Maize response to free air CO_2 enrichment under ample and restricted water supply: field experimental data and output of a process-based hydrological plant growth model

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Abstract: This paper is about data from a two year FACE experiment with maize (*Zea mays* L., cv. 'Romario') investigating the interaction of two CO_2 concentrations (378, 550 ppm) and two levels of water supply (sufficient: wet, limited: dry) on crop growth and plant composition. In the second year soil cover was also varied to test whether mitigation of evaporation by straw mulch increases the CO_2 effect on water use efficiency. In this year also a high impact of elevated CO_2 in the dry treatment was observed, due to a particular correspondence between flowering stage and soil water deficit that was postponed under elevated CO_2. The datasets assembled herein contain data on weather, management, soil condition, soil moisture, phenology, dry weights and N concentrations of the plant (leaves, stems, cobs), green leaf area index, stem reserves, final yield and quality-related traits in the total plant and grains. Most of the experimental findings have already been published in scientific journals. Moreover, the data have been used in two crop modeling studies, and simulation results (on soil moisture, transpiration, evaporation and biomass) of one of these studies are also shown here.

Keywords: maize, free air CO_2 enrichment, drought, mulching, biomass, growth, yield, plant quality, soil moisture, modeling.

1 BACKGROUND: Climate change due to rising atmospheric CO_2 concentration and associated increase in temperature and drought periods will have important implications for global food production (IPCC, 2013). Maize is one of the most important crop species exhibiting the C_4 photosynthetic pathway. Rising concentrations of CO_2 (eCO_2) have little or no effect on carbon fixation of C_4 plants but decrease stomatal conductance (Kimball, 2016). Thus, the decrease in transpiration under eCO_2 can mitigate the negative effects of drought on plant growth. We have conducted a two-year field experiment with maize and investigated the interaction of free air CO_2 enrichment and water supply on growth, yield and plant composition. Corresponding results have already been published in scientific journals (Erbs et al., 2012, 2015; Manderscheid et al., 2014, 2016; Meibaum et al., 2012; Wroblewitz et al., 2014). The experimental data have also been used in two crop modeling studies (Durand et al., 2018; Kellner et al., 2019). The present paper contains most of the measurement results of this experiment as well as results of model simulations of Kellner et al. (2019).

2 METHODS

2.1 EXPERIMENTAL FIELD SITE: The experiments were conducted on the experimental field at the Johann Heinrich von Thünen-Institute, Federal Research Institute for Rural Areas, Forestry and Fisheries, Braunschweig, South-East Lower Saxony, Germany (52°18' N, 10°26' E, 79 m a.s.l.). The soil is a Luvisol of a loamy sand texture (69% sand, 24% silt, 7% clay) in the plough horizon (0-30 cm). The plough layer has a pH of 6.5 and a mean organic carbon content of 1.4% and a total N content of approx. 0.1%. The drained upper (0.01 MPa soil water tension) and lower limits (1.5 MPa water tension) in soil water content were 23% and 5%, respectively. The lower layers, in particular >70 cm, are characterized by a coarser soil texture (almost pure sand) and are structured by the succession of thin silt/clay layers. The soil has a plant available water content of ca. 18% in the plough layer, which decreases slightly with increasing soil depth. Maize roots went down up to ca. 100 cm soil depth, however, the largest share (≥ 95%) was concentrated in the 0-60 cm depth (Paeßens et al., 2019).

2.2 CO_2 TREATMENTS: Three circular plots (each with a diameter of 20 m) were equipped each with a free air CO_2 enrichment apparatus including vertical vent pipes and CO_2 injection driven by a blower (Erbs et al., 2012; Manderscheid et al., 2014). These rings comprised what is termed eCO_2 treatment or FACE rings. Three further circular plots without the CO_2 enrichment apparatus were used as control treatment (=aCO_2, 378 ppm, ambient rings). The target CO_2 concentration in the FACE rings was set to 550 ppm during daylight hours (i.e. daylight solar altitude θ >-0.833°). CO_2 enrichment was interrupted at wind speeds > 5.5 m s^{-1}. The FACE and ambient rings were set up after crop emergence and removed after final harvest. The CO_2 enrichment started at a leaf area index of about 0.5 (11th June in 2007, 9th June in 2008) and lasted until final harvest (2nd October in 2007, 30th September in 2008).

