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Can farmers use maize earliness choice and sowing dates to cope with future water scarcity? A modelling approach applied to south-western France

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ABSTRACT

To sustain food production in the future, the agricultural sector must adapt to climate change through agronomic means. In the Midi-Pyrénées (south-western France), maize is the main irrigated crop, and increasing pressure on water resources challenges the appropriateness of this crop in the region. In this study we evaluated the impact of temperature and precipitation changes on the sowing and harvesting period of maize and, consequently, on the suitability of cultivar earliness to this sowing-harvest window in the future. Next, we quantified the yield and irrigation requirements of three earliness choices (early, medium and late) for the appropriate sowing-harvest window. We ran three simulation models with climate-change scenarios. The first (a sowing model) predicts the days suitable for sowing maize, the second (MODERATO) predicts yield and irrigation requirements for all suitable sowing days, and the third (a harvest model) predicts the days suitable for harvesting. We ran these models with a simulated weather data series covering the reference period (1971–2000) and two future periods (2021–2050 and 2071–2100) for the study area. We also calculated climatic and agronomic indices to understand changes in maize sowing days, the maize growing period and suitable earliness choice due to climate change for the two future periods compared to the reference period. The results showed an increase in thermal time and decrease in rainfall in the future that will influence maize earliness choice, growing period, yield and irrigation requirements. The trade-off between farmers' maize earliness choices and suitable maize growing periods will increase in the future. Late-earliness maize cultivars can be cultivated in the future; however, the associated irrigation requirements also will be higher. Farmers need to cope with climate-induced water scarcity in the future by selecting a suitable sowing date, maize earliness and soil type to cultivate maize.

1. Introduction

Studies on climate change predict increased temperature and altered rainfall patterns with higher inter-annual variability in the future. These changes will depend largely on geographic location (IPCC, 2001; Olesen et al., 2011). The agricultural sector, and consequently food production, will be greatly influenced by these changing climatic conditions (Lobell et al., 2008). In most studies, crop simulation models are used to demonstrate the impact climate change may have on crop functioning and production (e.g. for maize, Islam et al., 2012). The impact of climate change on agricultural practices is rarely considered. For example, in their virtual experiments, Islam et al. (2012) assumed that agricultural practices will be similar in the future (e.g. fertilisation rates, sowing dates, irrigation rates). To adapt to decreased precipitation due to climate change, however, farmers may modify their practices, for example by irrigating more, thereby increasing the impact of climate change on water resources. Similarly, Bocchiola et al. (2013) demonstrated a negative impact of climate change on the water footprint of Po valley maize fields in the case of a future decrease in rainfall. To adapt to climate change without negatively impacting water resources, Mishra et al. (2013) explored the potential of using short-term weather forecasts to increase irrigation efficiency in rice cultivation.

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Several possibilities exist for agricultural adaptations to climate change through agronomic means, such as the use of improved germplasm and novel technologies, conservation agriculture or precision agriculture (Shiferaw et al., 2011). Responding with agricultural practices is one way to adapt. For example, sowing date and cultivar earliness can be adjusted based on expected weather conditions, e.g. length of the favourable period for crop growth, or a dry spell. Nevertheless, such adjustment is not straightforward. Farm resources (e.g. land area to be sown or harvested, water resources for irrigation, diversity of farm activities and availability of farm labour and equipment) influence how farmers sow. In particular, they can choose to sow rapidly or slowly, in one or several sessions, to place their mature crops in the best conditions for harvest: a rapid or prolonged harvest can be planned depending on how the harvesting and drying of grain maize will be organised (Maton et al., 2009; Van Oort et al., 2012). Information about the length and time of the sowing period and the growth and harvest of crops with different earliness would help farmers plan farm activities when coping with future climatic conditions (Araya et al., 2012). For example, farmers may face a trade-off between (i) choosing late maize earliness varieties that are productive, but with the risk of not completing the crop cycle or not harvesting if climatic conditions are not favourable, and (ii) choosing early earliness varieties that are less productive, but with higher probability of suitable climatic conditions up to harvest. Experiments may be useful for helping farmers, but they do not allow testing a range of climatic conditions broad enough to represent those expected with climate change. Modelling and simulation are more effective tools (Bergez et al., 2010, Loyce and Wery, 2006). Models that design crop management practices are complex because they combine a dynamic crop model that represents the behaviour of soil–plant–atmosphere interactions (e.g. Brisson et al., 1998; Stockle, 1997) with a decision model that represents a farmer's choices (e.g. Bergez et al., 2010; Chatelin et al., 2005). They also must provide the opportunity to assess the crop yield and crop inputs due to crop management options. The effect of irrigation can then be estimated as a preliminary step for estimating the impact on the water resource (Leenhardt et al., 2004).

