

Will climate change impact farmers' maize earliness choice? A modeling approach applied to south-western France

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Abstract: To sustain food production in the future, the agricultural sector must adapt to changing climate conditions through agronomic means. In the Midi-Pyrénées (south-western France), maize is the main irrigated crop, and increasing pressure on water resources questions 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. We ran two models with climate-change scenarios. The first model calculates the days suitable for sowing maize, and the second calculates the days suitable for harvesting. We ran these models with simulated weather data series covering the reference period (1971-2000) and two future periods (2021-2050 and 2071-2100) for the study area. Further, we calculated climatic and agronomic indices to understand the 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 and growing period. 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, more detailed analysis is needed on irrigation requirements for the changes in cultivar earliness, maize growing period and shift in maize growth stages to cope with climate change.

Keywords: Thermal time; maize earliness; sowing; harvesting; decision modelling.

1. INTRODUCTION

Studies on climate change predict increased temperature and altered rainfall patterns with higher inter-annual variability in the future, and these changes will largely depend on geographic location [IPCC, 2001]. The agricultural sector is influenced by changing climatic conditions and must adapt to sustain agricultural production [Lobell et al, 2008]. Agricultural adaptations to climate change by agronomic means are important [Shiferaw et al, 2011] through the selection of suitable cultivar earliness choices and crop management practices by farmers. For instance, sowing and harvesting must be adjusted based on anticipated weather conditions. Farmers may need short or long, intermittent or continuous sowing and harvesting periods depending on their farm resources, such as land area to be sown or harvested, availability of farm machinery, diversity of farm activities and availability of farm labour. Simulating the availability of suitable sowing and harvesting days will help them plan farm activities to cope with future climatic conditions. Since sowing is the most important technical operation, determining the length of the crop cycle [Girardin, 1998], detailed analysis on agronomic indices, such as total or consecutive suitable sowing days or frequency of a given day-of-year (DOY) suitable for sowing will help design future crop management options.

In this study, we aimed to analyze the impact of climate change on anticipated changes in the maize growing period and farmers' maize earliness choice in south-western France (the Midi-Pyrénées). 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. Due to climate change, pressure on water resources has increased, which increasingly calls into question the appropriateness of irrigated maize. However, climate change will not only impact irrigation but may also modify other agricultural practices, such as sowing and harvesting dates, and thus impact the maize growing period and farmers' choice of maize earliness.

The objectives of the present study were to evaluate the impact of temperature and rainfall changes on the sowing and harvesting period of maize and, as a consequence, on the cultivar earliness most suitable for this sowing-harvest window.

2. MATERIALS AND METHODS

We used two models: the first predicts days agronomically suitable for sowing maize, and the second predicts days agronomically suitable for harvesting maize. Both models were combined to identify windows for the maize growing period and to study suitable maize earliness choices. Further, we calculated several climatic and agronomic indices. The sowing model works for the sowing period (DOY 1-166), and the harvesting model works for the harvesting period (DOY 167-365[366]). The models were written using R.

2.1 Study area, study period and climate data

The study was conducted for the "Neste system", which is a water management area in south-western France. We used the weather data series valid for the center of the Neste system. There are two types of soils in the study area ("Boulbènes", a loamy acid soil, and "Terreforts", a clay soil), but the soil data used in the model were for the "Boulbènes" soil only. Climate data were obtained from the CERFACS database, which was generated using the ARPEGE V4.6 model developed by Météo France [Boé, 2007; Pagé et al, 2008], for three periods of 30 consecutive years each. The reference period corresponded to 1971-2000, and the near and far future periods corresponded to 2021-2050 and 2071-2100, respectively. The climate data used in the model were daily maximum and minimum temperature, rainfall, incident solar radiation and evapotranspiration. For the future periods, we used climate data for the climate-change scenario 'B1', which envisages rapid changes in economic structures and the introduction of resource-efficient technologies [IPCC, 2001].

2.2 Climatic indices

The climatic indices mean cumulative thermal time (*MCTT*) and mean cumulative rainfall (*MCRF*) were calculated for each 30-year period. First, the cumulative thermal time, $CTT(t,y)$, was calculated from DOY 1 to t in year y [Wallach et al, 2001]. The maximum temperature was limited to 30°C because higher temperatures do not influence photosynthate assimilation in maize [Lobell et al, 2011]. When the calculated thermal time was below 0°C-days, the available thermal time of the day was considered zero. We calculated $CTT(t,y)$ for each DOY of the 30 years in each period and *MCTT* for each DOY of each period's mean year. Similarly, the *MCRF* was calculated by replacing thermal time (TT) data with rainfall data.

