Europ. J. Agronomy 39 (2012) 62–70

Contents lists available at SciVerse ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Evaluating agronomic adaptation options to increasing heat stress under climate change during wheat grain filling in France

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ARTICLE INFO

Article history:
Received 29 September 2011
Received in revised form 18 January 2012
Accepted 26 January 2012

Keywords:
Triticum aestivum
Heat stress
Climate change
Grain filling
Adaptation
Simulation

ABSTRACT

There is much evidence that increasing temperatures due to climate change are having negative effects on yields of key staple crops, including wheat. In France particularly, a link has been shown between the stagnating wheat yields and an increase in heat stress occurrence during grain filling. We studied the occurrence of heat stress during grain filling of wheat under climate change by coupling downscaled weather scenarios from the ARPEGE climate model with a modified version of the ARCWHEAT phenology model. We also explored the effects of different agronomic solutions: earlier sowing, use of earlier cultivars and improved genetic tolerance to heat stress. Results show that in the near future (2020–2049) a small to null increase in heat stress may occur. In the far future (2070–2099), the frequency of heat stress during grain filling should increase significantly. Adaptation through earlier sowing dates proves to be the least efficient. Use of earlier heading cultivars is somewhat efficient, and should be sufficient for the near future. Tolerance to heat stress appears to be the most promising adaptation strategy. We discuss the importance of placing earliness and heat tolerance high on the agenda of wheat research and breeding, and the potential use of modelling in evaluating such strategies.

1. Introduction

Climate change has already been occurring in Europe and will likely continue during the 21st century (Christensen et al., 2007). In Europe, average temperature change under the IPCC A1B Greenhouse Gas (GHG) scenario is expected between 1 and 3 °C in 2050, accompanied by an increase of rainfall in Northern Europe along with a significant decrease near the Mediterranean Sea and in Southern Europe (Olesen et al., 2011). The potential impacts of climate change on global food security and the adaptations that will be required to face them are receiving increased attention (CCAFS, 2009). In France, Europe, and all around the world, a number of studies have shown negative relationships between increasing temperatures and national or regional crop yields: for maize, wheat and barley (Lobell et al., 2011; Lobell and Field, 2007) in many parts of the world, for rice in Asia (Peng et al., 2004), for maize and soybean in the United States of America (Schlenker and Roberts, 2009) and for spring wheat in Mexico (Lobell et al., 2005). Concerning wheat yields in Europe, Lobell et al. (2011) showed that recent temperature trends during the wheat growing season have significantly contributed to the levelling off or slow-down of national yield trends. Two recent studies in Denmark (Kristensen et al., 2011) and France (Brisson et al., 2010) confirmed the negative temperature effects and show more specifically that trends in summer temperatures or temperatures during grain filling are negatively linked to wheat yields.

One of the most obvious impacts of temperature increase on wheat is earlier occurrence of phenological stages (Porter and Gawith, 1999). Recent temperature increases in France have indeed been translated into earlier growth stages, with heading dates occurring a week earlier on average (Gate et al., 2008). Despite earlier heading, there has been a clear trend for increased frequency of high temperatures during grain filling (Gate, 2007). Porter and

Abbreviations: GHG, greenhouse gas; HSD, heat stress days (days with maximum temperature exceeding 25 °C during grain filling); HSD25, heat stress days specifically calculated with a 25 °C threshold; GCM, General Circulation Models; SRES, Special Report on Emissions Scenarios; RP, recent past (1970–1999); NF, near future (2020–2049); FF, far future (2070–2099); ANO, anomalies downscaling method; WT, weather typing downscaling method; QQ, quantile-quantile downscaling method; HSD26, heat stress days specifically calculated with a 26 °C threshold instead of 25 °C; T, heat stress tolerance adaptation strategy; E, use of an earlier cultivar adaptation strategy; S, use of an earlier sowing date adaptation strategy; Ref, reference strategy; RMSE, root mean square error.

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doi:10.1016/j.eja.2012.01.009

Gawith (1999) reported optimal temperatures for grain filling as residing between 19.3 °C and 22.1 °C. Empirical studies in France (Gate et al., 2010) have quantified the effect of heat stress during grain filling using the number of days during which maximum temperatures exceed 25 °C during grain filling (hereafter referred to as "Day of heat stress", HSD, or HSD25 in the particular case when it is explicitly calculated with a 25 °C threshold) as an indicator. These studies show that each HSD25 can be linked to an average loss of circa 0.8 g of thousand kernel weight, which translates approximately to 0.15 t/ha yield losses.

The impact of climate change through increased mean temperature on HSD is far from straightforward. Indeed, crop phenology responds approximately linearly to increased temperature (Gate and Brisson, 2010). However, the probability of exceeding any particular temperature threshold will not respond linearly (Schar et al., 2004). Finally, the advancement of the grain filling period may reduce the exposure to the warmest temperatures. Consequently, the use of simulation studies, linking projected climate date from climate models to crop models, is necessary. Such simulation studies of climate change impacts and adaptation strategies have only recently specifically addressed the link between grain yield losses and heat stress (Semenov, 2009; Semenov and Stratonovitch, 2010; Challinor et al., 2007, 2009a), although they had been called for by Porter (2005). These studies have mainly focused on elevated temperatures during the short period surrounding anthesis in which grain set is particularly sensitive to heat stress. Our study, on the other hand, has investigated the possible change in the frequency of heat stress throughout wheat grain filling which has not yet been calculated in these studies, and appears to be increasingly deleterious to wheat yields in Europe as stated earlier (Brisson et al., 2010; Kristensen et al., 2011).

