HEALTH-PROMOTING EFFECTS OF ELEVATED CO_2 ON COMMON FOOD PLANTS

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How will the ongoing rise in the air's CO_2 content alter the amounts of various health-promoting substances found in the plants that we commonly eat? Studies of the effects of atmospheric CO_2 enrichment on the *quality* of the different plants that comprise our diets have typically lagged far behind studies designed to assess the effects of elevated CO_2 on the *quantity* of plant production. Some noteworthy exceptions were the early studies of Barbale (1970) and Madsen (1971, 1975), who discovered that increasing the air's CO_2 content produced a modest increase in the vitamin C concentration of tomatoes, while Kimball and Mitchell (1981) demonstrated that enriching the air with CO_2 also stimulated the tomato plant's production of vitamin A. Then, a few years later, Tajiri (1985) found that a mere one-hour-per-day *doubling* of the air's CO_2 concentration actually *doubled* the vitamin C contents of bean sprouts, and that it did so over a period of only seven days.

Tajiri (1985) found that a mere one-hour-per-day *doubling* of the air's CO_2 concentration actually *doubled* the vitamin C contents of bean sprouts, and that it did so over a period of only seven days.

Fast-forwarding a couple of decades, we encounter the work of Idso *et al*. (2002)[1], who had grown well-watered and fertilized sour orange trees out-of-doors at Phoenix, Arizona, in clear-plastic-wall open-top enclosures maintained at atmospheric CO_2 concentrations of either 400 or 700 ppm since November of 1987, while evaluating the effects of the extra 300 ppm of CO_2 on the vitamin C concentrations of fully-ripened fruit harvested over the eight-year period 1992-1999. This work revealed that in years when the production of fruit was approximately doubled by the extra CO_2, the fruit produced in the two CO_2 treatments were of approximately the same size; and the vitamin C concentration of the juice of the oranges grown in the CO_2-enriched air was enhanced by approximately 7% above that of the juice of the ambient-treatment oranges. In years when CO_2-enriched fruit numbers were more than doubled, however, the CO_2-enriched fruit were slightly smaller than the fruit produced in normal air; and the vitamin C concentration of the juice of the CO_2-enriched fruit rose even higher, to as much as 15% above that of the ambient-treatment fruit. On the other hand, in years when fruit numbers were less than doubled, the CO_2-enriched fruit were slightly larger than the

[1] http://www.co2science.org/articles/V5/N32/B1.php.

ambient-treatment fruit; and the enhancement of the vitamin C concentration of the juice of the CO_2-enriched fruit was somewhat less than the base value of 7% typical of equal-size fruit.

With respect to the likely *long-term equilibrium response* of the trees, Idso *et al*. (2002) wrote that in five of the last six years of the study, "the 75% increase in atmospheric CO_2 concentration has increased: (1) the number of fruit produced by the trees by 74 ± 9%, (2) the fresh weight of the fruit by 4 ± 2%, and (3) the vitamin C concentration of the juice of the fruit by 5 ± 1%." On the basis of this study, therefore, in the words of the eight researchers, "there is reason to believe that an atmospheric CO_2 enrichment of the magnitude expected over the current century may induce a large and sustained increase in the number of fruit produced by orange trees, a small increase in the size of the fruit, and a modest increase in the vitamin C concentration of the juice of the fruit, all of which effects bode well for this key agricultural product that plays a vital role in maintaining good health in human populations around the globe."

Since vitamin C intake correlates strongly with the consumption of citrus juice, and since the only high-vitamin-C juice consumed in any quantity by children is orange juice, the modest role played by the ongoing rise in the air's CO_2 content in increasing the vitamin C concentration of orange juice could ultimately prove to be of considerable significance for public health in the United States and elsewhere.

