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Significant decrease in yield under future climate conditions: Stability and production of 138 spring barley accessions

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ABSTRACT

The response in production parameters to projected future levels of temperature, atmospheric carbon dioxide ([CO_2]), and ozone ([O_3]) was investigated in 138 spring barley accessions. The comprehensive set of landraces, cultivars, and breeder-lines, were during their entire life cycle exposed to a two-factor treatment of combined elevated temperature (+5 °C day/night) and [CO_2] (700 ppm), as well as single-factor treatments of elevated temperature (+5 °C day/night), [CO_2] (700 ppm), and [O_3] (100–150 ppb). The control treatment was equivalent to present average South Scandinavian climate (temperature: 19/12 °C (day/night), [CO_2]: 385 ppm). Overall grain yield was found to decrease 29% in the two-factor treatment with concurrent elevation of [CO_2] and temperature, and this response could not be predicted from the results of treatments with elevated [CO_2] and temperature as single factors, where grain yield increased 16% and decreased 56%, respectively. Elevated [O_3] was found to decrease grain yield by 15%. Substantial variation in response to the applied climate treatments was found between the accessions. The results revealed landraces, cultivars, and breeder-lines with phenotypes applicable for breeding towards stable and high yield under future climate conditions. Further, we suggest identifying resources for breeding under multifactor climate conditions, as single-factor treatments did not accurately forecast the response, when factors were combined.

1. Introduction

Climate change alters growth environments around the world and challenges agricultural production. At the same time the world population is growing with the need of an increased food production. Unprecedented climate conditions are reported to occur around 2047 (+/− 14 years; Mora et al., 2013), and already by now actual levels of temperature, and atmospheric concentration of the abundant greenhouse gasses carbon dioxide ([CO_2]; 400 ppm) and ozone ([O_3]; 32–62 ppb) have affected yields of cereals (Lobell and Field, 2007; Lobell et al., 2011; Trnka et al., 2012; Ellermann et al., 2013). Elevated temperature has been found to decrease crop yield e.g., by closing of stomata thus avoiding transpiration, but at the same time inhibiting photosynthesis and thereby disrupting anthesis and grain formation (Barnabás et al., 2008). The negative effect of elevated temperature is possibly reduced by increased [CO_2] boost-

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ing photosynthesis (Long et al., 2006). Ozone is highly reactive and can lead to reactive oxygen species detrimental to the photosynthetic apparatus (Fuhrer and Booker, 2003).

By the end of the 21st century temperature is expected to increase by 3–5 °C according to the worst-case scenario (RCP8.5) of IPCC (Collins et al., 2013). The [CO_2] is to reach 1415–1910 ppm and [O_3] to increase by 25% compared to the concentrations experienced today (32–62 ppb). The latest assessment report of IPCC, working group I, also considered three other climate scenarios with lower increase in the anthropogenic emission of greenhouse gases leading to less elevated temperature, however, a recent study suggests that the RCP8.5 worst-case scenario very probably is the one to expect (Sherwood et al., 2014). Along with climate change follows increase in frequency of extreme events such as floods, heatwaves, droughts, and storms with great risk of additional threat to future agricultural production (Collins et al., 2013; IPCC, 2014). The rapid changes in growth conditions induced by altered climatic conditions enhance the need to develop climate resilient cultivars and apply new management practices (Anwar et al., 2013).

The annual growth rate of the global agricultural production was on average 2.1% from 2003 to 2012, however, it is expected to decrease to 1.5% per year in the coming decades (OECD/FAO, 2013). The lower growth rate is due to limited expansion of agricultural land, rising production costs, restricted use of non-renewable resources together with reduced use of fertilizer, and pest control agents to limit their environmental side effects (Foley et al., 2011; OECD/FAO, 2013). Plant breeding has the enormous task to increase future primary production. In this context, gene bank material and exotic accessions can possess traits to be exploited in the development of stable and high yielding climate resilient cultivars. An obstacle to the use of these resources is the limited information on climate tolerance of plant accessions (Ceccarelli et al., 2010; Newton et al., 2011). Also the methodical complexity in the search for tolerance to conditions not earlier experienced by any crop is challenging. As emphasized by Powell et al. (2012), the utilization of genetic resources with tolerance to climate factors is impeded by lack of reliable and cost efficient screening methods.