Linking crop simulation models to projected climate data for the future from climate models is not straightforward. Indeed, the scale differences between General Circulation Models (GCMs) and crop simulation models must be bridged through downscaling approaches (Baron et al., 2005). Without downscaling, the number of days exceeding temperature thresholds may be very poorly estimated (Rivington et al., 2008a). Downscaling can significantly improve such estimates (Rivington et al., 2008b).

Simulation studies also allow to inform adaptation strategies (Challinor et al., 2009b). In our case, we investigated the possibilities for escaping heat stress through modifying the crop calendar by advancing sowing date or through genotypic adaptation, namely earlier crop phenology and improved tolerance to heat stress. Adapting sowing date is an easily feasible option. Sowing dates often vary by over one month in a given region in France and there are no indications that climate change will induce a reduction in available windows for sowing wheat crops in the future (Gate and Brisson, 2010; Gouache, 2010). It is one of the most cited adaptations in Olesen et al.'s (2011) study. Genotypic adaptation through modified crop phenology or improved tolerance to heat have both been evaluated through simulation studies (Semenov and Halford, 2009; Challinor et al., 2007, 2009a,b). There exists large variations in worldwide wheat germplasm for earliness to heading that is increasingly well characterized from both phenotypic and genetic standpoints (Rousset et al., 2011; Le Gouis et al., 2011). Likewise, genotypic variation for thousand kernel weight loss under heat stress has been identified (Sharma et al., 2008).

Our study proposes a method to quantify the increase in the occurrence of heat stress specifically during wheat grain filling, by coupling a wheat phenology model with four downscaled climate projections over 10 sites in France. We evaluate the uncertainties of the method, and then use it to evaluate and compare three adaptation strategies, namely advanced sowing dates, earlier crop phenology, and improved tolerance to heat stress. Finally, after discussing the advantages and limits of our approach, we discuss the opportunity and feasibility of the different adaptation options studied.

2. Materials and methods

2.1. Overview

Our approach consisted in coupling a wheat phenology model with four different downscaled climate projections over ten French sites. Its description is organized as follows:

- presentation of the wheat model, the climatic series used, and our reference (i.e. without adaptation) simulation protocol,
- description of the methodology used to analyse simulation results,
- presentation of the approaches developed to evaluate results and their uncertainty,
- presentation of the simulation protocols used to assess the different adaptation strategies evaluated, i.e. earlier sowing, earlier crop phenology, improved heat stress tolerance.

2.2. Wheat phenology model

The phenology model used is an adaptation of the ARCWHEAT model (Weir et al., 1984) to French conditions (Gate, 1995), which considers growth stages occurring once a given accumulated modified thermal time since the previous growth stage has been reached. Modified thermal time accounts for vernalization and photoperiod effects. In ARCWHEAT, emergence, double-ridge, anthesis and maturity are modelled. The key modification in the model used here is that it calculates growth stage BBCH 30 (Lancashire et al., 1991), i.e. start of stem elongation, instead of double-ridge, and heading, i.e. BBCH 55, instead of anthesis. In this study, the model was used with parameters of winter wheat cultivar Soissons and winter barley cultivar Esterel (for the adaptation study, see below). When relevant, differing parameters between both will be given.

Temperature summation for thermal time calculation is carried out using the same type of four-piece linear function described in Weir et al. (1984) characterized by 3 cardinal temperatures (T_{base}, T_{opt}, T_{max}). The cardinal temperatures used have been slightly modified to 0 °C, 24 °C, 35 °C, respectively.

As in Weir et al. (1984) emergence is reached once a specific temperature sum has been reached (152 °C-days and 145 °C-days for Soissons and Esterel, respectively). Temperature accumulation during the emergence-BBCH 30 phase is modified by vernalization and photoperiod effects. Photoperiod effect is modelled as a factor, calculated daily, FP, limited to vary between 0 and 1. Daily temperature is multiplied with daily FP, thus reducing daily temperature accumulation. It is calculated as $FP = (P_H - P_{base})/(P_{opt} - P_{base})$ where P_H is the effective photoperiod (hours) calculated daily and P_{base} and P_{opt} are parameters expressed in hours, equal to 6.3 h and 20 h respectively. Similarly, the vernalization factor, FV, is calculated daily as $FV = (VDD - V_{base})/(V_{sat} - V_{base})$, with VDD being the accumulated number of vernalizing days, and V_{base} and V_{sat} parameters expressed in number of vernalizing days. V_{base} is set to 0 days and V_{sat} to 45 and 40 for Soissons and Esterel, respectively. VDD is calculated as in Weir et al. (1984), using a five-piece linear function of temperature, defined by 4 cardinal temperatures, T_1, T_2, T_3, T_4. In Weir et al. (1984), the values were set to −4 °C, 3 °C, 10 °C, and 17 °C for T_1, T_2, T_3, and T_4 respectively. In our case, the values were set to −1 °C, 6 °C, 6 °C, and 17 °C for T_1, T_2, T_3, and T_4, respectively. The modified temperature sum threshold for reaching BBCH 30 is 221.8 °C-days and 181.2 °C-days for Soissons and Esterel respectively.