Nutritive Value of Plants Growing in Enhanced CO_2 Concentrations (eCO_2)

CO2 COALITION

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ABSTRACT

In the present article, we strongly argue against the published notion that enhanced atmospheric concentrations of carbon dioxide (eCO_2) threaten human nutrition. We review literature and provide arguments that arrive at quite a contrary view. In accordance with Liebig's Law of the Minimum, more vigorous growth of vegetation in eCO_2 will increase plants' need for more of other nutrients. However, the resulting nutrient deficiencies caused by eCO_2 are small, compared to the nutrient shortages that agriculture and livestock routinely face because of natural phenomena, such as severe soil fertility differences, nutrient dilution in plants due to rainfall or irrigation, and even aging of crops. These problems have been satisfactorily dealt with for generations through adequate use of mineral fertilizers, most importantly nitrogen; by proper species and cultivar selection; and with food supplements for livestock and humans. The same agricultural practices will ensure that the more abundant crops that result from eCO_2 will also provide good nutrition. Over most of geological history, atmospheric CO_2 concentrations have been several times higher than today's, which are much less than optimum for most plants. We also review the contribution of eCO_2 to global warming and conclude that doubling or even quadrupling CO_2 concentrations can only cause a few percent suppression of radiation to space. The resulting temperature increase will be small, compared to the natural increases and decreases of temperature that have characterized our current interglacial period. More CO_2 is beneficial to life on Earth.

INTRODUCTION

The concentration of atmospheric carbon dioxide (CO_2) has increased from a preindustrial value of about 280 ppm (parts per million by volume) to about 425 ppm in the year 2024. Much of this increase has come from burning fossil fuels. Despite many years of claims that increasing concentrations of CO_2 are an "existential threat" to life on Earth (a recent descriptor being "global boiling") one cannot identify any harm that has been done. In fact, the only clear result of increasing CO_2 has been an overall greening of the Earth and increasing productivity of agricultural and forest crops. For example, in a recent paper, Taylor and Schlenker (2023) [1] state:

> *"We consistently find a large CO_2 fertilization effect: a 1 ppm increase in CO_2 equates to a 0.4%, 0.6%, 1% yield increase for corn, soybeans, and wheat, respectively."*

Fig. 1 shows the dramatic increase of global food production over the past century. Major factors in this increase have been growing concentrations of atmospheric CO_2, which is "plant food," major improvements of crop varieties [2], and increased use of mineral fertilizers that provide adequate levels of nitrogen, phosphorus and other elements in soil for optimal plant growth [4].

The evidence for greening of the Earth from eCO_2 is now too obvious to deny. This is an embarrassment to the large and profitable movement to "save the planet" from "carbon pollution," aka CO_2. If CO_2 greatly benefits agriculture and forestry and has a small, benign effect on climate, it is not a pollutant at all.
In recent years, many research groups have shown that there are modest changes in the nutritional value of crops grown in elevated CO_2 concentrations. Media promoters of climate alarmism have seized on these results to further demonize CO_2. In this paper we explain why the nutritional value of our more abundant crops can and will remain high as atmospheric CO_2 concentrations increase toward values more representative of those existing throughout most of Earth's history.

SCIENTIFIC DISCUSSION

Carbon is the chemical element of life

Balanced nutrition has always been a requirement for life on Earth. Human beings, animals, agricultural crops, forests, and all living things are made of many chemical elements. The most abundant chemical elements in humans are shown in Fig. 2.

The largest fraction of body weight of a "standard human," about 65%, comes from oxygen, O, with the majority contained in water, H_2O, as 70 to 80% of the human body consists of water. As shown in Fig. 3, there is also a substantial amount of oxygen in most of the other important organic molecules of life: for example, the 6-carbon sugar glucose [5] shown at the top left or the 5-carbon sugar ribose [6] a component of the ATP molecule shown at the bottom. Glucose can be polymerized into the energy storage polymers glycogen [7] in the human body or starch in plants [8]. Plants also polymerize glucose

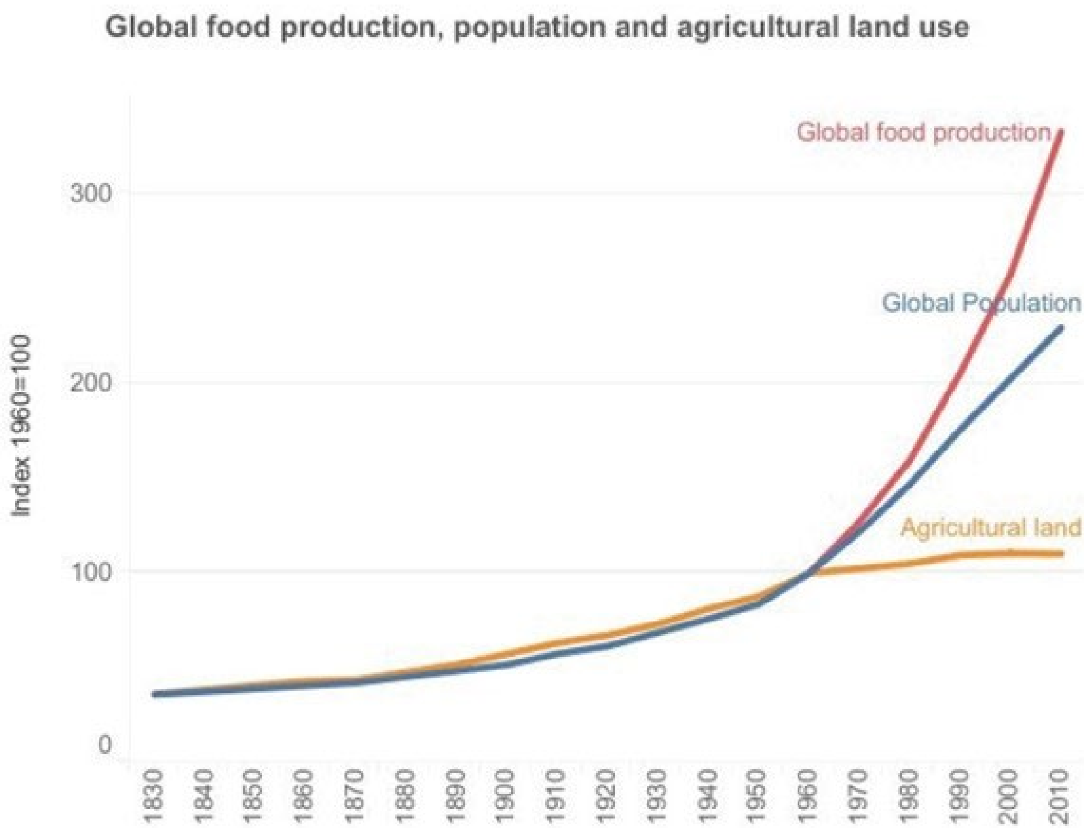
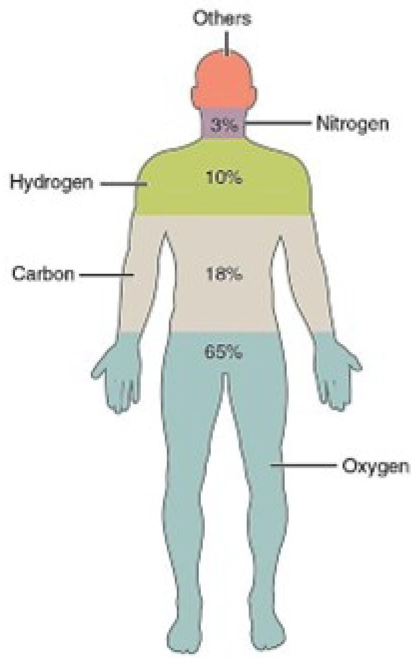


Figure 1: Important factors in the "green revolution," the dramatic increase in food production shown here, have been increased atmospheric CO_2, which along with water and sunlight is a key raw material for life, the development of greatly improved plant varieties [2], and intelligent use of mineral fertilizers. From OECD (2023) [3].

into the structural polymer cellulose [9] or hemicellulose. In fact, cellulose is the most abundant substance in the biosphere. Unlike calorie-rich carbohydrates like starch, most animals cannot directly metabolize cellulose. Humans derive no nutritional benefit from the fiber (cellulose) of vegetable foods, although the fiber does help to maintain proper functioning of the digestive system. Ruminants, like cattle [10] or sheep, can use cellulose as a principal source of nutrition with the aid of specialized rumen microbiota. Ruminants transform the cellulose in the herbage from at least one quarter of Earth's land surface to high-value human food, like milk and meat.

The much-demonized element carbon, C, is the second largest contributor to the weight of the human body with about 18.5% (Fig. 2). Ill-informed media constantly urge us to reduce our "carbon footprint" and to "decarbonize" our lives and activities. Let's be very clear: carbon is not a pollutant but is the basis for all life on Earth, including human life. Carbon atoms dominate the structure of all biological macromolecules that are essential for our very existence: proteins, lipids, carbohydrates and nucleic acids. A few building blocks for those are shown in Figure 3. For instance, the fatty acid known as myristic acid, is nearly a pure "hydrocarbon" with minimal amounts of oxygen in its structure.



Element	Symbol	Percentage in Body
Oxygen	O	65.0
Carbon	C	18.5
Hydrogen	H	9.5
Nitrogen	N	3.2
Calcium	Ca	1.5
Phosphorus	P	1.0
Potassium	K	0.4
Sulfur	S	0.3
Sodium	Na	0.2
Chlorine	Cl	0.2
Magnesium	Mg	0.1
Trace elements include boron (B), chromium (Cr), cobalt (Co), copper (Cu), fluorine (F), iodine (I), iron (Fe), manganese (Mn), molybdenum (Mo), selenium (Se), silicon (Si), tin (Sn), vanadium (V), and zinc (Zn).		less than 1.0

Figure 2: Chemical elements in the body of an "average" human. Adapted from reference [4]

Third in abundance is hydrogen, H, at about 9.5% of body weight. Much of the hydrogen is in water, but there are also substantial amounts bound in almost all the biological macromolecules of life.

