What Rising CO_2 Means for Global Food Security

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Executive Summary

Plant production has been boosted, the need for water and fertilizer has been brought down, and field experiments show that these effects are likely to increase in coming decades.

Global food security is one of the most pressing problems facing the planet's growing population. Continuing advances in agricultural technology and expertise will certainly increase food production in many regions, but the required doubling of production by 2100 as diets improve with rising income will still be a difficult task. Fortunately, carbon dioxide (CO_2), a non-polluting gas that is created when fossil fuels are converted into energy, has proved to be a powerful plant food.

Just as it does in commercial greenhouses every day, the CO_2 that has been added to the atmosphere has already "greened" the planet. Since 1900, crop production has been increased on the order of 15 to 30 percent. This White Paper's detailed review of the latest field research shows that this effect will only improve as carbon dioxide continues to rise from four percent of one percent of the atmosphere today to, perhaps, six percent of one percent in 50 years. In addition to boosting yields per unit of land area, CO_2 also boosts yields per unit of fertilizer applied and water used.

In regions where food shortages persist, these enhancements by industrial CO_2 will mean the difference between food security and food insecurity. They will aid in lifting hundreds of millions of people out of a state of hunger and malnutrition, preventing widespread starvation and premature death.

Society did not intend to boost plant productivity when it began using fossil fuels to power its drive to the wealth that has dramatically improved both personal health and the environment. However, now that the energy bonus of fossil-fueled CO_2 for agriculture has become well-established science, governments should promote research into crop varieties that perform best in enhanced CO_2 and be very cautious about restricting emissions of this non-polluting gas.

The clear benefits to humanity of plant fertilization by industrial carbon dioxide, let alone the wealth generated by the burning of fossil fuels that creates CO_2 as a byproduct, must of course be weighed against predictions of the potential costs. These are the well-known predictions, generated by computer models, of CO_2-driven warming leading to climate catastrophes. However, the modest, one-degree Celsius rise in average temperature since 1900, due to what all modelers acknowledge is a mixture of natural and industrial causes, has had a negligible effect to date on climate variables such as the rate of the rise of sea level, and the frequency of droughts and hurricanes. (Curry, 2018, pp. 70-72; Pielke Jr., 2017, Appendix B)

Some have begun to claim that increased CO_2 will greatly reduce the nutritional value of crops. A study promoting this narrative was published in 2018 by researchers at the Harvard School of Public Health, using this headline: "As CO_2 Levels Rise, Millions at Risk of Nutritional Deficiencies."[1] Field experiments have long shown that a few crops deliver perhaps five to ten percent less zinc, iron and protein per unit of mass when carbon dioxide levels are increased from today's levels to those predicted in 50 years. However, as the Harvard researchers acknowledge, because of economic growth people have been "dramatically" and "significantly" increasing their wealth and hence improving their diets for years.

Hence, a small decline in nutrients in a few crops, which in any event would be more than offset

by the CO_2 boost to production, is hardly likely to cause such a nutritional crisis. The researchers themselves acknowledge that plant breeding, modified fertilizers and new growing methods can reverse any nutritional decline. However, they unrealistically decided to freeze wealth, diets and agricultural methods at today's levels in their computer model's predictions of the future. That is what generated these dramatic but unfounded claims about "millions" being harmed.

The principal researcher for this White Paper is Craig D. Idso, chairman of the Center for the Study of Carbon Dioxide and Global Change and a member of the CO_2 Coalition. Dr. Idso has advanced degrees in both agronomy and climatology and is one of the world's pre-eminent scholars of carbon dioxide's impact on agriculture. The paper has been written for a general audience, but the relevant scientific studies are cited at every step and are included in the bibliography.

Introduction

Since 1950, global population has tripled to 7.6 billion.[2] The global fertility rate has been cut in half since 1950 and has stabilized at about 2.5 children per woman,[3] but the number of people on the planet is still expected to climb to 9.8 billion by 2050 and 11.2 billion by 2100, a 50 percent increase from today.[4]

One of society's great challenges is to produce enough food to meet the needs of this growing population. As purchasing power increases in poorer countries, diets are changing to include more meat. This requires much more crop production, to feed livestock. Scientists and organizations have concluded that unless there are significant advances in basic food production, food availability could decline dramatically in some countries within a few decades (Borlaug, 2000; Bruinsma, 2009; Parry and Hawkesford, 2010; Zhu *et al*., 2010). Yet, there is already cause for concern today.

At present more than one billion people are hungry or malnourished. The problem of food security, it must be stressed, is not primarily one of insufficient food production. The world's farmers currently produce more than enough food to feed Earth's entire population. Rather, food insecurity arises because the world's supply of food is not evenly distributed among the population. Obviously, there are a wide variety of political and economic reasons why sufficient nutrition is not distributed to all populations. (Conway and Toenniessen, 1999). However, we have to assume that such inefficiencies will continue, and try to address projections that global food security will be challenged by the income-driven increase in demand. Some estimates suggest that global food production needs to *double* its present value by the end of this century. How can this Herculean task be accomplished?

At first glance one might suggest simply increasing the amount of land presently farmed. However, bringing new land into agricultural cultivation often leads to habitat destruction and species extinctions (Tilman *et al*., 2001). Hence, more efforts must be devoted to raising yields on ***existing*** farmland in order to save land for nature.

One solution is to increase crop yield per unit of land. However, in many parts of the world the historical rate of increase in crop yield has been declining as the genetic ceiling for maximal yield potential has been approached. This highlights the need to engage in efforts to increase potential yield.

A second solution is to increase crop yield per unit of nutrients applied. It is clear that without synthetic fertilizers, world food production would not have increased at the rate that it has in the past, unless many natural ecosystems had been converted to agriculture. In order to minimize such conversions of ecosystems, there will have to be significant increases in the efficiency of crop nutrients, meaning greater production per unit of added nitrogen, phosphorus or potassium.

A third solution is to increase crop yield per unit of water used. Water is a regionally scarce resource. Many developing countries lack, or will soon lack, adequate water supplies to provide sufficient per capita food production on irrigated lands (Tilman *et al*., 2001). Hanjra and Qureshi (2010) conclude that "feeding the 2050 population will require some 12,400 km^3 of water, up from 6800 km^3 used today." This huge increase, in their words, "will leave a water gap of about 3300 km^3" beyond projections of supply or distribution.

As challenging as the situation appears, there is one reason to be optimistic about society's ability to achieve future global food security. The studies cited in this report show that Earth's rising concentrations of atmospheric CO_2 address all three possible solutions, raising yields per unit of land, fertilizer and water. These benefits are not only currently stimulating the growth and productivity of plants all across the globe. They are also virtually certain to continue to do so, and play a crucial role in meeting the planet's growing food needs in the next century and beyond.

How Rising Atmospheric CO_2 Increases Crop Yields

At a fundamental level, carbon dioxide (CO_2) is a colorless, odorless and tasteless non-polluting gas that has been increasing in the atmosphere for well over a century now, primarily due to increased combustion of fossil fuels. Since the dawn of the Industrial Revolution, rising energy production has elevated the air's CO_2 content by 45 percent. By the end of this century energy production is likely to raise it another 50 to 100 percent above its present concentration of approximately 410 parts per million, or ppm. (Another way of saying this is "4.1 percent of one percent of the atmosphere.") This range in estimation arises because it is extremely difficult to predict CO_2 levels many years from now. They are currently rising by about 3 ppm each year.

Fortunately, the modern rise in atmospheric CO_2 is proving to be a powerful ally in staving off regional food shortages that are projected to occur just a few decades from now. The unique characteristics of this miracle molecule are helping to raise crop yields per unit of land area, per unit of nutrients applied and per unit of water used. These characteristics are discussed in the three subsections that follow.

Increasing Crop Yield per Unit of Land Area

In addition to water, nutrients, climate and light, carbon dioxide is an essential factor for the growth and development of plants. CO_2 is the primary raw material from which they produce matter to build tissue. Plant tissues are the ultimate source of food for all animals, including humans. In this sense, carbon dioxide is the basis of nearly all life on Earth.