Considerable knowledge on climate change effects to crops are still needed to plan best breeding strategies to secure the production. For example the following two topics have received little attention: Climate change has been found to affect various crop species differently (e.g., Feng and Kobayashi, 2009; Kimball, 1986; Luo, 2011; Mills et al., 2007), however, the intraspecific variation - between and within accessions - in response to changes has received little focus (e.g., Craufurd et al., 2003; Pleijel, 2011; Weigel and Manderscheid, 2012). Also, in studies of climate change effects on crop accessions, rather few have investigated the effects of treatments, where more than one climate factor was changed (Alemayehu et al., 2014; Clausen et al., 2011; Frenck et al., 2011; Juknys et al., 2011; Kasurinen et al., 2012; Mitchell et al., 1993; Zhou et al., 2011).

In the Nordic countries, around half of the cultivated area (9 million ha) is used for growing cereals and in 2012 barley (*Hordeum vulgare* L.) was the main cereal (FAOSTAT, 2014). Also in the EU barley is an important crop cultivated on 21% of the cereal crop area (European Union, 2014). The grains are used for malt and feed, however, the yield is stagnating (FAOSTAT, 2014). Under mid to high latitude conditions a temperature increase exceeding 2 °C is expected to reduce cereal yields (IPCC, 2014). The Nordic agriculture is further in risk of summer drought and heavy rains with changes in precipitation patterns leading to decreased grain yield (Christensen et al., 2011; Högy et al., 2013).

In this study, the effects of elevated temperature and the most abundant greenhouse gasses, CO_2 and O_3 were analyzed on 138 spring barley accessions. The climate treatments were applied over the entire crop life cycle as single- and two-factor (elevated temperature and [CO_2]) treatments. Accessions with phenotypes that could alleviate or inhibit effects of future climate change on grain yield and harvest stability were identified.

2. Material and methods

2.1. Plant material

The spring barley material tested consisted of 48 landraces, 32 old cultivars (1883–1974), 53 modern cultivars (1978–2013), and 5 breeder-lines. The majority of the accessions had Nordic origin, viz. Denmark, Sweden, Norway, and Finland. Eight of the modern cultivars and 22 of the landraces had non-Nordic origin (e.g., Afghanistan, Belgium, Croatia, France, Germany) and 8 accessions had unknown origin (Appendix A). Modern cultivars and breeder-lines were supplied by the Nordic breeders in the network 'Sustainable primary production in a changing climate' (NordForsk) and a few cultivars were from the BAR-OF project (ICROFS, Denmark). All other accessions were supplied by the Nordic Genetic Resource Center (NordGen; http://www.nordgen.org/).

2.2. RERAF, technical description

All plants were cultivated in the RERAF phytotron (Risø Environmental Risk Assessment Facility) at the Technical University of Denmark. RERAF has six identical physically separated gas-tight chambers (width 6 m, depth 4 m and height 3 m). The chambers had individual control of light, temperature, humidity, and gasses (chamber atmospheres) and with continuous monitoring of all parameters. Air mixing within chambers was ensured by two wind turbines placed on opposite sides. Humidity was generated by a humidifier (HumiDisk 65, Carel) placed in front of one of the wind turbines. The light was supplied by 28 high-pressure mercury (1000 W or 400 W) and 14 halogen (250 W) lamps per chamber. The lamps could be turned on or off individually, which was used to simulate sunrise and sunset. The [CO_2] was supplied by Air Liquide Denmark A/S and the application controlled according to the continuous measurements. The [O_3] in the chambers was supplied by UV Pro 550 A (Crystal air products & services, Canada) generators, which were manually adjusted. Further details on RERAF are given by Alemayehu et al. (2014) and Frenck et al. (2011).

2.3. Growth conditions

Pots with a volume of 11 L were filled with 4 kg of sphagnum substrate (Pindstrup Substrate No. 6, Pindstrup Mosebrug A/S, Denmark) supplemented with 10 g NPK fertilizer (21-3-10, Yara). Twelve seeds of each accession were sown and seedlings thinned to eight plants per pot per treatment. The pots were placed on wheeled plant-tables, and plants were grown for their entire life-cycle in RERAF with different levels of temperature, [CO_2] and [O_3]. Water supply was identical in all treatments and above the average precipitation of Southern Scandinavia to compensate for loss of water, root distribution and drainage dictated by the pot setup. Watering was carried out by a surface dripping system that delivered 4.4 L m^{-2} day^{-1} at the beginning of the daytime regime. When 2/3 of the accessions had begun ripening at Zadoks Growth Stage (ZGS) 90, watering was reduced in a stepwise fashion and ended at maturity corresponding to ZGS 99 (Zadoks et al., 1974). All treatments had identical light and humidity conditions. The light regime was PAR (parabolic aluminized reflector) averaged at approximately 400 mol photons m^{-2} s^{-1} at canopy height (ca. 1 m), and a daily cycle of 16/8 h (day/night) with simulated sunrise and sunset within the first and last hour of the light regime. The humidity was 55/70% (day/night). To avoid biases of chambers,