INTERACTIVE EFFECTS OF TEMPERATURE AND ENHANCED CO_2 ON AGRICULTURAL CROPS

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SPPI & CO2SCIENCE ORIGINAL PAPER ◆ May 15, 2013

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Citation: Center for the Study of Carbon Dioxide and Global Change. "Interactive Effects of Temperature and Enhanced CO_2 on Agricultural Crops." Last modified May 15, 2013. http://www.co2science.org/subject/g/summaries/tempco2ag.php.

As the air's CO_2 content rises, most plants exhibit increased rates of photosynthesis and biomass production (see our Plant Growth Database[1]), which should enhance the amount of food, fiber and timber production that can be utilized to feed, clothe and shelter earth's expanding human population. However, some individuals have suggested that the growth-promoting effects of atmospheric CO_2 enrichment may be *largely negated* by the global warming that is predicted to occur in the near future by a number of state-of-the-art climate models, which outcome could compromise our ability to sustain a greater human population without increasing arable land acreage. Thus, we turn to the scientific literature to see if plants will - or will not - continue to exhibit CO_2-induced growth increases under conditions of predicted future warming, which we do here by reviewing what has been learned about the photosynthetic and growth responses of CO_2-enriched *agricultural crops* grown at both current and projected future growing-season temperatures.

In order to better comprehend the issues being addressed in this review, one must first realize that the optimum growth temperatures of several plants have already been demonstrated to rise substantially with increasing levels of atmospheric CO_2 (Berry and Bjorkman, 1980; Stuhlfauth and Fock, 1990; McMurtrie *et al*., 1992; McMurtrie and Wang, 1993). This phenomenon was explained by Long (1991), who calculated from well-established plant physiological principles that most C_3 plants[2]] should increase their optimum growth temperatures by approximately 5°C for a 300 ppm increase in the air's CO_2 concentration. One would thus expect plant photosynthetic rates to rise with *concomitant* increases in *both* the atmosphere's CO_2 concentration *and* its temperature, as has been shown to typically be the case by Idso and Idso (1994) and Cowling (1999)[3]. Hence, we here proceed to see if these positive CO_2 x temperature interactions are still being supported by subsequent scientific studies.

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[1] http://www.co2science.org/data/plant_growth/plantgrowth.php.

[2] http://www.co2science.org/dictionary/define_c.php#C3 plants.

[3] http://www.co2science.org/articles/V2/N20/EDIT.php.

In the study of Zhu *et al.* (1999)[4], it was found that pineapples grown at 700 ppm CO_2 assimilated 15, 97 and 84% more total carbon than pineapples grown at the current ambient CO_2 concentration in day/night air temperature regimes of 30/20 (which is optimal for pineapple growth at ambient CO_2), 30/25, and 35/25 °C, respectively. Similarly, Taub *et al.* (2000)[5] demonstrated that net photosynthetic rates of cucumbers grown at twice-ambient levels of atmospheric CO_2 and air temperatures of 40°C were 3.2 times greater than those displayed by control plants grown at ambient CO_2 and this same elevated air temperature. Thus, at air temperatures normally considered to be deleterious to plant growth, rates of photosynthesis are typically considerably greater for CO_2 enriched vs. ambiently-grown plants.

Reddy *et al.* (1999)[6] reported similar results when they grew cotton plants at air temperatures ranging from 2°C below to 7°C above ambient air temperature, finding that plants simultaneously exposed to 720 ppm CO_2 had photosynthetic rates that were 137 to 190% greater than those displayed by plants exposed to ambient CO_2 concentrations across this temperature range. In like manner, Cowling and Sage (1998)[7] found that a 200-ppm increase in the air's CO_2 concentration boosted photosynthetic rates of young bean plants by 58 and 73% at growth temperatures of 25 and 36°C, respectively, while Bunce (1998)[8] grew wheat and barley at 350 and 700 ppm CO_2 across a wide range of temperatures and found that elevated CO_2 stimulated photosynthesis in these species by 63 and 74%, respectively, at an air temperature of 10°C and by 115 and 125% at 30°C. Thus, the percentage increase in photosynthetic rate resulting from atmospheric CO_2 enrichment often increases substantially with increasing air temperature.