2.3 The sowing model

We used the sowing model developed by Maton et al [2007]. It identifies days suitable for sowing according to three field conditions: (1) frost, (2) temperature enabling crop emergence and growth, and (3) soil moisture allowing a tractor to enter the field. The sowing model consists of four modules that use weather and soil data to describe these three biophysical constraints (Figure 1). The first module estimates the risk of frost, which occurs when the minimum temperature is below -2°C . We considered that a risk of frost occurs when the probability of frost reaches 80%, which represents farmers' risk aversion [Lorgeou and Souverain, 2003]. The second module deals with temperature conditions for sowing. The third module deals with soil trafficability, i.e. soil conditions suitable for operating sowing machines. The last module estimates the days agronomically suitable for sowing. Details about these modules (formulae and calculation steps with threshold values) are presented in Maton et al [2007].

2.4 The harvest model

A harvest model was developed to identify days agronomically suitable for harvesting based on soil trafficability using rainfall data. As with sowing, harvesting machines cannot operate when the soil is too wet because they can damage the soil. Rainfall quantity is used to identify days suitable for harvesting (Figure 1). It was observed that farmers stopped field operations when rainfall exceeded 15 mm [Maton et al, 2007]. Based on this information and expert knowledge, we used a set of staggered rainfall thresholds. If the rainfall amount is greater than R_x , then the following x days are not suitable for harvesting:

$$\text{IF } R(t) > R_x \text{ THEN } H(t + \partial t) = 0 \text{ WITH } \partial t \in [1; x] \text{ ELSE } H(t) = 1 \quad (1)$$

where, $R(t)$ is rainfall on day t . R_1 to R_4 (R_x) are the thresholds of the rainfall rule and take the values 15, 20, 25 and 30 mm with a ∂t of 1, 2, 3 and 4 days, respectively. $H(t)$ is a Boolean variable (0 when the rainfall rule disallows harvesting and 1 otherwise).

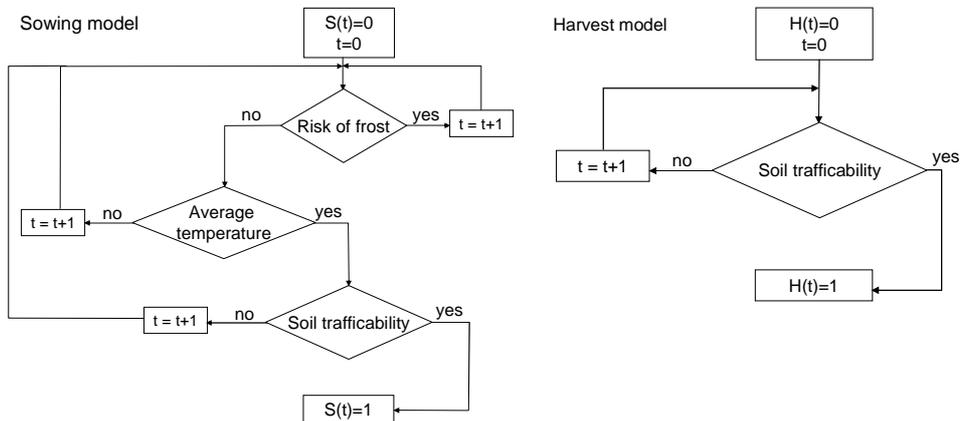


Figure 1. Design of sowing and harvesting models that determined days agronomically suitable for sowing and harvesting, respectively. The sowing model is adopted from Maton et al [2007].

2.5 Agronomic indices

To describe each climate period, we calculated indices. Cumulative suitable sowing days on a particular DOY t of year y , $CSSD(t,y)$, was calculated by summing the number of suitable days until day t .

$$CSSD(t, y) = \sum_{t=1}^t SSD(t, y) \quad (2)$$

where, $SSD(t, y)$ is the Boolean suitability of DOY t for sowing (0 or 1). $CSSD(t, y)$ represents the number of days suitable for sowing that occurred from DOY 1 to t for year y , $y = \text{year } 1-30$ and $t = \text{DOY } 1-166$. From this, the mean of the daily cumulative suitable sowing days for each DOY over the 30-year period $MCSSD(t)$ was calculated as:

$$MCSSD(t) = \frac{\sum_{y=1}^{ny} CSSD(t, y)}{ny} \quad (3)$$

where, $ny = \text{total number of years (30 years per period)}$.