Fourth in abundance in the human body is nitrogen, N, which makes up about 3.2% of body weight. Most of that weight is from the nitrogen atoms in amino acids. As shown in Fig. 3, amino acids [11], like the glycine molecule on the top right of Fig. 3, contain at least one N atom, and in some cases more than one. The amino acid arginine has four N atoms [11]. Nitrogen is also used in chitin, a structural material made by shrimp, insects, fungi and other forms of life, and second only to cellulose as a biopolymer.

Many nitrogen atoms are also contained in the "bases", the building blocks of deoxyribonucleic acids DNA, the "operating instructions" for living cells, and in closely related molecules of ribonucleic acid RNA. An example of a base is the double-ring molecule of adenine, one of the three constituents of the adenosine triphosphate molecule (ATP) of Fig.3. ATP [12] is the ubiquitous carrier of free energy that drives the biochemical machinery of living things. The adenine base contains 5 nitrogen atoms. The other components of ATP are a short triphosphate chain, and the 5-carbon sugar ribose. ATP molecules are like little rechargeable batteries that circulate through the tissue of living creatures. In the process of transferring free energy for some biological need, ATP loses one of the phosphate groups and becomes an adenosine diphosphate molecule (ADP), the discharged form of the battery. ATP can be regenerated (the battery can be recharged) by using some source of energy to attach a phosphate group PO^{3-} to an ADP molecule and transform it back to an ATP molecule. Using energy from sunlight, the chloroplasts of green plants convert large quantities of ADP to ATP as part of photosynthesis. But animals, too, which are unable to use the energy of sunlight directly, transform ADP to ATP during respiration and other metabolic processes. Most of the energy for manufacturing ATP in animals (or in plants at night when no solar energy is available) comes from the oxidation of sugar back to the CO_2 and H_2O molecules from which it was originally synthesized.

Most of the nitrogen in plants or animals is contained in proteins [13], which are long polymers of nitrogen-containing amino acids. The proteins of both plants and humans are assembled from about 20 amino acids that differ from the representative glycine molecule of Fig. 3 by having one of the hydrogens that is attached to the central carbon atom C replaced by a more complicated “side chain.” Some proteins -- enzymes -- catalyze otherwise impossible biochemical reactions. The most abundant protein in the world (and one of the most ancient) is ribulose-1,5-bisphosphate carboxylase/oxygenase, or *rubisco* for short [14]. Rubisco enzymes in plants incorporate CO_2 and H_2O molecules into simple sugars that are the raw materials from which most other biological molecules are made. The carbon fixation cycle, also called the Calvin cycle [15], also requires other nitrogen-containing enzymes and chemical energy from ATP molecules. Parts of the cycle require the addition or removal of hydrogen atoms, which are transported by molecules similar to ATP, most notably by hydrogenated nicotinamide adenine dinucleotide phosphate (NADPH), which includes 7 nitrogen atoms. Govindjee and Krogmann (2004) [16] summarized the fascinating 300-year history of scientific discoveries in oxygenic photosynthesis and assimilation of CO_2 by plants.

Proteins also constitute the muscles of the human body and of animals. Human hair and fingernails are made of the structural protein keratin, and so are animal horns and claws and the feathers of birds.

Scare stories about food from plants grown in higher than pre-industrial concentrations of atmospheric CO_2 (eCO_2) being less nutritious focus on protein (nitrogen) deficiencies. As we will discuss in more detail below, crops will in fact be much more abundant with eCO_2 and they will provide all the nitrogen needed by humans and animals that consume them.

The phosphates of ATP are just one example of the important role of phosphorus in cell biochemistry. Phosphorus and calcium, in the form of the mineral apatite [17], are a major part of teeth and bones. Calcium at about 1.5% body weight, and phosphorous, at about 1% of body weight are essential for life.

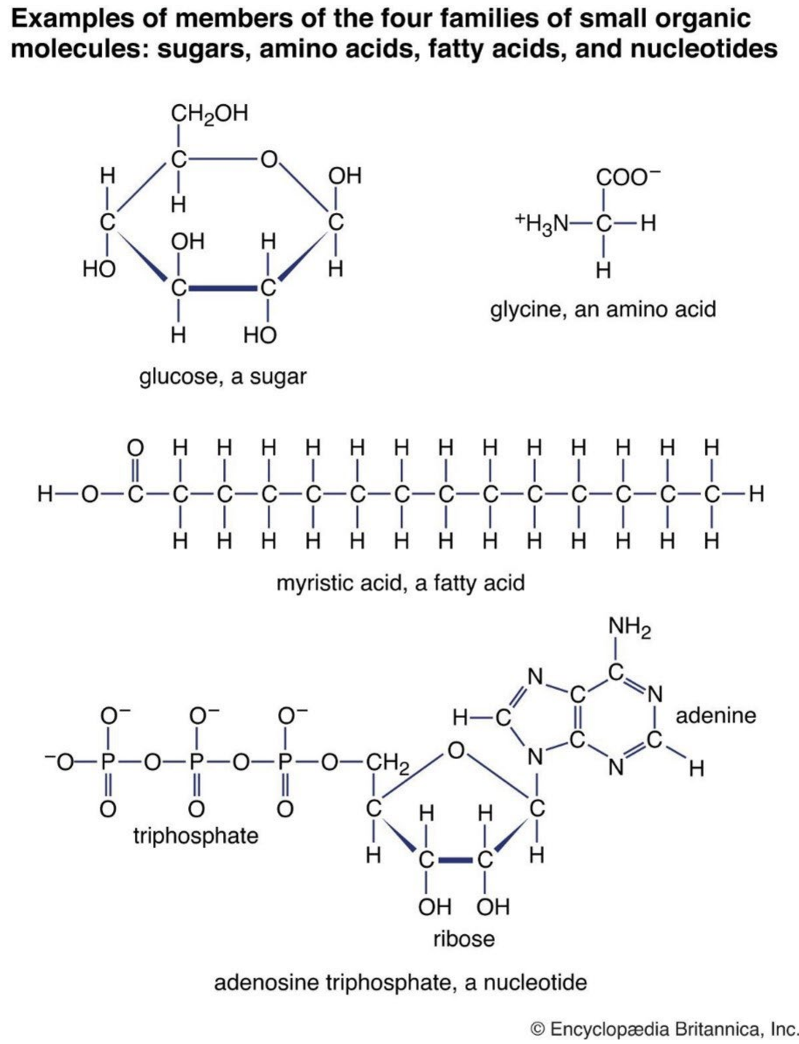


Figure 3: Representative small biological molecules from the human body that contain carbon and are the building blocks for large biomolecules. These same molecules occur in all forms of animal and plant life on Earth.

As illustrated in Fig. 2, potassium (K) makes up only about 0.4% of body weight. But potassium ions (K^+), along with sodium ions (Na^+), are essential for the operation of the human nervous system, the regulation of heart rhythm, and many other functions. And potassium, along with nitrogen and phosphorus, are often too scarce in agricultural soils for optimum plant growth. A typical bag of "all-purpose" fertilizer might have the label, 5-10-5. The numbers indicate that the weight of the ingredients comes 5% from N atoms, 10% from phosphorus pentoxide "molecules", P_2O_5 (actually half of the tetrahedral anhydride of phosphoric acid, P_4O_{10}), and 5% from potassium oxide molecules, K_2O.

A key concept of soil fertility is *Liebig's Law of the Minimum*: *"Plant growth is controlled not by the total nutrients available, but by the one in shortest supply, the limiting factor"* [18]. "Liebig's barrel," shown in Fig. 4 is often used to illustrate the Law of the Minimum. For tens of millions of years one of the most important plant nutrients, atmospheric CO_2 , has been falling further and further below optimum concentrations for plant growth. Now that CO_2 concentrations are beginning to recover to more optimum levels for growth, other nutrients will have to increase to sustain the more vigorous growth of plants.

Which fertilizers are needed to maintain a high nutritional value of crops depends on local conditions. With a few exceptions, like very young volcanic soils, naturally humid regions have less fertile soils than drier regions because essential minerals are leached out of the soil by rain and are carried by runoff to streams and eventually to the oceans. Some minerals, like nitrogen, phosphorus and potassium, are needed in large, "macro," amounts. Other equally essential minerals like iron, zinc, manganese, copper or iodine, are needed in only trace, "micro," amounts. All nutrients, whether macro or micro, are subject to Liebig's Law of the Minimum.