For millions of years now the concentration of CO_2 in the atmosphere has remained far below its geologic average of the past 300 million years (see Figure 1). Consequently, present-day CO_2 levels are about *five times lower* than the levels that existed during the Triassic, Jurassic and Cretaceous periods when many of our most useful plants evolved. Thus, for all of human history (and long before that), plants have been *underperforming* in their vital role as primary producers for the biosphere. Thanks to the modern rise in atmospheric CO_2, however, the gap between current and optimum performance of plant photosynthetic has been declining. Over the past two centuries, rising CO_2 has increased plant photosynthesis and growth.

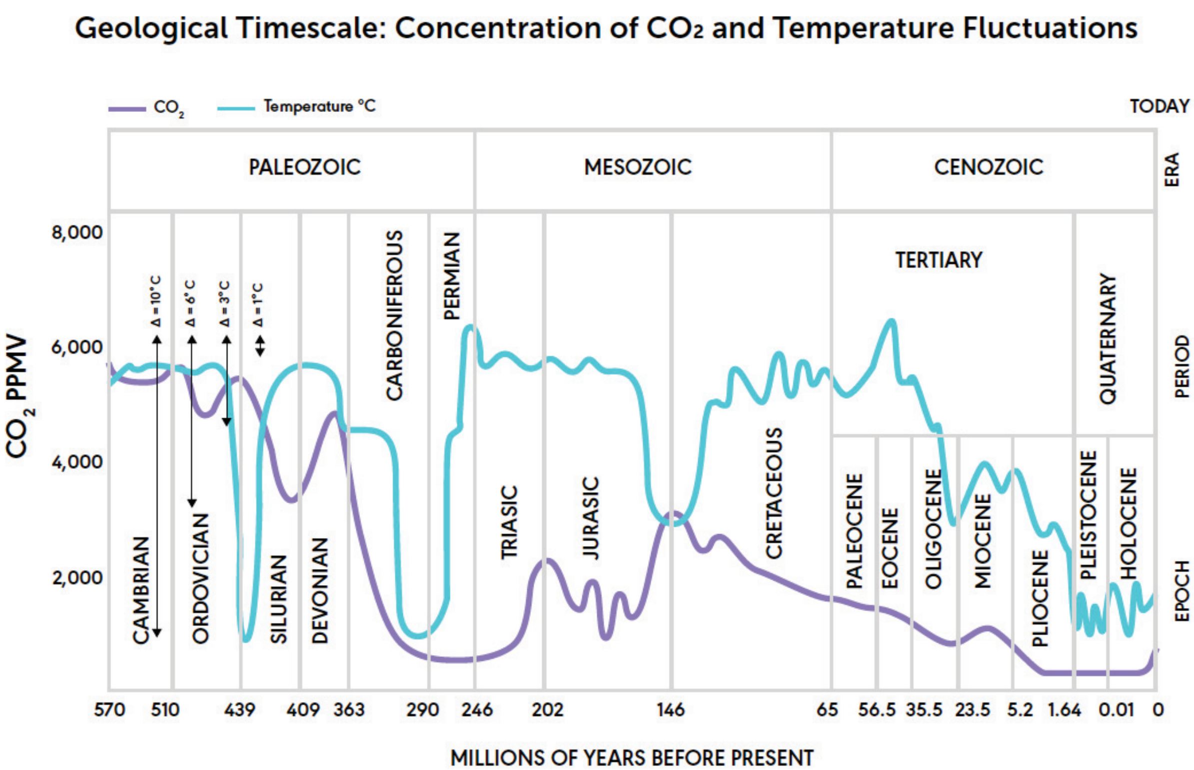

Figure 1. Graph of global temperature and atmospheric CO_2 concentration over the past 600 million years. Note both temperature and CO_2 are lower today than they have been during most of the era of modern life on Earth since the Cambrian Period. Also, note that CO_2 and temperature are not highly correlated; therefore this does not indicate a lock-step cause-effect relationship betweeen the two parameters.[5]

The fact that increased CO_2 in the air benefits plant growth was recognized over 200 years ago. As early as 1804, de Saussure showed that peas exposed to high CO_2 concentrations grew better than control plants in ambient air. Since that time, literally *thousands* of laboratory and field studies have been conducted on *hundreds* of different plant species, verifying the enhancement in growth that

Box 1: Rising Atmospheric CO_2 Stimulates the Growth of Pigeonpea by 29 Percent

Pigeonpea (*Cajanus cajan*) is an important food legume crop grown in equatorial and semiarid parts of the world. It is rich in protein (20-22 percent protein by dry seed weight) and commonly consumed in vegetarian diets in many countries (Bohra *et al*., 2011). And according to Sreeharsha *et al*. (2015), it responds well to rising concentrations of atmospheric CO_2.

Working at the high-CO_2 experimental research facility of the University of Hyderabad, India, the three researchers grew pigeon pea plants from seed to maturity on a red sandy loam soil in open-top chambers maintained at either the ambient CO_2 concentration of 395 ppm or at an enriched level of 550 ppm for two full growing seasons under both well-watered and fertilized conditions; only standard dressings of nitrogen were withheld from the plants. Results of the study revealed that, over the course of the two growing seasons, the 39 percent increase in atmospheric CO_2 concentration led to (1) a 36 percent increase in season-long net photosynthesis, (2) a 29.3 percent increase in total plant dry weight, (3) a 38.6 percent increase in the number of nitrogen-producing nodules that led to (4) a 74.9 percent increase in total nodule dry weight, and last of all (5) a 29.0 percent increase in seed yield, all of which results led Sreeharsha *et al*. to conclude that a "future elevated CO_2 atmosphere favors pigeonpea to sequester more atmospheric CO_2 and N_2 resulting in better economic yields under natural habitats." That is *great news* for growers and consumers of this protein-rich legume!

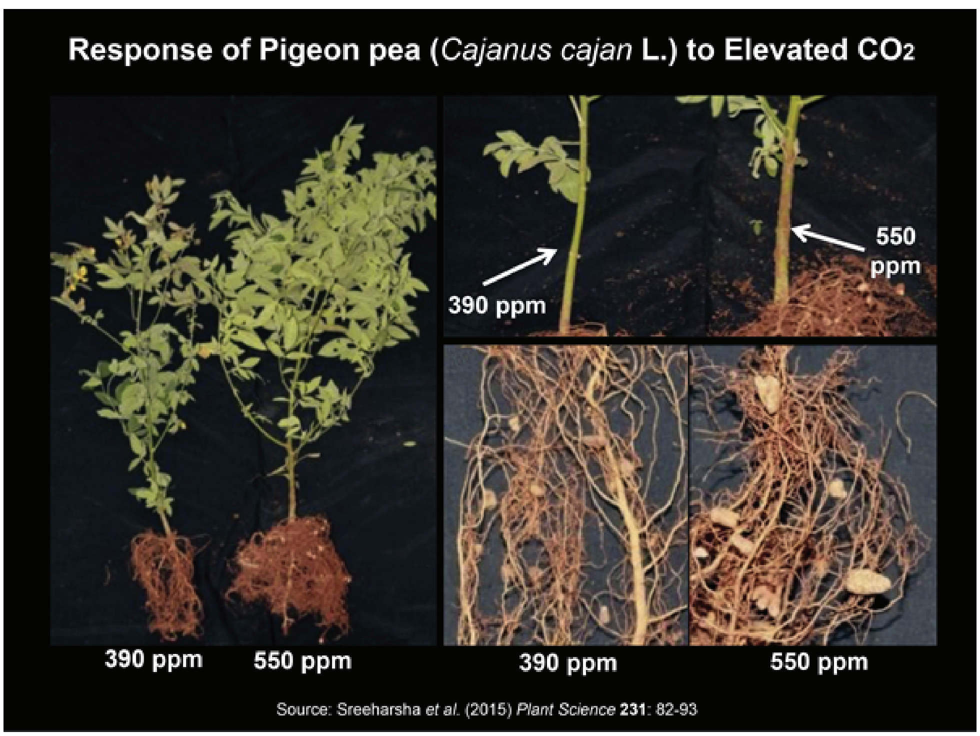

Figure 2. Growth differences (total plant size, stem thickness, nodule size and number) at the time of harvest of piegonpea plants grown under ambient (390 ppm) or elevated (550 ppm) atmospheric CO_2 concentrations.

elevated atmospheric CO_2 concentrations causes (see Box 1; Idso and Singer, 2009; Idso and Idso, 2011; Idso *et al*., 2014).