On another note, elevated CO_2 often aids in the *recovery* of plants from high temperature and drought induced reductions in photosynthetic capacity, as demonstrated by Ferris *et al.* (1998)[9], who grew soybeans for 52 days under normal air temperatures and soil water conditions at atmospheric CO_2 concentrations of 360 and 700 ppm, but then subjected them to an 8-day period of high temperature and water stress. Thereafter, when normal air temperatures and soil water conditions were restored, the CO_2-enriched plants attained photosynthetic rates that were 72% of their unstressed controls, while the plants grown at ambient CO_2 attained photosynthetic rates that were only 52% of their controls. And at the end of the growing season, Ferris *et al.* (1999)[10] report that plants grown in the elevated CO_2 treatment exhibited an average biomass that was 24% greater than that displayed by plants grown in ambient CO_2, and a seed yield that was 32% greater.

CO_2-induced increases in plant growth under high air temperatures have also been observed in a number of other agricultural plants. In the previously mentioned study of Cowling and Sage (1998)[11], for example, the 200-ppm increase in the air's CO_2 content boosted total plant

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[4] http://www.co2science.org/articles/V2/N21/B4.php.

[5] http://www.co2science.org/articles/V3/N25/B1.php.

[6] http://www.co2science.org/articles/V4/N15/B2.php.

[7] http://www.co2science.org/articles/V1/N4/B1.php

[8] http://www.co2science.org/articles/V1/N4/B2.php.

[9] http://www.co2science.org/articles/V1/N7/B1.php.

[10] http://www.co2science.org/articles/V2/N19/B4.php.

[11] http://www.co2science.org/articles/V1/N4/B1.php.

biomass for wheat and barley by a combined average of 59 and 200% at air temperatures of 25 and 36°C. Similarly, Ziska (1998)[12] reported that a doubling of the atmospheric CO_2 concentration increased the total dry weight of soybeans by 36 and 42% at root zone temperatures of 25 and 30°C, respectively, while Hakala (1998)[13] noted that spring wheat grown at 700 ppm CO_2 attained total biomass values that were 17 and 23% greater than those attained by ambiently-grown plants exposed to ambient and elevated (ambient plus 3°C) air temperatures. In addition, after inputting various observed CO_2-induced growth responses of winter wheat into plant growth models, Alexandrov and Hoogenboom (2000)[14] predicted 12 to 49% increases in wheat yield in Bulgaria, even if air temperatures were to ultimately rise by as much as 4°C. And in the study of Reddy *et al.* (1998)[15], it was shown that elevated CO_2 (700 ppm) increased total cotton biomass by 31 to 78% across an air temperature range of 20 to 40°C. Thus, it is clear that the beneficial effects of elevated atmospheric CO_2 on agricultural crop yields are often *significantly enhanced* by elevated air temperatures.

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In some cases, however, rising air temperatures do *not* interact with rising atmospheric CO_2 concentrations to further increase the growth-promoting effects of atmospheric CO_2 enrichment. Instead, they simply do not interfere with the *status quo*. In the study of Demmers-Derks *et al.* (1998)[16], for example, sugar beets grown at 700 ppm CO_2 produced 25% more biomass than ambiently-grown plants, regardless of air temperature, which was increased by 3°C. Similarly, in the study of Fritschi *et al.* (1999)[17], significant warming (4.5°C above ambient) simply had no impact on the growth of rhizoma peanut, where a 300-ppm increase in the air's CO_2 content increased its total biomass by 52%, regardless of air temperature. And in the unlikely event that the air's CO_2 content were to cease rising or to have no effect on the productivity of certain plants, it is possible that the temperature increase *itself* may promote plant growth and development, such as was found to be the case in the experiment conducted by Wurr *et al.* (2000)[18], where elevated CO_2 had essentially no effect on the yield of French beans, but where a 4°C increase in air temperature increased their yield by approximately 50%.

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[12] http://www.co2science.org/articles/V2/N11/B3.php.
[13] http://www.co2science.org/articles/V1/N4/B3.php.
[14] http://www.co2science.org/articles/V3/N29/B2.php.
[15] http://www.co2science.org/articles/V1/N4/B5.php.
[16] http://www.co2science.org/articles/V2/N13/B2.php.
[17] http://www.co2science.org/articles/V2/N15/B4.php.
[18] http://www.co2science.org/articles/V4/N14/B1.php.

