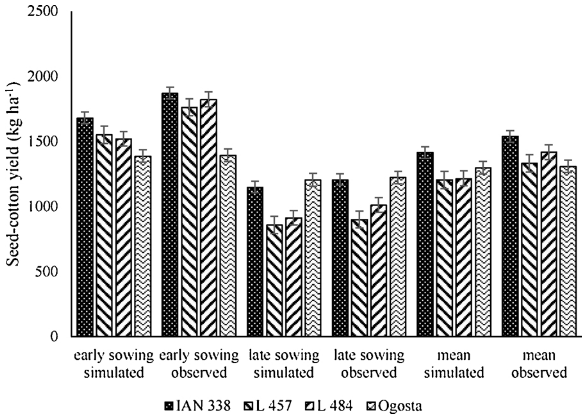

Fig. 2. Observed and simulated seed cotton yields for 4 cultivars and 2 planting dates (early = 10–20 June and late = 10–20 July). Means and standard deviations refer to 2 years and 2 locations.

yields and we changed four parameters to adjust observed and simulated yield whereas we changed only one (LFMAX or PODUR) to fit dry matter production or the number of seeds, respectively. The average observed yields was 1444 kg ha^{-1} and ranged from 488 to 2017 kg ha^{-1}, depending on the different cultural practices.

The model correctly predicted the interaction between the cultivars and the planting dates (see Fig. 2). Ogosta, the short cycle cultivar, was relatively more productive when sown late and IAN 338 the most productive cultivar whatever the planting date. However, the model underestimated mean yields, especially in early planting conditions. This may be due to a bad simulation of the seasonal pattern of N-mineralization, especially the high mineralization of inorganic N at the start of the rainy season in dry savanna tropical soils (Singh et al., 1991). Crops planted in early June grow in good nutritional conditions because the pool of inorganic-N is high.

3.2. Virtual experiments

Three virtual experiments were conducted. The first one found the best compromise between SLAVR and LFMAX, the second one fixed the optimum phenology with different planting dates, and with a delta in temperature, the third one tested the time trends of the performances from 2010 to 2050 with different cropping systems and climate models.

3.2.1. First experiment: sensitivity to coupled SLAVR and LFMAX

Results of these simulations are summarized in Table 8. Cultivars L457 V2 to V6 produced significantly more yield than the reference cultivar L457. The best yielding cultivar was L457 V4. An increase of

Table 8
Comparison of the relative seed-cotton yields, water use efficiency (kg dry matter per mm water transpired), maximum LAI (LAImax) and top weight in a seasonal experiment using 7 virtual cultivars with different values of SLA and LFMAX. Values are means of 40 generated years.

Virtual cultivar names	SLAVR-LFMAX	% increase in yield p/r real	WUE (kg. mm^{-1})	LAImax	Top weight (kg ha^{-1})
L457 V0 (real)	240-0.95	- c	28.9 g	3.1 a	3855 d
L457 V1	230-1.02	2.7 c	29.9 f	3.0 a	3941 c
L457 V2	220-1.09	4.6 b	30.9 e	2.9 b	3999 ab
L457 V3	210-1.16	5.9 a	31.9 d	2.8 c	4031 a
L457 V4	200-1.23	6.9 a	33.0 c	2.6 d	4042 a
L457 V5	190-1.30	6.7 a	34.1 b	2.4 e	4022 a
L457 V6	180-1.37	5.9 a	35.2 a	2.2 f	3969 bc

Cultivars with different letters differ significantly in the variable in the column at probability 0.05 using SNK test.

Table 9
Simulated anthesis date (ADAPS), maturity date (MDAPS) and seed cotton yield (HWAMS), degree of freedom (DF) and probability in the F test of a virtual experiment on 7 cultivars (L457 V4 and L457 V4 with longer cycle lengths)* 6 planting dates (period from June 1 to July 3)* 2 climate scenarios ("baseline" and "2050": T° + 3.5; CO2 500 ppm), and 40 generated years. Each year is assumed to be a repetition.

Source	DF	ADAPS	MDAPS	HWAMS
Cultivar	6	***	***	***
Climate scenario	1	***	***	ns
Planting date	5	***	***	***
Cultivar*climate scenario	6	*	**	ns
Cultivar*planting date	30	ns	***	***
Climate scenario*planting date	5	***	*	***
Climate scenario*cultivar*planting date	30	ns.	ns.	ns.

Significance (*** $Pr < 0.001$; ** $Pr < 0.01$; * $Pr < 0.05$;. $Pr < 0.1$; ns. $Pr > 0.1$).