The frequency $FSSD(t)$ at which a given DOY t was suitable for sowing over the 30 years was calculated as a percentage:

$$FSSD(t) = \frac{\sum_{y=1}^{ny} DASS(t, y)}{ny} \times 100 \quad (4)$$

where $DASS(t, y)$ is a Boolean value (0 or 1).

Farmers may require a certain number of consecutive suitable sowing days (i.e. a sowing session) to complete sowing. Hence, the number of sessions of 1- n consecutive suitable sowing days (S_n) per year was calculated by taking the mean S_n over the 30-year period. A TT matrix showing the mean cumulative TT for growing maize for each 30-year period was plotted to understand the available windows of opportunities for maize growth. The TT matrix was drawn with sowing period on the y-axis and harvesting period on the x-axis and then computing the cumulative thermal time between each of the suitable sowing and harvesting date combinations. IsoTT lines were drawn in the TT matrix to show the window of the growing period of a given cultivar earliness choice. However, the number of years in a 30-year period that a given sowing-harvest date combination exists is not shown in the TT matrix.

3. RESULTS AND DISCUSSION

3.1 Changes in climatic indices for future maize growth

The available TT for maize growth in south-western France is predicted to increase in the future compared to the reference period (Figure 2a). The maximum available TT is 2735 and 2950°C-days for the near and far future, respectively, which is 9% and 18% more than that for the reference period (2500°C-days). This implies that a given cultivar in the reference period will mature earlier in the future, and late-earliness cultivars can be introduced in the future. Introducing late-earliness cultivars in the future may result in higher maize yields. Thus, more food and feed can be produced without converting more land to agricultural use. However, available water resources for irrigation would limit the introduction of late-earliness maize cultivars in the future [Döll, 2002]. Predicting the suitable maize earliness choice for the future also helps plant breeders and geneticists determine appropriate maize cultivars to develop. Cumulative mean rainfall over the three periods showed that rainfall will be lower in the future than in the reference period (Figure 2b). Therefore, pressure on available water resources for agricultural use could further increase.

3.2 Changes in agronomic indices for future maize growth

The first suitable day for sowing maize occurs on DOY 76 and 66 in the near and far future, respectively, compared to DOY 82 in the reference period (Table 1).

Predicting the first suitable day for sowing and harvesting may not be useful for farmers since they do not perform these activities on the very first suitable day; however, it is useful for understanding the windows of available growing periods for maize and selecting the suitable earliness choice for higher production with minimal resource use. The total number of suitable sowing days in the sowing period is also higher in the future. A mean of 40 and 46 days are suitable for sowing in the near and far future periods, respectively, compared to 36 days in the reference period (Figure 3a).

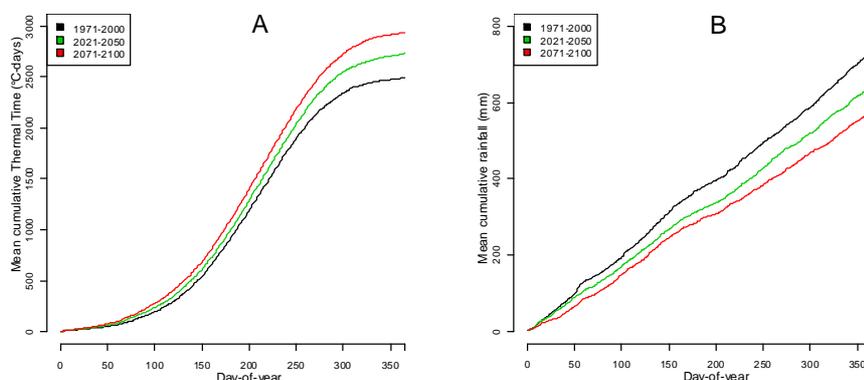


Figure 2. Predicted mean cumulative (A) thermal time and (B) rainfall for maize growth for the reference and two future periods.