Commenting on these benefits, Wittwer (1982) wrote that "the 'green revolution' has coincided with the period of rapid increase in concentration of atmospheric carbon dioxide, and it seems likely that some credit for the improved yields should be laid at the door of the CO_2 buildup." Similarly, Allen *et al*. (1987) concluded that yields of soybeans may have been rising since at least 1800 "due to global carbon dioxide increases," while more recently, Cunniff *et al*. (2008) hypothesized that the rise in atmospheric CO_2 following the most recent ice age was the trigger that launched the global agricultural enterprise.

In a test of this hypothesis, Cunniff *et al*. designed "a controlled-environment experiment using five modern-day representatives of wild C_4 crop progenitors, all 'founder crops' from a variety of independent centers." (C_3 and C_4 are two major types of plants.) These were grown individually in growth chambers maintained at atmospheric CO_2 concentrations of 180, 280 and 380 ppm. Those concentrations are characteristic of, respectively: the glacial period that ended 12,000 years ago; the post-glacial period starting 8,000 years ago, after the global mean temperature had risen by about six degrees Celsius, thereby releasing carbon dioxide trapped in land and oceans; and the modern industrial era.

The results revealed that the 100-ppm increase in CO_2 from glacial to postglacial levels (180 to 280 ppm) "caused a significant gain in vegetative biomass of up to 40 percent," together with "a reduction in the transpiration rate via decreases in stomatal conductance of ~ 35 percent," which led to "a 70 percent increase in water use efficiency, and a much greater productivity potential in water-limited conditions."

In discussing their findings, the 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 C_4 crop progenitors in early agricultural systems." For comparative purposes, they also included one C_3 species in their study, wild barley (*Hordeum spontaneum*); and they report that it "showed a near-doubling in biomass compared with [the] 40% increase in the C_4 species under growth treatments equivalent to the postglacial CO_2 rise." In light of these and similar findings (Mayeux *et al*., 1997), it appears that the early civilization, which could not have existed without agriculture, was largely made possible by the natural increase in the air's CO_2 content that accompanied deglaciation.

The same response has been found in the *additional* 130 ppm of CO_2 the atmosphere has more recently gained from industrial emissions, on the order of from 15 to 30 percent. (CO2 Coalition, 2015, p. 7; Campbell, J. E. *et al.*, 2017) As the CO_2 concentration of the air continues to rise, this enhanced crop production will benefit society in the decades and centuries to come. The evidence comes from literally *thousands* of experiments that have been performed over the past several decades, demonstrating that a 300-ppm increase in the air's CO_2 concentration above its current value will raise the productivity of Earth's herbaceous plants by another 30 to 50 percent (Kimball, 1983; Idso and Idso, 1994). The productivity of its woody plants will rise 50 to 80 percent (Saxe *et al*., 1998; Idso and Kimball, 2001). Such gains in productivity gains are generally shown by increases in the number of branches and tillers, more and thicker leaves, more extensive root systems, and more flowers and fruit (see Figure 2).

Table 1 lists the expected gains in mass for the top 45 crops, which account for 95 percent of total global food production, in response to a 300 ppm increase in the air's CO_2 content. These projected biomass gains will significantly enhance global agricultural production and help meet future food needs. Taking the growth of sugarcane, wheat, maize and rice as examples — crops which together account for approximately *half* of all global food produced annually — a future 300 ppm rise in atmospheric CO_2 is expected to increase the biomass and hence yield of these crops by 34, 35, 24, and 36 percent, respectively.

Table 1. Mean percentage biomass enhancements produced by a 300-ppm increase in atmospheric CO_2 concentration for the top 45 crops accounting for 95 percent of total global food production. *Source: Idso, (2013)*

Crop	% Biomass Change	Crop	% Biomass Change
Sugar cane	34.0%	Rye	38.0%
Wheat	34.9%	Plantains	44.8%
Maize	24.1%	Yams	47.0%
Rice, paddy	36.1%	Groundnuts, with shell	47.0%
Potatoes	31.3%	Rapeseed	46.9%
Sugar beet	65.7%	Cucumbers and gherkins	44.8%
Cassava	13.8%	Mangoes, mangosteens, guavas	36.0%
Barley	35.4%	Sunflower seed	36.5%
Vegetables fresh nes	41.1%	Eggplants (aubergines)	41.0%
Sweet potatoes	33.7%	Beans, dry	61.7%
Soybeans	45.5%	Fruit Fresh Nes	72.3%
Tomatoes	35.9%	Carrots and turnips	77.8%
Grapes	68.2%	Other melons (inc.cantaloupes)	4.7%
Sorghum	19.9%	Chillies and peppers, green	41.1%
Bananas	44.8%	Tangerines, mandarins, clem.	29.5%
Watermelons	41.5%	Lettuce and chicory	18.5%
Oranges	54.9%	Pumpkins, squash and gourds	41.5%
Cabbages and other brassicas	39.3%	Pears	44.8%
Apples	44.8%	Olives	35.2%
Coconuts	44.8%	Pineapples	5.0%
Oats	34.8%	Fruit, tropical fresh nes	72.3%
Onions, dry	20.0%	Peas, dry	29.2%
Millet	44.3%		

Recognizing these growth-enhancing benefits, some researchers have begun to explore ways in which to *maximize* the influence of rising CO_2 on crop yields. Many of these efforts are devoted to identifying "super" hybrid cultivars that can "further break the yield ceiling" presently observed in

many crops (Yang *et al*., 2009). One research team (De Costa *et al*., 2007) grew 16 genotypes of rice under standard lowland paddy culture with adequate water and nutrients within open-top chambers maintained at either the ambient atmospheric CO_2 concentration or at an elevated CO_2 concentration (200 ppm above today's). Their results indicated that the CO_2-induced enhancement of the grain yields of the 16 different genotypes ranged from near zero (no change) to a 175 percent increase.

Such findings demonstrate that variants within the same plant species can have different growth responses to CO_2. This suggests that more effort should be expended in (1) identifying crop genotypes that are the most responsive to elevated CO_2 and then (2) incorporating those genotypes into breeding programs designed to produce the highest possible yields in a future increased-CO_2 atmosphere. Doing so will help ensure that society can take full advantage of the growth benefits of the upward-trending atmospheric CO_2 concentration, which will increase the land-use efficiency of agriculture and raise crop yields per unit of land farmed. And although this phenomenon will certainly help increase global food security, it is not the only means by which rising CO_2 helps to increase world food supplies. As discussed in the next two sections, in addition to raising agricultural land-use efficiency, elevated atmospheric CO_2 concentrations also typically increase *nutrient-use efficiency* (nitrogen-use efficiency in particular) as well as *water-use efficiency*.

Increasing Crop Yield per Unit of Nutrients Applied

Plant growth and development are presently limited by a lack of carbon, which is why plants generally exhibit increased growth and biomass production in response to atmospheric CO_2 enrichment. Next to carbon, a lack of nitrogen is usually the second most limiting factor in plant growth, followed by phosphorus and potassium.

Many agricultural lands are nutrient-poor. The modern application of fertilizers — particularly nitrogen (referred to as N in tables and figures), phosphorus (P) and potassium (K) — has significantly countered this condition, and boosted crop yields (Smil, 2002; Erisman *et al*., 2008). In many regions, though, the use of fertilizers remains low or non-existent. As a result, in large areas of Africa, South Asia and Oceania new lands (typically nutrient-poor) continue to be brought into cultivation at the expense of wild nature (Lu and Tian, 2017). Increasing the crop yield per unit of nutrients applied (or per unit of available soil nutrients when fertilizers are not applied) is thus of considerable importance in meeting the future food demands of these regions. Rising concentrations of atmospheric CO_2 are helping in this regard, particularly for crops grown on nutrient-poor soils.

Nitrogen: As a good example of this phenomenon, Sultana *et al*. (2017) examined the interactive effects of elevated CO_2 and the application of nitrogen on wheat under both rainfed and irrigated conditions. As shown in Figure 3, elevated CO_2 stimulated the grain biomass in various nitrogen water treatments from 17 to 37 percent. More importantly, the percentage growth due to CO_2 was *greater* when the nitrogen fertilizer was not used.