6.9% in yield was obtained with cultivar L457 V4, with a SLAVR of 200 and a LFMAX of 1.23. The top weight followed a similar trend to seed cotton yields, indicating no changes in the harvest index. This is understandable as SLAVR and LFMAX are two parameters driving growth processes but not fruiting patterns or yield components. Further yield increase should be achieved by an increase in harvest index.

3.2.2. Second experiment: optimum phenology with different planting dates and with climate changes

Virtual cultivars L 457 V4 with increasing values for coefficients driving crop maturity were tested under two climate scenarios and six planting dates. Statistical analysis (Table 9) revealed that the cultivars had different flowering and maturity dates, and yields. The climate scenario had an effect on flowering and maturity dates but not on yields. The planting dates had an effect on flowering and maturity dates, and on yields. Many interactions were observed, see Table 9.

The interaction between cultivars and the climate scenario was significant for phenology. The yields did not differ statistically with variable cycle lengths but trends appeared and optimums appear to be between ref +14 and ref +28 (Table 10). This means that the best adaptations to baseline and future climate conditions would be a cultivar with a longer time for maturity, approximately 14–28 days longer than the local cultivars.

There was also an interaction between the cultivar and planting dates and the cultivar and the climate scenario (Table 10). The best average yield in baseline conditions is 1175 kg ha^{-1}. It can be obtained with a virtual cultivar that takes 21 days longer to reach maturity. With that cultivar, the best yield is 1351 kg ha^{-1} for a planting date of 176 Julian days. Under climate change conditions, the best yield is achieved with the same cultivar but with an earlier planting date (156 Julian days) (data not shown). The relative differences between "2050" and "baseline" climates (Table 11) show that climate changes will not favor

Table 10
Means for simulated anthesis date (ADAPS, days after planting), maturity date (MDAPS, days after planting) and seed cotton yield (HWAMS, kg ha-1) according to the climate scenario and virtual cultivar (cultivar L457 V4 = ref and successive with different time to reach crop maturity for baseline conditions).

	Cultivars with different cycle lengths						
variables	ref	ref + 7	ref + 14	ref + 21	ref + 28	ref + 35	ref + 42
ADAPS	60.8	62.3	65.3	67.7	70.0	72.0	74.3
MDAPS	111.8	118.6	125.9	132.8	140.1	147.3	154.6
HWAMS	1073	1153	1165	1175	1169	1159	1159
ADAPS	59.2	61.0	62.9	65.6	67.6	69.7	72.1
MDAPS	108.7	115.2	122.3	129.3	136.3	143.3	150.5
HWAMS	1059	1135	1169	1165	1183	1148	1146

Table 11
Relative changes in seed cotton yields simulated with climate change, 7 different cultivars and 6 planting dates. Each value is the mean of the relative difference using 40 generated weather per year.

Planting dates (Julian day)	Cultivars with different cycle lengths (cultivar L457 V4 = ref and virtual with longer maturity in days)						
	ref	ref + 6	ref + 14	ref + 21	ref + 28	ref + 35	ref + 42
156	4.5	2.3	−2.6	9.7	8.3	7.9	5.4
166	−0.6	2.6	4.5	0.3	9.5	0.0	−2.8
176	5.3	5.8	9.0	−7.3	4.4	8.0	9.6
186	3.9	−6.0	−2.0	4.6	7.0	2.2	11.7
196	−0.5	2.0	−4.5	3.1	−3.2	−1.9	−4.6
206	−8.1	−2.8	5.4	−4.5	−5.8	−15.9	−14.1
Mean	0.9	0.7	1.5	1.0	3.9	0.6	1.3

planting later than 196 Julian days as the relative changes are mainly negative for Julian days 196 and 206. For example, cultivar ref + 35 produces -1.9% less yield if planted on Julian day 196 and -15.9% less yield if planted on Julian day 206.

The longer maturing cultivars produce more cotton if sown early. This interaction can be seen in Fig. 3, which shows a depressive effect of planting date on harvested seed-cotton yield ranging from 1280-1380 kg ha^{-1} for the plots sown on Julian day 156, to 750-900 kg ha^{-1} for the latest planting date, Julian day 206. This represents an average depressive effect of 10 kg ha^{-1} per day after day 156. The interaction between cultivar and planting date is obvious in the inversion of the cultivar rankings. With the earlier planting dates, cultivars L457 + 21, +28, +35 or +42 produce more seed cotton, while with the latest planting dates, cultivars L457 + 7 and +14 are the most productive. This reflects the difficulties for long maturing cultivars to achieve their cycle when planted after Julian day 200. The best yields and stability should be obtained with ref +21 or +28 cultivars under both climate scenarios.

