WATER USE EFFICIENCY OF AGRICULTURAL SPECIES

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In the study of Serraj *et al.* (1999)[1], soybeans grown at 700 ppm CO_2 displayed 10 to 25% reductions in total water loss while simultaneously exhibiting dry weight increases of as much as 33%. Thus, elevated CO_2 significantly increased the water-use efficiencies of the studied plants. Likewise, Garcia *et al.* (1998)[2] determined that spring wheat grown at 550 ppm CO_2 exhibited a water-use efficiency that was about one-third greater than that exhibited by plants grown at 370 ppm CO_2. Similarly, Hakala *et al.* (1999)[3] reported that twice-ambient CO_2 concentrations increased the water-use efficiency of spring wheat by 70 to 100%, depending on experimental air temperature. In addition, Hunsaker *et al.* (2000)[4] reported CO_2-induced increases in water-use efficiency for field-grown wheat that were 20 and 10% higher than those displayed by ambiently-grown wheat subjected to high and low soil nitrogen regimes, respectively. Also, pea plants grown for two months in growth chambers maintained at atmospheric CO_2 concentrations of 700 ppm displayed an average water-use efficiency that was 27% greater than that exhibited by ambiently-grown control plants (Gavito *et al.*, 2000[5]).

In some cases, the water-use efficiency increases caused by atmospheric CO_2 enrichment are spectacularly high. De Luis *et al.* (1999)[6], for example, demonstrated that alfalfa plants subjected to atmospheric CO_2 concentrations of 700 ppm had water-use efficiencies that were 2.6 and 4.1 times greater than those displayed by control plants growing at 400 ppm CO_2 under water-stressed and well-watered conditions, respectively. Also, when grown at an atmospheric CO_2 concentration of 700 ppm, a 2.7-fold increase in water-use efficiency was reported by Malmstrom and Field (1997)[7] for oats infected with the barley yellow dwarf virus.

In addition to enhancing the water-use efficiencies of agricultural C3 crops, as reported in the preceding paragraphs, elevated CO_2 also enhances the water-use efficiencies of crops possessing alternate carbon fixation pathways. Maroco *et al.* (1999)[8], for example, demonstrated that maize - a C4 crop - grown for 30 days at an atmospheric CO_2 concentration of 1100 ppm exhibited an intrinsic water-use efficiency that was 225% higher than that of plants grown at 350 ppm CO_2. In addition, Conley *et al.* (2001)[9] reported that a 200-ppm increase in the air's CO_2 content boosted the water-use efficiency of field-grown sorghum by 9 and 19% under well-watered and water-stressed conditions, respectively. Also, Zhu *et al.*

1 http://www.co2science.org/articles/V2/N16/B2.php.
2 http://www.co2science.org/articles/V2/N12/B2.php.
3 http://www.co2science.org/articles/V4/N13/B2.php.
4 http://www.co2science.org/articles/V3/N23/B2.php.
5 http://www.co2science.org/articles/V4/N22/B1.php.
6 http://www.co2science.org/articles/V3/N10/B5.php.
7 http://www.co2science.org/articles/V2/N16/B1.php.
8 http://www.co2science.org/articles/V3/N11/B2.php.
9 http://www.co2science.org/articles/V4/N42/B2.php.

(1999)[10] reported that pineapple - a CAM plant - grown at 700 ppm CO_2 exhibited water-use efficiencies that were always significantly greater than those displayed by control plants grown at 350 ppm CO_2 over a range of growth temperatures.

Going into a little bit more detail, Olivo *et al.* (2002)[11] grew two potato species (*Solanum curtilobum* cv. Ugro Shiri, from high altitude, and *S. tuberosum* cv. Baronesa, from low altitude) in pots they placed within open-top chambers maintained at atmospheric CO_2 concentrations of 350 and 700 ppm for 30 days following the onset of reproductive growth, in order to study the effects of elevated CO_2 on gas exchange and biomass production in these two species, in the first-ever study of the CO_2 responsiveness of the high-altitude-adapted *Solanum curtilobum*, which is economically important in the highlands of the South American Andes. This work revealed that the elevated CO_2 treatment increased rates of net photosynthesis by 56 and 53% in the high- and low-altitude potato species, respectively, while reducing their stomatal conductances by 55 and 59%, thereby increasing their water-use efficiencies by 90 and 80%, respectively, while also increasing tuber dry mass production by 85 and 40% in the high- and low-altitude potato species, respectively.

Working concurrently, Dong-Xiu *et al.* (2002)[12] grew spring wheat (*Triticum aestivum* L. cv. Gaoyuan 602) in open-top chambers that they maintained at atmospheric CO_2 concentrations of 350 and 700 ppm and three levels of soil moisture (40, 60 and 80% of field capacity) in order to study the interactive effects of these environmental variables on the productivity and growth of this particular variety of wheat. And what they learned was that the elevated CO_2 treatment increased rates of net photosynthesis by 48, 120 and 97% at low, medium and high soil water capacities, respectively, while it reduced rates of transpiration by 56, 53 and 63% in the same order, with the end result that these changes led to CO_2-induced

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10 http://www.co2science.org/articles/V2/N21/B4.php.
11 http://www.co2science.org/articles/V6/N1/B1.php.
12 http://www.co2science.org/articles/V6/N5/B3.php.

increases in plant water-use efficiency of approximately 25, 15 and 30% under low, medium and high soil moisture conditions, respectively.