Moving into the 21st century, Aloni *et al*. (2001)[19] grew bell pepper (*Capsicum annuum* L. cv. Mazurka) plants under optimal conditions until eight days prior to anthesis, at which time they placed the plants in greenhouses maintained at atmospheric CO_2 concentrations of either 350 or 800 ppm and normal (28/22°C) or elevated (32/26°C) day/night air temperatures to determine the effects of these two environmental changes on various reproductive parameters associated with pollen, which is extremely sensitive to high temperatures. Interestingly, the high temperature stress reduced pollen germination by 75% at ambient CO_2; but atmospheric CO_2 enrichment *completely ameliorated* this negative effect. The high temperature treatment also reduced the number of seeds produced per fruit by 68%, while the elevated CO_2 treatment nearly compensated for this deleterious effect, reducing the warming-induced seed-per-fruit reduction to only 9%.

One year later, Tako *et al*. (2001)[20] grew rice (*Oryza sativa* L. cv. Mutsu-homare) plants hydroponically in controlled environment chambers having atmospheric CO_2 concentrations of 350 and 700 ppm and day/night air temperatures of 24/17 (ambient) and 26/19°C (elevated) to study the interactive effects of elevated CO_2 and temperature on the growth in this important crop. And after 18 weeks of treatment exposure, they found that elevated CO_2 had had no effect on whole-plant biomass at ambient growth temperatures; but with the additional 2°C of warming, they found that concomitant atmospheric CO_2 enrichment had produced a whole-plant biomass enhancement of 22%.

Contemporaneously, Bunce (2001)[21] grew strawberry (*Fragaria x ananassa* Duchesne cv. Honeoye) plants in the field in open-top chambers maintained at atmospheric CO_2 concentrations of 350, 650 and 950 ppm for a full two years, in order to study the effects of elevated CO_2 on photosynthesis in this important fruit crop, where measurements were made on a weekly basis to evaluate the temperature dependence of the photosynthetic stimulation resulting from the two levels of atmospheric CO_2 enrichment. This work revealed that plants grown at 650 and 950 ppm CO_2 exhibited mean photosynthetic rates that were 77 and 106% greater, respectively, than those displayed by control plants exposed to ambient air.

Two years later, Prasad *et al*. (2003)[22] grew peanuts (*Arachis hypogaea* L. cv. Georgia Green, of the Virginia Runner type) from seed to maturity in sunlit controlled-environment growth chambers maintained at atmospheric CO_2 concentrations of 350 and 700 ppm and daytime-maximum/nighttime-minimum air temperatures of 32/22, 36/26, 40/30 and 44/34°C. During this study, leaf photosynthetic rates were unaffected by air temperatures over the range studied; but they rose by approximately 27% in response to the experimental doubling of the air's CO_2 content. Concomitantly, vegetative biomass increased by 51% and 54% in ambient-air and CO_2-enriched air, respectively, as temperatures rose from 32/22 to 40/30°C. A further temperature increase to 44/34°C, however, caused moderate to slight *declines* in vegetative biomass in ambient and CO_2-enriched air, respectively, so that the final biomass increase over

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[19] http://www.co2science.org/articles/V4/N44/B3.php.

[20] http://www.co2science.org/articles/V4/N48/B1.php.

[21] http://www.co2science.org/articles/V5/N2/B3.php.

[22] http://www.co2science.org/articles/V7/N9/B1.php.

the entire temperature range investigated was 27% in the ambient air and 53% in the CO_2-enriched air. And when going from the *lowest* temperature *ambient* CO_2 treatment to the *highest* temperature *elevated* CO_2 treatment, there was a whopping 106% increase in vegetative biomass.

When going from the lowest temperature ambient CO_2 treatment to the highest temperature elevated CO_2 treatment, there was a whopping 106% increase in vegetative biomass.

In contrast, *seed* yields in both the ambient and CO_2-enriched air dropped dramatically with each of the three temperature increases studied, declining at the highest temperature regime to but a small percentage of what they were at the lowest temperature regime. Nevertheless, Prasad *et al*. report that "seed yields at 36.4/26.4°C under elevated CO_2 were similar to those obtained at 32/22°C under ambient CO_2," the latter pair of which temperatures they describe as "present-day seasonal temperatures." Therefore, it is clear that an *unrealistically-large warming* of 4.4°C above present-day growing temperatures for peanut production would have essentially *no effect* on peanut seed yields, *as long as the atmosphere's CO_2 concentration rose concurrently* by something on the order of 350 ppm. But for more *realistic* values of CO_2-induced global warming, i.e., temperature increases on the order of 0.4°C or *less* for a doubling of the air's CO_2 content (Idso, 1998), there would likely be a significant *increase* in peanut production.