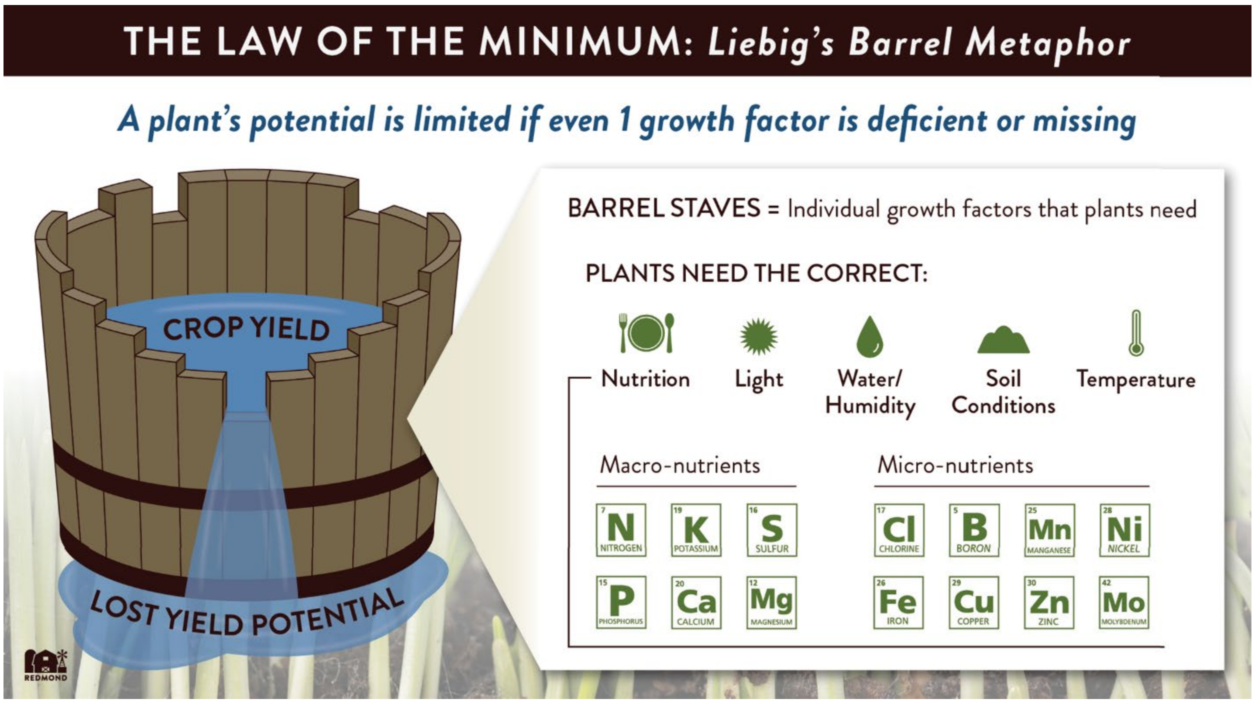


Figure 4: Liebig's barrel [18]. The yield of a crop is constrained by the scarcest nutrient or growth factor. Note that one of the three most important growth factors or nutrients, CO_2, is not illustrated along with the other two, sunlight and water. At the time of Liebig's pioneering work, in the mid 1800's, the CO_2 supply was seen as constant, and not something that could be influenced by humans.

Plant Growth in Enhanced CO_2 (eCO_2)

It is common knowledge that CO_2 is the sole source of carbon atoms in photosynthesis, where it is combined with water molecules (H_2O) to make simple sugars. These are then used to generate thousands of organic molecules, some of them exceedingly complex. In fact, CO_2 is the only source of the chemical element carbon for all life on Earth -- be it for plants, animals or fungi and bacteria -- through photosynthesis and food chains. Even chemotrophic microorganisms living, for example, in hydrothermal vent communities in the dark depths of the oceans [19] where no sunlight penetrates use CO_2 as their carbon source. On a dry weight basis, all biomass consists of almost 50% carbon. Therefore, CO_2 is clearly the most important nutrient of life. As explained later, CO_2 is, however, deficient in nature.

The increase of CO_2 since the beginning of the industrial era has greatly benefited plants of all types, including agricultural crops and entire ecosystems. This includes (i) > 30% increase in terrestrial Gross Primary Production as reported by Campbell *et al.* (2017) [20] and Haverd *et al.* (2020) [21]), (ii) higher leaf area index, that is, greening of parts of the vegetated terrestrial surface as published by Zhu *et al.* (2016) [22] and NASA (2016) [23], (iii) desert greening as shown in Fig. 5, (Donohue 2015) [24], (iv) a decrease in Global Bare Ground Cover by 3% since 1982 as reported by Song *et al.* (2018) [25], (v) and many more beneficial impacts as summarized by Goklany (2015) [26] and Idso and Moore (2019) [27]. Recently, Chen *et al.* (2024) [28] confirmed the ongoing greening of the Earth and found the increase of CO_2 to be the dominant driver of the positive so-called Leaf-Area-Index-trend on most of the global land surface.

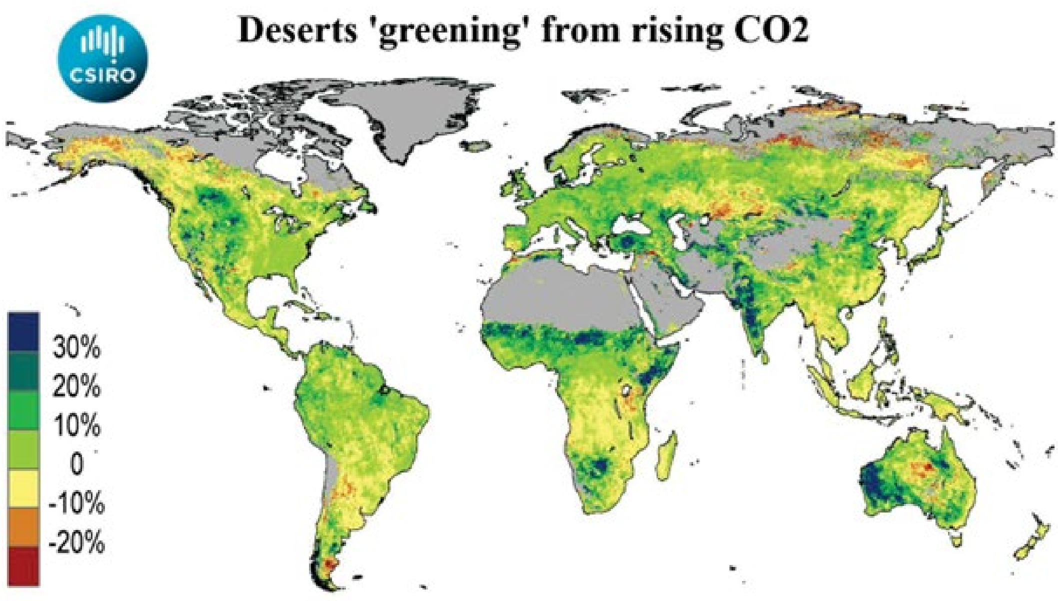


Figure 5: The greening of planet Earth because of increased concentrations of atmospheric CO_2. Donohue/CSIRO (2015) [24]. This was determined from satellite data recorded between 1982 and 2012. Note greening by 20-30% in India, West Australia, the Sahel zone in Africa and the Anatolian highlands (Turkey).

Enhanced plant growth due to eCO_2 is generally accompanied by a reduced concentration of nutrient minerals in the plant tissue. Loladze (2014) [29] performed a meta-analysis of 7,761 observations, including 2,264 observations at state-of-the-art FACE (free-air CO_2 enrichment) centers, covering 130 species/cultivars and 25 minerals. He observed an average decline of mineral concentration by about –8% under eCO_2, typically at 550 ppm (95% confidence interval −9.1% to −6.9%). The meta-analysis statistics reveal that this shift is systemic and global. Increases in mineral concentration under eCO_2 were rarely observed and had (very) low statistical significance, see Loladze (2014), Fig.1 [29]. Therefore, these values can be safely considered as outliers.

The observed decline in mineral concentration under eCO_2 has logically been interpreted as a dilution effect due to enhanced photosynthetic activity producing more non-structural carbohydrates, like sugar and starch, as well as structural carbohydrates like cellulose and hemicellulose. On the other hand, the content (total acquisition per plant or per unit area) of the various minerals continues to increase as plants grow more vigorously under eCO_2. This is an identical pattern (higher content but less concentration of the various nutrients) to what is routinely observed (under ambient CO_2) in growing plants as their physiological stage advances and the plant gets older. An example of the decline of nitrogen concentration in winter wheat is shown in Fig. 6. Note that the differences in nitrogen (N) concentration are greater between growth stages than between different N-supply levels.

Ferguson (2024) [30] estimated the influence of associative factors on the yield per hectare for eight major cereal crops (Barley, Maize, Millet, Oats, Rice, Rye, Sorghum, Wheat) using a SAS regression model (Statistical package for Agricultural Sciences). He used worldwide statistical data provided by the FAO (Food and Agriculture Organization of the United Nations) from 1961 to 2019 [31]. The associative factors analyzed were Nitrogen Fertilizer Intensity, moisture class of the countries' climate, temperature anomaly across the years, mean CO_2 concentration (Mauna Loa – data, NOAA) and year (which served as a proxy for unidentified agronomic practices that influence yield, such as hybrid selection, technical advances in agronomic practices, biocide application, and other fertilizer application such as phosphorus and potassium). He found a total increase of average yield (over all observed cereals and 156 countries) in the 59 years of observation of 1853 kg ha^{-1} to which the rise of CO_2 by 94 ppm contributed 26.5% (or 499 kg ha^{-1}), or a linear yield efficiency of 5.31 +/- 1.24 kg ha^{-1} per 1 ppm of CO_2 increase, respectively.

In this context, it is important to mention that cereal varieties with higher yield potential react with considerably higher yield increases to eCO_2 than low-yielding varieties (Ainsworth and Long (2021) [32]). We can expect more efficient cereal varieties to emerge over time as plants are exposed to the hidden selection pressure of gradually increasing concentrations of CO_2.

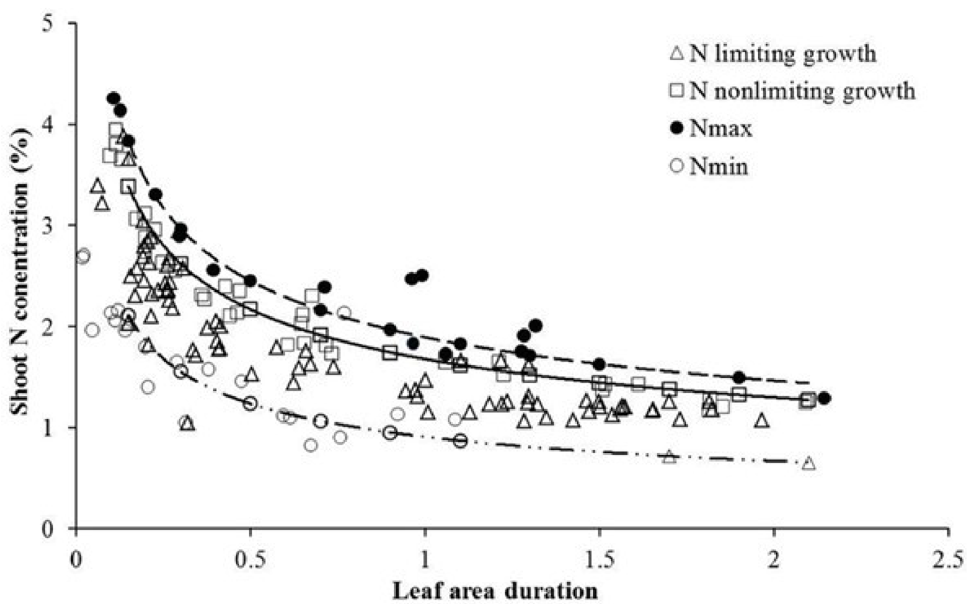


Figure 6: Nitrogen concentration dilution curves for winter wheat as the growth stage advances, described as leaf area duration, for different nitrogen supply levels (open circles: no nitrogen fertilization). Leaf area duration is the integral of leaf area over the growth period and comprehensively incorporates the size of photosynthetic area and the duration of photosynthetic activity and is therefore an indirect measure for cumulative dry matter formation. The natural N-dilution in the plant tissue as the plants mature and develop more structural fiber is too great to be compensated with N fertilization even at the highest N-level (375 kg N ha^{-1}), Wang et al. (2017), Fig. 2 [33].