One year later, Agrawal and Deepak (2003)[13] grew two other cultivars of wheat (*Triticum aestivum* L. cv. Malviya 234 and HP1209) in open-top chambers maintained at atmospheric CO_2 concentrations of 350 and 600 ppm alone and in combination with 60 ppb of sulfur dioxide (SO_2), in order to study the interactive effects of elevated CO_2 and this major air pollutant on the growth and yield of this important crop. And in doing so, they found that exposure to elevated CO_2 significantly increased photosynthetic rates by 58 and 48% in M234 and HP1209, respectively, while fumigation with elevated SO_2 did not significantly impact rates of photosynthesis in either cultivar. However, plants grown in the *combined* treatment of elevated CO_2 and elevated SO_2 displayed photosynthetic rates that were significantly less-enhanced to values of 42 and 38% greater than those measured in control plants for M234 and HP1209, respectively.

Of more significance to the topic of this review, however, plants grown in elevated CO_2 also displayed an approximate 20% reduction in stomatal conductance, while those grown in elevated SO_2 exhibited an average increase of 15%. But when exposed simultaneously to *both* gases, the plants displayed an average 11% reduction in stomatal conductance, which resulted in a 32% *increase* in water-use efficiency, whereas plants exposed to elevated SO_2 alone displayed an average *decrease* in water-use efficiency of 16%.

Working with a very different type of crop, Kyei-Boahen *et al*. (2003)[14] grew well watered and fertilized plants of four carrot (*Daucus carota* var. sativus L.) cultivars (Cascade, Caro Choice, Oranza and Red Core Chantenay) from seed in 15-cm-diameter plastic pots in a controlled environment facility for 30 days past emergence, whereupon leaf net photosynthetic rate (PN), stomatal conductance (Gs), and transpiration rate (E) were measured at 100-ppm intervals of short-term (5-minute) atmospheric CO_2 enrichment yielding absolute CO_2 concentrations (Ca) stretching from 50 to 1050 ppm. And in doing so, the five researchers found that "an increase in Ca from 50 to 350 ppm produced a 100-fold increase in PN and the value increased by 43% when Ca was elevated from 350 to 650 ppm," but that "only [a] 7% increase in PN was observed when Ca was increased from 650 to 1050 ppm."

Secondly, they said that "increasing Ca from 50 to 350 ppm increased Gs to a maximum and thereafter Gs declined by 17% when Ca was increased to 650 ppm," while "a three-fold increase in Ca from 350 to 1050 ppm decreased Gs by 53%." Third, they reported that "E reached maximum values (0.9-1.1 mmol m^{-2} s^{-1}) at 350 ppm followed by a decline to 0.40-0.60 mmol m^{-2} s^{-1} when Ca was increased to 1050 ppm." And fourth, "water use efficiency increased linearly with Ca due to increases in PN in addition to the decline in E at high Ca," such that "increasing Ca from 350 to 650 ppm improved water use efficiency by 76%, whereas a three-fold increase in Ca from 350-1050 ppm resulted in a three-fold increase in water use efficiency," leading them to conclude that "future enrichment in the atmospheric CO_2 may lead to adjustments in PN and Gs, which could improve carrot productivity and water utilization."

13 http://www.co2science.org/articles/V6/N4/B1.php.
14 http://www.co2science.org/articles/V9/N4/B2.php.

Moving on another year to another crop, Triggs *et al*. (2004)[15] grew sorghum (*Sorghum bicolor* (L.) Moench, a C4 grain crop) for two full seasons in control CO_2 plots (about 370 ppm) and FACE plots (Control + 200 ppm) under both well-watered (Wet) and water-stressed (Dry, less than half the total water received by the Wet treatment via rainfall and irrigation) conditions near Maricopa, Arizona, USA, while assessing evapotranspiration (ET) on a continuous basis by means of micrometeorological measurements designed to allow the calculation of all of the other elements (net radiation, sensible heat flux, and soil surface heat flux) of the energy balance of the crop-soil interface with the atmosphere. Simultaneously, final grain yields, which were used to calculate sorghum water use efficiency (WUE), were obtained by Ottman *et al*. (2001), with the result that "in the Wet treatments," in the words of Triggs *et al*., "a reduction in ET of about 19%, combined with only a slight increase in total biomass (+4%), resulted in a 28% increase in WUE in elevated CO_2 conditions," while "in the Dry treatments, the relatively large increase in total biomass (+16% for both years) more than compensated for the approximate 5% increase in total ET, giving the FACE-Dry treatments an increase in WUE of 16% over both seasons." Based on these results, Triggs *et al*. concluded that "even if future climate change results in less water available for agriculture, higher atmospheric CO_2 concentrations will still benefit C4 crops," but stating that "in regions with ample precipitation or irrigation, C3 crops with higher growth responses may be preferable."

Working with the same crop in the same place in the same years with seven of the same scientists, Grant *et al*. (2004)[16] adjusted the crop growth and water relations model *ecosys* to represent sorghum (*Sorghum bicolor* (L.) Moench) and run for a period of two growing seasons (1 May 1998 to 31 Oct 1999) under both wet and dry irrigation schedules at two atmospheric CO_2 concentrations (approximately 368 and 561 ppm) using hourly meteorological data measured at a field south of Phoenix, Arizona, USA, after which the crop's simulated energy balances and water relations - verified by measurements of energy flux and water potential - were used to infer the effects of free-air atmospheric CO_2 enrichment on various plant parameters and processes.

This work revealed, in the words of the twelve researchers, that "model results, corroborated by field measurements, showed that elevated CO_2 raised canopy water potential and lowered latent heat fluxes under high irrigation [both of which responses are beneficial] and delayed water stress under low irrigation [which is also beneficial]," such that the elevated CO_2 "reduced transpiration and hence improved water status of sorghum [and] lowered the vulnerability of sorghum CO_2 fixation to soil or atmospheric water deficits, even when irrigation was high." Also, in applying their reality-tuned model to a scenario where the air's CO_2 content was 50% higher and air temperature was 3°C greater, they calculated that sorghum yields would *rise* by about 13%, and that "current high sorghum yields could be achieved with ~120 mm or ~20% less irrigation water if these rises in temperature and CO_2 were to occur." And, therefore, their real-world data and their analysis of those data indicated that rising atmospheric CO_2 concentrations, even in the face of rising air temperatures, should be good for both sorghum and the people who grow it, in terms of both the higher yields that can be produced under these conditions and the smaller amounts of water required to produce them.