Also studying peanuts was Vu (2005)[23], who grew plants of the cultivar Florunner from seed to maturity in greenhouses maintained at atmospheric CO_2 concentrations of 360 and 720 ppm and at air temperatures that were 1.5 and 6.0°C above outdoor air temperatures, while a number of parameters related to the plants' photosynthetic performance were measured. This work revealed that Rubisco photosynthetic efficiency - the ratio of midday light-saturated carbon exchange rate to Rubisco initial or total activity - of the elevated-CO_2 plants was 1.3- to 1.9-fold greater than that of the ambient-CO_2 plants at both growth temperatures. It also indicated that leaf soluble sugars and starch of plants grown at elevated CO_2 were 1.3- and 2-fold higher, respectively, than those of plants grown at ambient CO_2. In addition, the leaf transpiration of the elevated-CO_2 plants relative to that of the ambient-CO_2 plants was 12% less at near-ambient temperatures and 17% less in the higher temperature regime, while the water use efficiency of the elevated-CO_2 plants relative to the ambient-CO_2 plants was 56% greater at near-ambient temperatures and 41% greater in the higher temperature environment. And, therefore, because less Rubisco protein was required by the elevated-CO_2 plants, the

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[23] http://www.co2science.org/articles/V8/N8/B3.php.

subsequent redistribution of excess leaf nitrogen, in the words of Vu, "would increase the efficiency of nitrogen use for peanut under elevated CO_2," just as the optimization of inorganic carbon acquisition and greater accumulation of the primary photosynthetic products in the CO_2-enriched plants "would be beneficial for peanut growth at elevated CO_2." Consequently, in the absence of other stresses, Vu's ultimate conclusion was that "peanut photosynthesis would perform well under rising atmospheric CO_2 and temperature predicted for this century."

Focusing on another important crop, Crafts-Brandner and Salvucci (2004)[24] explored the concurrent effects of elevated atmospheric CO_2 concentration and temperature on photosynthetic CO_2 fixation in cotton (*Gossypium hirsutum* L. cv. Coker 100A-glandless), using "intact plants and biochemical measurements to directly determine how environmental change impacts specific physiological mechanisms important to plant productivity." And in doing so, they found that "net photosynthesis of cotton leaves at ambient levels of CO_2 was inhibited at leaf temperatures above about 32°C." At a leaf internal CO_2 concentration that was 4.3 times greater than ambient, however, net photosynthesis did not begin to decline until leaf temperatures rose above 40°C. Viewed another way, the net photosynthetic rate of cotton leaves exposed to ambient air declined by approximately 77% as leaf temperature rose from 32 to 40°C, while that of leaves exposed to the CO_2-enriched air actually *rose* by about 9%, indicating that the increase in atmospheric CO_2 concentration *more than compensated* for the dramatic decrease in photosynthetic rate that would have occurred in its absence in response to the 8°C increase in temperature.

Aranjuelo *et al*. (2005)[25] grew the forage crop alfalfa (*Medicago sativa* L.) in 13-L pots for three consecutive June-July periods (2001-2003) out-of-doors in polyethylene-covered temperature gradient tunnels maintained at atmospheric CO_2 concentrations that averaged 405 and 730 ppm at ambient (AT) and elevated (ET) temperatures (ET = AT + 4°C) and at high (HW) and low (LW) soil water contents (LW = 0.5HW), all of which plants were fed adequate nutrients except for nitrogen, in order to insure that the only source of nitrogen for the plants was that which was fixed by their nodules, which was induced to form in response to inoculation with *Sinorhizobium meliloti* strain 102F78. This experiment revealed, as the researchers describe it, that "the effect of elevated CO_2 on plant growth interacted positively with temperature," and that "higher dry mass production of plants grown under elevated CO_2 and temperature was a consequence of enhanced photosynthetic rates," which conclusion derives directly from their data, where mean CO_2-induced increases in leaf net photosynthesis over the entire experiment were found to be: +5% (HW, AT), +50% (HW, ET), +17% (LW, AT) and +42% (LW, ET), as best can be determined from the bar graphs in the paper describing their study. Likewise, mean CO_2-induced increases in leaf biomass were +4% (HW, AT), +54% (HW, ET), +23% (LW, AT) and +58% (LW, ET), with the same caveat. For both leaf net photosynthesis and biomass production, therefore, these results indicate that the stimulatory effect of the elevated CO_2 of this study was about 2.5 times greater in the warmer of the two temperature treatments in the low soil water regime, and that it was *ten* times greater in the warmer of the two temperature treatments in the high soil water regime. In addition, plant water loss via transpiration was also benefited by the extra CO_2 of this study, declining by 25% (HW, AT), 41% (HW, ET), 31% (LW,

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[24] http://www.co2science.org/articles/V7/N44/B1.php.