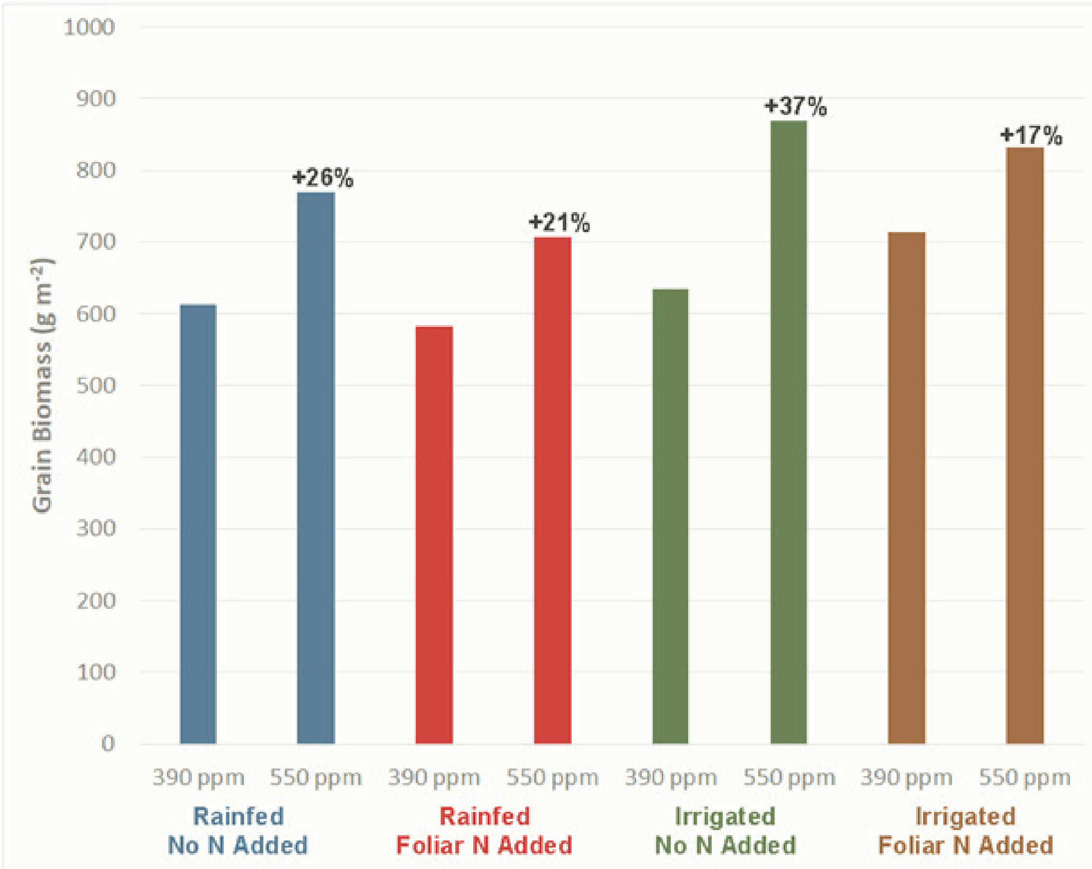

Figure 3. Grain biomass of spring wheat (Triticum aestivum, cv. Yitpi) grown for 190 days under various combinations of CO_2 (390 or 550 ppm), N treatment (no N or foliar added N), and water supply (rainfed or irrigated). The percentage difference in biomass due to CO_2 is listed in black above each treatment. *Source: Sultana et al. (2017).*

Sultana *et al*. examined both the content and the concentration of nitrogen in the grains. As expected, because of the increase in mass, the elevated CO_2 increased the total nitrogen *content* by 14 to 33 percent, depending on different inputs of nitrogen and water. In addition, there was no statistically significant difference in the concentration of nitrogen per unit of mass between current and elevated CO_2 levels under any of the treatments. Concentration of protein is often assessed as an indicator of grain *quality*. This means that Sultana *et al*. demonstrated the ability of elevated CO_2 to increase the quantity of wheat grains without sacrificing their quality, even under conditions of reduced nitrogen availability.

Other crops have also been shown to benefit from atmospheric CO_2 enrichment when a lack of nitrogen is a limiting factor. Increases in the amount of carbon fixed in plant tissues per unit of nitrogen under elevated CO_2 have been reported for cacao (Lahive *et al*.,2018), cowpea (Dey *et al*., 2017a),

garden bean (Haase *et al*., 2007), garden pea (Butterly *et al*., 2016), maize (Zong *et al*., 2014), papaya (Cruz *et al*., 2016), peanut (Tu *et al*., 2009), rice (Weerakoon *et al*., 1999; Weerakoon *et al*., 2000; Kim *et al*., 2001; Kim *et al*., 2003), soybean (Lam *et al*., 2012; Prevost *et al*., 2012; Li *et al*., 2017a), strawberry (Deng and Woodward, 1998), sugar beet (Demmers-Derks *et al*., 1998; Romanova *et al*., 2002) and sunflower (Zerihun *et al*., 2000; Lakshmi *et al*., 2017).

Phosphorus: Nitrogen is not the only limiting nutrient for plant growth that can be addressed by a rise in CO_2. Although it is a less significant component of plant tissues than carbon and nitrogen, phosphorus (P) is still required for successful completion of the life-cycle in many plant species. Only a few studies have investigated whether CO_2 enrichment spurs plants to acquire more phosphorus from the soil, and whether that increases biomass. Their results show that even when phosphorus concentrations in soils are less than optimal, the future looks promising.

In an early study of the subject, Barrett *et al*. (1998) demonstrated that a doubling of the air's CO_2 content under continuous phosphorus deficiency increased phosphatase activity in wheat root by 30 to 40 percent, thus increasing the inorganic phosphorus supply for plant utilization. Phosphatase is the primary enzyme responsible for the mineralization of organic phosphate, which makes phosphorus available for plant use. An increase in its activity could lead to sustained plant growth as a response to the ongoing rise in the air's CO_2 content, even in areas where growth is currently limited by a lack of phosphorous. The increase in phosphatase activity was observed under sterile growing conditions. This indicates that this response can be spurred directly by plant roots without relying on soil microorganisms, which are already known to aid in the mineralization of phosphorus.

As the air's CO_2 content rises, phosphatase activity in wheat roots is expected to increase, thereby converting organic phosphorus into inorganic forms that support the increased plant growth that is stimulated, in turn, by the higher CO_2 concentrations. A similar increase in phosphatase activity at elevated CO_2 levels has already been reported for a native Australian pasture grass, so these results may be applicable to most of Earth's vegetation. If so, then plants that are currently limited by a lack of phosphorus might increase their phosphorous acquisition from the soil.

This in turn may allow plants to sequester even greater amounts of carbon from the air as the atmosphere's CO_2 concentration increases. The result would be improved agricultural yields under phosphorus-limited conditions, confirmed in several studies subsequent to Barrett *et al*. In general, these additional studies demonstrate that phosphorous deficiency results in reductions in photosynthesis and growth, but that these reductions are countered by higher atmospheric CO_2 (Nguyen *et al*., 2006; Khan *et al*., 2010; Dey *et al*., 2017a; Dey *et al*., 2017b; Singh *et al*., 2017a).

Potassium: Plant growth is also limited by insufficient levels of potassium (K). According to Singh and Reddy (2017), potassium deficiency "limits crop growth and yield by adversely affecting vital plant processes, such as water relations and cellular turgidity, cell expansion, assimilate transport, and enzyme activation." However, such limitations are likely to be countered and potentially overcome in the future under enriched atmospheric CO_2.

Working in controlled-environment growth chambers, Singh and Reddy exposed soybean plants to two CO_2 treatment levels and three levels of potassium. Their results indicated that potassium deficiency significantly reduces growth for soybeans, regardless of CO_2 concentration. However, as illustrated in Figure 4, elevated CO_2 did partially compensate for and counter the reduction. Total plant dry matter at elevated CO_2 was greater (+63 percent and +28 percent) under the two levels of potassium deficiency (0.50 and 0.02 mM K) than when potassium was adequate (+23 percent CO_2-induced enhancement at 5.00 mM K level). Averaged across potassium treatments, elevated CO_2 increased the leaf, stem, root and pod weights by 28, 68, 23 and 33 percent, respectively, at maturity.

