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Nitrogen supply – A determinant in water use efficiency of winter wheat grown under free air CO_2 enrichment

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ABSTRACT

Global warming and associated decrease of summer precipitation will intensify the limitation of crop growth through water unavailability in Europe. Concomitantly, the rise of atmospheric CO_2 concentration ([CO_2]) decreases stomatal conductance and thus transpiration as evident at the leaf level. However, knowledge about the effect of elevated [CO_2] ([eCO_2]) on seasonal water use of crops is rather poor. In a two year field study, winter wheat was grown under ambient [CO_2] (393 ppm) and [eCO_2] (600 ppm) using free air CO_2 enrichment (FACE). In addition, subplots were established with three levels of nitrogen (N) supply (35, 190, 320 kg N ha^{-1}). Soil moisture was continuously measured and wheat was irrigated when necessary to keep field capacity at between 50% to 90%. Evapotranspiration (ET) from stem elongation until maturity was calculated using a soil water balance approach. Water use efficiency (WUE) was determined from the ratio of aboveground biomass production and ET during this period.

Increasing N supply increased canopy size and decreased radiation transmission to the soil surface. Moreover increasing N supply enhanced biomass production from 771–1569 g m^{-2}, ET from 227 to 336 mm and WUE from 4.07 to 6.20 g kg^{-1}. Biomass was increased under [eCO_2] by 17% among all N levels. [eCO_2] increased soil moisture especially in the upper soil layer (0–20 cm) and thus irrigation was reduced under [eCO_2] compared to [aCO_2]. This effect was intensified by rising N supply leading to a significant $CO_2 \times N$ interaction on ET and WUE. Thus, the [eCO_2] effect was for ET −2, −9 and −10% and for WUE + 20,+ 30 and +29% under 35, 190, 320 kg N ha^{-1}, respectively. Simultaneously, there seems to be a greater increase of evaporation by [eCO_2] under low than high N supply.

1. Introduction

The anthropogenic rise of the atmospheric CO_2 level and the related consequences for regional changes in temperature and annual precipitation pattern might intensify the water limitation of crop growth during the vegetation period (Porter et al., 2014). Concomitantly, the rising atmospheric CO_2 concentration ([CO_2]) increases photosynthesis of C3 crops and reduce stomatal conductance and thus transpiration at the leaf level of C3 and C4 crops (Ainsworth and Rogers, 2007). However, for reliable estimations of the consequences of water shortage on crop growth in future the effect of elevated [CO_2] ([eCO_2]) on crop water use under field conditions has to be quantified.

Previous CO_2 enrichment studies with wheat indicated that a rise of [CO_2] of approximately 200 ppm above the ambient [CO_2] decreases stomatal conductance by 30–40% (Bunce, 2004; Wall et al., 2000; Li et al., 2004; Tausz-Posch et al., 2013). Also, stomatal response to [eCO_2] was found to be stronger under low than high nitrogen (N) fertilization (Li et al., 2004; Wall et al., 2000). The reduction of stomatal conductance and transpiration at the leaf level can be counterbalanced by an increase of leaf area under [eCO_2]. This has been observed in controlled environment studies under high but not under low N supply (Li et al., 2004; Seneweera and Conroy, 2005). However, if plants were grown in the field under adequate N fertilization, effects of [eCO_2] on leaf area index were small (Brooks et al., 2000; Weigel and Manderscheid, 2012). Water loss from the canopy is strongly influenced by atmospheric conditions including radiation, air humidity and wind speed. Therefore, reliable estimation of the effect of [eCO_2] on canopy transpiration and seasonal water use are ideally possibly if plants are grown under free air CO_2 enrichment (FACE) (Long et al., 2004).

In FACE studies with wheat [eCO_2] decreased canopy transpiration

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by 15% to 22% (Senock et al., 1996; Tausz-Posch et al., 2013) and evapotranspiration (ET) by 4% to 20% (Burkart et al., 2011; Kimball et al., 1995; Hunsaker et al., 2000; O'Leary et al., 2015; Wang et al., 2018). Results for water savings by [eCO_2] under N deficiency are variable indicating ET reductions of 20% and 2% when estimated from an energy balance approach (Kimball et al., 1999) and from a soil water balance (Hunsaker et al., 2000), respectively.

Water use efficiency of biomass production of wheat was clearly stimulated under FACE (Kimball, 2016). The size of the effect of [eCO_2] was almost +20% under optimum growth conditions (Hunsaker et al., 2000). However, results obtained under limited N supply showed either an enlargement or a mitigation of the CO_2 effect as compared to the ample N treatment depending on the method used for measuring ET (Hunsaker et al., 2000; Kimball et al., 1999).

In a wheat field water flux to the atmosphere includes mainly evaporation from the soil and transpiration through the stomata of the plants and less importantly, evaporation of water intercepted by the canopy. Only transpiration is associated with plant productivity whereas evaporation is considered as an undesired component of ET. Evaporation can contribute 10% to 40% to ET in a wheat field (Caviglia and Sadras, 2001; Chen et al., 2010; Kool et al., 2014) and under normal growth conditions average seasonal evaporation amounts to about 30% of ET (Liu et al., 2002). Evaporation is controlled by soil water content of the topsoil and the amount of radiation incident to the soil surface. The latter depends on leaf area index which determines radiation transmitted to the soil surface.

