Agriculture, Ecosystems and Environment 259 (2018) 45–52

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

How a 10-day heatwave impacts barley grain yield when superimposed onto future levels of temperature and CO_2 as single and combined factors

Cathrine H. Ingvordsen[a,b,*], Michael F. Lyngkjær[c], Pirjo Peltonen-Sainio[d], Teis N. Mikkelsen[a], Anders Stockmarr[e], Rikke B. Jørgensen[a]

[a] Technical University of Denmark, Dept. Environmental Engineering, AIR, Bygningstorvet 115, DK-2800, Kgs. Lyngby, Denmark
[b] CSIRO Agriculture and Food, Black Mountain Laboratories, GPO Box 1600, Canberra, ACT, 2601, Australia
[c] University of Copenhagen, Section for Plant Biochemistry, Thorvaldsensvej 40, DK-1871 Frederiksberg C, Denmark
[d] Natural Resources Institute Finland (Luke), Management and Production of Renewable Resources, Latokartanonkaari 9, FI-00790 Helsinki, Finland
[e] Technical University of Denmark, Dept. Applied Mathematics and Computer Science, Matematiktorvet, Bld. 324, 2800 Kgs. Lyngby, Denmark

ARTICLE INFO

Keywords:
Biomass
Extreme events
Genotype differences
Heat exposure
Hordeum vulgare L.
Multifactor treatment
Stability

ABSTRACT

Heatwaves pose a threat to crop production and are predicted to increase in frequency, length and intensity as a consequence of global warming. Future heatwaves will occur in addition to the ongoing increase of mean temperature and CO_2. To test effects of heatwaves superimposed to future climate scenarios, 22 barley accessions were cultivated with elevated temperature (+5 °C) and CO_2 (700 ppm) as single factors and in combination. The control treatment mimicked ambient Scandinavian early summer conditions (19/12 °C, day/night; 400 ppm CO_2). Around flowering a 10-day heatwave of 33/28 °C (day/night) was superimposed to all treatments. The lowest average grain yield was observed when the heatwave was superimposed onto the combined elevated temperature and CO_2 treatment. Here the yield decreased by 42% compared to no heatwave and 52% compared to ambient conditions. When the heatwave was superimposed onto ambient conditions the average grain yield decreased by 37% compared to no heatwave. There was no significant difference between the relative grain yield decrease caused by the heatwave in the ambient and future climate scenarios. In contrast, the vegetative aboveground biomass increased upon heatwave exposure, leading to a strong decline in the harvest index. Our results strongly emphasize the need to produce heatwave resilient cultivars.

1. Introduction

Extreme weather events like heatwaves, floods, droughts and storms cause acute changes in growth conditions determining primary production (Fischer and Schär, 2009; Collins et al., 2013). Collected data from recent decades together with results from simulation studies suggest that the variability within seasons can be more unfavorable for crop production than the general changes from season to season (Reyer, 2013; Gourdji et al., 2013, Tack et al., 2015). In a statistical study, inter-annual climate variability was shown to account for > 60% of maize, rice, wheat and soybean yield variability (Ray et al., 2015). Hence, large variations in the climate within the crop seasons, such as a heatwave, are detrimental for the end result.

In the 2012–2013 growth season Australia experienced what became known as the 'angry summer', where over 100 temperature records were broken (BoM, 2014). An extreme heatwave caused large scale yield failures in Russia in 2010 (Trenberth and Fasullo, 2012), and Europe experienced extreme heatwaves in 2003 and 2006. In 2003, the European heatwave caused a 21% decrease in the French wheat production as temperatures were up to 6 °C above long-term means and precipitation being less than 50% of the average (Ciais et al., 2005). Losses in cereal crop production from heat and drought in the period from 1964 to 2007 were showed to reach 9–10% globally with the highest losses in recent years (Lesk et al., 2016). Unfortunately, predictions are that global warming will make summer heatwaves more frequent and severe together with decrease in precipitation during the summer period (Meehl and Tebaldi, 2004; Fischer and Schär, 2010; Collins et al., 2013).