Elevated CO_2 was also found to improve both the efficiency of potassium use (KUE) and nitrogen use (NUE), with the values of each of these parameters being higher under elevated CO_2 for each level of potassium treatment. According to Singh and Reddy, the enhancement of KUE under elevated CO_2 indicates that “soybean plants produced greater biomass and seed yield with relatively lower tissue K concentration under elevated CO_2 versus ambient CO_2; thus, exhibiting an efficient utilization of tissue-available K.”

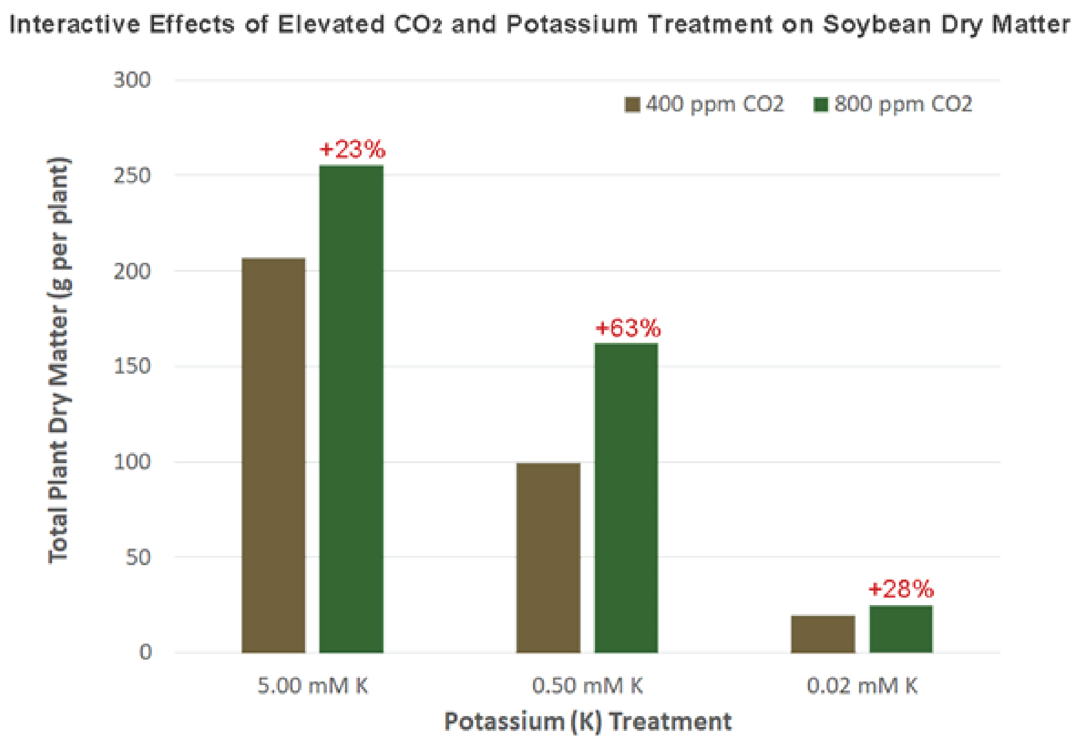

Figure 4. Effects of elevated CO_2 and potassium treatment on the total plant dry matter of soybean. *Source: Singh and Reddy (2017).*

In light of the several findings presented above, future agricultural production will benefit from CO_2-induced enhancements in the efficiency of nutrient-use. When crops are grown on nutrient-

deficient soils without the addition of fertilizers, elevated CO_2 will improve the crop's utilization of the existing low-level supply of nutrients. When fertilizers *are* added and soil nutrients are adequate, CO_2-induced yield increases will rise even more. Consequently, this unique characteristic of atmospheric CO_2 enrichment—increasing crop yields per unit of available nutrients—will help society meet its future food needs without converting more land from wild nature into agricultural production.

Increasing Crop Yield per Unit of Water Used

Agriculture-related water use presently accounts for approximately 80-90 percent of all fresh water used by humans. Hanjra and Qureshi (2010) predict that in the future competition for water resources "irrigation will be the first sector to lose water, as water competition by non-agricultural uses increases and water scarcity intensifies." These two researchers concluded that "increasing water scarcity will have implications for food security, hunger, poverty, and ecosystem health and services," where "feeding the 2050 population will require some 12,400 km^3 of water, up from 6800 km^3 used today." This huge increase "will leave a water gap of about 3300 km^3 even after improving efficiency in irrigated agriculture, improving water management, and upgrading of rainfed agriculture," agreeing with the findings of de Fraiture *et al*. (2007), Molden (2007) and Molden *et al*. (2010).

To alleviate this looming water deficiency, Hanjra and Qureshi proposed renewed efforts to conserve water and energy resources, develop and adopt climate-resilient crop varieties, modernize irrigation, shore up domestic food supplies and reform the global food and trade market. They say that "unprecedented global cooperation is required." However, reaching such unprecedented cooperation is doubtful, especially since the world presently fails in its cooperative ability to feed our current population, despite there being enough food to do so. Hence, to achieve future food security it will be important to increase crop yield per unit of water used, and here again the ongoing rise in the air's CO_2 content plays a pivotal role.

One of the principal benefits plants receive from elevated levels of atmospheric CO_2 is an increase in their water use efficiency. At higher CO_2 levels, plants generally do not open their leaf stomatal pores as wide as they do at lower CO_2 concentrations. The result is a reduction in most plants' rates of water loss by transpiration. The amount of carbon they gain per unit of water lost (i.e., *water-use efficiency*) therefore typically rises for a doubling of CO_2 on the order of 70 to 100 per cent. (Idso *et al.*, 2014) At higher atmospheric CO_2 concentrations, plants need *less* water to produce the *same*—or an even *greater*—amount of biomass. In the future, humanity will be able to grow more food and sustain the still-expanding population without usurping precious freshwater resources.

Examples of CO_2-induced improvements in plant water use efficiency are readily noted in the scientific literature. Fleisher *et al*. (2008), for instance, reported a near-doubling of water-use efficiency in potato plants when they were enriched with CO_2. Sanchez-Guerrero (2009) observed that a small 100-ppm increase in atmospheric CO_2 during daylight hours was sufficient to boost cucumber water-use efficiency by 40 percent. And Singh *et al*. (2017b) found that a 37 percent increase in atmospheric CO_2 increased the water-use efficiency of chickpea by 44 percent, while Kim *et al*. (2006) reported a *more than doubling* of instantaneous leaf water-use efficiency in maize in response to a doubling of CO_2.

Perhaps the most significant benefit to plants of improved water-use efficiency is their ability to counteract the negative impacts of drought. Global crop losses due to drought amount to over 40 billion dollars annually and often lead to a regional scarcity of food. In countering the negative effects of drought, elevated CO_2 typically stimulates the development of root systems that are larger than usual and more robust. This enables plants to probe greater volumes of soil for scarce moisture. Wechsung *et al*. (1999) observed a 70 percent increase in lateral root dry weights of water-stressed wheat grown at 550 ppm CO_2, while De Luis *et al*. (1999) reported a whopping 269 percent increase in root-to-shoot ratio of water-stressed alfalfa growing at 700 ppm CO_2. Thus, elevated CO_2 often elicits stronger than usual benefits in agricultural species under conditions of water stress.

CO_2-induced increases in root development together with CO_2-induced reductions in stomatal conductance contribute to the maintenance of a more favorable water status in plants during times of drought. Sgherri *et al*. (1998) reported that leaf water potential, which is a good indicator of overall plant water status, was 30 percent higher in water-stressed alfalfa grown at an CO_2 concentrations of 600 ppm rather than at 340 ppm. Wall (2001) found that leaf water potentials were similar in CO_2-enriched water-stressed plants and well-watered control plants frown at today's , CO_2 levels. This implies a complete CO_2-induced amelioration of water stress in the CO_2-enriched plants. Lin and Wang (2002) demonstrated that elevated CO_2 caused a several-day delay in the onset of the water stress-induced production of the highly reactive oxygenated compound hydrogen peroxide (H_2O_2) in spring wheat. They discovered that following the induction of water stress, plants grown in elevated CO_2 maintained higher enzymatic activities of two important *antioxidants,* superoxide dismutase and catalase, relative to those observed in plants grown at today's levels.

