Effects of Elevated CO₂ on Cotton and Wheat As Determined from FACE Experiments

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Abstract

In order to determine the effects of the increasing atmospheric CO₂ concentration on future crop productivity and water requirements, free-air CO₂ enrichment (FACE) experiments at 550 $\mu\text{mol/mol}$ CO₂ have been conducted in an open field at Maricopa, Arizona, U.S.A., on cotton (*Gossypium hirsutum* L., cv. Deltapine 77) and wheat (*Triticum aestivum* L. cv. Yecora Rojo) crops at ample (Wet) and limiting (Dry) levels of water supply. With ample water, canopy net photosynthesis rates of cotton and wheat crops increased about 30–40%, with little evidence of down-regulation. Under the Dry treatment, the stimulation was about the same for cotton but much larger for wheat. Cotton growth was stimulated about 30% at both Wet and Dry water levels, with lint yield being stimulated even more, up to 80% under Wet and 50% under Dry. Wheat growth was stimulated less than that of cotton, about 20% at mid-season. Moreover, the final wheat grain yields increased only about 10% under Wet, whereas under Dry, the increase was about 20%. The FACE treatment had very little effect on the water use of cotton, but, for wheat, there appeared to be a small (4%) but significant reduction in water use, as determined by the soil water balance. Water use efficiency increased due to the larger growth and yields.

Key words: global change, CO₂ enrichment, water stress, yield, growth, water use

1. Introduction

The CO₂ concentration of the atmosphere is increasing, and climate modelers have predicted a consequent global warming and changes in precipitation patterns. The report of the IPCC (Intergovernmental Panel on Climate Change; 1995) projects CO₂ increasing from present day concentrations of about 350 $\mu\text{mol/mol}$ to about 500 $\mu\text{mol/mol}$ by the end of the next century if emissions are maintained at 1994 levels. They project that the increase in CO₂ plus that of other radiatively active "greenhouse" gases -- methane, nitrous oxide, chlorofluorocarbons (CFC's), ozone -- will cause an increase in global mean temperature of 0.9 to 3.5°C depending on future emission rates. Some regions might receive increases in precipitation, while others might receive less. However, these projected changes in climate are very uncertain. In any event, the security of food production, as well as of fiber, in the future under conditions of global change is an issue of concern.

Higher levels of atmospheric CO₂ can stimulate photosynthesis and could potentially increase agricultural productivity. Doubled CO₂ concentrations have been shown to increase crop yields by 30% or more on the average, in experiments conducted mostly under greenhouse and growth chamber conditions (Kimball 1983a,b, 1986; Cure, 1985; Poorter, 1993; Idso and Idso, 1994). However, chambers can affect the growth of plants inside, independent of any CO₂ effect, (Drake *et al.*, 1985; Allen *et al.*, 1992; Kimball *et al.*, 1996), and uncertainty exists as to whether such chamber results adequately represent actual field conditions. Therefore, several cooperating researchers developed the free-air CO₂ enrichment (FACE) technique for exposing plants to elevated CO₂ (Hendrey, 1993; Hendrey and Kimball, 1994) in open field plots under realistic natural conditions. Three FACE experiments were conducted on cotton from 1989-1991, the latter two at both ample and stress levels of water supply (Hendrey, 1993; Wall and Kimball, 1993; Dugas and Pinter, 1994). Then an additional two FACE experiments were conducted on wheat in the winter growing seasons of 1992-1993 and 1993-1994, also at ample and limited water supplies (Kimball *et al.*, 1995; Pinter *et al.*, 1996). This paper presents some of the results from those experiments, in particular photosynthesis, biomass growth, yield, and water use data.

2. Materials and Methods

As mentioned in the Introduction, three crops of cotton (*Gossypium hirsutum* L., cv. Deltapine 77) and two of wheat (*Triticum aestivum* L. cv. Yecora Rojo, a hard red spring semi-dwarf variety) have been exposed to season-long elevated CO₂ concentrations using free-air CO₂ enrichment (FACE) apparatus. The experiments were conducted at the University of Arizona, Maricopa Agricultural Center, Maricopa, Arizona, USA, on Trix clay loam [fine-loamy, mixed (calcareous), hyperthermic Typic Torrifluvent]. Details of the experiments and of the FACE technology have been reported previously (Hendrey, 1993; Wall and Kimball, 1993; Dugas and Pinter, 1994; Kimball *et al.*, 1995; Pinter *et al.*, 1996). Briefly, four replicate circular 25-m-dia. vertical vent pipe arrays were used to elevate the CO₂ concentration to 550 µmol/mol in the air across circular open-field plots from the time of plant emergence until maturity. Four similar Control arrays at ambient CO₂ (about 370 µmol/mol during daytime) were also included which had similar piping but no air flow. The array centers were spaced 90 m apart. Seasonal average concentrations were within 0.5 µmol/mol of the set point and 93% of the 1-min. averages were within 10% of the set point (Hendrey *et al.*, 1993). For the cotton experiments, the FACE plots were enriched only during daytime, whereas for the wheat, enrichment was done 24 hr/day.

