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 (CO₂), 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 CO₂ 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, CO₂ also boosts yields per unit of fertilizer applied and water used.

In regions where food shortages persist, these enhancements by industrial CO₂ 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 CO₂ for agriculture has become well-established science, governments should promote research into crop varieties that perform best in enhanced CO₂ 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 CO₂ 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 CO₂-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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 km³ of water, up from 6800 km³ used today.” This huge increase, in their words, “will leave a water gap of about 3300 km³” 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 CO₂ 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 CO₂ Increases Crop Yields

At a fundamental level, carbon dioxide (CO₂) 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 CO₂ 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 CO₂ levels many years from now. They are currently rising by about 3 ppm each year.

Fortunately, the modern rise in atmospheric CO₂ 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. CO₂ 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.

![Geological Timescale: Concentration of CO$_2$ and Temperature Fluctuations](image)

**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 between 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\textsubscript{2} Stimulates the Growth of Pigeonpea by 29 Percent

Pigeonpea (\textit{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\textsubscript{2}.

Working at the high-CO\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{2} atmosphere favors pigeonpea to sequester more atmospheric CO\textsubscript{2} and N\textsubscript{2}, resulting in better economic yields under natural habitats.” That is great news for growers and consumers of this protein-rich legume!

![Response of Pigeon pea (\textit{Cajanus cajan L.}) to Elevated CO\textsubscript{2}](image)

\textbf{Figure 2.} Growth differences (total plant size, stem thickness, nodule size and number) at the time of harvest of pigeonpea plants grown under ambient (390 ppm) or elevated (550 ppm) atmospheric CO\textsubscript{2} concentrations.
elevated atmospheric CO₂ 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 CO₂ 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 CO₂ 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 C₄ crop progenitors, all ‘founder crops’ from a variety of independent centers.” (C₃ and C₄ are two major types of plants.) These were grown individually in growth chambers maintained at atmospheric CO₂ 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 CO₂ 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 C₄ crop progenitors in early agricultural systems.” For comparative purposes, they also included one C₃ 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 C₄ species under growth treatments equivalent to the postglacial CO₂ 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 CO₂ content that accompanied deglaciation.

The same response has been found in the additional 130 ppm of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ concentration for the top 45 crops accounting for 95 percent of total global food production. Source: Idso, (2013)

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

Recognizing these growth-enhancing benefits, some researchers have begun to explore ways in which to maximize the influence of rising CO₂ 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 CO₂ concentration or at an elevated CO₂ concentration (200 ppm above today’s). Their results indicated that the CO₂-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 CO₂. This suggests that more effort should be expended in (1) identifying crop genotypes that are the most responsive to elevated CO₂ and then (2) incorporating those genotypes into breeding programs designed to produce the highest possible yields in a future increased-CO₂ atmosphere. Doing so will help ensure that society can take full advantage of the growth benefits of the upward-trending atmospheric CO₂ 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 CO₂ helps to increase world food supplies. As discussed in the next two sections, in addition to raising agricultural land-use efficiency, elevated atmospheric CO₂ 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 CO₂ 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 CO₂ 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 CO₂ and the application of nitrogen on wheat under both rainfed and irrigated conditions. As shown in Figure 3, elevated CO₂ stimulated the grain biomass in various nitrogen water treatments from 17 to 37 percent. More importantly, the percentage growth due to CO₂ 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 CO₂ (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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ have been reported for cacao (Lahive et al., 2018), cowpea (Dey et al., 2017a),
garden bean (Haase et al., 2007), garden pea (Buttley 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 CO₂ treatment levels and three levels of potassium. Their results indicated that potassium deficiency significantly reduces growth for soybeans, regardless of CO₂ concentration. However, as illustrated in Figure 4, elevated CO₂ did partially compensate for and counter the reduction. Total plant dry matter at elevated CO₂ 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 CO₂-induced enhancement at 5.00 mM K level). Averaged across potassium treatments, elevated CO₂ increased the leaf, stem, root and pod weights by 28, 68, 23 and 33 percent, respectively, at maturity.

Elevated CO₂ 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 CO₂ for each level of potassium treatment. According to Singh and Reddy, the enhancement of KUE under elevated CO₂ indicates that “soybean plants produced greater biomass and seed yield with relatively lower tissue K concentration under elevated CO₂ versus ambient CO₂; thus, exhibiting an efficient utilization of tissue-available K.”

![Interactive Effects of Elevated CO2 and Potassium Treatment on Soybean Dry Matter](image)

**Figure 4.** Effects of elevated CO₂ 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 CO₂-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 percent. (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 grown 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$_2$O$_2$) 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 CO₂ increased final grain weights only in the lower sections of the main stems and by only 14 percent. Thus, elevated CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ content remained unchanged, but that if the atmospheric CO₂ 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 CO₂ 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 CO₂ Benefits to Enhance Future Crop Yields**

Despite the well-documented and near-universal benefits of CO₂ 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 CO₂ 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 CO₂ (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 CO₂, 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 CO₂.
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 CO₂-Induced Global Stimulation of Terrestrial Carbon Uptake and Water Use Efficiency

How has the global biosphere benefitted from the modern increase in atmospheric CO₂?

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 CO₂. 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 CO₂ 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 CO₂ 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 CO₂ also help to minimize crop reductions induced by soils that are stressed by salt (García-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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂-carbon to the atmosphere. From 1940 onward, however, the terrestrial biosphere has become on average an increasingly greater sink for CO₂-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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ enrichment.

Elevated atmospheric CO₂ 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 CO₂ 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


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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.”