Further support for the significance of these observations was provided by Idso and Idso (2001), who noted that "these findings take on great significance when it is realized that scurvy - which is brought on by low intake of vitamin C - may be resurgent in industrial countries, especially among children (Ramar *et al*., 1993; Gomez-Carrasco *et al*., 1994), and that subclinical scurvy symptoms are increasing among adults (Dickinson *et al*., 1994)." In addition, they reported that "Hampl *et al*. (1999) have found that 12 to 20% of 12-18-year-old school children in the United States 'drastically under-consume' foods that supply vitamin C; while Johnston *et al*. (1998) have determined that 12 to 16% of U.S. college students have marginal plasma concentrations of vitamin C." Hence, as they continued, "since vitamin C intake correlates strongly with the consumption of citrus juice (Dennison *et al*., 1998), and since the only high-vitamin-C juice consumed in any quantity by children is orange juice (Hampl *et al*., 1999), the modest role played by the ongoing rise in the air's CO_2 content in increasing the vitamin C concentration of orange juice could ultimately prove to be of considerable significance for public health in the United States and elsewhere."

Shortly thereafter, Wang *et al*. (2003)[2], grew strawberry plants in six clear-acrylic open-top chambers - two of which were maintained at the ambient atmospheric CO_2 concentration, two of which were maintained at ambient + 300 ppm CO_2, and two of which were maintained at ambient + 600 ppm CO_2 - for a period of 28 months (from early spring of 1998 through June 2000), harvesting their fruit at the commercially ripe stage in both 1999 and 2000 and analyzing them for a number of antioxidant properties and flavonol contents.

Before reporting what they found, however, Wang *et al*. provided some background by noting that strawberries are good sources of natural antioxidants and by stating that "in addition to the usual nutrients, such as vitamins and minerals, strawberries are also rich in anthocyanins, flavonoids, and phenolic acids," and that "strawberries have shown a remarkably high scavenging activity toward chemically generated radicals, thus making them effective in inhibiting oxidation of human low-density lipoproteins (Heinonen *et al*., 1998)." And in this regard, they noted that previous studies (Wang and Jiao, 2000; Wang and Lin, 2000) "have shown that strawberries have high oxygen radical absorbance activity against peroxyl radicals, superoxide radicals, hydrogen peroxide, hydroxyl radicals, and singlet oxygen." In their experiment, therefore, they were essentially seeking to see if atmospheric CO_2 enrichment could make a good thing even better.

So what did the researchers find? They determined, first of all, that strawberries had higher concentrations of ascorbic acid (AsA) and glutathione (GSH) "when grown under enriched CO_2 environments." In going from ambient to +300 ppm and +600 ppm CO_2, for example, AsA concentrations increased by 10 and 13%, respectively, while GSH concentrations increased by 3 and 171%, respectively. They also learned that "an enriched CO_2 environment resulted in an increase in phenolic acid, flavonol, and anthocyanin contents of fruit." For nine different flavonoids, for example, there was a mean concentration increase of 55 ± 23% in going from the ambient atmospheric CO_2 concentration to +300 ppm CO_2, and a mean concentration increase of 112 ± 35% in going from ambient to +600 ppm CO_2. In addition, they reported that the "high flavonol content was associated with high antioxidant activity." As for the significance of these findings, Wang *et al*. noted that "anthocyanins have been reported to help reduce damage caused by free radical activity, such as low-density lipoprotein oxidation, platelet aggregation, and endothelium-dependent vasodilation of arteries (Heinonen *et al*., 1998; Rice-Evans and Miller, 1996)."

In summarizing their findings, Wang *et al*. thus stated that "strawberry fruit contain flavonoids with potent antioxidant properties, and under CO_2 enrichment conditions, increased their AsA, GSH, phenolic acid, flavonol, and anthocyanin concentrations," further noting that "plants grown under CO_2 enrichment conditions also had higher oxygen radical absorbance activity against radicals in the fruit." Hence, they determined that atmospheric CO_2 enrichment truly *did* make a good thing even better.

[2] http://www.co2science.org/articles/V6/N34/EDIT.php.

But what about a major staple crop such as soybeans? How do its health-promoting substances respond to atmospheric CO_2 enrichment? In a study designed to explore this specific question, Caldwell *et al*. (2005)[3] wrote that "the beneficial effects of isoflavone-rich foods have been the subject of numerous studies (Birt *et al*., 2001; Messina, 1999)," and that "foods derived from soybeans are generally considered to provide both specific and general health benefits," presumably via these substances. Hence, it is only natural that they would wonder how the isoflavone content of soybean seeds might be affected by the ongoing rise in the air's CO_2 content, and that *they* would thus conduct a set of experiments designed to find the answer.