3.2.3. Third experiment: trends and climate projection variability

The third experiment was designed to question the trends in climate change and their interaction with site and cropping systems. Analysis of covariance revealed that the year had a significant effect on temperatures and emergence date but not on yield, precipitation or N leaching (Table 12).

The effects of the year on temperatures are not surprising as the climate models takes global warming into account. With regard to the emergence date, two contradictory effects are in action. On one hand, global warming will certainly increase simulated soil temperatures. Therefore, we can expect a slightly negative effect of the year on the

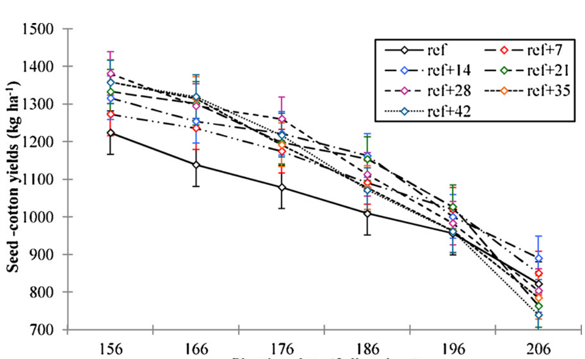

Fig. 3. Means of 40 simulated seed-cotton yields for 6 planting dates and 6 different versions of L457 V4 cultivar (ref) with longer time to reach maturity. Vertical bars are standard errors.

emergence date. On the other hand, the emergence date is dependent on the planting date, and the planting date is triggered by the soil humidity from June 1 to July 20. The rainfall pattern from the end of May to 20 July is thus determinant to simulated emergence date. As simulated emergence date is positively correlated with the year of the simulation (see Table 12) we conclude that the climatic models are predicting modifications in rainfall pattern in the beginning of the season and that it is the dominant effect. However, there is no effect of the year on the rainfall amounts during the whole rainy season. The crop will emerge 0.041 days later each year. Obviously, the difference is not very important as it represents an average planting date less than two days later in 2050 compared to 2005. However, the average effect masks differences in climate models and cropping systems. There are seven days difference in emergence date between the GKKS and UCLM models. Despite an easier rule set for planting in DMC and no-tillage parametrization, planting dates were not significantly different between conventional and other systems.

The rainfall amounts are not likely to change with the years but marked differences are observed between climate models. For example, DMI predicts 773 mm and METNO 975 mm, a difference of more than 20%. The differences in the rainfall pattern and in rainfall amounts among the climate models affect simulations of seed-cotton yields made with Cropgro. The gap between yields simulated with METNO and DMI is 328 kg ha^{-1}. This also represents an approximately 20% variation from the average yield. Yields are negatively correlated with rainfall and leaching. The best yield (with DMI) is obtained with the lowest rainfall and N leaching and vice versa (with METNO).

4. Discussion

Using a combination of real and virtual experiments, we compared cycle length, leaf area and dry matter production for adaptation to climate change in a set of cultivars with different phenotypic traits at selected locations in North Cameroon.

4.1. Having enough confidence in the experiments and the model

The years 2010 and 2011 in Garoua and Maroua represented a contrasted panel of climate variability with 2010 representing good conditions and 2011 dry conditions. In Garoua, 2011 it was a dry year considering the rainfall received in July, August and September, whereas in Maroua, 2011 it can be considered as a dry year with respect to the length of the growing season. Thus, the yields of cotton planted late in Maroua 2011 were very low: 744 kg ha^{-1} (see Table 2).

L457 was the most widely cultivated cultivar in Cameroon in 2011. It was designed and selected for its fiber quality and its adaptation to the southern and south-eastern parts of the cotton area in Cameroon, where rainfall is > 1000 mm and the cotton season is sufficiently long. As such, it has the lowest yield in the late planting treatments. L484, which was selected for short rainy seasons, has a better yield in late planting conditions than L457. Ogosta, a very fast fruiting cultivar is determinate. It has the best yield in late planting conditions but cannot compete with other cultivars if planted early. IAN338, a cultivar with smaller thicker leaves, a good assimilation rate and an intermediate cycle length appears to be the best adapted to planting dates, years and locations.

At this point, given that we had sufficient confidence in the model to represent the interactions between the traits of the different cultivars and the environment, we decided to test the performances of the cultivars in more fluctuating environments to find optimum virtual cultivars and cropping systems.