[15] http://www.co2science.org/articles/V7/N40/B2.php.
[16] http://www.co2science.org/articles/V8/N10/B2.php.

One year later, Yoshimoto *et al*. (2005)[17] grew rice (*Oryza sativa* L. cv. Akita-Komachi) from hand-transplanting to harvest (May to September) under normal paddy culture near Shizukuishi, Iwate, Japan, within FACE rings maintained at either ambient or ambient + 200 ppm CO_2 for 24 hours per day. Over this period they measured a number of micrometeorological parameters and plant characteristics that enabled them to calculate both the amount of water lost directly from the paddy-water surface and that lost by plant transpiration, which together with the plant biomass data they obtained at harvest enabled them to calculate total growing-season crop water use efficiency. And this is what they learned.

As world population continues to grow, the increase in rice-crop water use efficiency provided by the concomitant increase in the atmosphere's CO_2 concentration should prove to be a great asset in helping to produce the extra food that will be needed to feed the planet's many newcomers, while it simultaneously spares some of the precious water that will be needed to slake their thirst.

Yoshimoto *et al*. determined that "elevated CO_2 reduced stomatal conductance by 13% in upper leaves and by 40% in lower leaves at the panicle initiation stage," but that the reduction declined thereafter. In addition, they observed that "stomata closed more in the elevated CO_2 plot as vapor pressure deficit increased," i.e., during drier conditions. In more common terms, and averaged over the entire growing season, the Japanese researchers determined that the total water used by the crop was 268.7 mm in the ambient CO_2 treatment and 246.7 mm in the elevated CO_2 treatment. And combining this CO_2-induced reduction in total evaporative water loss (8.2%) with the CO_2-induced increase in total plant biomass that was observed (9.1%) thus indicated that season-long crop water use efficiency rose by about 19% in response to the approximate 54% increase in atmospheric CO_2 concentration provided by the FACE apparatus. Thus, as world population continues to grow, the increase in rice-crop water use efficiency provided by the concomitant increase in the atmosphere's CO_2 concentration should prove to be a great asset in helping to produce the extra food that will be needed to feed the planet's many newcomers, while it simultaneously spares some of the precious water that will be needed to slake their thirst.

Taking another step forward in time, Kim *et al*. (2006)[18] grew well-watered and fertilized maize (*Zea mays* L. cv. Pioneer 3733) plants from seed to developmental stage R3 (milky ripe stage, 70 days after planting) in sunlit soil-plant-atmosphere research (SPAR) chambers maintained at either 370 (ambient) or 750 (elevated) ppm CO_2 concentrations, while periodically measuring a number of plant physiological parameters. And in doing so, they discovered that at saturating

[17] http://www.co2science.org/articles/V9/N19/B3.php.
[18] http://www.co2science.org/articles/V9/N27/B3.php.

photosynthetically-active radiation (PAR, 2000 µmol m^{-2} s^{-1}), rates of leaf net photosynthesis in the elevated CO_2 chambers were only 4% greater than those in the ambient CO_2 chambers. However, upper-canopy leaves grown at elevated CO_2 exhibited reductions in excess of 50% in both leaf stomatal conductance and transpiration; and as a result of these changes, instantaneous leaf water use efficiency was *more than doubled* in the high-CO_2 treatment. Because of shading within the canopy, however, and because the difference in stomatal conductance between ambient and elevated CO_2 declines as PAR drops, the CO_2-induced reduction in *canopy* evapotranspiration was only a little over 20%, but which is still very good.

In commenting further on their findings, the seven scientists wrote that "although several previous studies reported that CO_2 enrichment enhanced the growth of maize under well watered and fertilized conditions," in their study "there was little evidence of increased biomass accumulation." On the other hand, they said that the sizable CO_2-induced reduction in canopy evapotranspiration "is comparable to findings from other studies of C4 plants." And although the maize plants of their study were somewhat anomalous in their failure to significantly boost their growth in response to atmospheric CO_2 enrichment, their more characteristic transpiration response enabled them to produce their slightly enhanced biomass with a considerably smaller consumptive use of water than that of the plants growing in ambient air.

Two years later, Cunniff *et al*. (2008)[19] noted that "early agriculture was characterized by sets of primary domesticates or 'founder crops' that were adopted in several independent centers of origin," all at about the same time; and they speculated and that "this synchronicity suggests the involvement of a global trigger." Further noting that Sage (1995) saw a causal link between this development and the rise in atmospheric CO_2 concentration that followed deglaciation (a jump from about 180 to 270 ppm), they hypothesized that the *aerial fertilization effect* caused by the rise in CO_2 combined with its *transpiration-reducing effect* led to a large increase in the water use efficiencies of the world's major C4 founder crops, and that this development was the *global trigger* that launched the agricultural enterprise. Consequently, as a test of this hypothesis, they designed "a controlled environment experiment using five modern day representatives of wild C4 crop progenitors, all 'founder crops' from a variety of independent centers."