[25] http://www.co2science.org/articles/V8/N23/B2.php.

AT) and 31% (LW, ET). Thus, according to the results of this study, under both well-watered and droughty conditions, atmospheric CO_2 enrichment tends to enhance both photosynthesis and biomass production in alfalfa, while simultaneously decreasing transpirational water losses.

Working with three varieties (Emma, Martina and Mezofold) of winter wheat (*Triticum aestivum*), Bencze *et al.* (2005)[26] grew specimens of them in controlled environment chambers under ambient (375 ppm) and elevated (750 ppm) CO_2 at a minimum, maximum and mean temperature regime of 10,12 and 10.7°C, respectively. In addition, twelve days after the average date of heading, several plants of each variety were subjected to fifteen more days of elevated temperatures (min/max/mean of 20, 35 and 25.2°C) in an effort to assess the independent effects of both elevated CO_2 and temperature on wheat growth and yield. The result of this experiment was that the temperature treatment accelerated the aging process in the three wheat varieties, while concurrent atmospheric CO_2 enrichment generally helped them maintain a higher and longer level of photosynthetic activity during grain-filling and maturation. As a result, Bencze *et al*. report that the CO_2-enriched plants "suffered less damage from heat stress and produced a higher yield than at the ambient level." What is more, in the case of the Emma cultivar, the extra CO_2 supplied to the plants meant the difference between life and premature death, since by the end of the 15-day high-temperature treatment, the plants growing in ambient air were dead, while those growing in elevated CO_2 were able to survive for a few more days. Therefore, in a future world of higher atmospheric CO_2 concentrations, wheat crops should be better able to withstand the stress of potentially higher temperatures, suffering less damage and producing greater yields.

In a future world of higher atmospheric CO_2 concentrations, wheat crops should be better able to withstand the stress of potentially higher temperatures, suffering less damage and producing greater yields.

In a contemporary study, Cen and Sage (2005)[27] grew well watered and fertilized sweet potato (*Ipomoea batatas* L.) plants in 20-L pots of soil in a greenhouse, periodically measuring light-saturated rates of net photosynthesis in new but fully-expanded leaves in response to short-term changes in air temperature and atmospheric CO_2 concentration. This work revealed that in response to an approximate 370-ppm increase in the air's CO_2 concentration, the *optimum* leaf temperature for net photosynthesis in sweet potato, i.e., the leaf temperature at which net

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[26] http://www.co2science.org/articles/V8/N26/B3.php.
[27] http://www.co2science.org/articles/V9/N1/B2.php.

photosynthesis proceeds at its maximum rate, rose by approximately 4.5°C, while its *maximal* rate of net photosynthesis rose by about 75%. Viewed another way, the doubling of the air's CO_2 concentration had no impact on net photosynthesis at a leaf temperature of 15°C, but it boosted it by 28% at 21°C, by 43% at 27°C, by 56% at 33°C, and by 70% at 39°C. And viewed in yet another way, in order for the net photosynthetic rate of sweet potatoes growing in air of 740 ppm CO_2 to drop below the maximum rate exhibited by plants growing in air of 370 ppm CO_2 (which occurred at a leaf temperature of 30°C), leaf temperature would have to rise by a full 12°C to a value of 42°C.

Another group of researchers to study rice was the team of De Costa *et al*. (2006)[28], who wrote that "doubts have been expressed whether the expected yield increases in response to increased CO_2 could be sustained under high temperature regimes," and who thus decided to see what might happen in sub-humid Sri Lanka, where weekly maximum temperatures during both the *maha* (January to March) and *yala* (May to August) growing seasons typically range from 30-33°C. More specifically, they grew two crops of rice (one in the *maha* season and one in the *yala* season) in open-top chambers maintained at atmospheric CO_2 concentrations of either 363 or 567 ppm under normal field conditions at the Rice Research and Development Institute of Sri Lanka, measuring a number of meteorological and plant physiological parameters throughout both seasons, as well as total biomass production and grain yield at the times of final harvest. Among other things, this work revealed that the CO_2-induced increase in total plant biomass at the time of final harvest was 23% in the *maha* season and 37% in the *yala* season, while final grain yields were enhanced by 24% and 39% in the *maha* and *yala* seasons, respectively. And this occurred in spite of the fact that air temperatures in the CO_2-enriched chambers were an average of 1.6°C higher than air temperatures in the ambient-air chambers.