4.2. What is the best compromise between two strategies: acquisitive or conservative?

Water use efficiency ranged from 28.9 to 35.2 kg DM mm^{-1} water

Table 12
Analysis of covariance of the emergence date (EDAPS), the seed cotton yield (HWAMS), the precipitation received from planting to harvest (PRCP) and nitrate leaching from planting to harvest (NLCM), probability of the F test and means of a virtual experiment using 6 climate models* 3 cropping systems* and 50 successive years from 2020 to 2070. Year is the quantitative effect of the covariance analysis.

Source	Tmax (°C)	Tmin (°C)	EDAPS (Julian day)	HWAMS (kg ha^{-1})	PRCP (mm)	NLCM (kg ha^{-1})
Covariance analysis	Pr > F	Pr > F	Pr > F	Pr > F	Pr > F	Pr > F
Years (quantitative)	***	***	***	ns	ns	ns
Site (qualitative)	ns	***	*	***	***	***
Cropping system (qualitative)	ns	ns	*	***	ns	*
Climate model (qualitative)	*	*	***	*	*	**
Coefficient and means	Tmax	Tmin	EDAPS	HWAMS	PRCP	NLCM
intercept	−45.1 ***	−100.5 ***	77.5 *	−659 ns	830 ns	147 *
years	0.039***	0.061***	0.042*	1.1 ns	−0.01 ns	−0.06.
Climate model 1 (KNMI)	33.89 cd	23.43 b	166.4 b	1757 b	803 c	25.4 c
Climate model 2 (DMI)	33.99 bc	23.32 b	164.3 c	1855 a	773 c	20.9 d
Climate model 3 (GKKS)	34.10 ab	23.67 a	171.0 a	1648 c	868 b	32.4 b
Climate model 4 (METNO)	33.76 d	23.66 a	165.4 bc	1527 d	975 a	44.4 a
Climate model 5 (SMHI)	34.14 ab	23.78 a	163.9 c	1672 c	782 c	34.3 b
Climate model 6 (UCLM)	34.28 a	23.75 a	162.0 d	1622 c	873 b	35.6 b
Site: Garoua	34.06	24.00 b	166.5 a	1644 b	907 a	36.8 a
Site: Maroua	34.00	23.19 a	164.4 b	1722 a	784 b	27.5 b
Cropping systems Conv.	34.03	23.60	165.5	1648 b	846	29.4 b
Cropping systems DMC	34.03	23.60	165.4	1874 a	846	36.9 a
Cropping systems No-tillage	34.03	23.60	165.4	1529 c	846	30.2 b

Significance (*** Pr < 0.001; ** Pr < 0.01; * Pr < 0.05;. Pr < 0.1; ns. Pr > 0.1). Means with letters are significantly different at probability 0.05 using the SNK test.

transpired. This is in accordance with the known water use efficiencies of cotton (Tennakoon and Milroy, 2003). WUE was negatively correlated with LAI, which ranged from 2.2 to 3.1. This negative correlation is what one would expect from the model which calculates transpiration according to leaf area.

A low specific leaf area (SLA) crop is supposed to have increased photosynthetic capacity (Stitt and Schulze, 1994), but the extent to which it can achieve increased crop yield is doubtful because of compensation and dampening (Sinclair and Purcell, 2005). Ecological scientists have established the existence of a fundamental trade-off between traits allowing rapid resource capture and efficient resource conservation (Wright et al., 2004). The prevailing view is that high SLA plants work better in rich environments whereas low SLA plants prefers resource-poor environments (Wilson et al., 1999). The “high SLA” cultivars are acquisitive, they increase their leaf area rapidly and thus intercept more light, but they have higher transpiration and lower water use efficiency. Conversely, low SLA cultivars are conservative; they have thicker leaves with high photosynthetic capacity, good water use efficiency but lower light interception and high N demand in their early stages. These two strategies are reflected in our small cultivar panel in the Fig. 4, which represents the trade-off regression for SLAVR and LFMAX after calibration.