The five crops employed in their study were *Setaria viridis* (L.) P. Beauv, *Panicum miliaceum* var. *ruderale* (Kitag.), *Pennisetum violaceum* (Lam.) Rich., *Sorghum arundinaceum* (Desv.), and *Zea mays* subsp. *parviglumis* H.H. Iltis & Doebley. Each was grown individually in 6-cm x 6-cm x 6-cm pots filled with a 1:1 mix of washed sand and vermiculite for 40-50 days within growth chambers maintained at atmospheric CO_2 concentrations of 180, 280 and 380 ppm, characteristic of glacial, post-glacial and modern times, respectively. And this work revealed that the "increase in $CO_2$from glacial to postglacial levels [180 to 280 ppm] caused a significant gain in vegetative biomass of up to 40%," together with "a reduction in the transpiration rate via decreases in stomatal conductance of ~35%," which led to "a 70% increase in water use efficiency, and a much greater productivity potential in water-limited conditions."

[19] http://www.co2science.org/articles/V11/N22/EDIT.php.

In discussing their results, the five researchers concluded that "these key physiological changes could have greatly enhanced the productivity of wild crop progenitors after deglaciation ... improving the productivity and survival of these wild C4 crop progenitors in early agricultural systems." And in this regard, they rightly noted that "the lowered water requirements of C4 crop progenitors under increased CO_2 would have been particularly beneficial in the arid climatic regions where these plants were domesticated."

For comparative purposes, the researchers had also included one C3 species in their study - *Hordeum spontaneum* K. Koch - and they reported that it "showed a near-doubling in biomass compared with [the] 40% increase in the C4 species under growth treatments equivalent to the postglacial CO_2 rise."

In light of these several findings, it can be appreciated that the civilizations of the past, which could not have existed without agriculture, were largely made possible by the increase in the air's CO_2 content that accompanied deglaciation, and that the peoples of the earth today are likewise indebted to this phenomenon, as well as to the *additional* 100 ppm of CO_2 the atmosphere has subsequently acquired. And with an eye to the *future*, one could also logically conclude that the *ongoing* rise in the air's CO_2 content will similarly play a pivotal role in enabling us to grow the food we will need to sustain our still-expanding global population in the year 2050 without usurping all of the planet's remaining freshwater resources and much of its untapped arable land, which latter actions would likely lead to our driving most of what yet remains of "wild nature" to extinction. Clearly, rising atmospheric CO_2 concentrations have served both humanity and the rest of the biosphere well in the past; and they will do the same in the future, unless we succeed in dramatically curtailing anthropogenic CO_2 emissions for clearly invalid reasons.

Against this backdrop, Morison *et al*. (2007)[20] reported in the Biological Sciences section of *the Philosophical Transactions of the Royal Society* that (1) "agriculture accounts for 80-90% of all freshwater used by humans," that (2) "most of that is in crop production," and that (3) "in many areas, this water use is unsustainable." They also noted that (4) "farmers in many countries are now faced with legislative restrictions on use of water," indicating that the Chinese government has (5) "set a target of a reduction of 20% in water use in agriculture by the year 2020," but noting that (6) "if food security for the region is not to be threatened, this must be achieved without a loss in production." So how is this global food and water crisis to be met and overcome?

In their many pages of discussion of the subject, the four UK researchers examined underlying relationships that connect crop carbon uptake, growth and water loss, noting that "much effort is being made to reduce water use by crops and produce 'more crop per drop'." Some of the topics they examined in the course of this discussion were designed to alter various crop characteristics that might possibly increase their *water use efficiency*, such as by genetic engineering, while others dealt with crop management strategies, such as how and when to apply irrigation water.

[20] http://www.co2science.org/articles/V11/N30/EDIT.php.

Clearly, all of these approaches to getting "more crop per drop" out of our agricultural activities should be pursued. But what if we had a magical substance we could release to the air that would *automatically* lead to greater crop yields? And what if it produced those greater crop yields while using *less water*? And what if the many processes that put this super substance into the air were incredibly useful in their own right ... or even *essential*, both to our individual well-being and to the security of nations?

Why, everyone would be *clamoring* for its release to the air, right? Wrong! Al Gore, for one, is adamantly against it. So is James Hansen, as are **a host of climate alarmists**, all of whom feel that the water-use-efficiency-enhancing *carbon dioxide* that is released to the air by the burning of coal, gas and oil - which is no different from the CO_2 that every single one of us emits to the atmosphere with every breath we exhale - should not only *not* be allowed to continue to rise, but should be stopped in its tracks, all because tenuous speculations spawned by woefully inadequate computer-run climate models suggest that releasing more CO_2 into the air will ultimately lead to catastrophic global warming.

A tiny hint of what we will experience if Al Gore and his followers have their way with the world is already upon us.

It is the soaring price of basic foodstuffs caused by farmers growing *biofuels* in place of *food crops*, as well as by the increased price of oil and gas that is needed to produce and move those foods - and move us as well - which is caused by a reduction in gas and oil availability that is *miniscule* compared to what the world's climate alarmists would force us to go without.

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Truly, insanity is upon us, as real catastrophes lie at the doorstep, and as they are actually made *worse* by those who would fight imaginary ones. Indeed, the situation is as described by an astute observer of some three-plus centuries ago: *The World ran Mad, and each distempered Brain, Did Strange and different Frenzies entertain*. (Mrs. Aphra Behn. 1688. A Poem to Sir Roger L'Estrange on his third Part of the History of the Times, Relating to the Death of Sir Edmund Bury-Godfrey.)