2.3 VARIATION OF WATER SUPPLY: Based on past experience maize suffers frequently from drought at this field site. Each of the six circular plots was split into a well-watered (WET) and a dry (DRY) semicircular subplot separated by a 1 m wide track. In the WET subplots, water content in the main rooted soil profile (0.6 m) was kept above 50% maximum plant available water. In the DRY treatment, it was intended to reduce soil water content to below 50% during midsummer. Soil water content was regularly controlled by TDR sensors (Manderscheid et al. 2014). A separated drip irrigation system in WET and DRY allowed for controlled water supply. Two different rain exclusion methods were applied in the DRY semicircles. In 2007, wooden racks equipped with PVC shelves (0.6 m width) were positioned in every second inter row area and the rain intercepted was drained to the outside of the rings. The racks were operated from 24th August until 30th September and 11% of the daily precipitation could be excluded which corresponded to 9 mm over this period. However, the DRY treatment could not be achieved in 2007 because of exceptional rainfall. In 2008, the DRY subplots were equipped with aluminum frames of tents with a ground area of 20 m x 12 m each (Erbs et al., 2012). The frames were covered with transparent PVC tarpaulins during periods of forecasted rainfall >10 mm day^{-1}. The frames reduced incident photosynthetic active radiation (PAR) by 6.6% without tarpaulins based on the exposed horizontal area and by 24.1% with tarpaulins. The tarpaulins were installed during three periods (3rd to 4th July, 17th to 22nd July, and 22nd to 25th August) resulting in total rain exclusion of 55 mm based on the weather data included in this paper. According to PAR sensors operated in a DRY and WET semicircle incident radiation was reduced by 7% in the DRY area as compared to the WET area over the season (Erbs et al., 2012).

2.4 VARIATION OF SOIL COVER: Water saving through reduced transpiration under eCO_2 may be lost by enhanced evaporation. Therefore soil cover was varied in 2008. Each semicircle of the WET and DRY treatments was divided in a quarter without soil cover (BARE) and a quarter in which the soil surface was covered at the 1st July by hand with 7 t ha^{-1} barley straw (MULCH). Such an amount of residue on the soil surface reduced the rate of evaporative water loss by ca. 80% as compared to the bare soil.

2.5 CROP CULTIVATION: Agricultural management measures of the 10 ha field and the experimental plots were performed according to local farm practice and included plough tillage, mineral fertilization and pesticide treatment. Maize (*Zea mays* L., cv. 'Romario') was sown (in 5 cm soil depth) with a row distance of 0.75 m and a seeding density of 10 plants m^{-2}.

2.6 MEASUREMENTS

2.6.1 WEATHER: Weather data including rainfall were provided by the German Weather Service from a weather station (Stations_ID 662), which was 400 meters away from the experimental field site. Rainfall data shown herein are slightly different from those used by Manderscheid et al. (2014) and Kellner et al. (2019) and thus rain excluded by rain-out shelter in 2008 amounts to 55 mm in the provided file and not to 57 mm. Weather data of the German Weather Service is freely available on OpenData. The data presented here were downloaded January 2020. (https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/hourly/)

2.6.2 SOIL MOISTURE: Volumetric soil water content (SWC) was recorded with TDR-sensors (from IMKO, Ettlingen, Germany), which had measuring rods of 16 cm length. Two measurements were taken every week from 12th of June until final harvest. To account for different spatial variation in SWC in the various treatments due to the discharge of precipitation to the plant row area and the variation due to the different water supply, soil moisture measurements were done at different positions depending on the treatment. In the top soil layer (0–0.2 m) water content was measured by a handheld TDR probe vertically put into the ground at three positions from the plant row up to the centre between two rows. In each of the six WET plots two TDR probes were positioned horizontally at 0.3 m soil depth with a horizontal distance of 0.2 m from the plant rows with one probe in the BARE and in the MULCH quarter, respectively, in 2008. A similar positioning was used for the DRY treatment in 2007, while in 2008 an additional probe was installed in the BARE quarter. The records were used for the quantification of SWC in the 0.2–0.4 m soil layer. Values in the 0.4–0.6 m layer were obtained by one (2007) or two probes (2008, in BARE and MULCH) installed in the DRY plots at 50 cm depth. Irrigation of the experimental plots was controlled by manual application based on records of SWC.