Our calibration results showed a similar trade-off with a photosynthesis parameter ranging from 0.9 to 1.25 and a SLAVR from 210 to 240 $cm^2\ g^{-1}$. The best yields were obtained with a SLAVR of 190 and a LFMAX fixed at 1.3. The left part of the regression represents the acquisitive strategy and the right part the conservative one. IAN 338, the best yielding cultivar, has 1.24 LFMAX and 210 SLAVR, it is a conservative candidate. Moreover, in our search for an ideotype, the best yielding cultivar was L457 V4 a very conservative cultivar with a LFMAX of 1.23 and a SLAVR of 200. It has high water use efficiency (33 $g.ml^{-1}$) but intermediate maximum LAI (see Table 8). The best adapted strategy appears to be high radiation use. It is the conservative strategy adapted to resource-poor environments. Such an ideotype can be considered as having high photosynthetic capacity with relatively thick leaves and theoretically high N demand. This is not in accordance with agronomists’ common sense, which looks for a resilient rustic cultivar capable of producing on poor soils with low N inputs. Still, in our experimental conditions and under our simulations the real cultivar IAN338 and the high yielding virtual cultivars L457 V4, produced

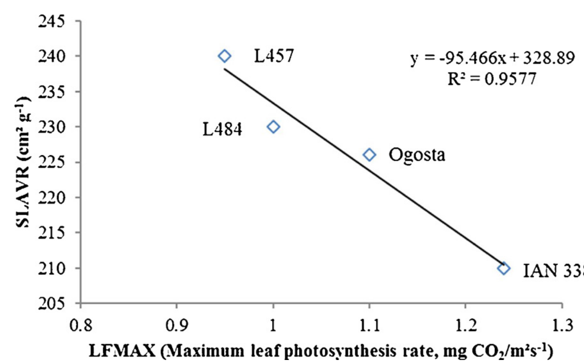

Fig. 4. Negative correlation between 2 cultivar coefficients of cotton for DSSAT-Cropgro: SLAVR and LFMAX representing respectively specific leaf area and photosynthetic capacity. Values obtained after manual calibration process using observed leaf area dynamics, dry matter and yield variables in Cameroon in 2010 and 2011. The thinner the leaves, the lower their photosynthetic capacity.

better yields than the fast fruiting Ogosta or the local reference cultivars L457.

4.3. What is the appropriate cycle length to cope with the baseline climate and with climate changes?

Having fixed the growth dynamics and their two main parameters LFMAX and SLAVR, we next questioned time to crop maturity. Drought tolerant cotton is expected in sub-Saharan Africa but it is still not clear if people want drought escaping genotypes that mature early, or drought tolerant genotypes that produce more biomass with a limited water supply. Early maturing cultivars are known to produce more cotton only when the growing season is shortened by the rainfall pattern (Rosenow et al., 1983). If the rainfall pattern remains unchanged but the amount of rainfall is insufficient, the crop will experience drought. In this case, early maturing cultivars will be less productive than others. To discover the best length for maturity, we set virtual cultivars with varying cycle lengths and we tested them on a set of 40 generated years, using different planting dates and under different climate conditions. The best yielding ideotypes shared common characteristics with respect to crop cycle length. Their thermal time requirement for crop cycle length (emergence to boll opening) was longer than that of the reference cultivar L457. This is in accordance with the result of recent similar studies on peanuts in West Africa (Singh et al., 2014) and on cotton (Loison et al., 2017). These authors found that increasing crop duration by 10% increased the yield under both the baseline climate and climate change scenarios, underlining the scope available for improving groundnut or cotton productivity by growing longer duration varieties. Moreover, the shortening of the crop cycle length due to the climate change in 2050 is around 1.6 days for anthesis and 3.1 days for maturity (see Table 10). There is no marked difference in the optimum crop cycle lengths between those cultivated under current weather conditions (baseline) and those cultivated under warmer conditions. The optimum yield is obtained with a time to crop maturity extended by 21–28 days.

New plant types with high potential should have increased source and sinks capacities (Aggarwal et al., 1997). Our ideotype has a higher sink demand combined with a longer time to reach plant maturity. Obviously, crop model parameters are only "sound like" physiological mechanisms and used as a "proxy" for the expression of genetic diversity. We argue that shifts in these parameters should reflect genetic variability, but this is only partially true (Hammer et al., 2002).

The climate models had different impacts on simulated planting dates and yields. They predicted a shift in the rainy season but that has limited consequences in terms of planting dates and no effects on yields. The six climate models were consistent with respect to yields. The crop simulations run with the climate models that predicted less precipitation had the highest yields (see Table 12). The difference between the most optimistic and the most pessimistic scenario led to more than 20% difference in seed-cotton yields, which represents considerable uncertainty. The reduced yield under higher rainfall is due to N leaching. As expected, yields in CA systems were higher while the lowest yields were obtained with no-tillage systems. However, more N leaching is expected under conservation tillage due to the effect of the residues covering the soil and limited run-off.