As far as the current nutrient concentrations of protein and minerals for major cereal crops are concerned, they are extremely variable in nutrient composition in the grains. Local conditions, soils, water availability, cultivar, and agronomic practices all contribute to this variation. According to Ferguson (2024) [30], the changes reported to occur under eCO_2 fall well within the current ranges reported by NASEM (2021) [34] and Feedipedia [35]. Therefore, the nutrient content of crops grown under eCO_2 is not likely to exacerbate the nutrient imbalances across the globe, which are associated with an insufficient diversity of food groups and a lack of nutrient supplements.

The decline in mineral concentration and the increase in mineral content under eCO_2 do vary in their extent, depending on the type of mineral, the plant species etc. It is common knowledge that many factors influence the mineral content of plants. These include nutrient availability in the soil, chemical fixation and mobilization processes, root exudates, mycorrhiza, soil water potential, transpiration rate, resistance to the nutrient flow in the soil and the root cortex, active and passive absorption and transportation mechanisms of minerals (in the xylem and phloem), general stress conditions of the plant, incorporation of nutrients into the metabolism or deposition of minerals, e.g., in the cell vacuole, Rengel (2023) [36]. The complexity of plant nutrient acquisition and transportation might explain the diverse observed responses to eCO_2 which ranged from zero to strong negative effects on mineral concentration, as reported by Broberg *et al.* (2017) [37].

Besides the obvious dilution effect mentioned above, another contributor to reduced plant mineral content is the reduced transpiration of water caused by the reduction of stomatal conductance, of plants growing in eCO_2, as published by Soussana and Hartwig (1995) [38], Ainsworth and Long 2004)[39], Taub and Wang (2008) [40], McGrath and Lobell (2012) [41], and Kimball (2016) [42]. Fig. 7 shows the strong inverse correlation between stomatal conductance and water use efficiency (WUE). Transpiration of water might be reduced by up to 30% by eCO_2. The combination of a higher photosynthetic activity and lower transpiration due to eCO_2, along with a CO_2-induced reduction of photorespiration (see Lim et al. (2020) [43]), inevitably improves “water use efficiency,” (WUE), or “instantaneous transpiration efficiency,” or “crop water productivity” in plants, as reported by Eamus (1991) [44], Allen et al. (2011) [45], Keenan et al. (2013) [46], and Deryng et al. (2016) [47]. In addition to inducing a higher WUE, eCO_2 also stimulates root growth for improved access to sub-soil water (see Uddin et al. (2018) [48]), both of which can dramatically increase wheat yields in semi-arid environments and buffer against heat waves, as suggested by Fitzgerald (2016) [49]. Ainsworth and Long (2004) [39] have also reported an increase in photosynthetic light use efficiency by eCO_2.

It is obvious that lower transpiration will also reduce mass flow in the soil towards the roots as well as nutrient accumulation in shoots through diminished translocation via the xylem sap, see Gifford et al. (2000) [50]. As this applies also for nitrate, the most common nitrogen source in the soil, it is not surprising that energy-demanding nitrate reductase activity is down-regulated in the leaves as the substrate (NO3−) concentration is reduced, see Gojon et al. (2022) [51].

In addition to a reduction in the mineral concentration in plants, there are also reports of an impairment of the carotenoid metabolism by eCO_2, see Loladze *et al.* (2019) [52]. A more than doubling of the CO_2 supply to tomatoes led to a reduction in the carotenoid concentration in the plant tissue of up to one third, as reported by Boufeldja *et al.* (2022) [53]. Carotenoids are a precursor of vitamin A. In parts of southeast Asia and Africa, where carotenoid-free white rice is a major part of the diet, vitamin A deficiencies are already common. Further reductions of vitamin A would exacerbate an already serious problem. However, the use of golden rice, which is rich in carotenes and an excellent source of vitamin A, would quickly correct this nutrient deficiency [54]. Unfortunately, demonization of golden rice, much like the demonization of CO_2 by extreme environmentalists, has hindered its adoption in countries where it is most needed.

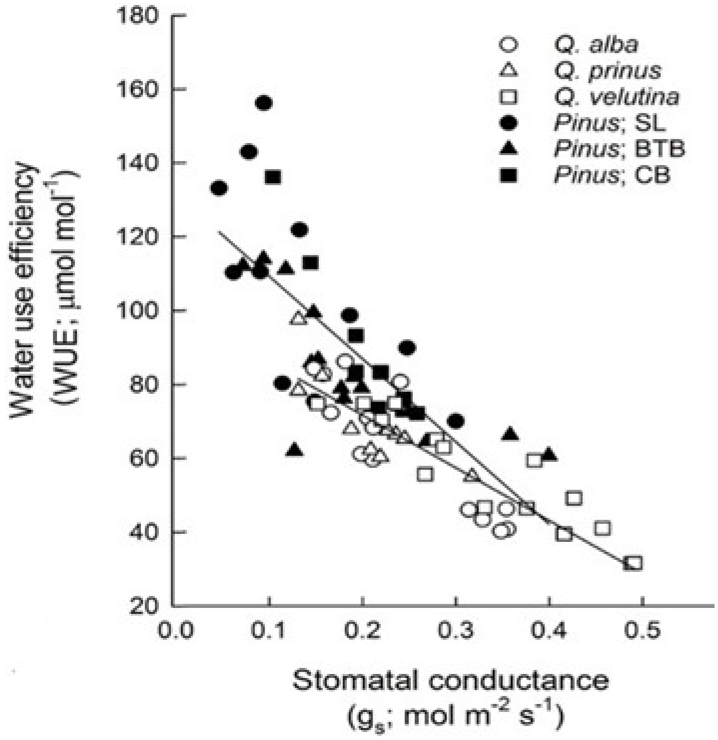


Figure 7: Inverse correlation between water use efficiency (WUE, µmol CO_2 captured per mol H_2O lost), and stomatal conductance (gs; mol H_2O m^{-2} s^{-1}) for oaks (Quercus, y = −143 x +100.3; r^2 = 0.79) and pines (Pinus, y = −224 x +131.6; r^2 = 0.54), Renninger et al. (2013), Fig. 3, adapted [55]. In this experiment, the reduction of stomatal conductance was drought induced. However, we also observe a reduced stomatal conductance under eCO_2, when a higher photosynthetic rate even more enhances water use efficiency.

In plant metabolism carotenoids play a role in the photosynthesis apparatus in that they protect chlorophyll from photo-oxidation. As the photosynthetic activity is significantly increased under eCO_2, downregulating the biosynthesis of carotenoids could be a resource-saving measure for plants, as fewer carotenoids might be needed to maintain the same level of photosynthesis. While eCO_2 can somewhat suppress the content of major nutrients and carotenoids, it may have a favorable impact on the accumulation of carbon-based phytochemicals in food crops. *"Elevated CO_2 and nitrogen-limiting conditions have been known to favor the accumulation of carbon-based secondary metabolites which have a key role in healthfulness of food crops and in plant defense against herbivory in many species. While the effect of elevated CO_2 on the health-promoting phytochemical accumulation in food crops is variable, a great number of studies support the fact that elevated CO_2 may favor the accumulation of carbon-based phytochemicals. Thus, although elevated CO_2 can diminish the contents of major nutrients, it may enhance certain groups of health-promoting phytochemicals in food crops,"* Rajashekar (2018) [56]. Boufeldja *et al.* (2022) [53] also conclude that eCO_2 can produce a decrease of nutritional potential but at the same time an increase of properties beneficial to health through the enhanced biosynthesis of antioxidant and anti-inflammatory compounds.

In legumes the reduced N assimilation due to the reduced NO_3^--uptake and the down-regulated nitrate reductase activity is compensated for by an increased N fixation activity in the nodules as reported by Guo *et al.* (2013) [57] and Jin *et al.* (2019) [58]. Nitrogen fixation depends on the energy supply from the respiration of non-structural carbohydrates, like sugars and starch, which are photosynthesized in abundance under eCO_2, as published by Taub and Wang (2008) [40] and Loladze (2014) [29]. It is for this reason that legumes generally do not suffer from a reduced N-acquisition or even from reduced N-concentration in the plant tissue despite increased biomass production under eCO_2, as reported by Ainsworth and Long (2004) [39] and Guo *et al.* (2013) [57]. For soybeans, Li *et al.* (2017) [59] found that increased yield in response to eCO_2 correlated highly ($r^2 = 0.95$) with an increase in symbiotically fixed nitrogen between the initial seed filling stage and full maturity, as shown in Figure 8. In contrast, eCO_2 only led to small increases in the uptake of fertilizer-derived and soil-derived N, and these increases did not correlate with enhanced yield.