Since enriched atmospheric CO_2 allows plants to maintain a better water status during times of water scarcity, it is logical to expect that they should exhibit greater rates of *photosynthesis* than plants growing in water-deficient soil in air that has not been CO_2-enriched. And they typically do. Rabha and Uprety (1998) showed that experimentally-induced water stress in India mustard (*Brassica juncea*) drove photosynthetic rates down by 40 percent in plants growing in today's concentrations, while plants growing in air containing 600 ppm CO_2 only experienced a 30 percent reduction in net photosynthesis. Ferris *et al*. (1998) reported that after imposing water-stress conditions on soybeans and allowing them to recover following complete rewetting of the soil, plants grown in air containing 700 ppm CO_2 reached pre-stressed rates of photosynthesis after six days, while plants grown at today's levels air *never* recovered to pre-stressed photosynthetic rates.

Hence, it is likely that plant biomass production will also be enhanced by elevated CO_2 concentrations under drought conditions. In exploring this possibility, Ferris *et al*. (1999) reported that water-stressed soybeans grown at 700 ppm of CO_2 attained seed yields that were 24 percent greater than those of similarly-water-stressed plants grown at ambient CO_2 concentrations. Hudak *et al*. (1999) reported that water-stress had *no* detrimental effect on yield in CO_2-enriched spring wheat.

Many similar studies have demonstrated that the percent increase in biomass under enrichment is greater for water-stressed plants than for well-watered plants. Li *et al*. (2000) reported that under water-stressed conditions a 180-ppm increase in the air's CO_2 content increased final grain weights

in the upper and lower sections of the main stems of the spring wheat they studied by 10 and 24 percent, respectively. Under well-watered conditions, the elevated CO_2 increased final grain weights only in the lower sections of the main stems and by only 14 percent. Thus, elevated CO_2 had a greater positive impact on final grain weights of spring wheat under water-stressed field conditions, compared to non-water-stressed field conditions. This again demonstrates that atmospheric CO_2 enrichment is more important to stressed plants than it is to non-stressed plants.

Similarly, spring wheat grown in air containing an additional 280 ppm of CO_2 exhibited 57 and 40 percent increases in grain yield under water-stressed and well-watered conditions, respectively (Schutz and Fangmeier, 2001). Ottman *et al*. (2001) found that elevated CO_2 increased plant biomass in water-stressed sorghum by 15 percent, while no biomass increase occurred in well-watered sorghum. Kumar *et al*. (2017) reported that elevated levels of CO_2 increased rice yields by 15-18 percent under well-watered conditions, and by a *larger* 39-43 percent under water-deficit conditions. In predicting maize and winter wheat yields in Bulgaria under future scenarios of increased air temperature and decreased precipitation, Alexandrov and Hoogenboom (2000) noted that yield losses were likely to occur if the air's CO_2 content remained unchanged, but that if the atmospheric CO_2 concentration doubled, then maize and winter wheat yields would likely increase, even under the combined stresses of elevated temperature and reduced rainfall.

In summary, as the CO_2 content of the air rises, nearly all of Earth's agricultural plants will become more efficient at utilizing water, helping to counteract the negative impact of water scarcity. Food and fiber production per unit of water used will increase on a worldwide basis, even in areas where productivity is severely restricted due to limited availability of soil moisture.

Additional CO_2 Benefits to Enhance Future Crop Yields

Despite the well-documented and near-universal benefits of CO_2 enrichment, as described above, there are other factors that might complicate the future of agricultural production. Researchers have cited other factors that could reduce yields, such as excessive heat, ozone pollution, light stress, soil toxicity or consumption by animals. Yet, here again there is reason for optimism. Multiple studies show that atmospheric CO_2 enrichment tends to enhance growth and improve plant functions so as to minimize or overcome these and other environmental constraints (Idso and Singer, 2009; Idso and Idso, 2011; Idso *et al*., 2014).

With respect to temperature stress, the optimum temperature for plant growth and development typically *rises* with increasing concentrations of atmospheric CO_2 (Bjorkman *et al*., 1978; Berry and Bjorkman, 1980; Nilsen *et al*., 1983; Jurik *et al*., 1984; Seeman *et al*., 1984; Harley *et al*., 1986; Stuhlfauth and Fock, 1990; McMurtrie *et al*., 1992; McMurtrie and Wang, 1993; Idso and Idso, 1994; Idso *et al*., 1995; Cowling and Sykes, 1999; Taub *et al*., 2000; Borjigidai *et al*., 2006; Gutierrez *et al*., 2009). This response, coupled with expected increases in plant photosynthetic rates from the parallel rise in CO_2, is generally more than enough to compensate for any temperature–induced plant stress that are part of most scenarios of climate models that attribute most of global warming over the past 30 years to CO_2.

As Figure 5 shows, by combining elevated temperature and enriched CO_2 researchers increased today's yields in soybeans by 65 percent. (See Figure 5; Zhu *et al*., 1999; Vu, 2005; De Costa *et al*., 2006; Alonso *et al*., 2009; Gutierrez *et al*., 2009; Martins *et al*., 2016; Broughton *et al*., 2017; Reardon and Qaderi, 2017; Wang *et al*., 2018).

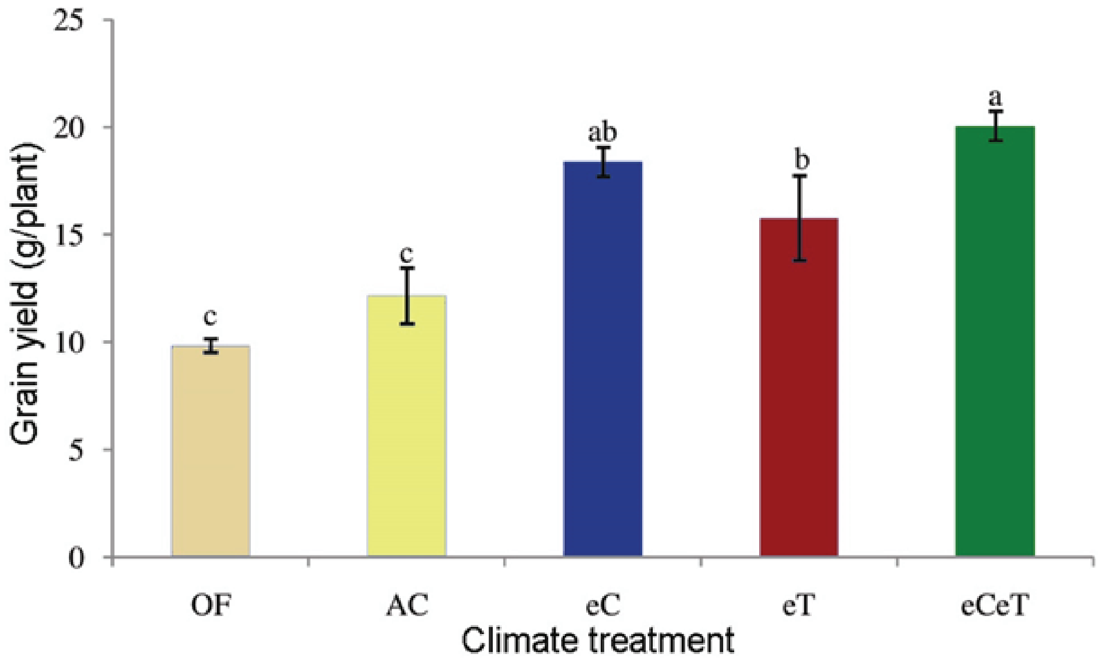

Figure 5. Soybean grain yield under different CO_2 and temperature treatments, as reported in Lenka et al. (2017). Elevated temperature improved soybean grain yield by 30 percent, whereas elevated CO_2 stimulated it by a much larger 51 percent. When combined, elevated CO_2 and elevated temperature boosted the grain yield by an even greater 65 percent! Legend: treatment conditions included open field (OF), consisting of ambient temperature and ambient CO_2 (~400 ppm) conditions, ambient conditions (AC), which was also maintained at ambient temperature and ambient CO_2, but in a chamber setting so the authors could discern whether or not there were any chamber effects influencing their findings, elevated CO_2 (eC), elevated temperature (eT), and elevated CO_2 and elevated temperature (eCeT). Bars with different lower-case letters are significant according to Duncan's multiple range test ($P < 0.05$). Error bars indicate standard error of the mean.