The three researchers consequently grew well watered and fertilized soybean plants from seed to maturity in pots within two controlled-environment chambers, one maintained at an atmospheric CO_2 concentration of 400 ppm and one at 700 ppm. The chambers were initially kept at a constant air temperature of 25°C; but at the onset of seed fill, air temperature was reduced to 18°C until seed development was complete, in order to simulate average outdoor temperatures at this stage of plant development. Thereafter, in a second experiment, this protocol was repeated, except that the temperature during seed fill was maintained at 23°C, with and without drought (a third treatment), while in a third experiment, seed-fill temperature was maintained at 28°C, with or without drought.

In the first experiment, where air temperature during seed fill was 18°C, the elevated CO_2 treatment increased the total isoflavone content of the soybean seeds by 8%. In the second experiment, where air temperature during seed fill was 23°C, the extra CO_2 increased total seed isoflavone content by 104%, while in the third experiment, where air temperature during seed fill was 28°C, the CO_2-induced isoflavone increase was 101%. Then, when drought-stress was added as a third environmental variable, the extra CO_2 boosted total seed isoflavone content by 186% when seed-fill air temperature was 23°C, while at a seed-fill temperature of 28°C, it increased isoflavone content by 38%.

Under all environmental circumstances studied, therefore, enriching the air with an extra 300 ppm of CO_2 increased the total isoflavone content of

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[3] http://www.co2science.org/articles/V8/N21/B2.php.

soybean seeds. In addition, the percent increases measured under the stress situations were always greater than the percent increase measured under optimal growing conditions. Consequently, the direct effects of atmospheric CO_2 enrichment on the health-promoting properties of soybean seeds are likely universally beneficial and a boon to the entire human race, especially in light of the fact that Bernacchi *et al*. (2005) characterize the soybean as "the world's most important seed legume."

A second research team to study soybeans within this context and timeframe was that of Kim *et al*. (2005)[4], who indicated that important flavoniods "are mainly found in the form of isoflavones in soybean seeds," including "phytoestrogens with various biological potentials such as antioxidative, pharmaceutical, oestrogenic and anticarcinogenic properties, with some acting as antiestrogens and being used as anticancer agents (Peterson and Barnes, 1991; Anderson *et al*., 1995; Anthony *et al*., 1996; Arjmandi *et al*., 1996; Holt, 1997, Chung *et al*., 2000)." In their further study of this important crop, well watered plants were grown from seed to maturity in pots of sandy loam soil within the closed-environment plant growth facility of the National Horticultural Research Institute of Korea, where the plants were exposed to natural solar radiation and the natural daily course of ambient air temperature or elevated air temperature (= ambient + 5°C) with either normal soil nitrogen content or added nitrogen equivalent to an extra 40 kg N/ha, and where they were maintained at either ambient CO_2 (360 ppm) or elevated CO_2 (650 ppm). Then, at the end of the growing season, the plants were harvested and their total biomass determined, while the concentrations of twelve different isoflavones found in their seeds were quantitatively analyzed, including three aglycons, three glucosides, three acetyl conjugates and three malonyl conjugates.

As the atmosphere's CO_2 concentration continues to rise in the years and decades ahead, both the amount and potency of many important health-promoting substances found in soybean seeds should be significantly enhanced, providing huge benefits to humanity.

The results of this study indicated that the CO_2-induced increase in total plant biomass at normal ambient temperatures was 96% in the case of normal soil nitrogen and 105% in the case of added nitrogen, while at the warmer temperatures it was 59% in the case of normal soil nitrogen and 68% in the case of added nitrogen. With respect to seed isoflavone concentrations, the CO_2-induced increases of all twelve isoflavones were fairly similar to each other. As a group, at normal ambient temperatures the mean increase was 72% in the case of normal soil nitrogen and 59% in the

4 http://www.co2science.org/articles/V9/N12/B3.php.

case of added nitrogen, while at the warmer temperatures it was 72% in the case of normal soil nitrogen and 106% in the case of added nitrogen. Irrespective of soil nitrogen status and air temperature, therefore, increases in the air's CO_2 content produced large increases in soybean biomass, as well as soybean seed concentrations of twelve major isoflavones. Hence, it can be appreciated that as the atmosphere's CO_2 concentration continues to rise in the years and decades ahead, both the amount and potency of many important health-promoting substances found in soybean seeds should be significantly enhanced, providing huge benefits to humanity.