Feng *et al.* (2015) [60] explored the ecosystem-scale relationship between responses of plant productivity and nitrogen acquisition to eCO_2 in free-air CO_2 enrichment (FACE) experiments in grassland, cropland and forest ecosystems. They found that in all three types of ecosystems, this relationship was positive, linear and strong ($r^2 = 0.68$) but exhibited a negative intercept such that plant acquisition of N was decreased by 10% when eCO_2 caused neutral or modest changes in productivity. Whenever plants hardly react or do not react at all with increased productivity to the supply of a deficient nutrient, this reliably indicates -- according to Justus Liebig's minimum law -- that another nutrient or another growth factor such as light, water (drought or waterlogging) or temperature (too high or too low) is limiting plant growth. It is not surprising that a plant (community) under stress can only provide inadequate metabolic performance and may react unpredictably to environmental changes (including eCO_2). This is in line with Feng et al. (2015) [60] who found a higher response to nitrogen fertilization in stress-free plants under eCO_2.

Elevated CO_2 does increase the C/N ratio in non-leguminous plants and plant residues, without external addition of nitrogen fertilizer, owing to enhanced photosynthesis of carbohydrates, as suggested by Runion *et al.* (1999) [61], Gill *et al.* (2002) [62], Taub and Wang (2008) [40], and Loladze (2014) [29]. This could promote temporary N-immobilization which might also reduce the availability of soil nitrogen. In addition, an increased N demand for the decomposition of plant residues with a large C/N ratio will result, under elevated CO_2, in a larger nitrogen sink of the whole ecosystem, as suggested by Soussana and Hartwig (1995) [38]. However, as both the percentage and the amount of fixed N increases for legumes grown under elevated CO_2, and the contribution of fixed N to the nitrogen nutrition of co-occurring non-legumes also improves (Soussana and Hartwig (1995) [38], Lee *et al.* (2003) [63]) in the long run, over entire ecosystems and at a global scale, the nitrogen supply to plant communities and soils seems to catch up under eCO_2. While there are reports of a higher soil organic matter mineralization rate (Hasegawa *et al.* (2016) [64]) and of little or no change in soil carbon pools under eCO_2 (Ross *et al.* (2004) [65], and van Groenigen *et al.* (2017) [66]) in many ecosystems an increase of not readily degradable soil organic carbon (SOC) due to higher above-ground and below-ground biomass under increasing CO_2 is expected and has been shown (e.g., by Scurlock and Hall (1998) [67], Smith (2006) [68], Eclesia et al. (2012) [69], Kell (2012) [70], Grüneberg *et al.* (2014) [71], Chambers *et al.* (2016) [72], Jonard *et al.* (2017) [73], Xu *et al.* (2018) [74], Viglizzo *et al.* (2019) [75], and Koyama *et al.* (2019) [76]).

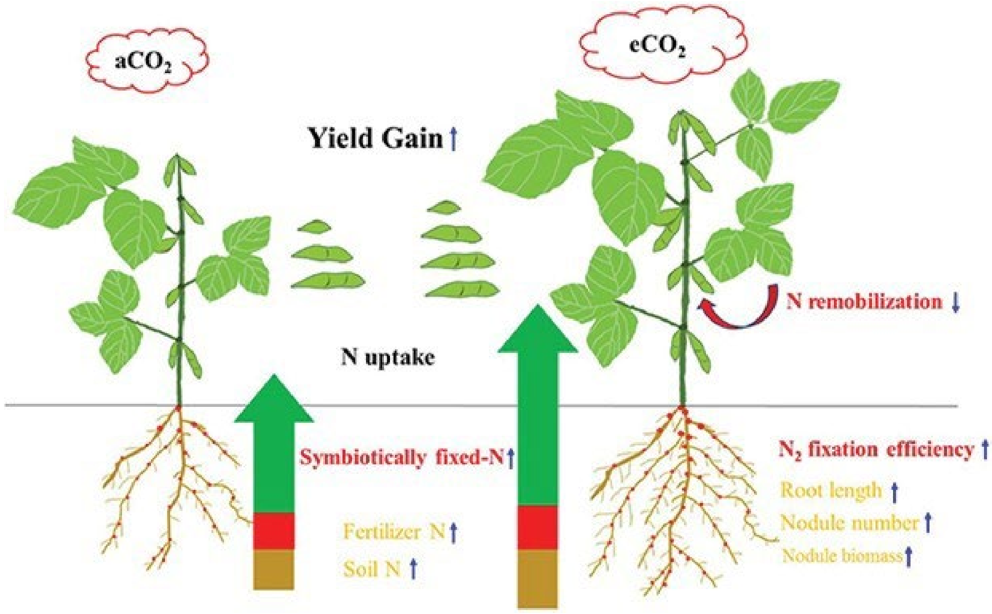


Figure 8: Diagram illustrating the N origins, root morphology, N remobilization, and yield gain of soybean in response to elevated CO_2 (eCO_2 at 550 ppm) as compared to ambient CO_2 (aCO_2 at 390 ppm). The measurements that were significantly correlated with yield gain ($P < 0.05$) are indicated in red-bold, while the measurements responding to eCO_2 but not correlated with yield gain are shown in orange. Upward and downward arrows indicate increase and decrease under the eCO_2 condition, respectively (Li et al. (2017), Fig. 7 [59])

Given this premise, it is plausible and has been partly demonstrated that nitrogen also is steadily increasing in the world's ecosystems. Enhanced photosynthesis, due to eCO_2, of non-structural carbohydrates like sugars and starch, which are readily broken down by respiration by all kinds of primary and secondary consumers, and of reasonably easily degradable structural carbohydrates, such as pectin and cellulose, leads to greater energy-requiring nitrogen fixation in legumes and soils on an ecosystem level (Guo et al. (2013) [52], Ainsworth and Long (2004) [39], Feng et al. (2014) [60], and Koyama et al. (2019) [76]).

Furthermore, the easy degradability of most carbohydrates gives us reasons to assume that the general turnover rate of carbohydrates is higher than that of nitrogen compounds at a global level. According to Zheng et al. (2020) [77], global mean Gross Primary Production between 1982 and 2017 was about 106 Pg C yr^{-1} with an annual increase of about 0.15 Pg C yr^{-1} due to rising CO_2. Given a total of atmospheric carbon of about 750 Pg (in the form of CO_2), this means an enormous annual turnover of about one-seventh of total atmospheric CO_2 through photosynthesis and respiration.

Ammonia liberated from biomass degradation (mineralization) is much less volatile. At a global scale, losses by NH_3 volatilization do not occur, as it will be washed back eventually into the soil or the oceans by rainfall. The only major pathway for nitrogen compounds to be recycled to elementary N_2 is denitrification. Large scale denitrification in soil requires a location with alternating aerobic and anaerobic conditions. Nitrification takes place and nitrate is produced by oxidizing ammonia in aerobic soils. In anaerobic soils, nitrate serves as an electron acceptor to be finally reduced to N_2. This latter process requires easily degradable carbohydrates as an energy source.

In summary, it is unlikely that the Earth's biosphere will be depleted of nitrogen in an eCO_2 atmosphere. To the contrary, there are reasons to believe that over time extra CO_2 has caused an increase of nitrogen in the biosphere. Li et al. (2012) [78] found a significant correlation between soil carbon and nitrogen stocks following afforestation in a global meta-analysis. This correlation is corroborated by satellite images -- like that of Fig. 5 -- which show a greening of the Earth due to increasing CO_2. The greening is caused by more chlorophyll, a molecule where a Mg++ ion is held by 4 nitrogen atoms in a porphyrin prosthetic group surrounded by a large photosynthetic apparatus, consisting of nitrogen-containing protein enzymes. So, there is good reason to assume that our CO_2 emissions since the beginning of industrialization have not only increased CO_2 in the atmosphere and therefore photosynthetic activity of the vegetation cover but also increased the nitrogen content of the biosphere. The noticeable increases in atmospheric nitrogen deposition generated by the worldwide expansion of industry and agriculture likewise contribute to this development, as suggested by Zhu et al. (2017) [79].

The more-or-less native ecosystems of the Earth do not seem to suffer from a greater deficiency of nitrogen than in pre-industrial times. To the contrary, today the Earth's vegetation cover has a higher leaf area index, in accord with Fig. 5, and has become greener under increasing CO_2 (Zhu et al. (2016) [22], Chen et al.(2024) [28]). This indicates a greater nitrogen content of the vegetation. Any experienced cereal producer can judge the adequacy of nitrogen by the dark or light green color of the cereal crop. Also, in relation to the extended rangelands and grasslands on large proportions of the Earth's land surface no additional nitrogen deficit problem is likely to occur in the long run due to gradually rising CO_2, particularly when there are co-occurring legumes, as suggested by Soussana and Hartwig (1995) [38], Lee et al. (2003) [63], Guo et al. (2013) [57], and Koyama et al. (2019) [76]. In any case, grazing animals try to compensate for any nutritional deficiencies by making use of their "nutritional wisdom", for example, by selective browsing of higher quality leaves or legumes (Glatzle (1990) [80]). Furthermore, there are economical means for cattle herders and managers of low-intensity grazing systems to help compensate for possible protein deficiencies. Ruminants can synthesize protein themselves through their rumen bacteria when they have a sufficient energy supply and access to a suitable nitrogen source such as urea-molasses lick blocks or even ammonium-rich chicken manure.

In efficient modern agriculture, huge quantities of nutrients, and especially nitrogen, are extracted with each harvest. So, nitrogen remains the most deficient nutrient, the shortest stave in Liebig's barrel, with the highest yield response. Whenever cropping has been intensified in the past and yields rose, the nutrients removed with the harvest had to be replaced. Since Malthus' times, average cereal yields in Central Europe rose about tenfold. To maintain these high yields and satisfactory nutritional values, mineral fertilizers were used intensively, in accordance with Liebig's fundamental findings. Modest extensions of these routinely practiced and constantly perfected uses of fertilizer will ensure that there will be still more abundant and nutritious yields from crops grown in eCO_2.

Indeed, commonly observed reductions in mineral concentration under eCO_2 are tiny compared to what nature, agriculture, livestock and humans cope with daily. In their long-term FACE study, Jin el al. (2019) [53] reported far more significant effects on nutrient concentrations in grain from soil conditions than from eCO_2. Under water shortage, irrigation leads to considerable yield increases. It is obvious that this has an enormous impact on mineral acquisition and concentration in the plants, as well as nutrient extraction and depletion in the soil. Similar effects on rangeland productivity and grass quality have been found by Breman and de Wit (1983) [81] along the rainfall gradient, from the Sahara via the Sahel to the West African Savanna, as shown in Fig. 9. More rain produces much more herbage, but the nitrogen (protein) concentration of the herbage decreases enormously due to nitrogen dilution in the plant tissue and nutrient leaching from soils in a wetter (more humid) climatic zone.