The reduction of transpiration under [eCO_2] can result in an increase of soil water content (Hunsaker et al., 1996; Burkart et al., 2011). Thus, it is possible that water saved by transpiration under [eCO_2] is wasted by an increase of evaporation. Since evaporation is much more facilitated under low than high N supply due to the associated changes in canopy size (Debaeke and Aboudrare, 2004), it is conceivable that an increase of evaporation as a result of a decrease of transpiration under [eCO_2] is more important under low than under high N supply.

In a recent study with different wheat growth models the effect of global warming and [eCO_2] on seasonal transpiration and evaporation was estimated (Cammarano et al., 2016). According to this study, a doubling of [CO_2] hardly decreases seasonal water use and the effect on seasonal evaporation was even stronger (-9%) than on transpiration (-2%). However, there was a great varibility among the models regarding the contribution of evaporation to total water use which points to the need of more reliable data for this interaction.

FACE experiments addressing ET of wheat carried out so far were conducted in an arid (Hunsaker et al., 1996, 2000) or a semi-arid environment (O'Leary et al., 2015) using a water balance or an energy balance approach (Kimball et al., 1999). In the only large-scale FACE study done in the temperate climate zone of Central Europe ET was measured with a canopy chamber which, however, altered the aerial environment of the plant (e.g. wind speed; radiation environment) influencing ET (Burkart et al., 2011). Thus, there is a lack of data and knowledge, respectively, with respect to the effect of [eCO_2] on seasonal ET of wheat which is especially true for the temperate climate zone.

The present paper describes the first study that addresses the effects of FACE on ET and water use efficiency of winter wheat over the main growing seasons of two years under temperate climate conditions combined with three N fertilizer levels (severe deficiency, adequate and excess N supply). The main objective was to quantify the effect of [eCO_2] on ET and on water use efficiency and to examine whether the response to [eCO_2] is modified by N fertilization.

2. Materials and methods

2.1. Experimental site and FACE system

The experiment was conducted on a field site (52°18'N, 10°26'E, 79 m a.s.l.) at the Thünen-Institute in Braunschweig, Germany, in 2014 and 2015. The mean annual temperature is 9.1 °C and the mean annual precipitation is 617 mm.The soil is a luvisol of a loamy sand texture (69% sand, 24% silt, 7% clay) in the plough horizon (0–40 cm). The soil profile has a depth of about 60 cm (−30 cm Ap, −15 cm Al, −15 cm Bt, > 60–70 cm CII). The lower layers are almost pure sand. Overall, the soil is of low to intermediate fertility and provides a comparatively shallow rooting zone.

CO_2 enrichment was carried out by a FACE system constructed according to the Brookhaven National Laboratory design (Lewin et al., 1992). Three circular plots were equipped each with a free air CO_2 enrichment apparatus including vertical vent pipes and CO_2 injection driven by a blower and each with a diameter of 20 m. This rings comprised what is termed [eCO_2] treatment. Three further circular plots without the CO_2 enrichment apparatus were used as control treatment (=[aCO_2]). The FACE and ambient rings were set up after crop emergence and removed at grain maturity. The target CO_2 concentration in the FACE rings was set to 600 ppm. The CO_2 enrichment lasted from the three leaf stage in March until end of grain filling in July (Table 1). CO_2 enrichment took place during the daytime hours and was interrupted if wind speed exceeded 6 m s^{-1} or if air temperature fell below 5 °C.

Climate data (hourly/daily mean values of air temperature, global radiation and precipitation) measured at 2 m height close to the experimental field site (< 500 m) were provided by the German Weather Service at Braunschweig

2.2. Crop management

Winter wheat (*Triticum aestivum* L. variety "Batis") was sown at the experimental field site in late autumn with a density of 380 kernels m^{-2} (Table 1). Crop management measures were performed according to local farm practice with adequate nutrient supply and pesticide applications.

In each of the FACE and ambient rings three subplots (3 m × 5 m) with different N fertilization were randomly established. The N treatments comprised three levels of calcium ammonium nitrate (deficient: N1, adequate: N2, excessive: N3). The total amount of N fertilizer applied in the two years were 40/35 kg N ha^{-1} (N1), 180/200 kg N ha^{-1} (N2) and 320 kg N ha^{-1} (N3). A detailed description of the different N treatments is described elsewhere (Dier et al., 2018).

2.3. Measurement of soil water content and seasonal water use

According to a previous study with the same wheat cultivar at this site the greatest part of roots is in the 0–30 cm topsoil layer (Pacholsky et al., 2015). Thus, soil water content (SWC) was measured in the 0-0.2 m and 0.2-0.4 m soil layer by time domain reflectometry (TDR, from

Table 1
Important cultivation measures and growth stages.

Event	2014	2015
Sowing	Oct 29th	Nov 4th
Emergence	Nov 18th	Nov 19th
Start CO_2 enrichment	Mar 31th	Mar 12th
1st node stage	Apr 18th	Apr 30th
First Harvesting	Apr 24th	May 4th
Anthesis	June 6th	June 12th
End of CO_2 enrichment	July 21th	July 24th
Final harvest	July 22th	July 27th