Getting back to basics, Fleisher *et al.* (2008)[21] grew potato (*Solanum tuberosum* cv. Kennebec) plants from "seed tubers" in soil-plant-atmosphere research (SPAR) chambers maintained at daytime atmospheric CO_2 concentrations of either 370 or 740 ppm in a 75/25 mix of coarse sand and vermiculite at well-watered and progressively water-stressed conditions until they were harvested when canopy photosynthetic rates dropped to below 50% of their seasonal peak values, before and after which they measured a variety of plant physical properties and physiological parameters. This work revealed, in their words, that "elevated CO_2 plants maintained a higher daily net assimilation rate throughout most of the growing season," and that "at moderate and more severe levels of water stress, CO_2 enrichment appeared to encourage shifting of assimilate into tubers as opposed to additional vegetative growth." Hence, they indicated that "total biomass, yield and water use efficiency increased under elevated CO_2, with the largest percent increases occurring at irrigations that induced the most water stress," and that "water use efficiency was nearly doubled under enriched CO_2 when expressed on a tuber fresh weight basis." Overall, as the three researchers thus stated, "the results indicate that increases in potato gas exchange, dry matter production and yield with elevated CO_2 are consistent at various levels of water stress as compared with ambient CO_2." And, of course, they provide what we so desperately need in today's world, and what we will need even more as the world's population continues to grow: significantly enhanced food production per unit of water used.

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Contemporaneously, Ceusters *et al.* (2008)[22] measured gas exchange and diel metabolite (e.g. malate, soluble sugars, starch) dynamics in the youngest fully-expanded leaves of well watered and fertilized CAM bromeliad *Aechmea* 'Maya' plants - a spineless cultivar resulting from a cross between *A. tessmannii* and *A. fasciata* - after exposure of half of the original seven-month-old plants to 700 ppm CO_2 for five more months in one of two controlled-environment compartments of a greenhouse, the other of which compartments was maintained at the original atmospheric CO_2 concentration of 380 ppm. As a result of this procedure, they reported "there was a 60% increase in 24-hour carbon gain under elevated CO_2 due to a stimulation of daytime C3 and C4 carboxylation," and they noted that water use efficiency was *two-fold higher* during the night under elevated CO_2 and *three- to four-fold higher* during the day.

In discussing their findings, the six scientists stated that the great increase they observed in plant water use efficiency "could be a major physiological advantage to growth under elevated CO_2 in this CAM bromeliad," and they felt that this fact further suggested that CAM species should "be considered in an agronomic context as potential sources of biomass production on arid, marginal lands."

21 http://www.co2science.org/articles/V11/N30/B3.php.
22 http://www.co2science.org/articles/V11/N40/B3.php.

Moving ahead another year, Sanchez-Guerrero (2009)[23] grew cucumber plants from seed to maturity in standard perlite bags within climate-controlled greenhouses at Almeria, Spain, during which time the plants were "fertigated" (fertilized and irrigated) via a nutrient-solution drip system that was regulated to maintain the same electrical conductivity in the leached solution draining from the perlite bags of each greenhouse, one of which greenhouses was also supplied with extra CO_2 during daylight hours (through outlets below each plant) when the greenhouse side vents were closed or when the roof vent was less than 20% of full opening, resulting in a mean daytime concentration of about 450 ppm around the plants, which was approximately 100 ppm more than the CO_2 concentration around the plants in the other greenhouse.

As a result of these manipulations, the total season-long yield of the CO_2-enriched cucumber crop was increased by 19% by the extra 100 ppm of CO_2 supplied to it during daylight hours, while the overall water use efficiency of the CO_2-enriched plants, based on the amount of water supplied to them, was about 40% higher. And in light of these findings, the five Spanish scientists concluded their report by stating that their study "confirms the potential interest of using moderate CO_2 enrichment strategies in greenhouses located in areas such as the Mediterranean basin, where the agricultural sector is facing scarce and declining water resources, and needs to drastically reduce the contamination due to fertilizer emission to ensure the sustainability of greenhouse production." And, of course, it demonstrates the significant benefits that may come to *open-field* agriculture, as the CO_2 content of earth's atmosphere continues to rise.

Moving ahead another year, Shimono *et al*. (2010)[24] introduced their study by writing that "by 2050, the world's population will have increased by about 37%, from the current level of 6.7 billion to an estimated 9.2 billion (UN, 2009), with a corresponding increase in global food demand." They also stated that "about 0.6 billion Mg of rice is produced annually from an area of 1.5 million km^2, making rice one of the most important crops for supporting human life," *especially*, as noted by Pritchard and Amthor (2005), since it supplies the planet's human population with an estimated 20% of their energy needs (on a caloric basis) and 14% of their protein requirements (on a weight basis).

Within this context, the six scientists further noted that "rice production depends heavily on water availability," stating that "irrigated lowlands account for 55% of the total area of harvested rice and typically produce two to three times the crop yield of rice grown under non-irrigated conditions (IRRI, 2002)." And because mankind's demand for ever greater quantities of water will continue to rise, due to our need to adequately feed our growing numbers, they concluded that "efficient use of water will thus be essential for future rice production."

In an attempt to determine how the agricultural enterprise may be impacted in this regard by the ongoing rise in the air's CO_2 content, the Japanese researchers conducted a two-year free-air CO_2 enrichment or FACE study in fields at Shizukuishi, Iwate (Japan) to learn how elevated CO_2 may reduce crop water use via its impact on the leaf stomatal conductances (gs) of three

[23] http://www.co2science.org/articles/V12/N19/B3.php.
[24] http://www.co2science.org/articles/V13/N20/B2.php.

varieties of rice (Oryza sativa L.): early-maturing Kirara397, intermediate-maturing Akitakomachi, and latest-maturing Hitomebore. And what did they find?

In response to the 53% increase in daytime atmospheric CO_2 concentration employed in their experiments, Shimono *et al*. determined that "the reduction in g_s due to elevated CO_2 was similar across measurements, averaging around 20% in the morning, 24% around noon and 23% in the afternoon across all growth stages." And they added that "there was no significant CO_2 x cultivar interaction." Therefore, with the concomitant increase in grain yield that also results from atmospheric CO_2 enrichment, it should be apparent to all that a continuation of the historical and still-ongoing rise in the air's CO_2 content will play a major role in enabling us to meet our food needs at the mid-point of the current century, without having to lay claim to all of the planet's remaining fresh water resources and much of its undeveloped land and thereby driving many of the species with which we share the terrestrial biosphere to extinction for lack of land and water to meet *their* needs.

