Thünen à la carte

FACE with crops: data for climate change impact models

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The rapid rise of the atmospheric CO_2 concentration [CO_2] is the most prominent example of climate change. Beside its role as a "greenhouse gas" CO_2 is of fundamental importance for photosynthesis of all plants and elevated [CO_2] is known to stimulate photosynthesis of most plant species. Will such an effect enhance growth and yield of our crop plants in the course of the overall climate change? We are running unique field experiments to help to answer this question.

Global atmospheric [CO_2] is rapidly increasing and has already approached 400 parts per million (ppm). Projected future [CO_2] are expected to reach 470 to 600 ppm by 2050 and 900 ppm by the end of 2100. With respect to climate change impacts on crop yields and agricultural production, plant growth and agroecosystem models are commonly used to assess the implications of future changes in temperature and precipitation along with increasing [CO_2].

Most often the results of these models strongly depend on whether or not and to what extent the "CO_2-fertilization" is included into these models (Figure 1; Hertel 2015). Thus, it is of particular importance to know the magnitude of such a CO_2 effect under real field conditions.

HOW DO PLANTS RESPOND TO ELEVATED ATMOSPHERIC CO_2 CONCENTRATIONS?

In C_3 crops like wheat, rice, sugar beet and soybean the enzyme RuBisCO is converting CO_2 into an organic molecule with three carbon atoms. However, at current ambient CO_2 levels RuBisCO remains non-saturated with respect to CO_2. Consequently, elevated [CO_2] enhances carbon assimilation of these crops. For example, an enhancement of the photosynthetic rate of up to 35-50 % may be possible at a [CO_2] of 550 to 750 ppm. Due to a different CO_2 fixation mechanism photosynthesis of C_4 crops like maize, sorghum and sugarcane is not enhanced by elevated [CO_2]. However, under elevated [CO_2] leaf stomatal conductance of both plant types is reduced resulting in a decrease of leaf transpiration. This again may lead to a more

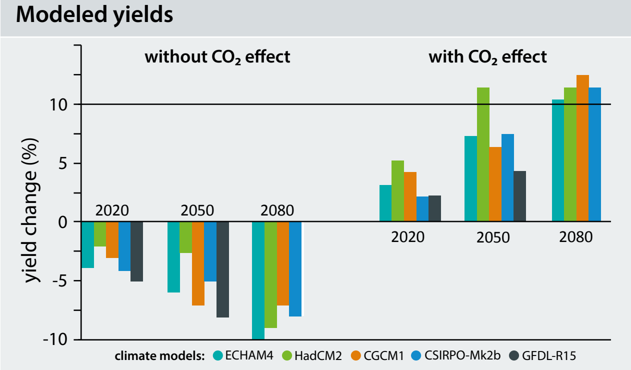

Figure 1: Modeled (DSSAT-CERES) yields of winter wheat in Austria for different climate change scenarios with and without "CO_2-fertilization" (Alexandrov et al. 2002; modified)

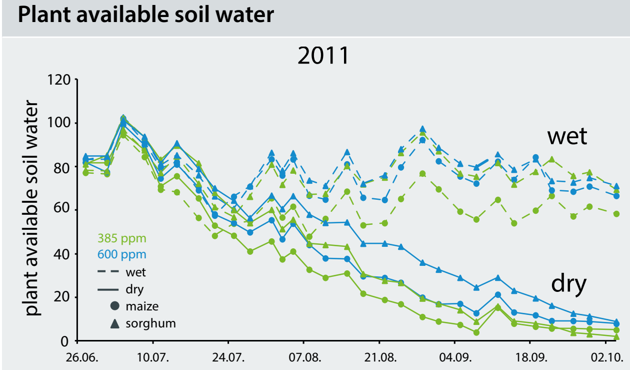

Figure 2: Plant available soil water content (mm; 0-60 cm) of maize (cv. Simao) and sorghum (cv. Bulldozer) canopies during FACE-experiments in Braunschweig under adequate (wet) and reduced (dry) water supply

Photo 1: Free air CO_2 enrichment (FACE) rings in a winter wheat field during July (Braunschweig). Across the area surrounded by the vertical vent pipes (light green) the CO_2 concentration is elevated to 600 ppm.

efficient plant water use. Moreover, in C_3 plants elevated [CO_2] leads to changes in the plants tissue composition with consequences for e.g., plant quality. For any climate change impact assessments it is important to know how these primary effects of elevated [CO_2] translate into effects on crop yields and yield quality. We are addressing these questions in FACE experiments.

FACE: OPTIMAL TOOL TO STUDY THE "CO_2 FERTILIZATION EFFECT"

The FACE technology (**F**ree **A**ir **C**arbon Dioxide **E**nrichment) allows to simulate future atmospheric CO_2 levels under open field conditions – without any enclosure of plant canopies by chambers or greenhouses. In Braunschweig (North Germany) we have applied a circular FACE system in an arable crop field for now more than 10 years (Photo 1). The system is used to raise the atmospheric [CO_2] to 550 or 600 ppm during the growing season (daylight only). In order to assess the interaction between elevated [CO_2] and drought stress we developed a rain-out shelter system that can be combined to the FACE apparatus (Manderscheid et al. 2014; Photo 2). FACE experiments are currently considered as the optimal tool to simulate future atmospheric CO_2 scenarios for plants close to reality, e.g. as canopy microclimate and overall in situ growth conditions are not affected. Only a limited number of FACE experiments has been carried out as they are technically complex and expensive to run due to high CO_2 costs.