4.4. Did we capture interactions between genetic environment and the cropping system?

The simulations investigated the role of the genetic modification of cotton to adapt to climate change in the future. Due to limited access to wide genetic variability and soil types, we only explored a small proportion of the possible interactions between cropping systems, climate and genetics. Moreover, other adaptations such as fertilization management or supplementary irrigation may be faster than achieving genetic improvements (Howden et al., 2007). Our ideotypes were designed in controlled conditions and of course farmers may have other considerations. For example, they may prefer cultivars with rapid LAI dynamics for better weed competitiveness or bigger bolls to speed up manual harvesting. Although our representation of conservation agriculture is strictly biophysical and does not account for the biological modification associated with no plowing, it may change crop performances, especially with weed and pest infestations, soil properties and nutrient mineralization.

5. Conclusion

Based on field experiments conducted at Garoua and Maroua in North Cameroon in 2011–2012, the CROPGRO-cotton model was calibrated and tested to simulate seed cotton production under rainfed conditions using different cultivars, planting dates, conventional and direct mulch cropping systems and climate change scenarios. The results of these investigations revealed that under Cameroonian conditions, compared to existing cultivars, the ideotype should have a longer time to reach crop maturity and thicker smaller leaves with good photosynthetic capacity. Climate change will shorten time to crop maturity by increasing temperature, but this should not cause yield losses. The rainfall distributions and amounts are likely to increase but the climate models are inconsistent in this respect. There was a more than 20% difference in rainfall amounts between the climate models. Those that predict higher rainfall amounts predict lower simulated yields because excessive rainfall causes N leaching and vice versa. In these conditions, direct mulch cropping does not appear to be a good adaptation strategy as it decreases water runoff and hence increases infiltration and leaching.

Climate changes in 2050 are not expected to profoundly modify the cropping conditions for cotton in Cameroon except maybe by an increase in rainfall amount and in leaching. Fertilization should be adjusted to that risk (fractioning, using less soluble fertilizer). Crop breeders in Africa may select cultivars with longer time to reach crop maturity and thicker leaves. They will have to ensure the quality standards and the fiber percentages are as high as before while selecting changes in genetic traits for better productivity in seed-cotton. Crosses between African and South American cultivars already began in the 2010s in Mali and Cameroon. Some are already available to farmers.