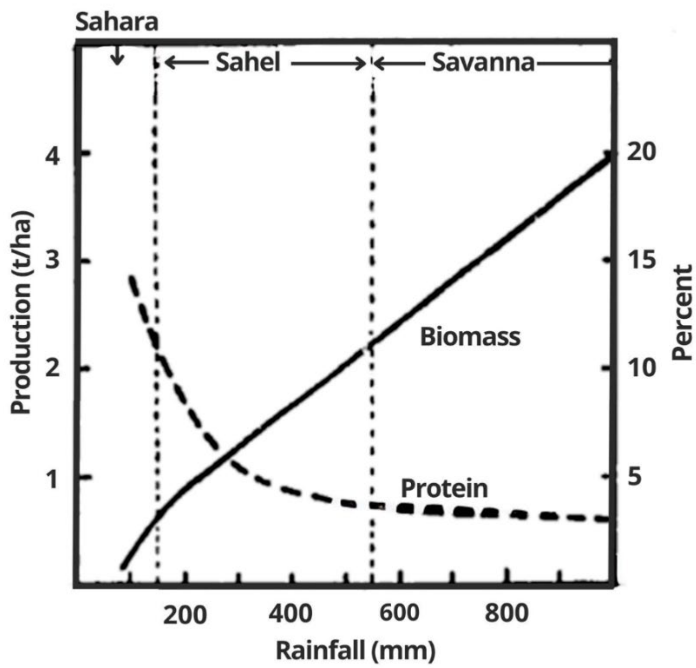


Figure 9: Mean rangeland production (tons of above ground dry matter ha^{-1}) and the protein content in the biomass (percentage at the end of September) in relation to mean annual rainfall along the gradient from the Sahara, via the Sahel to the West African Savanna. Note the enormous increase in biomass production along with a decline of protein content as the most deficient growth factor, rainwater, gets less and less limiting, and the soils get poorer in the average. This is a natural phenomenon, with little, if any, human influence, Breman and de Wit (1983), Fig. 3 [81].

For more than 100 years, modern agricultural and nutrition technologies, most importantly mineral fertilizer, improved crop varieties, as well as nutrient supplements have been used to compensate for mineral and other deficiencies in soils, food and animal feed. Those same technologies can ensure that large yield increases from eCO_2 will provide nutritious food for livestock and people. For many decades, it has been common practice to increase the yield of vegetables by growing them in greenhouses that are highly enriched with CO_2. This provides high quality food at affordable prices for millions of consumers. Yes, flawless, mass-produced tomatoes or cucumbers from greenhouses rarely have the unique flavor of the heirloom varieties that our grandparents grew in backyard gardens. Nonetheless, we are unaware of complaints about nutritional deficiencies in these greenhouse-grown vegetables, nor is there a reason to expect any.

CO_2 and Climate History

Although the focus of this paper is on the nutritional value of crops grown in enhanced CO_2 concentrations (eCO_2), we include two more sections because some readers may not be familiar with the geological history of plants and atmospheric CO_2 or of how little even large changes of CO_2 concentrations affect the thermal radiation emitted by Earth to space.

Geological history is relevant to how the nutritional value of plants will be affected by more CO_2. Abundant plant fossils first appear when there were much greater concentrations of CO_2 than those of today, or than those of the next few centuries if human society continues the rational use of fossil fuels. It is generally accepted that the CO_2 content of the atmosphere was very high in the early era of Earth's geological history (Archean). Oxygen (O_2) was nearly absent. About 3 billion years ago, cyanobacteria (Demoulin et al. (2019) [82]) developed the first form of oxygenic photosynthesis, where the energy of sunlight is used to synthesize organic matter from CO_2 and H_2O, resulting in the release of waste O_2 to the atmosphere. Due to burial in sediments, the fixed carbon in dead organisms could not be oxidized by the O_2 in the air. So, the O_2 content of the atmosphere steadily rose over hundreds of millions of years as atmospheric CO_2 levels fell and fossil organic carbon increased in sediments.

When land plants with a relatively modern photosynthetic apparatus first appeared about 470 million years ago, the CO_2 content in the atmosphere was still around 5,000 ppm (more than ten times the current level). In the millions of years that followed, the atmospheric CO_2 content continued to decrease, with significant fluctuations. The fluctuations had little correlation with the considerable temperature changes during numerous, extended geological eras. Modern seed plants (angiosperms) appeared at the beginning of the Cretaceous period about 140 million years ago. At that time, the CO_2 content was still at least 5 times higher than today. From this point onwards, the CO_2 content declined continuously until it leveled off to its current order of magnitude around 2 million years ago (the beginning of the Pleistocene). The first primates appeared in the fossil record some 50 million years ago, with still relatively high CO_2-levels in the atmosphere. This history is summarized in Fig. 10.

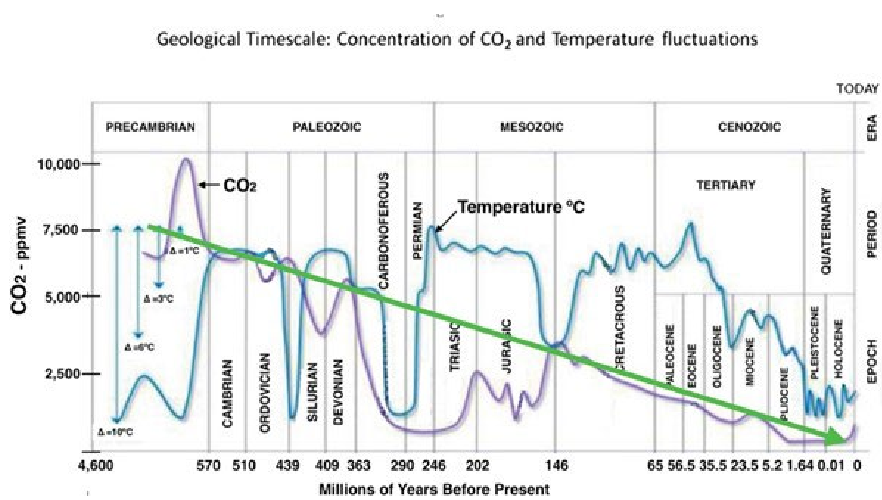


Figure 10: History of temperature and atmospheric CO_2 concentrations during the Phanerozoic eon, when abundant fossils first appear in the geological record. There is insufficient correlation between temperature (blue) and CO_2 concentrations (purple) to imply a cause-effect relationship. The systematic decline of average CO_2 concentrations during this time, indicated by the green line, has limited the productivity of plants, Moore (2016) [83].

For the last 720,000 years, the CO_2 content (averaged by nature over several decades) can be determined relatively accurately from air inclusions in ice cores obtained from Antarctica and

Greenland. An example is shown in Fig. 11. This was the period in which continental glaciations, lasting almost 100,000 years, alternated with warmer interglacial periods lasting about 10,000 years. Mean temperature differences between continental glaciations and interglacial periods were considerable – up to 12 °C. During the last glacial advance, the regions where Hamburg or New York are located today were at least one mile under ice. “Findlinge” or glacial erratics can be found in northern Germany today. These are rocks from the Scandinavian mountains that were transported by glaciers and deposited close to Hamburg. The sea level fluctuated by at least 400 feet (120 m) between glacial and interglacial periods, just to give an idea of the magnitude of the effects of these natural climate changes.

The most recent glacial maximum ended only 18,000 years ago, and the relatively stable climate of the Earth over the past 10,000-year interglacial period is an exception to the much more unstable climate that characterizes most of Earth’s geological history. The enormous temperature fluctuations of the past 2.6 million years or so are believed to have been triggered by Milankovitch cycles [84]. These result from the precession of the Earth’s spin axis (axis of rotation), the inclination (obliquity) of the Earth’s spin axis to the axis of orbital precession around the Sun, the eccentricity (non-circularity) of the Earth’s orbit and the intensity of solar radiation (solar forcing). The orbital parameters change with time due to gravitational interactions with the Moon, Jupiter and other planets. This results in complicated cyclic variations of the solar energy Earth receives at various latitudes and seasons. The cycle periods range from as short as 26,000 years for the precession of Earth’s spin axis to a hundred thousand years or more for changes in the ellipticity.

The mean CO_2 concentration of the atmosphere was about 280 ppm during the warm interglacial periods and about 180 ppm during the glacial maxima, not far above the threshold of 150 ppm where plants begin to starve from inadequate CO_2 (Temme (2019) [86]). During the younger Pleistocene when periods of continental glaciation alternated with warm interglacials, a strong correlation between CO_2 and temperature can be seen in Fig. 11.

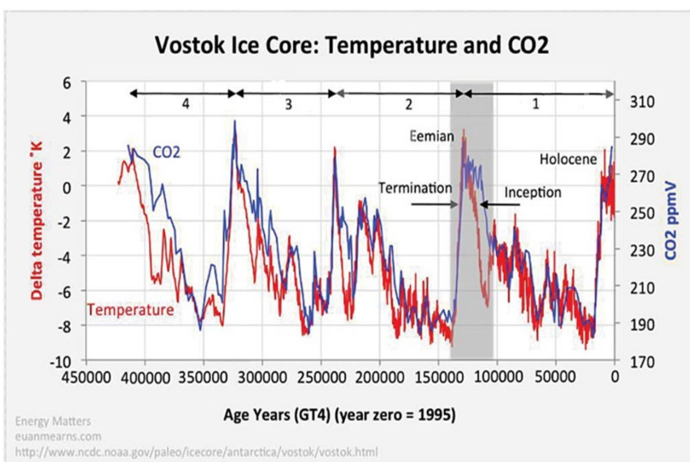


Figure 11: Temperature (red) and atmospheric CO_2 concentration (blue) during the late Pleistocene, as determined by analyses of East Antarctic ice cores [85]. Temperature changes are inferred from variations of the fractions of the oxygen isotope 18O in the ice. Atmospheric CO_2 changes are inferred from variations in the composition of air bubbles. Glacial maxima alternate with warmer interglacial periods. The fluctuations seem to be driven by changes of the tilt and orientation of Earth’s spin axis and by changes of its orbital eccentricity, as first suggested by Milutin Milankovitch in the early 20th century [84]

However, the temperature increases or decreases always preceded the CO_2 increases and decreases by several centuries. An example is shown in Fig. 12. The colder oceans absorbed more CO_2 and the warmer ocean outgassed more CO_2. This alternating retention and release of CO_2 by the oceans determined the CO_2 content of the atmosphere. The change of CO_2 concentration was therefore always the result and not the cause of the temperature change (Caillon et al. (2003) [87], Koutsoyiannis et al. [88]).

