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Designing future barley ideotypes using a crop model ensemble

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ABSTRACT

Climate change and its associated higher frequency and severity of adverse weather events require genotypic adaptation. Process-based ecophysiological modelling offers a powerful means to better target and accelerate development of new crop cultivars. Barley (*Hordeum vulgare* L.) is an important crop throughout the world, and a good model for study of the genetics of stress adaptation because many quantitative trait loci and candidate genes for biotic and abiotic stress tolerance have been identified in it. Here, we developed a new approach to design future crop ideotypes using an ensemble of eight barley simulation models (i.e. APSIM, CropSyst, HERMES, MCWLA, MONICA, SIMPLACE, *SiriusQuality*, and WOFOST), and applied it to design climate-resilient barley ideotypes for Boreal and Mediterranean climatic zones in Europe. The results showed that specific barley genotypes, represented by sets of cultivar parameters in the crop models, could be promising under future climate change conditions, resulting in increased yields and low inter-annual yield variability. In contrast, other genotypes could result in substantial yield declines. The most favorable climate-zone-specific barley ideotypes were further proposed, having combinations of several key genetic traits in terms of phenology, leaf growth, photosynthesis, drought tolerance, and grain formation. For both Boreal and Mediterranean climatic zones, barley ideotypes under future climatic conditions should have a longer reproductive growing period, lower leaf senescence rate, larger radiation use efficiency or maximum assimilation rate, and higher drought tolerance. Such characteristics can produce substantial positive impacts on yields under contrasting conditions. Moreover, barley ideotypes should have a low photoperiod and high vernalization sensitivity for the Boreal climatic zone; for the Mediterranean, in contrast, it should have a low photoperiod and low vernalization sensitivity. The drought-tolerance trait is more beneficial for the Mediterranean than for the Boreal climatic zone. Our study demonstrates a sound approach to design future barley ideotypes based on an ensemble of well-tested, diverse crop models and on integration of knowledge from multiple disciplines. The robustness of model-aided ideotypes design can be further enhanced by continuously improving crop models and enhancing information exchange between modellers, agro-meteorologists, geneticists, physiologists, and plant breeders.

1. Introduction

The global demand for agricultural crop production is expected to roughly double by 2050 according to the projected increases

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in population (Gerland et al., 2014), consumption, and changes in diets (Godfray et al., 2010; Tilman et al., 2011). However, climate change and weather extremes will exacerbate the constraints on increasing food supplies and food security (Ray et al., 2015). Recently, the IPCC (Porter et al., 2014) reported that for the major crops (wheat, rice, and maize) in tropical and temperate regions, without adaptation, climate change will have negative impacts on production when local temperature increases by 2 °C or more above late-20th-century levels, although it also may have positive impacts at some individual locations. Furthermore, some studies suggest that climate change may progressively increase the inter-annual variability of crop yields in some regions, resulting in an increased risk of more severe impacts (Porter et al., 2014; Ray et al., 2015). In recent years, yields for important crops have stagnated in several important agricultural regions around the world due to changes in climate and agronomic management (Peltonen-Sainio et al., 2008; Brisson et al., 2010; Ray et al., 2012; Grassini et al., 2013; Tao et al., 2015), although in some other parts of the world yields have kept increasing despite ongoing climate change as a consequence of new cultivars and improved crop management (Ray et al., 2012; Tao et al., 2012, 2015).

Crop cultivar development and improved agronomic practices are pivotal to climate change adaptation for agriculture (Hatfield et al., 2011; Tao et al., 2012; Challinor et al., 2014; Ewert et al., 2015; Rötter et al., 2015). One of the most effective adaptation options for future climates is the development of climate resilient crop cultivars (Tao and Zhang, 2010; Challinor et al., 2014). In parallel, agronomists are trying to develop new agronomic practices for a changing climate (FAO, 2010). Plant breeders are increasingly using genomics and biotechnology to develop cultivars that have greater yield stability (lower inter-annual yield variation) in our current production systems (Mir et al., 2012). It is, however, difficult to develop crop ideotypic traits for a targeted environment (Reynolds et al., 2016). It is also expensive in terms of labor, time, and funding requirements to determine the values of the different traits particularly under future climatic conditions (Li et al., 2012; Gouache et al., 2016).