Rising atmospheric CO_2 has also been shown to counter the negative effects of increased levels of ozone pollution on crop yields (Rao *et al*., 1995; Heagle *et al*., 1998; Booker and Fiscus, 2005; Donnelly *et al*., 2005; Plessl *et al*., 2005; Yonekura *et al*., 2005; Burkey *et al*., 2007; Kumari *et al*., 2013; Singh *et al*., 2017b). Typically, CO_2 enrichment reduces the negative effects of ozone on carbon assimilation, leading to far less injury to leaves and maintaining significantly greater leaf chlorophyll content than control plants at today's CO_2 concentrations.

Box 2: A CO_2-Induced Global Stimulation of Terrestrial Carbon Uptake and Water Use Efficiency

How has the global biosphere benefitted from the modern increase in atmospheric CO_2?

According to Li *et al.* (2017c) there has been a 21.5 percent increase in global terrestrial net primary production (NPP) over the past half century, thanks in large measure to the growth-enhancing, water-saving and stress-reducing benefits of enriched atmospheric CO_2. Cheng *et al.* (2017) presented similar findings with respect to global terrestrial carbon uptake (i.e., gross primary production, or GPP). Using a combination of ground-based and remotely-sensed land and atmospheric observations, Cheng and his colleagues performed a series of calculations to estimate changes in global GPP, water use efficiency (WUE) and evapotranspiration (E) over the period 1982 to 2011. Results of the analysis are shown in the figures below.

Cheng *et al.* estimated that global PPP has increased by 0.83 ± 0.26 Pg C per year, or a total of 24.9 Pg C over the past three decades (Figure 6a, c). Global WUE also "increased at a mean rate of 13.7 ± 4.3 mg C mm-1 H2O per year from 1982 to 2011 ($p < 0.001$), which is about 0.7 ± 0.2 percent per year of mean annual WUE" (Figure 6b, c). Global E [better to use evapotranspiration to avoid multiple abbreviations], on the other hand, experienced a non-significant very small increase of 0.06 ± 0.13 percent per year (Figure 1c). Thus, both WUE and E were found to "positively contribute to the estimated increase in GPP," though the contribution from WUE accounted for 90 percent of the total GPP trend. Consequently, Cheng *et al.* conclude that the "estimated increase in global GPP under climate change and rising atmospheric CO_2 conditions over the past 30 years is taking place at no cost of using proportionally more water, but it is largely driven by the increase in carbon uptake per unit of water use, i.e. WUE."

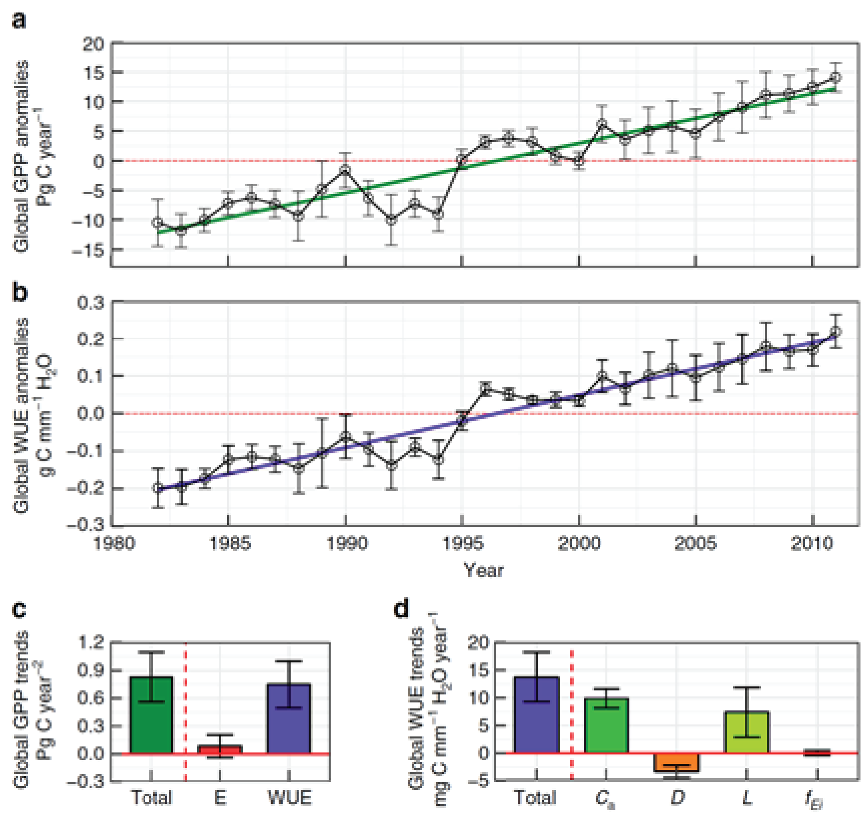

Figure 6. Estimated trends in global gross primary production (GPP) and water use efficiency (WUE) and their drivers over 1982-2011. Annual mean anomalies (with linear trend line) and associated standard deviations of (panel a) global GPP and (panel b) global WUE. (Panel c) Contribution of evapotranspiration (E) and WUE to total global trends in GPP (Total). (Panel d) Contributions of atmospheric CO_2 concentration (Ca), vapor pressure deficit (D), leaf area index (L) and fraction of canopy interception (fEi) to total ecosystem water use to the total increase in global WUE (Total). *Source: Cheng et al. (2017).*

In order to explain the increasing WUE trend, Cheng *et al.* examined the relative contribution of four possible factors, including rising atmospheric CO_2, vapor pressure deficit, leaf area index and the fraction of canopy radiation interception to total ecosystem water use. This effort revealed that atmospheric CO_2 enrichment and leaf area index (which parameter has itself been shown to be linked to elevated CO_2) are responsible for the lion's share of the trend (Figure 6).

From a spatial point of view, Cheng *et al.* report that 82 percent of the global vegetated land area show positive trends in GPP (Figure 7a) despite "the large-scale occurrence of droughts and disturbances over the study period." Similarly, ecosystem WUE was found to increase in 90 percent of the world's vegetative areas (Figure 7b); and there was a high correlation between the spatial trends in these two parameters.

Commenting on their several findings, Cheng *et al.* write that their results show that "terrestrial GPP has increased significantly and is primarily associated with [an] increase in WUE, which in turn is largely driven by rising atmospheric CO_2 concentrations and [an] increase in leaf area index." However, they add that "the most important driver for the increases in GPP and WUE from 1982 to 2011 is rising atmospheric CO_2." And in this regard, they note that a 10 percent increase in atmospheric CO_2 induces an approximate 8 percent increase in global GPP and a 14 percent increase in global WUE.

Thus terrestrial carbon uptake over the past three decades has increased because of the ongoing rise in atmospheric CO_2. What is more, this increase has not come at a cost of enhanced global terrestrial water use. Instead, rising atmospheric CO_2 has improved the global carbon uptake per unit of water use, which holds extremely important ramifications for the future survival of both plant and animal species.

