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Sensitivity of European wheat to extreme weather

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ABSTRACT

The frequency and intensity of extreme weather is increasing concomitant with changes in the global climate change. Although wheat is the most important food crop in Europe, there is currently no comprehensive empirical information available regarding the sensitivity of European wheat to extreme weather. In this study, we assessed the sensitivity of European wheat yields to extreme weather related to phenology (sowing, heading) in cultivar trials across Europe (latitudes 37.21° to 61.34° and longitudes −6.02° to 26.24°) during the period 1991–2014. All the observed agro-climatic extremes (≥31 °C, ≥35 °C, or drought around heading; ≥35 °C from heading to maturity; excessive rainfall; heavy rainfall and low global radiation) led to marked yield penalties in a selected set of European cultivars, whereas few cultivars were found to with no yield penalty in such conditions. There were no European wheat cultivars that responded positively (+10%) to drought after sowing, or frost during winter (−15 °C and −20 °C). Positive responses to extremes were often shown by cultivars associated with specific regions, such as good performance under high temperatures by southern-origin cultivars. Consequently, a major future breeding challenge will be to evaluate the potential of combining such cultivar properties with other properties required under different growing conditions with, for example, long day conditions at higher latitudes, when the intensity and frequency of extremes rapidly increase.

1. Introduction

The adverse impacts of climate change present a potentially considerable challenge to global food security (Porter et al., 2014; Trnka et al., 2014; Asseng et al., 2015; Ray et al., 2015). Whereas positive impacts on food production may occur in some locations (Porter et al., 2014) under climate change with warming exceeding 2 °C compared with the pre-industrial era, negative impacts for the major food and feed crops are projected both in tropical and temperate regions (Porter et al., 2014). In addition, there is currently considerable uncertainty surrounding climate change and its potential local impacts (Rötter et al., 2013). Variability and extremes in weather are projected to

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increase both in intensity and frequency (Porter and Semenov, 2005; Ray et al., 2015). If the availability of cultivars with yield stability under the range of extreme weather likely to occur in the main production regions is not secured (Reyer et al., 2013; Challinor et al., 2014; Trnka et al., 2014; Tao et al., 2017), increased weather variability will have detrimental consequences for yield amount and quality, and thus for food supply (Semenov and Shewry, 2011; Porter et al., 2014; Trnka et al., 2014; Ray et al., 2015).

Wheat is the most important food crop in temperate regions, and in 2015 this crop constituted 48% of the cereal grain produced in the European Union (Eurostat, 2015). Globally, an increase of one degree (°C) in temperature is projected to decrease wheat yields by 6% (Asseng et al., 2015), mainly as a consequence of phenology acceleration with a reduced grain-filling phase and of an increasingly suboptimal relation of photosynthesis and respiration of the crop. Under the projected climate for 2060 in Europe (Taylor et al., 2012), the probability of wheat yield reductions is likely to increase by one-third (and even double in some locations) relative to the present, due to at least one adverse weather condition caused by extreme events (Trnka et al., 2014). Such extreme weather events include heat, frost, drought, and heavy rainfall. Their consequences on wheat production include heat and frost damages to tissue and reproductive organs, significant reduction of photosynthesis up to irreversible tissue damages due to water deficit, early-stage lodging after critical coaction of wind and rain and root damages from oxygen deficit as a consequence of soil water logging after heavy rain (Malik et al., 2002; Marti et al., 2015). Heavy rains cause also soil erosion and nutrient leaching. The occurrence of different extreme weather events will vary between localities in Europe. For example, in the UK, the Netherlands, and Denmark, the probability of excessive wet conditions, and thus waterlogging, from sowing to flowering will increase by 2060, whereas other parts of Europe, particularly southern parts, may face more frequent and longer dry periods during growing seasons (Trnka et al., 2014). The ability of wheat to withstand extreme weather is linked to its development stages (Porter and Semenov, 2005): susceptibility to frost increases after flower initiation (Janda et al., 2007) and the periods when wheat is most sensitive to high temperatures are the anthesis and grain-filling stages (French and Schultz, 1984; Hawker and Jenner, 1993; Porter and Gawith, 1999; Luo, 2011; Peltonen-Sainio et al., 2011; Prasad and Djanaguiraman, 2014). For instance, a temperature of 35 °C during anthesis has been found to decrease grain weight by 45% (Wollenweber et al., 2003). In combination of drought and heat, productivity of wheat is reduced more than drought or heat alone, and much of such effect is exerted on the rate of photosynthetic (Barnabás et al., 2008).