Table 1. The mean (in bold) and range (in parentheses) of the day-of-year (DOY) when three sowing conditions and the day suitable for sowing first occur in the reference and two future periods.

Period	Frost	Growth temperature	Soil trafficability	Day suitable for sowing
1971-2000	1 (1 – 1)	26 (7 – 78)	76 (37 – 129)	82 (55 – 129)
2021-2050	1 (1 – 1)	23 (7 – 66)	70 (34 – 109)	76 (39 – 120)
2071-2100	1 (1 – 1)	19 (7 – 53)	64 (18 – 113)	66 (18 – 113)

Among the three conditions considered in the sowing model, the most limiting is soil trafficability, followed by growth temperature and frost (Table 1). Further, in future periods both growth temperature and soil trafficability will become more favourable for maize sowing because of temperature increases and rainfall reduction (Figure 2).

The frequency of a given DOY being suitable for sowing maize was also higher in the two future periods compared to the reference period (Figure 3b). This implies that farmers can complete sowing earlier. Also, the length of the period, including days not suitable for sowing, allowed sowing to be completed in less time in the future.

The length of sowing sessions, i.e. consecutive suitable sowing days, will be higher in the future. For example, a sowing session of 5 consecutive days occurs on 13.2 and 16.0 years out of 30 years in the near and far future, respectively, compared to only 10.6 years out of 30 years in the reference period. Thus, when a farmer needs a sowing session of 5 days to complete sowing, the probability of getting it will be 25% and 51% higher in the near and far future, respectively (Figure 3c). In addition, the frequency of long sowing sessions will be greater: up to 21 and 28 consecutive days in the near and far future, respectively, but their probability of occurrence is low (once in 30 years).

3.3 Window of maize growing period and earliness choice

The TT matrix with isoTT lines shows the windows of maize growing periods and gives indications for maize earliness choices for the three periods studied (Figure 4). Maize farmers will have more time for sowing and harvesting in the future. A maize cultivar requiring 2200°C-days of TT to attain harvest maturity in the

reference period, for example, must be sown from DOY 55-118 and can be harvested only from DOY 274-365 along the IsoTT line (Figure 4). But the same