Except for the first cotton experiment which was amply watered, the main CO₂ plots were split into semi-circular halves that were well-watered (Wet) by replacement of potential evapotranspiration using a sub-surface drip irrigation system (1.0 and 0.5 m tube spacing for cotton and wheat, respectively; 0.3 m emitter spacing; 0.2 m depth) or that were subjected to water stress (Dry) by supplying only 2/3 (cotton) or 1/2 (wheat) as much water as the Wet plots. The plots were fertilized by amounts intended to be ample so that nutrients would be non-limiting.

3. Results and Discussion

Net Canopy Photosynthesis. Measurements of net whole canopy photosynthesis of the cotton were made on several days during 1989 and 1990 by Hileman *et al.* (1994) using a transient “pop-on” chamber technique. They reported that midday photosynthetic rates were stimulated 26 to 31% in both years for the Wet treatment, with the stimulation slightly less at 21% in the Dry treatment in 1990 (Fig. 1). For 1991, Pinter *et al.* (1996) report measurements for a mid-season and an end-of-season day using a flow-through chamber technique. This method yielded absolute rates that were considerably larger than the previous transient method, possibly because of improved circulation and equilibration within the chamber. In any event, this method also indicated a larger stimulation (about 60%) of midday photosynthetic rates of the FACE-grown cotton on the mid-season day for the Wet treatment.

The flow-through chamber technique was utilized again for the FACE wheat experiment (Kimball *et al.*, 1995; Pinter *et al.*, 1996). The stimulation of photosynthesis was about 40% at midday for a typical clear day at mid-season for the Wet treatment (16 Mar, Fig. 1). However, there was a strong interaction between the CO₂ and irrigation treatments, so that the stimulation of photosynthesis due to elevated CO₂ in the Dry treatment on this particular day amounted to more than a doubling (+113%) with respect to the ambient Control. Integrated daily values for 17 selected days through the 1993-4 growing season showed net canopy photosynthesis was stimulated by 19 and 44% due to the FACE treatment in the Wet and Dry treatments, respectively (Kimball *et al.*, 1995).

In some CO₂ enrichment studies initial stimulations of photosynthetic rate have decreased with time due to decreased photosynthetic capacity associated with a decrease in the maximum velocity of carboxylation that the leaf can support *in vivo*, which results from a decrease in Rubisco activity and content (Sage, 1994). These studies have generally been conducted using chambers and small pots with root restrictions. In contrast, in these unconstrained open-field FACE Wheat experiments, measurements of leaf photosynthetic proteins (Nie *et al.*, 1995b) and of photosynthetic gene transcript levels (Nie *et al.*, 1995a) showed little evidence of such acclimation or down-regulation until the onset of senescence.

Biomass production. Elevated CO₂ caused highly significant increases in cotton biomass production, although the magnitude varied from year to year (Mauney *et al.*, 1994). At the end of the growing season, the increases in above-ground biomass amounted to about 23% in 1990 and about 35% in 1990 and 1991 for the Wet treatment (Fig. 1). In contrast to some studies that have tended to show greater stimulation under conditions of water stress (e.g. Kimball, 1993; Idso and Idso, 1994), there actually was only about an 18% stimulation in 1990 for the Dry treatment. In 1991, on the other hand, the stimulation was about the same for both Dry and Wet at about 35% (Fig. 1). There was a greater stimulation of below-ground biomass, contained mostly in the tap roots, than above-ground (Prior *et al.*, 1994; Fig. 2), amounting to 38 and 60% for 1990 and 1991, respectively.

Figure 1. Percentage change of midday canopy net photosynthesis due to FACE ($550 \mu\text{mol/mol CO}_2$) of cotton (Hileman et al., 1994 - Pop-on chamber technique; Pinter et al., 1996 - Flow-through chamber technique) and of wheat (Pinter et al., 1996).

Figure 2. Percentage change of biomass production due to FACE ($550 \mu\text{mol/mol CO}_2$) of cotton (Mauney et al., 1994 - above-ground; Prior et al., 1994 - below-ground and of wheat, Kimball et al., 1995).

Figure 3. Percentage change of cotton lint and wheat grain yields due to FACE ($550 \mu\text{mol/mol CO}_2$) (Pinter et al., 1996).

Figure 4. Percentage change of seasonal water use due to FACE ($550 \mu\text{mol/mol CO}_2$) of cotton (Hunsaker et al., 1994) and of wheat (Hunsaker et al., 1996) as determined as a residual in the soil water balance.

For wheat, the elevated levels of CO₂ from FACE stimulated wheat growth relatively less than that of the cotton (Fig. 1; Kimball *et al.*, 1995), amounting to 20%. Under the Wet treatment, the below-ground biomass was stimulated somewhat more than above-ground, whereas under the Dry treatment, the below-ground biomass was stimulated somewhat less.