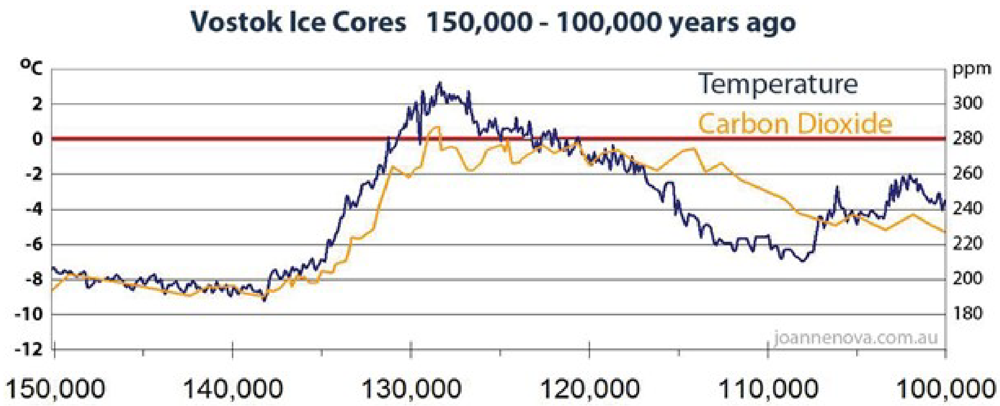


Figure 12: Proxy temperature and CO_2 from Vostok Ice Cores 150,000 – 100,000 years ago, redrawn from J. R. Petit. et al. (1999) [89] by J. Nova [90]. Changes in CO_2 concentration follow changes in temperature, not vice versa, so the orbital changes first affect temperature. Increasing or decreasing temperatures then cause CO_2 concentrations to increase and decrease, probably as a result of warming or cooling of the oceans.

The present warm, interglacial period (Holocene) began around 10,000 years ago. Estimated changes of temperature during the Holocene are shown in Fig. 13. During this period, CO_2 concentrations were low (between about 260 ppm and 270 ppm) by the standards of geological history shown in Fig. 10 until the mid-19th century (Alley (2000) [91], Alley (2004) [92]). Then CO_2 concentrations began to increase by much more than the small (a few ppm) increases and decreases recorded from bubbles in ice cores for the previous 10,000 years. It is natural to ascribe most of the recent increase of atmospheric CO_2 to the greatly increased burning of fossil fuels that began with steam engines and the Industrial Revolution after 1800. As we write this in the year 2024, CO_2 concentrations measured at the Scripps Mauna Loa Observatory are about 420 ppm. There is good evidence that there has been a modest warming of the Earth since the year 1800, and climate alarmists have been quick to ascribe all this warming to the increase of CO_2 from human activities.

But there is a serious problem with this narrative. As shown in Fig. 13, during the past 10,000 years there have been many similar warmings, as large or larger than the current one, when there was very little change in the atmospheric concentrations of CO2. During the Medieval Warm Period, Norse settlers established successful farms in the southern part of Greenland, where they grew grain and raised cattle. During the Roman Warm Period, Hannibal traversed the almost ice-free Alps with his elephants.

During the Minoan Warm Period, the great antique civilizations of Crete and Egypt reached peaks of prosperity. In fact, ancient tree trunks preserved and recovered well above modern days' tree lines in the Alps (Fischer and Patzelt (2018) [93]), in Alaska [94] and other glacial areas around the world are clear evidence of many periods during the Holocene that were warmer than today but had lower concentration of CO2. Most notable was the Holocene Climate Optimum during the Early and Middle Neolithic (Kalis (2003) [95]).

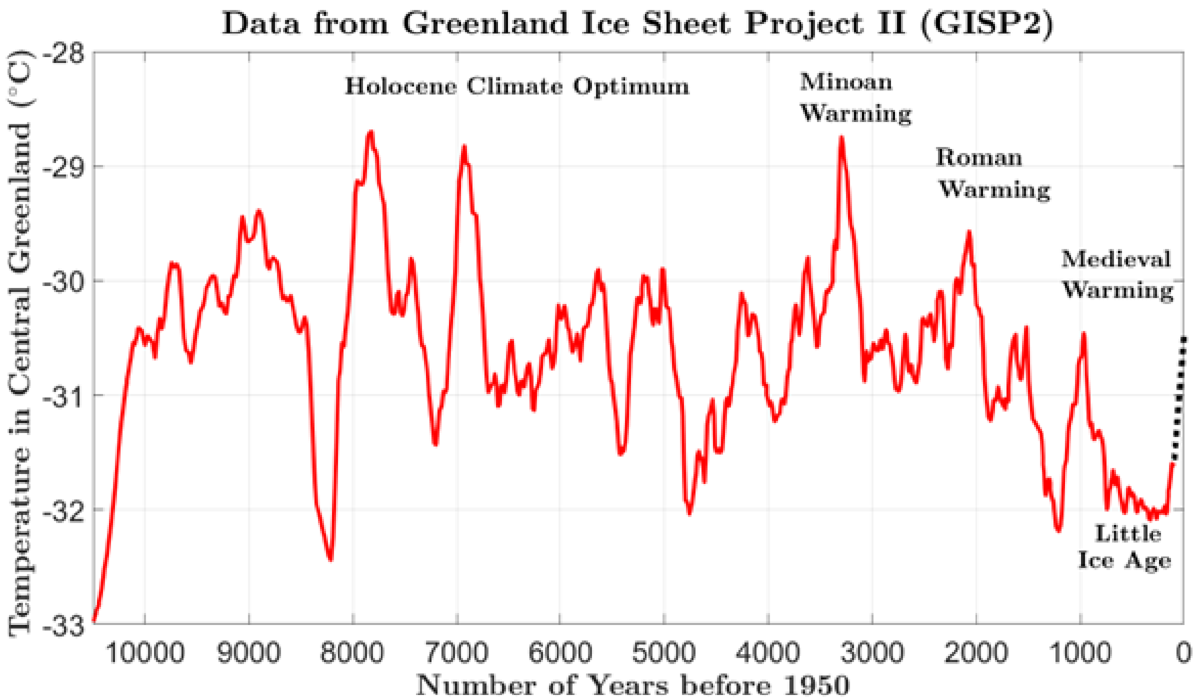


Figure 13: Estimates of the temperatures in central Greenland during the current interglacial period up to the year 1855. Even during this relatively stable climatic period, there are relatively large century-to-century variations of temperature. The large temperature variations could not have been caused by CO_2, since ice core bubbles show that CO_2 concentrations varied by no more than a few percent until about the early 1800s when a rapid increase of atmospheric CO_2 concentrations coincided with the use of fossil fuels. The estimated 1.1 °C temperature increase since 1855, shown as the black dotted line, does not differ from past temperature changes in either magnitude or duration. (Alley (2000) [91], Alley (2004) [92]). Based on Alley (2000) [91], the "present" time in the data refers to 1950. Because the data only go as far as about 95 years before the "present", then, taking the difference, the data go only as far as 1855.

The Medieval Warm Period was followed by substantial cooling which led to the Little Ice Age and to the final abandonment of Norse settlements in Greenland in the mid-1400s. The Little Ice Age, from about 1250 to 1850, was not a good time for humanity in northern Europe, where crop failures and plagues decreased the population by nearly 50%. During that period, somewhere between 200,000 and 500,000 people, 85% women, were cruelly executed as “witches” in Continental Europe (Ben-Yehuda (1980) [96]). They were blamed for bad weather and poor harvests. The end of the Little Ice Age (when Christmas markets in London used to be held on the frozen Thames) coincided more or less with the beginning of the industrial era.

Trivial climate effects of more CO_2

Many people point to the continuous rise of CO_2 since the start of the Industrial Revolution as the cause of the modest warming during that time. But "correlation is not necessarily causation!" Much of the warming has probably been due to natural processes after the end of the Little Ice Age. The current warming in no way differs from the many warmings and coolings that have occurred throughout the Holocene (Fig. 13). The greenhouse gas CO_2 has probably contributed some of the warming of the past 170 years, but it has certainly not been the primary cause. The (rather poor) correlation between CO_2 and temperature rise is the dominant justification for today's misguided climate policy in many countries. Apparently, in order to "save the planet," governments will be obliged to control all areas of people's lives and force them to minimize their "carbon footprint." But as we have outlined above, more CO_2 brings great benefits to agriculture and forestry. And as we will briefly review in this section, the effects of CO_2 on climate will be trivial compared to the natural fluctuations that have characterized Earth's climate throughout geological history and will continue to do so in the future. However, proposed policies to combat this nonexistent threat from greenhouse gases are bad news for those who still believe that every person has an inalienable right to "life, liberty and the pursuit of happiness."