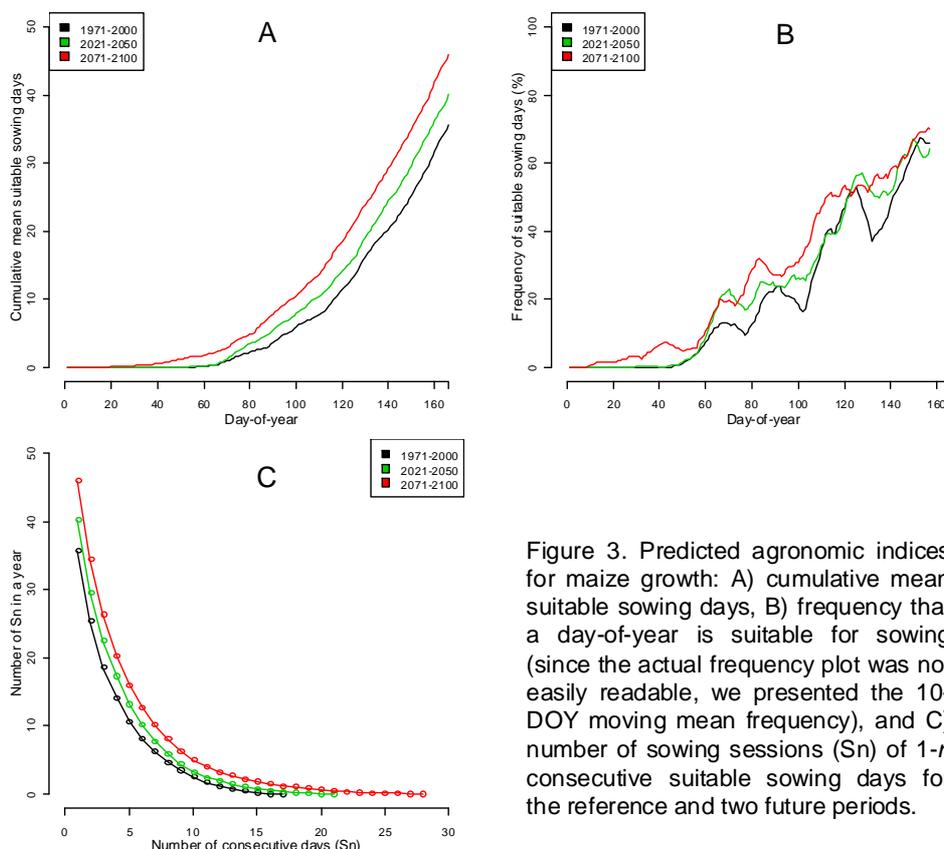


Figure 3. Predicted agronomic indices for maize growth: A) cumulative mean suitable sowing days, B) frequency that a day-of-year is suitable for sowing (since the actual frequency plot was not easily readable, we presented the 10-DOY moving mean frequency), and C) number of sowing sessions (S_n) of 1- n consecutive suitable sowing days for the reference and two future periods.

cultivar can be sown from DOY 39-143 and harvested from DOY 258-366 in the near future. Similarly, in the far future it can be sown from DOY 18-156 and harvested from DOY 252-366. The window of the selected IsoTT line (2200°C-days) is larger in the two future periods than in the reference period (Figure 4). Thus, maize farmers in south-western France will have more windows of opportunity for sowing and harvesting in the future. Moreover, farmers can cultivate late varieties that require more than 2700 and 2900°C-days of TT in the near and far future, respectively. The trade-off between farmers' maize earliness choices and suitable maize growing periods increases in future periods compared to the reference period.

3.4 Shift in maize growth stages due to climate change

Changes in maize earliness choice and the growing period due to climate change in the future will also shift the most important maize growth stages, such as flowering and harvest maturity. This can be demonstrated by selecting three cultivar choices (early, medium and late) and assuming that they are sown on the first suitable sowing day in each period. All three maize cultivars reach the flowering stage 7 and 15-16 days earlier in the near and far future, respectively, than in the reference period (Table 2). Similarly, harvest maturity advances by 8-14 days and 17-26 days in the near and far future, respectively. Due to this shift in maize growth stages, crop irrigation demand could change greatly in the future. Irrigation is particularly needed around the flowering stage. Thus, irrigation scheduling of maize may need to be redesigned when considering these shifts in maize growth periods temporally and spatially, especially given regional differences in climate in south-western France.