ELEVATED CO_2 REDUCES PLANT WATER CONSUMPTION AND ENHANCES YIELDS

In FACE experiments in an arable crop rotation with winter barley, sugar beet and winter wheat (C_3 plants) and with different genotypes of maize and sorghum (C_4 plants) we were able to shown that due to a reduced leaf transpiration total canopy transpiration also decreased. At the same time soil water content in all these experiments increased under elevated [CO_2] (Figure 2). One may speculate that such an effect may help plants to better cope with dry conditions which are expected to increase along with climate change.

A great number of CO_2 enrichment experiments during the last 30 years – mostly carried out under artificial, non-natural growth conditions – revealed positive growth and yield effects of elevated [CO_2] on various crop species. Growth enhancements of up to 30 % were observed at CO_2 concentrations ranging between 200 to 300 ppm above the respective ambient air levels (350-380 ppm). However, these results vary considerably across the individual experiments. In comparison, growth stimulating effects observed in FACE experiments carried out in USA, Japan, China and Australia were mostly lower and amounted – on average – to ca. 15 % under a [CO_2] of 550 ppm (Long et al. 2006).

Similar growth and yield enhancements ranging between 9 to 15 % (Table 1; Weigel and Manderscheid 2012) were observed in our FACE experiments in Braunschweig, which are the only FACE experiments carried out in Europe in arable crop rotations. While it has mostly been observed that the relative growth stimulation by elevated [CO_2] is lower at low compared to adequate nitrogen supply, this could hardly been observed in our experiments (Table 1). Also, for the first time we were able to show in a field experiment under FACE conditions that for maize a "CO_2 fertilization effect" could only be observed if the plants suffer from water stress conditions which clearly decrease above-ground biomass production (Table 2; Manderscheid et al. 2014).

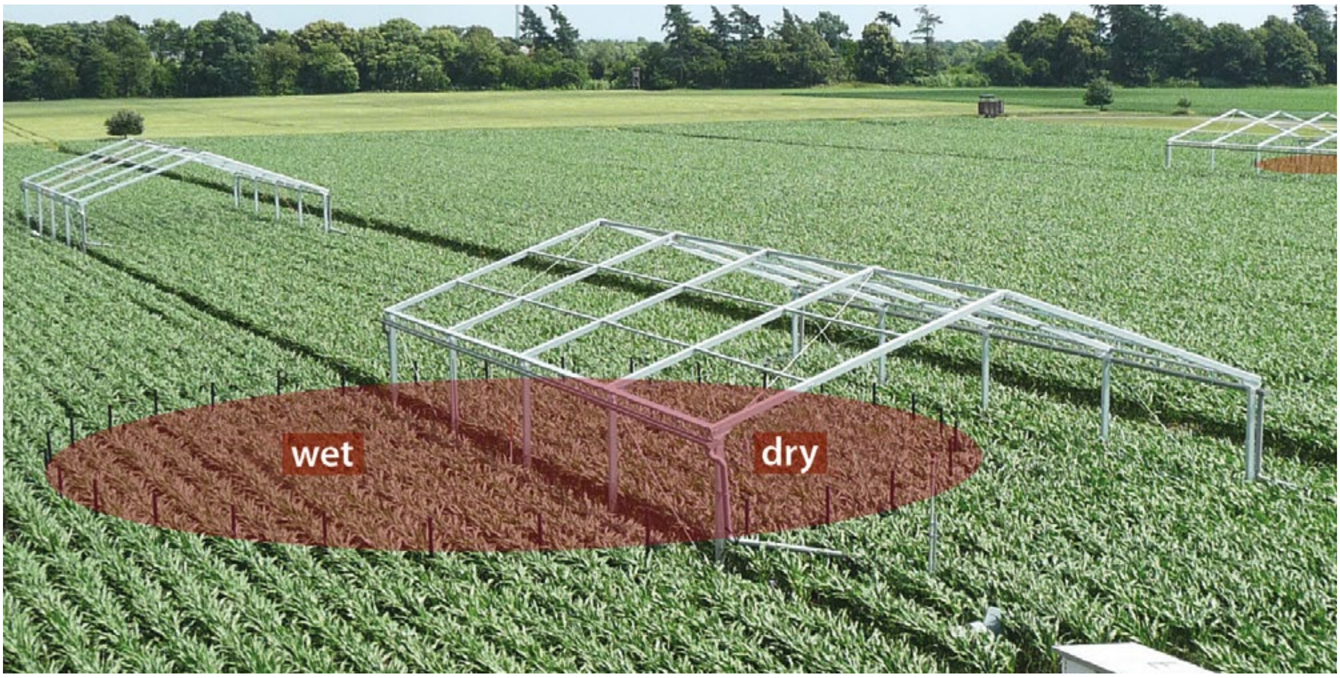

Photo 2: Free air CO_2 enrichment (FACE) system in Braunschweig combined to "rain-out shelters" in order to simultaneously simulate drought stress conditions (coloured area = CO_2 enrichment).

