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Review

Adapting wheat in Europe for climate change

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ABSTRACT

Increasing cereal yield is needed to meet the projected increased demand for world food supply of about 70% by 2050. Sirius, a process-based model for wheat, was used to estimate yield potential for wheat ideotypes optimized for future climatic projections for ten wheat growing areas of Europe. It was predicted that the detrimental effect of drought stress on yield would be decreased due to enhanced tailoring of phenology to future weather patterns, and due to genetic improvements in the response of photosynthesis and green leaf duration to water shortage. Yield advances could be made through extending maturation and thereby improve resource capture and partitioning. However the model predicted an increase in frequency of heat stress at meiosis and anthesis. Controlled environment experiments quantify the effects of heat and drought at booting and flowering on grain numbers and potential grain size. A current adaptation of wheat to areas of Europe with hotter and drier summers is a quicker maturation which helps to escape from excessive stress, but results in lower yields. To increase yield potential and to respond to climate change, increased tolerance to heat and drought stress should remain priorities for the genetic improvement of wheat.

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1. Introduction

Food security has become a major challenge given the projected need to increase world food supply by about 70% by 2050 (Anon., 2009). Considering the limitations on expanding crop-growing areas, a significant increase in crop productivity will be required to achieve this target (Parry et al., 2011; Reynolds et al., 2011). Wheat production is highly sensitive to climatic and environmental variations (Porter and Semenov, 2005). Global warming is characterised by shifts in weather patterns and increase in frequency and magnitude of extreme events (Lobell et al., 2012; Semenov and Shewry, 2011; Sillmann and Roeckner, 2008). Increasing temperature and incidence of drought associated with global warming are posing serious threats to food security (Lobell et al., 2013). Climate change, therefore, represents a considerable challenge in achieving the 70%-increase target in world food production. New wheat cultivars better adapted for future climatic conditions will therefore be required. However, the intrinsic uncertainty of climate change predictions poses a challenge to plant breeders and crop scientists who have limited time and resources and must select the most appropriate traits for improvement (Foulkes et al., 2011; Semenov and Halford, 2009; Zheng et al., 2012). Modelling provides a rational framework to design and test *in silico* new wheat ideotypes optimised for target environments and future climatic conditions (Hammer et al., 2006, 2010; Semenov and Halford, 2009; Semenov and Shewry, 2011; Sylvester-Bradley et al., 2012; Tardieu and Tuberosa, 2010; Zheng et al., 2012). Eco-physiological process-based crop models are commonly used in basic and applied research in the plant sciences and in natural resource management (Hammer et al., 2002; Passioura, 1996; Rötter et al., 2011; Sinclair and Seligman, 1996; White et al., 2011). They provide the best-available framework for integrating our understanding of complex plant processes and their responses to climate and environment. Such models are playing an increasing role in guiding the direction of fundamental research by providing quantitative predictions and highlighting gaps in our knowledge (Hammer et al., 2006; Hammer et al., 2010; Semenov and Halford, 2009; Semenov and Shewry, 2011; Tardieu, 2003).

The objective of our study was to assess wheat yield potential under climate change in Europe and identify challenges which must be overcome to achieve high wheat yields in the future. Firstly, we used the Sirius wheat model to optimise wheat

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Abbreviations: A, maximum area of flag leaf area; ABA, abscisic acid; CV, coefficient of variation; FC, field capacity; Gf, grain filling duration; GMT, Greenwich mean time; GS, growth stage; HSP, heat shock protein; LAI, leaf area index; HI, harvest index; Ph, phylochron; Pp, photoperiod response; Ru, root water uptake; S, duration of leaf senescence; SF, drought stress factor.

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ideotypes for future climate scenarios (Jamieson and Semenov, 2000; Lawless et al., 2005; Semenov, 2009; Semenov and Stratonovitch, 2013). A wheat ideotype was defined as a set of Sirius cultivar parameters. By changing cultivar parameters, we change wheat growth and development in response to climatic and environment variations and can select ideotypes with better performance under future climates and environments. Sirius is a well validated model and was able to simulate accurately wheat growth and grain yield in a wide range of environments, including Europe, USA, New Zealand and Australia, and for experiments reproducing conditions of climate change, e.g. Free-Air Carbon dioxide Enrichment (FACE) experiments (Ewert et al., 2002; He et al., 2012; Jamieson et al., 2000; Lawless et al., 2008; Martre et al., 2006; Asseng et al., 2013).

Despite the current utility of Sirius, it remains a challenge for such models to capture the yield response of wheat to extreme events, particularly when they coincide with sensitive growth stages (Craufurd et al., 2013). Crop models need an overhaul to incorporate such responses to extreme weather events (Rötter et al., 2011). For example, it has been established that wheat yield is particularly sensitive to abiotic stresses during microsporogenesis, anther dehiscence and fertilization because of effects on grain set (as reviewed by Barnabas et al., 2008; Craufurd et al., 2013); and just after fertilization because of effects on grain size (Gooding et al., 2003). To facilitate model development additional data from carefully designed experiments will be required. The second approach presented here is, therefore, to describe the response of wheat to heat and drought stress as imposed at booting and anthesis, using pot-grown plants and controlled environment facilities.