In yet another study of rice (cv Akitakomachi), Borjigidai *et al*. (2006)[29] grew plants from seed in greenhouses maintained at atmospheric CO_2 concentrations of 370 and 570 ppm, after which they were transplanted to the field and grown in well-fertilized paddy culture in a FACE study conducted at the same CO_2 concentrations under which the seeds were sprouted in both 2003 and 2004, where at various times throughout the two growing seasons during the field portion of the experiments, photosynthetic measurements were made on the most recently fully-expanded leaves in full sunlight at a variety of different leaf temperatures. This work revealed, as they describe it, that "the optimal temperature of photosynthesis (Topt, the value where the photosynthetic rate was maximum) was significantly higher at elevated CO_2: it ranged from 22 to 34.5°C with an average value of 28.9°C at ambient CO_2, and from 29.5 to 37°C with an average value of 33.5°C at elevated CO_2." And as a result, since the increase in the air's CO_2 concentration employed in this study was only 200 ppm, the 4.6°C mean increase in Topt observed in this experiment would roughly translate to a 6.9°C mean increase in Topt for a CO_2 increase of 300 ppm, which is the concentration increase that is more commonly used in climate modeling studies of the effects of elevated CO_2 on planetary temperature. And, therefore, since the mean increase in global temperature that is predicted to result from a 300-ppm increase in the air's CO_2 concentration is considerably less than the 6.9°C increase in the

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[28] http://www.co2science.org/articles/V9/N26/B2.php.

[29] http://www.co2science.org/articles/V9/N29/B2.php.

Topt of rice that is implied by this study to result from such a CO_2 increase, and since the mean increase in global temperature predicted to result from an increase in the air's CO_2 concentration is greater than that expected to occur in regions where rice is grown, it would appear that this particular variety of rice should have no problem at all in adapting to any warming that might possibly be produced by the ongoing rise in the air's CO_2 concentration.

Shifting to soybeans (*Glycine max* (L.) Merr.), Bernacchi *et al.* (2006)[30] grew them for three years at the SoyFACE facility of the University of Illinois at Urbana-Champaign, Illinois (USA) at atmospheric CO_2 concentrations of either 375 or 550 ppm under natural field conditions, while a number of weather and plant physiological parameters were measured from pre-dawn to post-dusk on several days during the three growing seasons. This significant undertaking revealed that the mean daily integral of leaf-level net photosynthesis (A) was enhanced by nearly 25% in the CO_2-enriched air. In addition, to quote the eleven scientists, "there was a strong positive correlation between daytime maximum temperatures and mean daily integrated A at elevated CO_2." And from their graphical representation of this relationship, it can be seen that at a daily maximum temperature of approximately 26.5°C, A was stimulated by about 14%, while at a daily maximum temperature of approximately 34.5°C, it was stimulated by about 35%.

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Shortly thereafter, Koti *et al.* (2007)[31] used Soil-Plant-Atmosphere-Research (SPAR) chambers at Mississippi State University (USA) to investigate the effects of doubled atmospheric CO_2 concentration (720 vs. 360 ppm) on the growth and development of six well watered and fertilized soybean genotypes that they grew from seed in pots filled with fine sand and exposed to the dual stresses of high day/night temperatures (38/30°C vs. 30/22°C) and high UV-B radiation levels (10 vs. 0 $kJ/m^2/day$). This effort revealed that the elevated CO_2 partially compensated for the damaging effects on vegetative growth and physiology caused by both high temperatures and enhanced UV-B radiation levels, and that elevated CO_2 had a positive influence on the physiological parameters of plant height, leaf area, total biomass, net photosynthesis, total chlorophyll content, phenolic content and wax content, as well as relative plant injury.

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[30] http://www.co2science.org/articles/V10/N1/B1.php.

[31] http://www.co2science.org/articles/V10/N25/B2.php.

Also studying soybeans were Mishra *et al*. (2008)[32], who documented the positive impact of atmospheric CO_2 enrichment on the photosynthetic rates of field-grown plants experiencing the simultaneous negative effects of (1) acute heat stress and (2) elevated atmospheric ozone (O_3) concentrations at the SoyFACE facility of the University of Illinois. More specifically, the seven scientists discovered that elevated ozone exacerbated heat-related decreases in photosynthetic electron transport; but they also found that "elevated CO_2 minimized or prevented light-dependent O_3-related decreases in electron transport (and thus photoinhibition) during heat stress."

