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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