Expanding upon this thesis one year later, Fereres *et al*. (2011)[25] wrote that "forecasts on population growth and economic development indicate that there will be substantial increases in food demand for the forthcoming decades," and as a result, they noted that "food security has not only moved to the forefront of agricultural research, but is now perceived as an important topic for more fundamental research," citing numerous items published in *Nature* (2010) and *Science* (2010). However, they went on to add that "the question of whether there will be enough food in the future should immediately be followed by the question: Will there be enough water to produce sufficient food?" And they stated, in this regard, that "given the competition for water faced by the agricultural sector, and the uncertainties associated with climate change, improving the efficiency of water use in both rain-fed and irrigated systems is the main avenue to face the challenge."

But what about developing *new* sources of water, or *transferring* water from one place to another, in order to increase food production where water shortages exist? The three Spanish researchers said that such measures have "limited potential in some areas," but they indicated that they are "no longer possible in other world regions." They *did* note, however, that many agriculturalists have significantly increased crop water use efficiency "by reducing water losses (and some of the water consumed in evaporation from soil) through improved agronomy and engineering of irrigation systems." But they lamented the fact, as they put it, that "science has been much less successful so far in reducing the water consumed in transpiration." Fortunately for us, however, mankind en masse *has* had a measurable amount of success in this area, albeit unintentionally and unknowingly.

What we are talking about here is the extraction of fossil fuels from the crust of the earth, which has provided so much coal, gas and oil to fuel the engines of industry that the carbon dioxide given off to the air in the combustion process has raised the atmosphere's CO_2 concentration by some 40% since the inception of the Industrial Revolution. And that phenomenon has had two major effects on man's production of food. It has significantly increased the leaf photosynthetic rates of our crops, while it has significantly reduced their

[25] http://www.co2science.org/articles/V14/N48/EDIT.php.

transpiration rates, which has led to significant increases in leaf *water use efficiency*, or the amount of biomass produced per unit of water transpired in the process.

In spite of these well-documented facts, to quote Morgan *et al*. (2011), "many believe that CO_2-induced reductions in transpiration at the leaf level will be largely offset at the canopy level by increases in leaf area," and that "global warming is predicted to induce desiccation in many world regions through increases in evaporative demand." But in a real-world test of these two potentially negative phenomena in a **Prairie Heating and CO_2 Enrichment** (PHACE) experiment conducted in a native mixed-grass prairie in Wyoming (USA), they found that *the positive effects of elevated CO_2 prevailed*, indicating, in their words, that "in a warmer, CO_2-enriched world, both soil water content and productivity in semi-arid grasslands may be higher than previously expected," providing what Baldocchi (2011) described as "one of the first and best views of how a mixed-grass ecosystem growing in a semi-arid climate will respond to future CO_2 and climatic conditions," while a full decade earlier, in fact, Robock *et al*. (2000) had already developed a *massive* collection of soil moisture data from more than 600 stations spread across a variety of climatic regimes, including the former Soviet Union, China, Mongolia, India and the United States; and in analyzing those observations, they had determined that "in contrast to predictions of summer desiccation with increasing temperatures, for the stations with the longest records, summer soil moisture in the top one meter has increased while temperatures have risen."

Everyone needs to realize that instead of being the "bane of the biosphere," as many make them out to be (think of Al Gore and James Hansen), mankind's CO_2 emissions may ultimately prove a godsend to humanity, as they just might make the difference between our being able to adequately feeding our expanding population in the very near future or our failing to do so in a catastrophe of unimaginable proportions.

Nevertheless, prudence suggests that we still pursue all avenues available to us to further increase both *individual* ***plant*** water use efficiency and *whole-field* crop water use efficiency. And everyone needs to realize that instead of being the "bane of the biosphere," as many make them out to be (think of Al Gore and James Hansen), mankind's CO_2 emissions may ultimately prove a *godsend* to humanity, as they just might make the difference between our being able to adequately feeding our expanding population in the very near future or our failing to do so in a catastrophe of unimaginable proportions.

About this same time in one final study, Allen *et al*. (2011)[26] wrote that "plants of the C4 photosynthetic pathway have a CO_2-concentrating mechanism that overcomes limitations of low atmospheric CO_2" and which thereby provides them with "a near-saturating photosynthetic capability at current atmospheric CO_2." And in this circumstance, as they continued, "a rise in atmospheric CO_2 will theoretically have a limited direct impact on C4 photosynthesis." Nevertheless, they made a point of noting that "a number of C4 crop plants express a positive response to elevated growth CO_2, although to a smaller extent compared to C3 plants," citing the analyses of Kimball (1993) and Poorter *et al*. (1996).

Having their curiosity thus piqued, the four researchers planted seeds of maize (*Zea mays* L. cv. Saturn Yellow) and grain sorghum (*Sorghum bicolor* L. cv. DeKalb 28E) in pots and grew them for 39 days in sunlit controlled-environment chambers at 360 and 720 ppm CO_2 concentrations, while throughout this period canopy net photosynthesis and evapotranspiration were measured and summarized daily from 08:00 to 17:00 hours, with irrigation being withheld from matched pairs of treatments starting 26 days after sowing, and with biomass determinations being made at 34 and 39 days after sowing for maize and grain sorghum, respectively.