Returning to wheat, Alonso *et al*. (2009)[33] sequentially grew well watered and fertilized plants of the cultivar Alcala in 16-liter pots of perlite (sown at a rate of 35 seeds per pot) in a controlled-environment growth chamber -- first at an atmospheric CO_2 concentration of 370 ppm and then at 700 ppm -- from sowing through anthesis, measuring gas exchange in flag leaves at ear emergence in order to obtain the values of various plant physiological parameters required for the biochemical photosynthesis model developed by Farquhar *et al*. (1980), along with the responses of those parameters to changes in temperature. This work revealed, in their words, that the "photosynthesis response to temperature was negative at low air CO_2 concentrations and became progressively positive as CO_2 increased," which might have been expected, as they put it, "from the increase in photorespiration with temperature and the gradual inhibition of this process as CO_2 increases (Long, 1991)." In addition, they report that "at high chloroplastic CO_2, photosynthesis in elevated growth CO_2 was lower at 15-25°C and higher at 30-35°C, than in ambient growth CO_2, implying an enhanced photosynthesis response to temperature in plants grown in elevated CO_2."

In other recent work with wheat, Gutierrez *et al*. (2009)[34] grew well watered and fertilized spring wheat (*Triticum aestivum* L. cv. Gazul) plants from seed to maturity out-of-doors in Salamanca, Spain, in two different years (2004 and 2005) within temperature-gradient chambers that were maintained at ambient (370 ppm) and elevated (700 ppm) atmospheric CO_2 concentrations and ambient air temperature (TA) and elevated air temperature (TE = TA plus 4°C), during which time they measured several plant physiological properties and processes. As for what they learned from this endeavor, their findings are perhaps best summed up by the title of their paper: "Acclimation to future atmospheric CO_2 levels increases photochemical efficiency and mitigates photochemistry inhibition by warm temperatures in wheat." In this regard, for example, they report that net photosynthesis was increased by 62-72% in both years in the CO_2-enriched chambers; while at the conclusions of the two growing seasons, total plant biomass production in the CO_2-enriched chambers was increased by 12-18%. And in light of these findings they conclude that "future increases in atmospheric CO_2 and temperature may have a positive effect on photochemical efficiency," and they say that their work "provides evidence that with air CO_2 enrichment a reallocation of resources favoring light capture may occur."

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[32] http://www.co2science.org/articles/V11/N53/B2.php.

[33] http://www.co2science.org/articles/V12/N15/B3.php.

[34] http://www.co2science.org/articles/V12/N50/B3.php.

Squeezing in one final study on wheat, Xiao *et al.* (2010)[35] introduce their contribution to the subject by noting that "the impact of future climate change on crop production has been widely predicted by *modeling* the interaction between crops and climate change," adding that it is currently believed that "overall crop yields will decrease by 5-10% in China by 2030 as a result of climatic changes, and that the yields of wheat, rice and maize will be greatly reduced." However, they report that "the direct fertilization effect of rising CO_2 will offset these losses," citing Ewert *et al*. (2002) and Long *et al*. (2006). In addition, they report that few real-world *observations* of the impacts of climate change on crop production have been reported; and they thus decided to address this deficiency as it pertains to an important part of China.

> *As the air's CO_2 content continues to rise, agricultural crops will likely exhibit enhanced rates of photosynthesis and biomass production that will not be diminished by any global warming that might occur concurrently.*
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> *In fact, if the ambient air temperature rises, the growth-promoting effects of atmospheric CO_2 enrichment will likely rise right along with it, becoming more and more robust.*

The seven scientists conducted two sets of field experiments to evaluate the effects of different degrees of warming on the productivity of winter wheat from 2006 to 2008 in the semiarid northwestern part of China: one set at the Tongwei County experiment station located at the foot of Lulu Mountain (35°13'N, 105°14'E) at an altitude of 1798 meters above sea level, and another set at the mountain's summit at an altitude of 2351 meters. At each of these locations, they established four different air temperature treatments (ambient and ambient plus 0.6, 1.4 and 2.2°C), which they created by placing electric heating wires on the surface of the soil between the rows of wheat, which induced the 0.6-2.2°C air temperature increases they measured at a height of 20 cm above the tops of the wheat canopies. This effort revealed that this increase in

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[35] http://www.co2science.org/articles/V13/N45/B3.php.

temperature "will lead to a significant change in the growth stages and water use of winter wheat," such that "crop yields at both high and low altitudes will likely increase," by 2.6% at low altitudes and 6.0% at high altitudes. And it can thus be appreciated that even *without the benefits* of the *aerial fertilization effect* and the *anti-transpiration effect* of the ongoing rise in the air's CO_2 content, just the increase in temperature that is predicted by climate models for the year 2050, if it ever comes to pass, will likely lead to *increases* in winter wheat production in the northwestern part of China, and not the *decreases* that some modeling studies have long predicted.