In the north of Europe, barley (*Hordeum vulgare* L.) – especially spring barley – is the cereal species occupying most of the cultivated area (19%), and the grains are predominantly used for feed and malt (FAOSTAT, 2017). The annual average increase in grain yield of barley and wheat (*Triticum aestivum* L.) observed up to 1995 has ceased in Scandinavia (FAOSTAT, 2017). Stagnation of grain yield might, at least

* Corresponding author: Tel.: +61 0402 475 053.
E-mail addresses: cathrine.ingvordsen@csiro.au (C.H. Ingvordsen), mlyn@plen.ku.dk (M.F. Lyngkjær), pirjo.peltonen-sainio@luke.fi (P. Peltonen-Sainio), temi@env.dtu.dk (T.N. Mikkelsen), anst@dtu.dk (A. Stockmarr), rijq@env.dtu.dk (R.B. Jørgensen).

https://doi.org/10.1016/j.agee.2018.01.025
Received 5 August 2017; Received in revised form 19 January 2018; Accepted 21 January 2018
0167-8809/

Table 1
The tested barley accessions with mean yield and stability across all treatments; ambient, elevated temperature, elevated CO_2, elevated temperature and elevated CO_2 in combination and all four treatments ± heatwave. Modern cultivar (mCV), old cultivar (oCV), landrace (LR), genebank number (NGB), environmental variance (S^2) and Wricke's ecovalence (W^2). The accessions are sorted after the mean grain yield across the eight treatments (m_i), and numbers in brackets are the ranking based on their stability indices.

Accessions name	NGB/Breeder	Culton type	Sub type	Country of origin/Country of breeding	Year of release	m_i	S^2	W^2
Bjørne	NGB9326	LR	6	unknown		6.25	6.19 (18)	5.23 (6)
Evergreen	Nordic Seed A/S Plant Breeding	mCV	2	Denmark	2010	6.19	9.35 (22)	17.46 (21)
Brio	NGB9327	oCV	6	Sweden	1924	6.13	6.04 (16)	5.93 (9)
Brage	Graminor Plant Breeding	mCV	6	Norway	2010	5.97	5.15 (8)	5.89 (8)
Anakin	Sejet Plant Breeding I/S	mCV	2	Denmark	2006	5.91	5.83 (12)	5.09 (5)
Solenbyg	NGB13402	LR	6	Norway		5.90	7.38 (19)	8.41 (14)
Prestige	NGB16750	mCV	2	France	2000	5.88	2.68 (2)	9.00 (15)
Kushteki	NGB6288	LR	6	Afghanistan		5.87	5.48 (10)	2.37 (1)
Moscou	NGB9482	LR	2	unknown		5.83	5.93 (14)	4.00 (3)
Drost P.*	NGB6281	oCV	2	Denmark	1951	5.81	4.90 (7)	7.30 (13)
Alliot	NGB16757	mCV	2	Denmark	1999	5.73	4.42 (6)	15.03 (19)
Sebastian	Sejet Plant Breeding I/S	mCV	2	Denmark	2002	5.72	3.89 (4)	5.98 (10)
Griechische	NGB9333	LR	6	Greece		5.56	5.57 (11)	4.11 (4)
Arve	NGB11311	mCV	6	Norway	1990	5.36	5.90 (13)	3.72 (2)
Grenoble I	NGB9378	LR	6	France		4.63	8.67 (21)	23.32 (22)
Edvin	Boreal Plant Breeding	mCV	6	Finland	2008	4.54	7.95 (20)	11.76 (17)
Vilm	NGB9435	LR	2	Germany		4.21	5.98 (15)	5.34 (7)
Anita	NGB15250	oCV	6	Norway	1962	4.20	6.15 (17)	7.27 (12)
Mari	NGB1491	oCV	2	Sweden	1960	4.12	5.36 (9)	12.03 (18)
Oslo	NGB9315	LR	6	Norway		4.09	1.80 (1)	10.25 (16)
Königsberg	NGB9310	LR	6	unknown		3.65	3.12 (3)	16.71 (20)
Alf	NGB4707	mCV	2	Denmark	1978	3.41	4.20(5)	6.32(11)

* Values for Drost P. based on seven of the eight treatments (eTemp + H excluded due to faulty watering).

partly, be alleviated by the development of climate resilient cultivars. However, to develop climate resilient cultivars, assessing the effects of the most likely and relevant climate changes to a range of genotypes is essential. Studying the effects of future extreme events are challenging due to the high complexity of their timing, frequency and intensity, and the fact that they will be superimposed on the seasonal changes.