In following this protocol, the four researchers found that for both maize and grain sorghum, there was a "maintenance of relatively high canopy photosynthetic rates in the face of decreased transpiration rates [that] resulted in enhanced water use efficiency when these plants were grown at elevated CO_2 of 720 ppm, but not at 360 ppm." And as a result, they demonstrated that "both plants maintained growth better at double-ambient CO_2 than their counterparts at ambient CO_2 in the presence of drought," such that reductions in total above-ground biomass due to drought were 42% for maize and 36% for sorghum at ambient CO_2, but only 18% for maize and 14% for sorghum at double-ambient CO_2. And so it was that in discussing their several findings, Allen *et al*. wrote in their paper's last paragraph that they "agree with Leakey (2009) that drought stress in C4 crop plants can be ameliorated at elevated CO_2 as a result of lower stomatal conductance and sustained intercellular CO_2."

In summary, it is clear that as the CO_2 content of the air continues to rise, nearly all of earth's agricultural plants will respond favorably by exhibiting increases in water-use efficiency. It is also thus likely that food and fiber production will increase on a worldwide basis, even in areas where productivity is severely restricted due to limited availability of soil moisture. Therefore, one can expect global agricultural productivity to rise in tandem with future increases in the atmosphere's CO_2 concentration, *unless wrong-headed climate alarmists have their way and convince the nations of the world to attempt to drastically reduce their countries' anthropogenic CO_2 emissions*.

REFERENCES

Agrawal, M. and Deepak, S.S. 2003. Physiological and biochemical responses of two cultivars of wheat to elevated levels of CO_2 and SO_2, singly and in combination. *Environmental Pollution* **121**: 189-197.

[26] http://www.co2science.org/articles/V15/N8/B2.php.

Allen Jr., L.H., Kakani, V.G., Vu, J.C.V. and Boote, K.J. 2011. Elevated CO_2 increases water use efficiency by sustaining photosynthesis of water-limited maize and sorghum. *Journal of Plant Physiology* **168**: 1909-1918.

Baldocchi, D. 2011. The grass response. *Nature* **476**: 160-161.

Ceusters, J., Borland, A.M., Londers, E., Verdoodt, V., Godts, C. and de Proft, M.P. 2008. Diel shifts in carboxylation pathway and metabolite dynamics in the CAM Bromeliad *Aechmea* 'Maya' in response to elevated CO_2. *Annals of Botany* **102**: 389-397.

Conley, M.M., Kimball, B.A., Brooks, T.J., Pinter Jr., P.J., Hunsaker, D.J., Wall, G.W., Adams, N.R., LaMorte, R.L., Matthias, A.D., Thompson, T.L., Leavitt, S.W., Ottman, M.J., Cousins, A.B. and Triggs, J.M. 2001. CO_2 enrichment increases water-use efficiency in sorghum. *New Phytologist* **151**: 407-412.

Cunniff, J., Osborne, C.P., Ripley, B.S., Charles, M. and Jones, G. 2008. Response of wild C4 crop progenitors to subambient CO_2 highlights a possible role in the origin of agriculture. *Global Change Biology* **14**: 576-587.

De Luis, J., Irigoyen, J.J. and Sanchez-Diaz, M. 1999. Elevated CO_2 enhances plant growth in droughted N_2-fixing alfalfa without improving water stress. *Physiologia Plantarum* **107**: 84-89.

Dong-Xiu, W., Gen-Xuan, W., Yong-Fei, B., Jian-Xiong, L. and Hong-Xu, R. 2002. Response of growth and water use efficiency of spring wheat to whole season CO_2 enrichment and drought. *Acta Botanica Sinica* **44**: 1477-1483.

Fereres, E., Orgaz, F. and Gonzalez-Dugo, V. 2011. Reflections on food security under water scarcity. *Journal of Experimental Botany* **62**: 4079-4086.

Fleisher, D.H., Timlin, D.J. and Reddy, V.R. 2008. Elevated carbon dioxide and water stress effects on potato canopy gas exchange, water use, and productivity. *Agricultural and Forest Meteorology* **148**: 1109-1122.

Garcia, R.L., Long, S.P., Wall, G.W., Osborne, C.P., Kimball, B.A., Nie, G.Y., Pinter Jr., P.J., LaMorte, R.L. and Wechsung, F. 1998. Photosynthesis and conductance of spring-wheat leaves: field response to continuous free-air atmospheric CO_2 enrichment. *Plant, Cell and Environment* **21**: 659-669.

Gavito, M.E., Curtis, P.S., Mikkelsen, T.N. and Jakobsen, I. 2000. Atmospheric CO_2 and mycorrhiza effects on biomass allocation and nutrient uptake of nodulated pea (*Pisum sativum* L.) plants. *Journal of Experimental Botany* **52**: 1931-1938.

Grant, R.F., Kimball, B.A., Wall, G.W., Triggs, J.M., Brooks, T.J., Pinter Jr., P.J., Conley, M.M., Ottman, M.J., Lamorte, R.L., Leavitt, S.W., Thompson, T.L. and Matthias, A.D. 2004. Modeling elevated carbon dioxide effects on water relations, water use, and growth of irrigated sorghum. *Agronomy Journal* **96**: 1693-1705.

Hakala, K. Helio, R., Tuhkanen, E. and Kaukoranta, T. 1999. Photosynthesis and Rubisco kinetics in spring wheat and meadow fescue under conditions of simulated climate change with elevated CO_2 and increased temperatures. *Agricultural and Food Science in Finland* **8**: 441-457.

Hunsaker, D.J., Kimball. B.A., Pinter, P.J., Jr., Wall, G.W., LaMorte, R.L., Adamsen, F.J., Leavitt, S.W., Thompson, T.L., Matthias, A.D. and Brooks, T.J. 2000. CO_2 enrichment and soil nitrogen effects on wheat evapotranspiration and water use efficiency. *Agricultural and Forest Meteorology* **104**: 85-105.