2. Assessing yield potential of future wheat ideotypes

We selected ten sites for our study representing wheat growing regions in Europe (Table 1). Wheat ideotypes were described by nine model parameters used in the Sirius wheat model to describe wheat cultivars and considered as most promising for improvement of yield potential under climate change (Table 2). We used an evolutionary algorithm to optimize ideotypes for future climatic conditions as predicted by the HadCM3 global climate model.

2.1. Cultivar parameter space for optimisation

The ranges of parameter values used in optimization are presented in Table 2. The ranges were based on parameters calibrated by Sirius for modern cultivars allowing for variations reported in the literature for existing wheat germplasm (He et al., 2012; Semenov et al., 2009).

2.1.1. Photosynthesis

We assume that a 10% increase in light conversion efficiency could be achieved in the future. Using a model of canopy photosynthesis, (Tambussi et al., 2007) showed that the value of parameter λ (Rubisco specificity factor that represents the discrimination between CO$_2$ and O$_2$) found in current C3 crops exceeds the level that would be optimal for the present CO$_2$ concentration ([CO$_2$]), but would be optimal for [CO$_2$] of about 220 ppm, the average over the last 400,000 years. The simulation results showed that up to 10% more carbon could be assimilated, if λ was optimal for the current [CO2] level.

In Sirius, radiation use efficiency (RUE) is proportional to [CO$_2$] with an increase of 30% for doubling in [CO$_2$] compared with the baseline of 338 ppm, which is in agreement with the recent meta-analysis of field-scale experiments on the effects of [CO$_2$] on crops (Vanuytrecht et al., 2012). A similar response was used by other wheat simulation models, e.g. CERES (Jamieson et al., 2000) and EPIC (Tubiello et al., 2000).

2.1.2. Phenology

Three cultivar parameters are directly related to phenological development of wheat, i.e. phylochron ***Ph***, daylength response ***Pp*** and duration of grain filling ***Gf*** (Table 2). Modifying the duration and timing of crop growth cycle in relation to seasonal variations of solar radiation and water availability may have significant effects on yield (Akkaya et al., 2006; Richards, 2006). An optimal flowering time has been the single most important factor to maximise yield in dry environments (Richards, 1991). The phyllochron ***Ph*** is the thermal time required for the appearance of successive leaves, and is a major driver of phenological development (Jamieson et al., 1995, 2007, 1998a). Details of the response of final leaf number to daylength ***Pp*** could be found in Brooking et al. (1995); Jamieson et al. (1998b). By modifying phyllochron ***Ph*** and daylength response ***Pp*** we alter the rate of crop development and, therefore, the date of flowering and maturity. Increasing the duration of the grain filling period ***Gf*** has been suggested as a possible trait for increasing grain yield in wheat (Evans and Fischer, 1999). In Sirius, ***Gf*** is defined as a cultivar-specific amount of thermal time which needs to be accumulated to complete grain filling (Jamieson et al., 1998b). During grain filling, assimilates for the grain are available from two sources: new biomass produced from intercepted radiation and water-soluble carbohydrates stored mostly in the stem before anthesis. In Sirius, the labile carbohydrate pool is calculated as a fixed 25% of biomass at anthesis, and is translocated to the grain during grain filling. Increasing ***Gf*** will increase the amount of radiation intercepted by the crop and, consequently, grain yield. However, in the model, water-soluble carbohydrates accumulated before anthesis are transferred into the grain at a rate inversely proportional to ***Gf***. Therefore, any increase of ***Gf*** will also reduce the rate of biomass remobilisation. Under stress conditions, when grain growth could be terminated as a results of leaves dying early due to water or heat stress, grain yield could decrease not only because of the reduction in intercepted radiation but also because of the

Table 1
Characteristics of 10 European sites.

Site	Country	ID	Longitude	Latitude	Annual precipitation (mm)	Minimum temperature in January	Maximum temperature in July	Cultivar	Sowing
Tylstrup	Denmark	TR	9.9	57.2	668	−2.9	19.8	Avalon	18/10
Edinburgh	UK	ED	−3.3	55.9	650	0.5	19.0	Claire	10/10
Warsaw	Poland	WS	21.1	52.1	458	−3.6	24.4	Avalon	18/10
Wageningen	Netherlands	WA	5.7	52.0	765	−0.8	21.5	Claire	01/11
Rothamsted	UK	RR	−0.35	51.8	693	0.3	20.8	Mercia	10/10
Mannheim	Germany	MA	8.6	49.5	641	−1.4	24.6	Claire	18/10
Debrecen	Hungary	DC	21.6	47.6	563	−5.5	26.3	Thesee	18/10
Clermont-Ferrand	France	CF	3.1	45.8	600	−0.7	25.5	Thesee	15/11
Montagnano	Italy	MO	11.8	43.3	752	−0.6	28.8	Creso	25/11
Seville	Spain	SL	−5.88	37.42	524	4.3	35.2	Cartaya	30/12

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