This study aims to analyse in silico how climate change influences farmers' maize earliness choice and irrigation demand. In the first section we describe the models, virtual experiments and indices used to analyse the impacts of climate change on maize management. In the second section we present and discuss the main results obtained, in particular their implications for farmers, water managers and plant breeders.

2. Materials and methods

In this study we conducted a virtual experiment based on the use of a model chain that simulates the impact of change in climate variables on the soil water, maize growth and thus maize management. The study area is located in the Midi-Pyrénées (south-western France), and maize was selected as a case study since it is the main irrigated crop in south-western France, with a sown area of roughly 140,000 ha. We describe below (i) the model chain, composed of three models; (ii) the virtual experiment conducted; and (iii) the indices that allow us to describe the impact of climate change on crop and water management.

2.1. The model chain

We used three models (Fig. 1). First, the sowing model predicts days agronomically suitable for sowing maize. The sowing model, initialised with full soil water holding capacity on 1 January, provides a list of days suitable for sowing. Second, the bio-decisional model MODERATO (Bergez et al., 2001) predicts the yield and irrigation used on a given sowing day and the soil water content at the physiological maturity of maize. Third, the harvest model, initialised with the soil water content at maize physiological maturity output of MODERATO, predicts soil trafficability to determine which days are agronomically suitable for harvesting maize. The sowing model works for the first part of the year, from day-of-year (DOY) 1–166, while the harvest model works from DOY 167 until the end of the year.

2.1.1. The sowing model

We used the sowing model developed, calibrated and validated by Maton et al. (2007). It calculates whether a day is suitable for sowing, considering that frost and low temperatures may be unfavourable for plant emergence and growth, and excessive wetness of the soil surface may be unfavourable for operating sowing machines. One module checks the risk of frost, a second module estimates whether temperature conditions are suitable for sowing, and a third estimates whether the soil is trafficable (Fig. 1). The days agronomically suitable for sowing are predicted to occur when these three conditions are favourable. The parameters and threshold values used for our soil and climate conditions were obtained from Maton et al. (2007), as this study was conducted in the same area.

2.1.2. The bio-decisional model, MODERATO

MODERATO is a management-oriented cropping system model used for designing maize irrigation schedules (Bergez et al., 2001, 2002). The model calculates crop growth and soil water on a daily basis. Crop development stages are based on cumulative thermal units. Biomass accumulation is based on the general interception/conversion of solar radiation, and grain yield is calculated as final aboveground biomass times a harvest index (Wallach et al., 2001). The harvest index can be affected by water stress, but not by CO_2 changes, since the effect of atmospheric CO_2 concentration is not included in the model.

2.1.3. The harvest model

The harvest model, developed for the present study, identifies days agronomically suitable for harvesting based on soil trafficability, calculated with soil moisture content. As with sowing, harvesting machines cannot operate when the soil is too wet because they can damage the soil. The criterion, which is the ratio of soil water content (θ) to available soil water holding capacity (θ_x), was used to estimate soil trafficability (Leenhardt and Lemaire, 2002). Calculation of θ_x takes soil properties into account, as follows:

$$\text{IF } \frac{\theta(t)}{\theta_x} > P \quad \text{THEN} \quad H_w(t) = 0 \quad \text{ELSE} \quad H_w(t) = 1 \tag{1}$$

where, $\theta(t)$ is soil water content on day t, P is the trafficability threshold (equal to 0.7) and $H_w(t)$ is a Boolean variable that equals 0 if the soil is too wet to harvesting. Dynamics of $\theta(t)$ are simulated using the same water budget as in the sowing model.

The sowing and harvest models were written using R (R Development Core Team, 2012). MODERATO is written in C++, but called by R in the model chain.

2.2. Virtual experiment

The virtual experiment was conducted for a study area in south-western France, the "Neste system" area, where maize is the main irrigated crop and is of major importance for water management. The experiment consisted of a combination of various options of model inputs: weather data, soil type and maize earliness.