This summary of crop growth responses to atmospheric CO_2 enrichment within the context of a possible concomitant warming of the world, concludes with the study of Yoon *et al*. (2009)[36], who grew well watered and fertilized cotton plants from seed to maturity -- one plant to each container of washed sand, with spacing between plants similar to the plant spacing found in typical cotton fields -- within the Georgia Envirotron (located at the University of Georgia Griffin Campus), where the containers with their plants were placed within chambers maintained at all combinations of two day/night air temperatures regimes (25/15°C and 35/25°C) and three atmospheric CO_2 concentrations (400, 600 and 800 ppm), during which time, as well as at the end of the experiment, a number of plant characteristics were measured. And as a result of this study, they found that at the *lower* of the two air temperature regimes, "final boll weight at harvest was 1.59 times (at 600 ppm) and 6.3 times (at 800 ppm) higher compared to ambient CO_2," while noting that *further* increasing the temperature tremendously increased this difference, as "the final boll weight was 34.1 times (at 600 ppm) and 23.3 times (at 800 ppm) higher compared to ambient CO_2." In addition, they state that "the response of final lint yield to CO_2 was more or less similar to the response of boll weight."

In summation, a significant body of scientific literature continues to suggest that as the air's CO_2 content continues to rise, agricultural crops will likely exhibit enhanced rates of photosynthesis and biomass production that will not be diminished by any global warming that might occur concurrently. In fact, if the ambient air temperature rises, the growth-promoting effects of atmospheric CO_2 enrichment will likely rise right along with it, becoming more and more robust in agreement with the experimental observations reviewed by Idso and Idso (1994). Thus, the biosphere's ability to continue producing the food and fiber needed to feed and clothe the increasing population of humanity looks good indeed ... as long, that is, as the CO_2 content of the air continues its 350-year habit of rising hand-in-hand with the population of the planet (see our Editorial of 29 August 2001[37]).

Yet even beyond this *natural* phenomenon, Meerburg *et al*. (2009)[38] describe how crop yields will continue to increase in years to come because of "the development and adoption of new technologies and improved farm management," citing in this regard, the results of Ewert *et al*. (2005), which indicate that continuing advances in technology have historically been the most important drivers of productivity change, even outweighing the negative effects of detrimental

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[36] http://www.co2science.org/articles/V12/N51/B3.php.

[37] http://www.co2science.org/articles/V4/N35/EDIT.php.

[38] http://www.co2science.org/articles/V13/N16/EDIT.php.

climate change. And in further illustration of this phenomenon, they report that between 1961 and 2007, "average US corn yields increased by 240%, from 3.9 tons per hectare per year to 9.4 tons per hectare per year," citing the FAO (2009), while noting that some researchers have predicted that "advances in agronomics, breeding, and biotechnology will lead to an average corn yield in the US of just over 20 tons per hectare per year in 2030," citing Duvick (2005).

Meerburg *et al*. also make note of the fact that farmers in Brazil successfully increased the productivity of soybeans, maize, and cotton during the last decade, despite the fact that the cumulative number of days of exposure to temperatures above the three crops' optimum values "is far greater than in the US." In the Brazilian state of Mato Grosso, for example, they say that "maximum average day temperature exceeds 35°C for 118 days per year, of which 75 days are in the average soybean-growing season." Nevertheless, they report that in 2008 average production of soybeans was about 3.1 tons per hectare per year in Mexico, while the average yield in the US was 2.8 tons per hectare per year. Similarly, they note that the mean cotton yield in Brazil in 2006/2007 was 1.4 tons per hectare per year, while in the US it was only 0.9 tons per hectare per year.

The seven scientists thus conclude that "temperatures higher than currently experienced in the US do not necessarily need to coincide with lower crop yields and that already existing technology and future advances (new varieties, optimized farm management, biotechnology, etc.) can overrule the negative effect of increasing temperatures on yield," as has in fact been observed to be the case in the historical crop yield data of the United States.

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