Two years later, Schonhof *et al*. (2007)[5] introduced their study of the well-known broccoli plant by stating that the *glucosinolates* it contains comprise a group of bioactive compounds that are responsible for many physiological effects, including enhancing the plant's flavor and - most important of all - *helping to prevent cancer* in people who consume them, citing the work of Mikkelsen *et al*. (2002) in this regard. Thus, in a set of three experiments conducted in a controlled greenhouse environment, Schonhof *et al*. grew well watered and fertilized broccoli plants in large soil-filled containers at ambient (430-480 ppm) and elevated (685-820 ppm) atmospheric CO_2 concentrations to the stage where fully developed heads could be harvested for glucosinolate analyses. This work indicated that the roughly 65% increase in atmospheric CO_2 concentration increased the fresh weight of the broccoli heads by approximately 7%, while it increased the total glucosinolate concentration of the broccoli inflorescences by 14%, due primarily to identical 37% increases in two particular glucosinolates: glucoiberin and glucoraphanin. Thus, in a succinct concluding statement, the four researchers wrote that atmospheric CO_2 enrichment "can enhance the health-promoting quality of broccoli because of induced glucosinolate content changes."

Atmospheric CO_2 enrichment can enhance the health-promoting quality of broccoli because of induced glucosinolate content changes.

Working with another food plant, Jin *et al*. (2009)[6] grew well-watered and fertilized spinach from seed (five to each 3.5-liter pot filled with a loam soil) for approximately three weeks in controlled-environment chambers containing air of either 350 ppm or 800 ppm CO_2, after which they harvested the plants, weighed them and measured the concentrations of several of the nutritive substances contained in their leaves. And as best as can be determined from the graphs of their results, the extra 450 ppm of CO_2 increased the fresh weight of the spinach shoots by about 67% and their dry weight by approximately 57%. In addition, it boosted the soluble sugar concentrations of their leaves by approximately 29% and their soluble protein concentrations by about 52%. And as an added bonus, the extra CO_2 also increased spinach leaf concentrations of ascorbate, glutathione and total flavonoids by 21%, 16% and 3%, respectively.

[5] http://www.co2science.org/articles/V10/N18/B1.php.

[6] http://www.co2science.org/articles/V12/N43/B1.php.

Contemporaneously, La *et al*. (2009)[7] wrote that "epidemiological studies show there is a negative relationship between Brassicaceae vegetable intake and the risk of a number of cancers (Wattenberg, 1993; Kohlmeier and Su, 1997; Price *et al*., 1998)," and that "it has been widely recognized that some of the cancer-chemoprotective activities in these vegetables are attributable to their contents of glucosinolates (Zhao *et al*., 1992; Wattenberg, 1993; Tawfiq *et al*., 1995; Fahey *et al*., 1997; Rosa *et al*., 1997; Holst and Williamson, 2004)." Hence, they decided to see what effect the ongoing rise in the air's CO_2 content might have on the production of these important cancer-fighting agents in yet another common food plant.

Working with seedlings of Chinese kale, the five scientists placed them in pairs in 1.8-L pots "fixed in a foam cavity with sponge" within growth chambers maintained at either 350 or 800 ppm CO_2, where the plant's roots were immersed in culture solutions treated with either 5.0 mmol nitrogen (N) per L (low N), 10 mmol N per L (medium N), or 20 mmol N per L (high N) and allowed to grow for 35 days, after which the plants were separated into their primary morphological parts and weighed, while their bolting stems were ground into powder for glocosinolate analyses.