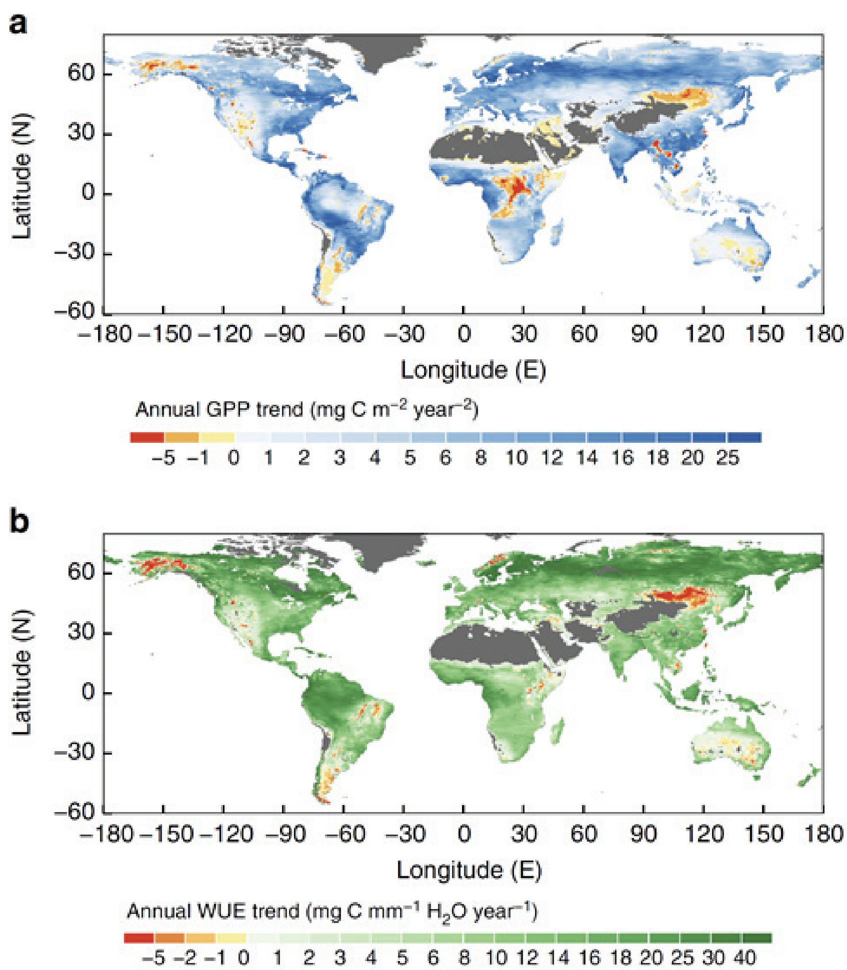

Figure 7. Estimated spatial trends in annual gross primary production (panel a) and water use efficiency (panel b) over 1982-2011. *Source: Cheng et al. (2017).*

Other studies have shown that higher levels of CO_2 also help to minimize crop reductions induced by soils that are stressed by salt (Garcia-Sanchez and Syvertsen, 2006; Perez-Lopez *et al.*, 2013; Sánchez-González et al., 2015; Sgherri *et al*., 2017) or contamination by heavy metals (Tang *et al*., 2003; Jia *et al*., 2007; Jia *et al*., 2016; Zhu *et al*., 2017) soils. Additionally, elevated atmospheric CO_2 has also been observed to improve resistance to plant disease by inducing changes in physiology, anatomy and morphology (Malmstrom and Field, 1997; Plessl *et al*., 2007; Li *et al*., 2015; Trébicki *et al*., 2016; Gilardi *et al*., 2017). In some cases, these benefits completely counterbalance the negative effects of pathogenic infections on overall plant productivity (Huang et al., 2012). Furthermore, elevated CO_2 can counter and reduce damage suffered from herbivore attacks (Joutei *et al*., 2000; Coll and Hughes, 2008; Klaiber *et al*., 2013; Xie *et al*., 2015) and improve the growth and yield of plants subjected to stresses of UV-B radiation (Qaderi and Reid, 2005; Koti *et al*., 2007; Tohidimoghadam *et al*., 2011; Wijewardana *et al*., 2016) and low levels of light (Harnos *et al*., 2002; Pérez-López *et al*., 2015; Li *et al*., 2017b). Consequently, it is unlikely that any future environmental stress or constraint will negate the expected increases in crop yields forecasted to accompany the air's rising CO_2 concentration.

Analysis of recent trends reinforces this prediction. The productivity of the planet's terrestrial biosphere, on the whole, has been *increasing* with time (see Box 2; Eastman *et al*., 2013; Wu *et al*., 2014; Zhu *et al*., 2016). More specifically, satellite-based analyses of net terrestrial primary productivity reveal an increase of 6 to 13 percent since the 1980s (Nemani *et al*., 2003; Chen *et al*., 2004; Young and Harris, 2005; De Jong *et al*., 2012; Li *et al*., 2017c; Campbell *et al*., 2017; Cheng *et al*., 2017). Additionally, observational and model-based studies indicate that Earth's land surfaces have long been a net source of CO_2-carbon to the atmosphere. From 1940 onward, however, the terrestrial biosphere has become on average an increasingly greater sink for CO_2-carbon: over the past 50 years global carbon uptake has *doubled* from 2.4 ± 0.8 billion tons in 1960 to 5.0 ± 0.9 billion tons in 2010 (Ballantyne *et al*., 2012).

With respect to the *cause* of these trends, there is compelling evidence that the increasing CO_2 content of the atmosphere is the chief factor. Many studies have acknowledged as much by recognizing the growth-enhancing, nutrient-use-improving, water-saving and stress-alleviating benefits that enhanced CO_2 provide to plants (Piao *et al*., 2006; Mao *et al*., 2013; Andela *et al*., 2013; Donohue *et al*., 2013; Lu *et al*., 2016; Zhu *et al*., 2016; Li *et al*., 2017c; Cheng *et al*., 2017). But what makes the rising global productivity trends even *more impressive* is the fact that they have occurred despite all the many assaults on Earth's vegetation over the past several decades, including wildfires, disease, pest outbreaks, deforestation, and changes in temperature and precipitation. On the whole, plants have *more than compensated* for any of the negative effects of these stresses on the global biosphere. Elevated CO_2 has helped to counter these growth-retarding influences in the past, and there is no reason to believe it won't continue to do so in the future, thus strengthening the outlook for future global food security.

Conclusion

One of humanity's most pressing challenges is the need to produce enough food to sustain a growing population without using additional land and freshwater resources that are vital to world's natural ecosystems, and that protect untold numbers of species from extinction.

To meet this challenge the world must engage in a united effort to increase crop yields on existing farmland per unit of land area, per unit of nutrients applied and per unit of water used. The only way of successfully accomplishing this task is to invest the effort and capital required to identify, and to then *grow*, the major food crop genotypes that respond most strongly to atmospheric CO_2 enrichment. Elevated atmospheric CO_2 concentrations have conclusively been shown to stimulate all three of the factors needed to maintain global food security: (1) raising the *land-use efficiency* of agriculture by increasing plant photosynthesis, biomass and yield, (2) increasing plant *nutrient-use efficiency*, which also stimulates yields per unit of nutrients applied or that are available in nutrient-deficient soils, and (3) enhancing plant *water-use efficiency*, which enables greater yields under the same or reduced unit of water applied, and which helps counteract the growth-inhibiting impacts associated with water stress.

Consequently, it would appear that a continuation of the current upward trend in the atmosphere's CO_2 concentration is *essential* for securing future food security. Any efforts to slow it because of the risks of predicted climate changes must also consider the risks of limiting its benefits to agricultural, nature and humanity.

Endnotes

1. *https://phys.org/news/2018-08-co2-climb-millions-nutritional-deficiencies.html#jCp*
2. *http://www.worldometers.info/world-population/world-population-by-year/*
3. *http://www.un.org/en/development/desa/population/publications/pdf/fertility/world-fertility-patterns-2015.pdf*
4. *https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html*
5. Sources for Figure 1: Nasif Nahle. "Cycles of Global Climate Change." Biology Cabinet Journal Online, July 2009 (*http://www.biocab.org/Climate_Geologic_Timescale.html*), referencing C.R. Scotese, *Analysis of the Temperature Oscillations in Geological Eras,* 2002; W.F. Ruddiman, *Earth's Climate: Past and Future,* New York, NY: W.H. Freeman and Co., 2001; Mark Pagani *et al.*, "Marked Decline in Atmospheric Carbon Dioxide Concentrations during the Paleocene." *Science* 309, No. 5734 (2005): 600-603.

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The mission of the CO2 Coalition is to promote broader understanding of the beneficial effects of more carbon dioxide in the atmosphere around the world. The Coalition fosters informed debate on the scientific evidence, as summarized in this Primer. The Coalition's initial paper, published in the fall of 2015, urged the public to "see for yourself."

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