IRRI (International Rice Research Institute). 2002. *Rice Almanac: Source Book for the Most Important Economic Activity on Earth*. CABI Publishing, Oxnon, United Kingdom.

Kim, S.-H., Sicher, R.C., Bae, H., Gitz, D.C., Baker, J.T., Timlin, D.J. and Reddy, V.R. 2006. Canopy photosynthesis, evapotranspiration, leaf nitrogen, and transcription profiles of maize in response to CO_2 enrichment. *Global Change Biology* **12**: 588-600.

Kimball, B.A. 1993. Effects of elevated CO_2 and climate variables on plants. *Journal of Soil and Water Conservation* **48**: 9-14.

Kyei-Boahen, S., Astatkie, T., Lada, R., Gordon, R. and Caldwell, C. 2003. Gas exchange of carrot leaves in response to elevated CO_2 concentration. *Photosynthetica* **41**: 597-603.

Leakey, A.D.B. 2009. Rising atmospheric carbon dioxide concentration and the future of C4 crops for food and fuel. *Proceedings of the Royal Society B* **276**: 2333-2343.

Malmstrom, C.M. and Field, C.B. 1997. Virus-induced differences in the response of oat plants to elevated carbon dioxide. *Plant, Cell and Environment* **20**: 178-188.

Maroco, J.P., Edwards, G.E. and Ku, M.S.B. 1999. Photosynthetic acclimation of maize to growth under elevated levels of carbon dioxide. *Planta* **210**: 115-125.

Morgan, J.A., LeCain, D.R., Pendall, E., Blumenthal, D.M., Kimball, B.A., Carrillo, Y., Williams, D.G., Heisler-White, J., Dijkstra, F.A. and West, M. 2011. C4 grasses prosper as carbon dioxide eliminates desiccation in warmed semi-arid grassland. *Nature* **476**: 202-205.

Morison, J.I.L., Baker, N.R., Mullineaux, P.M. and Davies, W.J. 2007. Improving water use in crop production. *Philosophical Transactions of the Royal Society B* **363**: 639-658.

Nature. 2010. Can science fed the world? http://www.nature.com/news/specials/food/index.html

Olivo, N., Martinez, C.A. and Oliva, M.A. 2002. The photosynthetic response to elevated CO_2 in high altitude potato species (*Solanum curtilobum*). *Photosynthetica* **40**: 309-313.

Ottman, M.J., Kimball, B.A., Pinter Jr., P.J., Wall, G.W., Vanderlip, R.L., Leavitt, S.W., LaMorte, R.L., Matthias, A.D. and Brooks, T.J. 2001. Elevated CO_2 increases sorghum biomass under drought conditions. *New Phytologist* **150**: 261-273.

Poorter, H., Roumet, C. and Campbell, B.D. 1996. Interspecific variation in the growth response of plants to elevated CO_2: a search for functional types. In: Korner, C. and Bazzaz, F.A. (Eds.). *Carbon Dioxide, Populations, and Communities*. Academic Press, New York, New York, USA, pl 375-412.

Pritchard, S.G. and Amthor, J.S. 2005. *Crops and Environmental Change*. Food Production Press, New York, New York, USA.

Robock, A., Vinnikov, K.Y., Srinivasan, G., Entin, J.K., Hollinger, S.E., Speranskaya, N.A., Liu, S. and Namkhai, A. 2000. The global soil moisture data bank. *Bulletin of the American Meteorological Society* **81**: 1281-1299.

Sage, R.F. 1995. Was low atmospheric CO_2 during the Pleistocene a limiting factor for the origin of agriculture? *Global Change Biology* **1**: 93-106.

Sanchez-Guerrero, M.C., Lorenzo, P., Medrano, E., Baille, A. and Castilla, N. 2009. Effects of EC-based irrigation scheduling and CO_2 enrichment on water use efficiency of a greenhouse cucumber crop. *Agricultural Water Management* **96**: 429-436.

Science. 2010. Food security. http://www.sciencemag.org/site/special/foodsecurity/

Serraj, R., Allen, L.H., Jr., Sinclair, T.R. 1999. Soybean leaf growth and gas exchange response to drought under carbon dioxide enrichment. *Global Change Biology* **5**: 283-291.

Shimono, H., Okada, M., Inoue, M., Nakamura, H., Kobayashi, K. and Hasegawa, T. 2010. Diurnal and seasonal variations in stomatal conductance of rice at elevated atmospheric CO_2 under fully open-air conditions. *Plant, Cell and Environment* **33**: 322-331.

Triggs, J.M., Kimball, B.A., Pinter Jr., P.J., Wall, G.W., Conley, M.M., Brooks, T.J., LaMorte, R.L., Adam, N.R., Ottman, M.J., Matthaias, A.D., Leavitt, S.W. and Cerveny, R.S. 2004. Free-air CO_2 enrichment effects on the energy balance and evapotranspiration of sorghum. *Agricultural and Forest Meteorology* **124**: 63-79.

UN (United Nations). 2009. *The 2006 World Population Prospects. The 2008 Revision Population Database.* United Nations, New York, New York, USA. [WWW document]. URL http://esa. un.org/unpp/.

Yoshimoto, M., Oue, H. and Kobayashi, K. 2005. Energy balance and water use efficiency of rice canopies under free-air CO_2 enrichment. *Agricultural and Forest Meteorology* **133**: 226-246.

Zhu, J., Goldstein, G. and Bartholomew, D.P. 1999. Gas exchange and carbon isotope composition of *Ananas comosus* in response to elevated CO_2 and temperature. *Plant, Cell and Environment* **22**: 999-1007.

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