In general, overall assessments of the extent of the "CO_2 fertilization effect" under real field conditions in the future remain difficult. There still is information with only a limited number of crop species and very little is known about the possible interactions of elevated [CO_2] with other growth variables (temperature, water and nutrient supply). Also, possible differences in the CO_2 response between different genotypes of a species remain mostly unknown. Controversy also remains whether data from field or also from laboratory experiments provide suitable information that can be used in models for climate change impact assessments. For example, growth chamber experiments are assumed to overestimate the positive growth effects of elevated [CO_2] in comparison to FACE experiments, and thus too strongly qualify negative effects of climate change. This is equally true for assessments of possible effects of increasing frequencies of climate extremes and climate variability.

ELEVATED CO_2 CHANGES PLANT QUALITY

Almost all studies under elevated [CO_2] revealed changes of the concentrations of macro- and micro-elements (e.g. nitrogen sulfur, iron, zinc) and of other organic compounds (e.g. soluble sugars, vitamins, secondary metabolites etc.) in the plant tissue. For example, in grains of various cereal species elevated [CO_2] induced a reduction of the total nitrogen concentration which corresponds to a loss of protein. In our FACE experiments with winter wheat we not only observed a loss of crude protein content of 10-15 % but also changes in the relative amounts of individual protein fractions (glutenines vs. gliadines) which contribute to the total protein content, an effect which may have consequences for the baking quality of flour (Wieser et al. 2008). Changes of important plant constituents (e.g. protein, mineral and trace element content) induced by elevated [CO_2] are of importance as this might exacerbate the problem of "hidden hunger" (Myers et al. 2014) which is particularly relevant for developing countries.

FACE-DATA FOR MODELS

Data from the FACE experiments in Braunschweig are used by modeling groups from Germany and abroad, in order to validate, calibrate and improve different models for the assessment of future crop yields under climate change. For example, this was done for an analysis of climate change impacts on German wheat production (Kersebaum and Nendel 2014). Data of our maize experiments were provided to the maize modeling team of AgMIP (the **Ag**ricultural **M**odel **I**ntercomparison **P**rojects) in order to test if current maize crop models catch the impact of future [CO_2] on maize yield and water use. Crop modeling for climate change impact assessments came up with the prediction some years ago that under future climate change wheat yield might be more impaired by heat stress rather than by drought conditions. However, these models were mainly based on findings from growth chamber and greenhouse studies. Therefore, most recent FACE experiments in Braunschweig were initiated, where CO_2 enrichment is combined to simultaneous short-term heat treatments of wheat canopies (Photo 3), in order to elucidate possible interactions of heat stress and elevated [CO_2] effects under real field conditions and to provide new data for the related modeling approach.

IMPLICATIONS FOR PLANT BREEDING

FACE and open-top chamber experiments in Braunschweig have shown that (i) some of our current crop species are unable to fully exploit the positive growth effects of elevated [CO_2] and (ii) that

Photo 3: Free air CO_2 enrichment (FACE) combined to heat stress treatments of winter wheat during anthesis (Braunschweig). Inside the FACE area surrounded by the black vertical vent pipes the CO_2 concentration is elevated to 600 ppm. H-1 and H-2 = plots with temperature treatments applied by six infrared heaters. Con = control treatment with dummy heaters.

Crop	Nitrogen supply	Parameter	CO_2-effect (%)
Barley	100 50	Grain yield	+ 12.0 + 13.1
Ryegrass	100 50	Above-ground biomass	+ 8.8 + 9.8
Sugar beet	100 50	Sugar yield	+ 10.3 + 14.2
Wheat	100 50	Grain yield	+ 15.6 + 11.7

Table 1: Effects of FACE (550 ppm) and different nitrogen (N) fertilization levels on yield parameters of different crop species in a crop rotation in Braunschweig (100 = adequate fertilization; 50 = 50 % of adequate). Results are shown as percent change compared to ambient air [CO_2].

	1st growing season		2nd growing season		Drouht stress effect (2nd season)
	wet	dry	wet	dry	
385 ppm	10.4	10.0	11.3	7.3	- 39.5 %
550 ppm	10.3	10.2	11.2	10.2	- 14.5 %
CO_2-effect	-1 %	1 %	-1 %	41 %	

Table 2: Effects of FACE on grain yield (t/ha) of maize in Braunschweig under adequate (wet) and reduced (dry) water supply and relative CO_2- and drought effects. During the 1st growing season drought stress could not be induced.

different genotypes of a particular species differ in their response to more CO_2. This raises the question, whether and to what extent there might be possibilities for more targeted breeding strategies to "optimize" the "CO_2 fertilization effect" in order to maximize the benefits from the high atmospheric CO_2 supply. Further FACE experiments are required to screen large numbers of genotypes of a particular crop species (e.g. winter wheat) for their relative growth responses to elevated [CO_2].

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