Genotype, environment, and genotype × environment interactions constitute the basis of cultivar sensitivity to weather. Breeders select traits with a high yielding capacity and/or inter-annual yield stability under various conditions (Finlay and Wilkinson, 1963) and they carefully balance these traits with other property requirements, such as resistance to diseases or tolerance against lodging conditions. Advanced methods in genomics selection and biotechnology, as well as process-based eco-physiological modelling, may expedite breeding programmes and help to target the breeding objectives towards future climates (Tao et al., 2017). Uncertainty regarding spatial and temporal climate change patterns (Coumou and Rahmstorf, 2012; Rötter et al., 2011; IPCC, 2012; Ray et al., 2015; Pfahl et al., 2017) hampers efforts to identify optimal cultivars for future local or regional climates where tolerance to extreme weather will become an important character. As an alternative, a set of cultivars with advantageous traits and trait combinations could be identified and further developed to cover the feasible range of projected future extreme conditions. Consequently, in this paper, we report the first empirical Europe-wide study on the sensitivity of wheat (winter wheat, spring wheat, and durum wheat) cultivars to weather extremes critical for yield. At the outset, we posed the following research questions:

1. How sensitive are European wheat cultivars to weather extremes critical to yield?
2. Does the European set of wheat cultivars lack material for breeding towards tolerance to different weather extremes?

2. Materials and methods

2.1. Data

The cultivar trial data used included 991 cultivars (from 2500 cultivars that fulfilled the requirement of 20 trials) from northern to southern Europe from Finland, Denmark, Germany, Czech Republic, Slovakia, Belgium, France, Spain, and Italy, with latitudes between 37.21° and 61.34° originating from rain-fed experiments. The data were collected during the period from 1991 to 2014 and consist of records from 636 trial sites, including winter wheat, spring wheat, and durum wheat. Annual grain yield (kg ha^{-1} year^{-1}) was used as the response variable. Data sources were: MTT Official Variety Trials, Grupo para la Evaluación de Nuevas Variedades de Cultivos Extensivos en España, Group for evaluating new varieties of field crops in Spain, GENVCE, GEVES (Groupe d'Études et de contrôle des variétés et des semences", variety and seed study and control group, University of Florence, The Research Unit for Cropping Systems in Dry Environments (CRA-SCA), the Central Controlling and Testing Institute in Agriculture in Bratislava, Slovak dataset and Agricultural Centre for Cereals (complete list of institutions providing data's in acknowledgement). Yield data were of particular interest and the yields used were official confirmed results of national variety testing, that according to the respective national methodologies was quality checked and screened for methodological errors or other influences (e.g. damage by animals). As the grain water content was known the final yield was recalculated to dry matter.

The annual weather data from stations closest to the trial sites were used for assessing the yield sensitivity to weather extremes during different crop phenological stages (Zadoks et al., 1974). Sources of data were: Finnish Meteorological Institute, German Weather Service DWD (www.dwd.de), the Belgian Royal Meteorological Institute (www.meteo.be), Czech Hydrometeorological Institute, Slovak Hydrometeorological Institute, Royal Meteorological Institute of Belgium and State Meteorological Agency of Spain as well as additional stations from agrometeorological network from Spain, Italy and France. All the stations were in line with the official World Meteorological Organisation standards for the temperature measurement heights. The closest and representative (in terms of altitude and surrounding) weather station to the experimental site was used with all sites being within 10 km of the weather closest station. However great majority of the experimental sites was in the vicinity of the trial site i.e. less than 2 km. For Denmark and the Czech Republic required weather input data were estimated from high resolution daily weather dataset taking into account much larger number of sites in the region surrounding the experimental site. High density of station in the Czech Republic allowed for testing decay of the selected indicators with the distance from the trial site, concluding that 10 km provides still acceptable estimate over individual seasons. In cases where data on one of three dates (sowing, heading, or maturity) were missing, they were estimated based on the corresponding dates for all the cultivars from the same site and year. In the case of sowing it was assumed that the sowing date of all cultivars did not differ (unless stated otherwise by the metadata). If no sowing date was available for the given site and year then all data were discarded from further analysis. In case of heading and maturity date the missing values were estimated using correlation analysis with the overlapping data with the cultivars from the same site across the previous/following seasons. If not overlapping data occurred or limited (5 and less) data pairs were available, then the heading and/or maturity date was estimated using thermal time above 5 °C for the given cultivar obtained for the given cultivar from nearby sites and precedent/antecedent seasons

Analysis was based on the procedure suggested by Hakala et al.