The effect of elevated temperature (eTmp) and elevated atmospheric carbon dioxide concentration (eCO_2) on grain yield have been evaluated as single-factors and combined-factors under experimental conditions in FACE (free air carbon dioxide enrichment) and in enclosure studies as well as in simulation studies (Lawlor and Mitchell, 1991; Conroy et al., 1994; Jablonski et al., 2002; Ainsworth and Long, 2005; Lobell et al., 2011; Challinor et al., 2014; Ingvordsen et al., 2015a; Cai et al., 2016). The numerous studies generally report decreasing grain yield by eTmp and increasing grain yield from eCO_2. In combinations, the harmful effect of eTmp is not fully complemented by eCO_2, and therefore, grain yield generally decreased (Conroy et al., 1994; Long et al., 2006; Ingvordsen et al., 2015a). The above mentioned studies reported results from a maximum of four accessions, and crop responses to climate change are almost exclusively reported from studies including a very limited number of genotypes. In contrast the present study includes 22 accessions representing a diverse genetic origin and thereby widening our knowledge on genotypic effects in response to eTemp and eCO_2.

Temperature stress caused by exposure to constantly increased eTmp affects cereal yield differently than exposure to an extreme temperature event like a heatwave. The negative effect of a heatwave on grain yield is mainly determined by the timing in relation to the cereal development stage, with the most susceptible stage being around flowering (Barnabas et al., 2008, Barber et al., 2017). In turn, the physiological response mechanisms of individual cultivars vary and are associated with their final yield (Stone and Nicolas, 1994; Hakala et al., 2012). Under field conditions, the differences observed in development between the accessions together with time of sowing for each accession would have influenced at which development stage the heatwave would have had its effect. Sufficient variability in cultivar earliness/lateness, cultivation of mixed cultivars and agricultural management can enable partial escape from the deleterious effects of heatwaves (Tewolde et al., 2006).

Few studies have so far investigated the effect on crop production caused by heatwaves superimposed to projected future levels of temperature and/or CO_2. One study applied a 15-day heatwave of maximum 35 °C, 8 h a day during grain filling on three wheat cultivars under simultaneous exposure to eCO_2 (750 ppm; Bencze et al., 2004). However, none have, to our knowledge, applied a heatwave under the realistic future climate scenario of eTmp and eCO_2 in combination and assessed a large number of genotypes.

In the present study a 10-day heatwave of 33/28 °C (day/night) was induced around the time of flowering to 22 spring barley accessions. The heatwave was timed around flowering, which is known to be the most critical developmental phase of barley yield determination at high latitudes (Peltonen-Sainio et al., 2011). The heatwave was superimposed to projected future levels of temperature and CO_2 as single factors and combined, conditions close to IPCC's worst case scenario for the end of this century (~RCP8.5; Collins et al., 2013). We ask if heat waves will be more or less devastating when superimposed on future growth conditions with eTmp and eCO_2 considering grain yield, biomass, calculated harvest index (HI) and stability of grain yield.

2. Material and methods

2.1. Plant material

Based on their performance, 22 barley (*Hordeum vulgare* L.) accessions were selected from a previous study on production under eTmp, eCO_2, and eCO_2 combined with eTmp (Ingvordsen et al., 2015a). The accessions represent both high and low yielding lines and include landraces, old (1924–1962) and new (1978–2010) cultivars. Details on the 22 accessions can be found in Table 1. The accessions were supplied by NordGen (the Nordic Genetic Resource Center; http://www.nordgen.org/) and Nordic breeding companies.

2.2. Growing conditions

The accessions were cultivated in the RERAF (Risø Experimental Risk Assessment Facility) phytotron at the Technical University of Denmark, Campus Risø, Roskilde. RERAF has the advantage of six identical 24 m^2 (6 m × 4 m × 3 m) gastight chambers individually