We speculate that one reason for a smaller stimulation of wheat by elevated CO₂ compared to cotton is because wheat is a cool weather crop (winter crop in Arizona), whereas cotton is a warm weather crop (summer crop in Arizona). Such a seasonal differences in CO₂ growth response between cool and warm season crops are consistent with a strong positive CO₂ by temperature interaction (Idso *et al.*, 1987; Allen *et al.*, 1990; Kimball, 1993). Another reason for a smaller CO₂ response in wheat compared to cotton could be that wheat is an herbaceous determinate plant, whereas cotton is woody and indeterminate. Thus, cotton almost always has sinks in the form of newly added fruits or wood to accommodate any additional photosynthate resulting from additional photosynthesis in elevated CO₂. Moreover, because cotton is grown in summer, the photosynthesis and biochemical growth processes are less restricted by cool temperatures. In contrast, wheat withstands freezing temperatures, but it grows slowly in winter with little CO₂ response (Kimball *et al.*, 1995). The number of tillers is set during this cold slow-growth time, which restricts the number of sinks for photosynthate. Then, when temperatures warm in the spring, the fact that it has already fixed the number of tillers and can not add more flowers makes it sink-limited and unable to respond as much as cotton to elevated CO₂.

Cotton lint and wheat grain yields. The FACE treatment greatly stimulated lint yields by about 80% in 1990 and 1991 and 20% in 1989 for the wet treatment (Fig. 3). As already mentioned above for biomass, in contrast to some other studies showing greater stimulation under water stress (e.g. Kimball, 1993; Idso and Idso, 1994), the stimulation under the Dry treatment was somewhat less, about 50%.

The stimulation of wheat yields differed markedly from those of cotton (Fig. 3). First, they were much smaller, about 10% under the Wet treatment and about 20% under the Dry. Second, the stimulation under the Dry treatment was greater than under the Wet, more consistent with other studies (e.g. Kimball, 1993; Idso and Idso, 1994), but opposite to the trend in the cotton. Referring to Figs. 2 and 3, the stimulations under the Dry treatment of wheat biomass at mid-season and final yield were about the same (20%), whereas for the Wet treatment, the stimulation of mid-season biomass was about 20% but that of final yield was only about 10%.

Water use. The FACE treatment had little effect on the evapotranspiration or water use of either crop, as determined as a residual in the soil water budget (Hunsaker *et al.*, 1994, 1996) and shown in Fig. 4. Note the drastically expanded scale for Fig. 4 compared to the other Figures. For cotton there was a slight reduction in water use, less than 2% for both 1990 and 1991 and for both Wet and Dry treatments, a result that was consistent with measurements of transpirational sap flow (Dugas *et al.*, 1994) and of the energy balance (Kimball *et al.*, 1994).

For the Wet treatment in wheat, there was a somewhat greater water savings than with cotton, amounting to about 4% in 1992-93 and 1993-94. The changes in water use due to FACE for the Dry treatment were inconsistent between the two growing seasons amounting to a 5% increase in 1992-93 and a 2% decrease in 1993-94.

That elevated CO₂ has such a small effect on water use per unit of land area (Fig. 4) is somewhat remarkable considering that the CO₂ causes stomata to partially close (e.g. Morison, 1987), thereby reducing water use per unit of leaf area. In the case of the FACE cotton experiments for the Wet treatment, Hileman *et al.* (1994) reported that the FACE treatment reduced stomatal conductance by about 22% in 1990, and Bhattacharya *et al.* (1994) reported a similar reduction in 1991. For wheat under the Wet treatment, Garcia *et al.* (1996) reported that FACE reduced stomatal conduction by 38%. Effects of the FACE treatment on leaf area were very small for both cotton and wheat (Mauney *et al.*, 1994; Kimball *et al.*, 1995; Pinter *et al.*, 1996). However other compensatory factors were operative. Cotton canopy temperatures for the Wet treatment were increased 0.8°C at midday (Kimball *et al.*, 1992) and those of wheat were increased an average 0.6°C all season long (Kimball *et al.*, 1995). Moreover, determination of energy balance components of the wheat (Kimball *et al.*, 1995) showed that net radiation was reduced about 3% while sensible heat increased leading to an estimate that evapotranspiration was reduced about 8%, which is a somewhat greater reduction than that obtained by the soil water balance method (Fig. 4).

4. Conclusions

Increasing the atmospheric CO₂ concentration to 550 µmol/mol in an open field using FACE technology with ample water increased canopy photosynthetic rates of cotton and wheat crops about 30-40%, with little evidence of down-regulation. Under water-stress, the stimulation was about the same for cotton but much larger for wheat.

The stimulation of cotton growth by FACE was about 30% at both ample and limited water, with lint yield being stimulated even more, up to 80% under ample water and 50% under water stress.

Wheat biomass growth was stimulated less than that of cotton by FACE, about 20% at mid-season. Moreover, the final wheat grain yields increased only about 10% at ample water, whereas under water-stress, the grain yield stimulation was close to the same size as the biomass stimulation at about 20%.

The FACE treatment had only slight effects on the water use of cotton. For wheat, there appeared to be about a 4% reduction in water use as determined by the soil water balance or perhaps a little more as indicated by the energy balance. Nevertheless, the none to slight reductions in water use represent large increases in water use efficiency because of the FACE-caused increases in biomass and yield.

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