"Regardless of N concentration," wrote the researchers in describing their findings, the elevated CO_2 treatment "significantly increased plant height [15.64%], stem thickness [11.79%], dry weights of the total aerial parts [11.91%], bolting stems [15.03%], and roots [16.34%]." Also, they reported that the elevated CO_2 increased the total glucosinolate *concentrations* of the bolting stems in the low and medium N treatments by 15.59% and 18.01%, respectively, compared with those at ambient CO_2, although there was no such effect in the high N treatment. Consequently, in terms of the *total amount* of glucosinolate production within the bolting stems of Chinese kale, these results suggest that increases of 33 to 36% may well be obtained for plants growing in low to medium N conditions in response to a 450-ppm increase in the air's CO_2 concentration.

In the final study of this subject, Gwynn-Jones *et al*. (2012)[8] wrote that "dwarf shrub berries are particularly valued by the human populations at Northern Latitudes as an autumn harvest, but are also consumed by a wide range of animals (Anderson, 1985)." From a human perspective, they said that the fruit of these shrubs contain high concentrations of flavonoids and anthocyanins (Heinonen *et al*., 1998; Faria *et al*., 2005; Heinonen, 2007), which can scavenge cancer-causing free-radicals (Martin-Aragon *et al*., 1998; Taruscio *et al*., 2004) and reduce the oxidative stress caused by these compounds in animals (Johnson and Felton, 2001)." And as one example of the latter benefit, they stated that "there is already laboratory evidence suggesting that the consumption of *Vaccinium myrtillus* berry flavonoids by small mammals can increase the antioxidant capacity of their blood plasma which could promote their fitness," citing Talavera *et al*. (2006).

[7] http://www.co2science.org/articles/V12/N51/EDIT.php.
[8] http://www.co2science.org/articles/V16/N4/B2.php.

Getting on to their experiment, in an open-top chamber study conducted at the Abisko Scientific Research Station in Northern Sweden, Gwynn-Jones *et al*. assessed the impact of atmospheric CO_2 enrichment (600 vs. 360-386 ppm) on the berry quality of both *Vaccinium myrtillus* and *Empetrum hermaphroditum* in the final year (2009) of a 17-year experiment. And as best as can be determined from the ten researchers' graphically-presented results, it appears that the mean concentration of quercetin glycosides in *V. myrtillus* was increased by approximately 46% by the approximate mean CO_2 concentration increase of 227 ppm. In *E. hermaphroditum*, on the other hand, syringetin glycoside concentrations were increased by about 36% by the extra CO_2, while five anthocyanins had their concentrations increased as follows: delphinidin-3-hexoside by about 51%, cyanidin-3-hexoside by about 49%, petunidin-3-hexoside by about 48%, malvidin-3-pentoside by about 46% and malvidin-3-hexoside by about 59%. And in light of their several findings and their implications for humans, Gwynn-Jones *et al*. concluded that "consumers of *E. hermaphroditum* may gain higher antioxidant intake at elevated CO_2," while adding that "some European bird species show preferential feeding towards berries with higher antioxidant contents (Catoni *et al*., 2008), which could have important implications for the palatability and, therefore, seed dispersal of these species."

The ongoing rise in the air's CO_2 content is not only increasing the productivity of earth's common food plants, it is significantly increasing the quantity and potency of the many health-promoting substances found in their tissues, which are the ultimate sources of sustenance for essentially all animals and humans.

In conclusion, it is becoming ever more evident that the ongoing rise in the air's CO_2 content is not only increasing the *productivity* of earth's common food plants, it is significantly increasing the *quantity* and *potency* of the many *health-promoting substances* found in their tissues, which are the ultimate sources of sustenance for essentially all animals and humans. Thus, as these foods make their way onto our dinner tables, they improve our health and help us better contend with the multitude of diseases and other maladies that regularly afflict us. In fact, it is possible, if not *likely*, that the lengthening of human life-span that has occurred over the past half-century or more - as described by Horiuchi (2000) and Tuljapurkar *et al*. (2000)[9] - may in some significant part be due to the concomitant CO_2-induced increases in the concentrations of the many health-promoting substances found in the various plant-derived foods that we eat.

9 http://www.co2science.org/articles/V3/N13/B2.php.

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