References

Aggarwal, P.K., Kropff, M.J., Cassman, K.G., ten Berge, H.F.M., 1997. Simulating genotypic strategies for increasing rice yield potential in irrigated, tropical environments. Field Crops Res. 51 (1–2), 5–17.
Amin, A., et al., 2017. Optimizing the phosphorus use in cotton by using CSM-CROPGRO-cotton model for semi-arid climate of Vehari-Punjab, Pakistan. Environ. Sci. Pollut. Res. 24 (6), 5811–5823.
Anapalli, S., et al., 2016. Climate-optimized planting windows for cotton in the Lower Mississippi Delta region. Agronomy 6 (4), 46.
Asseng, S., Turner, N.C., Ray, J.D., Keating, B.A., 2002. A simulation analysis that predicts the influence of physiological traits on the potential yield of wheat. Eur. J. Agron. 17, 123–141.
Blanc, E., Quirion, P., Strobl, E., 2008. The climatic determinants of cotton yields: evidence from a plot in West Africa. Agric. For. Meteorol. 148 (6-7), 1093–1100.
Boote, K.J., 2004. Using a crop growth model to hypothesize genetic traits to improve peanut yield under water-limited environments. In: Fischer, R. (Ed.), Australian Agronomy Conference, 4th International Crop Science Congress. The Regional Institute Ltd., Brisbane, Australia.
Boote, K.J., Tollenaar, M., 1994. Modeling genetic yield potential. In: Boote, K.J., Bennett, J.M., Sinclair, T.R., Paulsen, G.M. (Eds.), Physiology and Determination of Crop Yield. ASA-CSSA-SSSA, Madison, WI, USA, pp. 533–565.
Boote, K.J., Kropff, M.J., Bindraban, P.S., 2001. Physiology and modelling of traits in crop plants: implications for genetic improvement. Agric. Syst. 70 (2-3), 395–420.
Cao, T.-V., Oumarou, P., Gawrysiak, G., Klassou, C., Hau, B., 2011. Short-season cotton (Gossypium hirsutum) may be a suitable response to late planting in sub-Saharan regions. Field Crops Res. 120 (1), 9–20.
Challinor, A.J., et al., 2014. A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Change 4 (4), 287–291.
Chipanshi, A.C., Chanda, R., Totolo, O., 2003. Vulnerability assessment of the maize and Sorghum crops to climate change in Botswana. Clim. Change 61 (3), 339–360.
Gérardeaux, E., Giner, M., Ramanantsoanirina, A., Dusserre, J., 2012. Positive effects of climate change on rice in Madagascar. Agron. Sustain. Dev. 32 (3), 619–627.
Gérardeaux, E., et al., 2013. Positive effect of climate change on cotton in 2050 by CO2 enrichment and conservation agriculture in Cameroon. Agron. Sustain. Dev. 33 (3), 485–495.
Gijsman, A.J., Hoogenboom, G., Parton, W.J., Kerridge, P.C., 2002. Modifying DSSAT crop models for low-input agricultural systems using a soil organic matter–Residue module from CENTURY. Agron. J. 94 (3), 462–474.
Godwin, D., Ritchie, J.T., Singh, D.P., Hunt, L., Alocilja, E.C., 1989. A Users Guide to CERES-Wheat V-2.1, Hawaii.
Hammer, G.L., Kropff, M.J., Sinclair, T.R., Porter, J.R., 2002. Future contributions of crop modelling - from heuristics and supporting decision making to understanding genetic regulation and aiding crop improvement. Eur. J. Agron. 18, 15–31.
Harb, O.M., Abd El-Hay, G.H., Hager, M.A., Abou El-Enin, M.M., 2016. Calibration and validation of DSSAT V.4.6.1, CERES and CROPGROModels for simulating No-Tillage in Central Delta, egypt. Agrothechnolgy 5 (2).
Howden, S.M., et al., 2007. Adapting agriculture to climate change. Proc. Natl. Acad. Sci. 104 (50), 19691–19696.
ICAC, 2016. Cotton: World Statistics. Bulletin of the International Cotton Advisory Committee. Secretariat of the International Cotton Advisory Committee, 1629 K Street, N.W., Suite 702, Washington, D.C. 20006, U.S.A, pp. 298. https://www.icac.org/.
Jagtap, S.S., Abamu, F.J., 2003. Matching improved maize production technologies to the resource base of farmers in a moist savanna. Agric. Syst. 76 (3), 1067–1084.
Jones, J.W., et al., 2003. The DSSAT cropping system model. Eur. J. Agron. 18 (3–4), 235–265.
Jones, J.W., Hoogenboom, G., Wilkens, P.W., Porter, C.H., Tsuji, G.Y., 2010. Decision Support System for Agrotechnology Transfer Version 4.5. Crop Model