2.6.3 TIME SERIES DATA ON CROP GROWTH, CONCENTRATION OF N AND WATER SOLUBLE CARBOHYDRATES: Plant samples were taken at four (2007) or five dates (2008) from June until end of September, separated into different fractions (stems, leaves, cobs, grains) and used for measuring their dry weights and areas where appropriate. Plant material was also used for measuring concentration of N (Erbs et al., 2015) and water soluble carbohydrates in stems (Manderscheid et al., 2009).

2.6.5 DATA ON ELEMENTAL COMPOSITION AND QUALITY CHARACTERISTICS OF ABOVEGROUND BIOMASS AND GRAINS: Samples of total above ground biomass and grains taken at the final harvest were used for analysis of plant composition (Erbs et al., 2015). Measurements included i) elemental composition, i.e. concentration of macro- (Ca, K, Mg, N, P, S) and microelements (Fe, Mn, Zn), and ii) quality characteristics of the total plant, i.e. concentration of crude fiber, acid detergent fiber, neutral detergent fiber, lignin, fat, sucrose and starch, and of the grains, i.e. fat, sucrose, starch and proteins (glutelins, prolamins; analysed only for the 2008 plant material).

2.7 MODEL SIMULATIONS: The results of our modeling study with maize FACE data (Kellner et al., 2019) and the results of a previous FACE study with winter wheat (Manderscheid et al., 2018) indicate that evaporation plays a key role in the water balance of crops under eCO_2. Therefore, the simulated water fluxes (evaporation, transpiration and evapotranspiration), plant biomass and soil water content are provided herein. The coupled hydrological-plant growth model CMF-PMF (Kraft et al., 2011, 2018, Multsch et al., 2011, 2018) was used to investigate the non-mulched treatments of the maize FACE study. Kellner et al. (2019) identified 46 parameter sets for accurate model runs. Hence, the individual results of each of the 46 parameter sets are provided herein. Data of the year 2007 had been taken for model calibration and 2008 for model validation. Note: The simulated water fluxes could not be tested against field data.

3 DATA FORMAT AND STRUCTURE: The field data are available in „maize_data.xlsx", an Excel file with 12 worksheets (Table 1).

Table 1: Content of each of the 12 worksheets from the file "maize_data.xlsx".

Worksheet name	**Content**
data files & abbreviations	Name of the data files, abbreviations and units
TRNO definition	Code and definition of the different treatments
soil properties	Drained upper and lower limit of water content in 0-60 cm depth
meteo	1 hour average weather data for 2007 and 2008
management	Management measures (ploughing, sowing, fertilization, pesticide application, operation of rain shelter)
irrigation	Irrigation water per treatment
rain shelter	Excluded precipitation water by use of rain shelter in 2008 only
soil moisture	Soil water content measured with TDR sensors in 2007 and 2008
phenology	Phenological data of both experimental years
growth	Time series data on growth and on plant concentrations of N and water soluble carbohydrates
whole plant quality	Elemental composition and quality characteristics of the whole plant
grain quality	Elemental composition and quality characteristics of the grains

The simulated data are available in “maize_modeloutput.xlsx“. The file includes 8 worksheets. In line with “maize_data.xlsx“ the file contains the worksheets “data files & abbreviations” and “TRNO definition”. Furthermore, the parameter values for each of the 46 parameter sets are listed, followed by the model outputs for the individual parameter sets: simulated daily biomass and volumetric soil moisture in the three soil depths. In addition, the simulated water fluxes transpiration, evaporation and evapotranspiration are provided as sums over the growing periods 2007 and 2008.

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