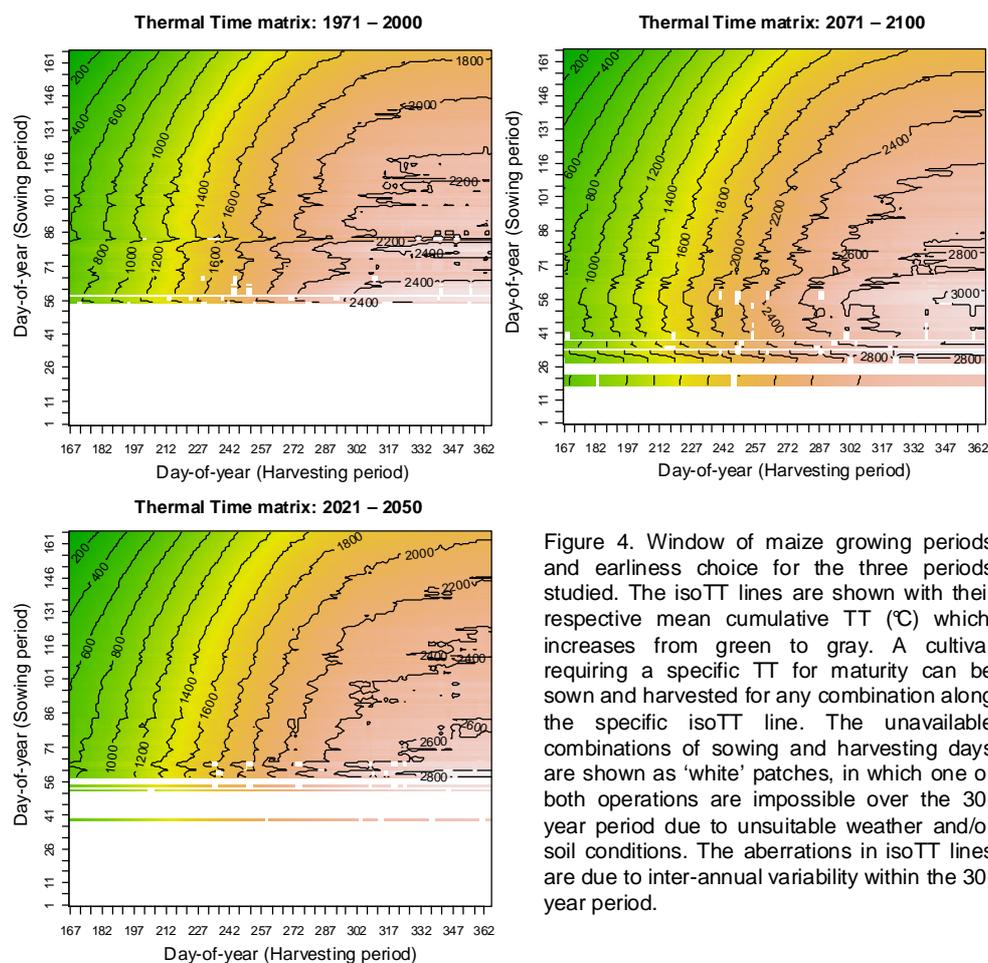


Figure 4. Window of maize growing periods and earliness choice for the three periods studied. The isoTT lines are shown with their respective mean cumulative TT ($^{\circ}\text{C}$) which increases from green to gray. A cultivar requiring a specific TT for maturity can be sown and harvested for any combination along the specific isoTT line. The unavailable combinations of sowing and harvesting days are shown as 'white' patches, in which one or both operations are impossible over the 30-year period due to unsuitable weather and/or soil conditions. The aberrations in isoTT lines are due to inter-annual variability within the 30-year period.

Table 2. Mean predicted day-of-year (DOY) of flowering and harvest maturity* of three maize earliness choices during 30 years of current and future climates.

Event	1971-2000	2021-2050	2071-2100
First suitable DOY for sowing	55	39	18
Flowering			
Early cultivar (e.g. <i>Anjou 190</i>)	176	169	161
Medium cultivar (e.g. <i>Dk 300</i>)	186	179	170
Late cultivar (e.g. <i>Bounti</i>)	194	187	179
Maturity with 32% or 35% grain humidity			
Early cultivar (e.g. <i>Anjou 190</i>)	230	222	213
Medium cultivar (e.g. <i>Dk 300</i>)	241	232	222
Late cultivar (e.g. <i>Bounti</i>)	269	255	243

* Thermal time ($^{\circ}\text{C}$ -days) requirement for flowering and harvest maturity of the selected maize cultivars are 787 and 1565 for the early cultivar; 917 and 1715 for the medium cultivar; and 1040 and 2055 for the late cultivar, respectively.

3.5 Validity of the model and options for improvement

The sowing model used in this study was previously calibrated and validated using recorded sowing dates, and its performance was considered satisfactory [Maton et al, 2007]. The harvest model in its present form is simple, simulating soil trafficability for harvesting based on rainfall. More accurate simulation of soil trafficability for harvesting can be achieved by calculating soil moisture, as done in the sowing model. However, we cannot use the same method to predict soil trafficability for harvesting since the standing crop may influence soil moisture through transpiration and shading. For this, we need to introduce a model that can

predict soil moisture with a standing crop for all growth stages and a given irrigation strategy. This can be done by introducing a biodecisional model, such as MODERATO [Bergez et al, 2002]. Further, the harvest model can be improved by adding one or more cropping system constraints, such as a time limit to prepare the field for the following crop.

4. CONCLUSION

The increase in available thermal time and decrease in rainfall in south-western France will influence the maize growing period and maize earliness choices in the future. The combined sowing-harvest model helped identify future windows of available maize growing periods and earliness choices. Maize sowing can be performed early, and the number of suitable sowing days will increase in the future, which creates increased trade-off between farmers' maize earliness choices and maize growing periods. Long-duration maize cultivars can be cultivated in the future; however, other agronomic constraints, such as availability of irrigation water, will limit farmers' maize earliness choice and future maize yield. Therefore, irrigation scheduling for maize must be redesigned both spatially and temporally, considering climate variability and associated shifts in maize growing periods and growth stages. Coupling biophysical and decisional modelling tools will be useful to identify the best-suited maize earliness choice, growing period and associated resource requirements in future climatic conditions.

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