Documentation, vol. 4 Univ. Hawaï, Honolulu, HI.
Kabat, P., Schulze, R.E., Hellmuth, M.E., Veraart, J.A., 2003. Coping With Impacts of Climate Variability and Climate Change in Water Management: a Scoping Paper. International Secretariat of the Dialogue on Water and Climate, Wageningen, Netherlands.
Kropff, M.J., Haverkort, A.J., Aggarwal, P.K., Kooman, P.L., 1995. Using Systems Approaches to Design and Evaluate Ideotypes for Specific Environments.
Loison, R., et al., 2017. Sixty years of breeding in Cameroon improved fibre but not seed cotton yield. Exp. Agric. 53 (2), 202–209.
Mbétid-Bessane, E., Havard, M., Djondang, K., 2006. Evolution des pratiques de gestion dans les exploitations agricoles familiales des savanes cotonnières d'Afrique centrale. Cah. Agric. 15 (6), 555–561.
Michelangeli, P.A., Vrac, M., Loukos, H., 2009. Probabilistic downscaling approaches: application to wind cumulative distribution functions. Geophys. Res. Lett. 36 (11), L11708.
Naudin, K., Gozé, E., Balarabe, O., Giller, K.E., Scopel, E., 2010. Impact of no tillage and mulching practices on cotton production in North Cameroon: A multi-locational on-farm assessment. Soil Tillage Res. 108 (1-2), 68–76.
Niang, I., et al., 2014. Contribution of working group II to the Fifth assessment report of the intergovernmental panel on climate change. In: Barros, V.R. (Ed.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199–1265.
Parton, W.J., 1996. The CENTURY model. In: Powlson, D.S., Smith, P., Smith, J.U. (Eds.), Evaluation of Soil Organic Matter Models: Using Existing Long-Term Datasets. Springer, Berlin Heidelberg, Berlin, Heidelberg, pp. 283–291.
Pathak, T.B., Fraisse, C.W., Jones, J.W., Messina, C.D., Hoogenboom, G., 2007. Use of global sensitivity analysis for cropgro cotton model development. Am. Soc. Agric. Eng. 50 (6), 2295–2302.
Pickering, N.B., et al., 1994. Weatherman - a utility for managing and generating daily weather data. Agron. J. 86 (2), 332–337.
Ramarohetra, J., Pohl, B., Sultan, B., 2015. Errors and uncertainties introduced by a regional climate model in climate impact assessments: example of crop yield simulations in West Africa. Environ. Res. Lett. 10 (12), 124014.
Rosenow, D.T., Quisenberry, J.E., Wendt, C.W., Clark, L.E., 1983. Drought tolerant sorghum and cotton germplasm. Agric. Water Manag. 7 (1), 207–222.
Roudier, P., Sultan, B., Quirion, P., Berg, A., 2011. The impact of future climate change on West African crop yields: what does the recent literature say? Glob. Environ. Change 21 (3), 1073–1083.
Saseendran, S.A., et al., 2007. Simulating management effects on crop production, tile drainage, and water quality using RZWQM–DSSAT. Geoderma 140 (3), 297–309.
Schlenker, W., Lobell, D.B., 2010. Robust negative impacts of climate change on African agriculture. Environ. Res. Lett. 5, 8.
Sillmann, J., Kharin, V.V., Zwiers, F.W., Zhang, X., Bronaugh, D., 2013. Climate extremes indices in the CMIP5 multimodel ensemble: part 2. Future climate projections. J. Geophys. Res. Atmos. 118 (6), 2473–2493.
Sinclair, T.R., Purcell, L.C., 2005. Is a physiological perspective relevant in a 'genocentric' age? J. Exp. Bot. 56 (421), 2777–2782.
Singh, R.S., Raghubanshi, A.S., Singh, J.S., 1991. Nitrogen-mineralization in dry tropical savanna: effects of burning and grazing. Soil Biol. Biochem. 23 (3), 269–273.
Singh, P., et al., 2014. Potential benefits of drought and heat tolerance in groundnut for adaptation to climate change in India and West Africa. Mitig. Adapt. Strat. Glob. Change 19 (5), 509–529.
Singh, P., et al., 2017. An assessment of yield gains under climate change due to genetic modification of pearl millet. Sci. Total Environ. 601-602, 1226–1237.
Soltani, A., Hoogenboom, G., 2007. Assessing crop management options with crop simulation models based on generated weather data. Field Crops Res. 103 (3), 198–207.
Stitt, M., Schulze, D., 1994. Does Rubisco control the rate of photosynthesis and plant growth? An exercise in molecular ecophysiology. Plant Cell Environ. 17 (5), 465–487.
Sultan, B., Bella-Medjo, M., Berg, A., Quirion, P., Janicot, S., 2010. Multi-scales and multi-sites analyses of the role of rainfall in cotton yields in West Africa. Int. J. Climatol. 30 (1), 58–71.
Tennakoon, S.B., Milroy, S.P., 2003. Crop water use and water use efficiency on irrigated cotton farms in Australia. Agric. Water Manag. 61 (3), 179–194.
Tingem, M., Rivington, M., Bellocchi, G., Azam-Ali, S., Colls, J., 2008. Effects of climate change on crop production in Cameroon. Clim. Res. 36 (1), 65–77.
Tingem, M., Rivington, M., Bellocchi, G., 2009. Adaptation assessments for crop production in response to climate change in Cameroon. Agron. Sustain. Dev. 29 (2), 247–256.
Tschirley, D.L., Poulton, C., Labaste, P., 2009. Organisation and Performance of Cotton Sectors in Africa: Learning from Reform Experience. Agriculture and Rural Development. The World Bank, Washington D.C., USA.
van der Linden, P., Mitchell, J.F.B. (Eds.), 2009. Ensembles-Based Predictions of Climate Changes and Their Impacts (ENSEMBLES). Exeter EX1, UK, pp. 166.
Wajid, A., et al., 2014. Modeling growth, Development and seed-cotton yield for varying nitrogen increments and planting dates using DSSAT. Pak. J. Agric. Sci. 51 (3), 639–647.
Wilson, P.J., Thompson, K.E.N., Hodgson, J.G., 1999. Specific leaf area and leaf dry matter content as alternative predictors of plant strategies. New Phytol. 143 (1), 155–162.
Wright, I.J., et al., 2004. The worldwide leaf economics spectrum. Nature 428 (6985), 821–827.