Process-based crop models developed for simulating interactions between genotype, environment, and management are widely applied to assess impacts of environmental change on crop development, growth, and yield (Boote et al., 2001; Asseng et al., 2015), as well as to design adaptation strategies to cope with climate risk (Bergez et al., 2010; Tao and Zhang, 2010; Rötter et al., 2011a; Dumont et al., 2015). In recent decades, crop modelling has become an important tool for evaluating new cultivars (Marcaida et al., 2014; Gouache et al., 2016) and supporting plant breeding (Boote et al., 2001; Li et al., 2012; Rötter et al., 2015), in particular in the design of ideotypes, i.e. 'model plants', for different crops and cultivation environments (Dingkuhn et al., 1991, 2015; Martre et al., 2015a; Rötter et al., 2015; Semenov and Stratonovitch, 2013). So far, such studies are limited to individual models, which differ in terms of the number of parameters and processes and their descriptions, complexity, and functionality (Palosuo et al., 2011; Asseng et al., 2013). Drawing conclusions based on a single crop model can generate quite large biases (Asseng et al., 2013). Recently, ensemble modelling has been proposed as a valuable approach for assessing and reducing uncertainties in crop simulations (Rötter et al., 2011b; Wallach et al., 2016). The strengths of inter-model comparison and ensemble modelling have been demonstrated in many studies (e.g., Palosuo et al., 2011; Rötter et al., 2012; Asseng et al., 2013, 2015; Bassu et al., 2014; Li et al., 2015; Martre et al., 2015b).

Food supply and food security in Europe as well as in many other parts of the world especially depend on the Triticeae crops, which include wheat, barley, rye, and fodder crops. Barley (*Hordeum vulgare* L.) is a good model for study of the genetics of stress adaptation (Moshelion et al., 2015). In this study, we aim to: 1) develop a new approach to design future crop ideotypes using a crop model ensemble; 2) apply this approach to design climate-resilient barley ideotypes for Boreal and Mediterranean climatic zones in Europe, representing contrasting climatic conditions for barley production in Europe.

2. Materials and methods

2.1. Study sites

Two study sites with contrasting climates were chosen to represent the North and South of current agro-climatic conditions for barley cultivation areas in Europe. One is Jokioinen (60.81°N, 23.50°E, 104 m a.s.l.) in Finland in northern Europe, and the other is Lleida (41.63°N, 0.60°E, 190 m a.s.l.) in Spain in southern Europe (Fig. 1). Jokioinen has a Boreal climate, with an average annual mean temperature and total precipitation of 4.6 °C and 628.2 mm, respectively, over 1980–2010. Lleida has a Mediterranean climate, with an annual mean temperature and total precipitation of 15.0 °C and 340.6 mm, respectively, over 1980–2010. At Jokioinen, spring barley is generally sown in the middle of May and harvested at the end of August. At Lleida, winter barley is generally sown in the middle of November and harvested at the beginning of July. During 1980–2010, the mean temperature, precipitation, solar radiation, and photoperiod for the barley growing season was respectively 13.6 °C, 252.4 mm, 17.5 MJ m^{-2} day^{-1}, and 17.6 h at Jokioinen and 11.5 °C, 227.3 mm, 13.6 MJ m^{-2} day^{-1}, and 11.8 h at Lleida.

2.2. Data

Detailed experimental field data including soils, tillage, fertilization, phenology, yield, and biomass were obtained for two growing seasons at Jokioinen in 2002 and 2009 (Salo et al., 2016) and for three growing seasons at Lleida from 1996 to 1999 (Cantero-Martinez et al., 2003). The barley cultivars used are representative of those currently grown at each location: Annabell at Jokioinen and Hispanic at Lleida. Annabell is a modern (released after 1985) and considered late-maturing. Hispanic is a member of the Spanish barley core collection. Hispanic has a much larger thermal requirement than does Annabell. The soils were a Vertic Cambisol (IUSS, 2006) with a clay texture at Jokioinen, and Typic Xerofluvent (USDA, 1999) with a loam texture at Lleida. The experimental data used for crop model calibration and validation are summarized in Table S1.

The observed daily weather data for solar radiation, minimum and maximum temperature, precipitation, wind speed, and air humidity for 1980–2010 at the two sites were obtained from the Finnish Meteorological Institute, the Spanish Agencia Estatal de Meteorología (AEMET), and from other sources, as detailed in Pirttioja et al. (2015).

For future climate scenarios, three representative climate projections (relatively hot, medium, and relatively cold) for the period of the 2050s, made by three global circulation models (GCMs), were selected from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) ensemble, driven by the emission scenario of Representative Concentration Pathway (RCP) 8.5. The atmospheric CO_2 concentrations assumed were 360 ppm for 1980–2010 and 560 ppm for the 2050s. The three GCMs were the Hadley Centre Global Environmental Model–Earth System, version 2 (HadGEM2-ES; hereafter HadGEM) (Jones et al., 2011), the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Sciences (GISS) coupled general circulation model (hereafter GISS) (Nazarenko et al., 2015), and the Australian Community Climate and Earth System Simulator (hereafter ACCESS) (Rashid et al., 2013). The climate projections were further down-scaled for local impact assessments using the LARS-WG weather generator, as

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