Because of fundamental radiation-transfer physics, it is hard to make a persuasive scientific case that more CO_2 will cause harmful warming. The basic reason is "saturation" of the effects of CO_2, a phenomenon illustrated in Fig. 14, which shows the spectra $\langle\tilde{Z}\rangle$ of the thermal radiation emitted by Earth to space (van Wijngaarden and Happer (2022) [97]). The jagged black curve is the calculated spectral flux at a CO_2 concentration of 400 ppm, close to the concentration of 420 ppm at the time we are writing this paper. Fluxes measured from satellites can hardly be distinguished from the black curve of Fig. 14. The areas under these curves,

$$Z = \int_0^\infty \langle\tilde{Z}\rangle d\nu \qquad (1)$$

are the total fluxes to space carried by radiation of all frequencies. These fluxes must dump the heat Earth has absorbed from sunlight back into cold space. The red, jagged curve is the spectral flux that would be emitted if CO_2 concentrations were "instantaneously" doubled to 800 ppm, with no changes of any other atmospheric properties like temperature, or the concentrations of other greenhouse gases. The flux difference, $\delta Z = 3.0$ W m^{-2} is called *"the instantaneous radiative forcing at the top of the atmosphere."* The relative forcing for doubling CO_2 concentrations, a 100% increase, is very small

$$\frac{\delta Z}{Z} = \frac{3}{277} = 1.1\% \qquad (2)$$

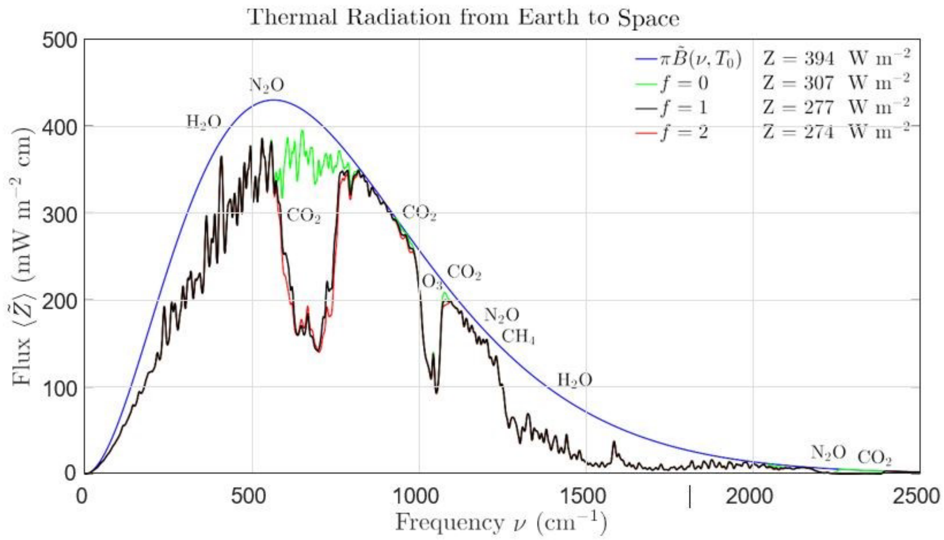


Figure 14: Representative spectra of radiative fluxes from Earth to space. The total fluxes Z of (1) are the areas under the curves. For no greenhouse gases at all, the flux Z would be the area under the blue curve, the Stefan-Boltzmann flux of $Z = \sigma T^4 = 394$ W m^{-2} for an assumed surface temperature of T = 288.7 K. This would be the cooling flux to space if the Earth's atmosphere had no greenhouse gases. Absorption and reemission of thermal radiation by the five most important greenhouse gases, near the frequencies marked for water vapor H_2O, carbon dioxide CO_2, ozone O_3, methane CH_4 and nitrous oxide N_2O, reduces the flux from 394 W m^{-2} to 277 W m^{-2}, a decrease of 117 W m^{-2}, to 70% of the initial value. Doubling the CO_2 concentration from the 400 ppm assumed for the black curve to 800 ppm, gives the red curve with a slightly smaller area of 274 W m^{-2}. This is a decrease of only $\delta Z = 3.0$ W m^{-2} or 1.1 % from the previous value.

To estimate the feedback-free warming we note that calculations like those of Fig. 14, done at absolute surface temperatures (in degrees Kelvin or K) somewhat larger or smaller than the value,

$$T = 288.7\,\mathrm{K} \tag{3}$$

used in the figure, show that flux depends very nearly on the fourth power of the temperature

$$Z \propto T^4 \tag{4}$$

The feedback-free temperature increase, δT needed to restore the 277 W m^{-2} of flux to space and stabilize Earth's temperature with the same solar heating is therefore given by

$$\frac{\delta T}{T} = \frac{1}{4}\left(\frac{\delta Z}{Z}\right) \tag{5}$$

Using the previous numbers, we see that the feedback-free warming should be

$$\delta T = \frac{1}{4} \times 1.1\% \times 288.7\,\mathrm{K} = 0.8\,°\mathrm{C} \tag{6}$$

The jagged green curve of Fig. 14 shows the modeled radiation to space if all the current 400 ppm of CO_2 could be instantaneously removed from the atmosphere. As can be seen from the legend, this would increase the radiation to space from the current 277 W m^{-2} to 307 W m^{-2}, a negative forcing 30 W m^{-2}. So, by starting from an atmosphere with no CO_2 and only the other naturally occurring greenhouse gases -- H_2O, O_3, CH_4 and N_2O -- and adding 400 ppm of CO_2, radiation to space decreases by a substantial 30 W m^{-2}, about 10%. But adding another 400 ppm of CO_2 to bring the concentration to 800 ppm, only decreases radiation to space by 3 W m^{-2}, a factor of 10 less. To decrease radiation to space by another 3 W m^{-2} would require another doubling of the CO_2 concentration to 1600 ppm, which would require an addition of 800 ppm. Every doubling of CO_2, for concentrations from about 1 ppm to 10,000 ppm, reduces the radiation to space by 3 W m^{-2}, a regularity first recognized by the Swedish chemist Arrhenius in 1896 [98]. Saturation does not mean that adding more CO_2 to the current atmosphere will have no effect; it means that there are "diminishing returns." The term saturation was first introduced in astrophysics, Gussman (1967) [99] to describe how the emission or absorption lines of atoms or ions radiated by stars change less and less as the densities of the emitting/absorbing species increase.

The Intergovernmental Panel on Climate Change (IPCC) touts much larger warmings the $\delta T = 0.8\ ^{\circ}C$ of (6), typically around $\delta T = 3\ ^{\circ}C$, or larger. These large numbers come from assuming huge (modelled, not measured) positive feedbacks. But most feedbacks in nature are negative, not positive, in accord with Le Chatelier's Principle, *"A change in one of the variables that describe a system at equilibrium produces a shift in the position of the equilibrium that counteracts the effect of this change"* [100]. Just one example: When a little heating (for whatever reason) causes more evaporation of water, the resulting water vapor (a greenhouse gas) could theoretically accelerate the heating. However, there are other aggregate states of gaseous water vapor: water droplets and ice crystals, into which more water vapor in the air readily transforms and thus sets in action the *"cloud-sunlight-reflectivity-thermostat-mechanism"*. In fact, all practical experience shows us that the atmosphere works like a thermostat and not like a warming accelerator.

We have no doubt some who promote ruinous social and economic policies to counter a nonexistent climate threat are sincere, if misguided. But *"the road to hell is paved with good intentions."* And it is worth remembering Upton Sinclair's famous and true remark: *"It is difficult to get a man to understand something, when his salary depends on his not understanding it"* [101]. With no sense of irony, Albert Gore used this quote in his book *"An Inconvenient Truth,"* where his lack of any real understanding of science is on full display.

SUMMARY

The significant enhancement of plant growth due to increasing CO_2 in the atmosphere is often accompanied by a slight dilution of some nutrients, notably nitrogen, in plant tissues if no attempts are made to make up for the increased demands for these nutrients with appropriate fertilizers. However, we have shown that the deficiencies in nutrients, and especially nitrogen, caused by eCO_2 are small, compared to the nutrient shortages that agriculture and livestock face because of natural phenomena, such as severe soil fertility differences, nutrient dilution in plants due to more rainfall or irrigation, and even in aging crops. These problems have been routinely dealt with for generations through adequate fertilization, proper species and cultivar selection, and food supplements for livestock and humans.

Other observed reactions to eCO_2 (such as reduced nitrate reductase activity, reduced photorespiration and reduced carotenoid biosynthesis) can be understood as a resource saving response mechanism of the plant metabolism. Generally, the additional inputs required for the correction of the nutritional deficits are tiny compared to the benefits of the higher photosynthetic rate due to eCO_2 and the associated yield increases. Moreover, there are reports that elevated CO_2 favors the accumulation of health-promoting carbon-based secondary metabolites such as antioxidants.

In addition, eCO_2 clearly promotes the efficiency of water use in plants and nitrogen fixation in legumes, which adds beneficial nitrogen to terrestrial ecosystems. Together, these two factors have led to a significant greening of Earth, particularly in arid regions. There is published evidence that gradually rising CO_2 levels have caused no additional nutrient deficiencies in the quarter of Earth's land surface that is covered with mostly arid rangelands, suitable only for grazing animals, and where fertilizer usage is ruled out for economic reasons. Grazing animals have innate "nutritional wisdom" that enables them to compensate for nutritional deficiencies by selective browsing of higher quality leaves or legumes. In addition, there are other economical ways to compensate for mineral or protein deficiencies in livestock nutrition.

In conclusion, field studies of plant growth with eCO_2, and the geological history of CO_2 and Earth's climate show that:

- Plants first appeared in the fossil record when atmospheric CO_2 levels were much higher than today. Therefore, one can be confident that plants are genetically equipped to cope with the moderate increase in CO_2 levels since the beginning of the industrial era and with additional increases of CO_2 in the future. The greening of Earth (Fig. 5) is only the beginning of benefits from more CO_2 for plants and for healthy and abundant human nutrition.

- Today's low concentration of atmospheric CO_2 is not typical of Earth's climate history, and this gaseous trace compound has not determined the fluctuations of temperature in the past and will not in the future.

- Man-made CO_2 emissions are not capable of triggering dangerous future warming. Its global warming potential is almost saturated.

- The numerous desirable and beneficial effects of more CO_2 in the atmosphere greatly outweigh "climate-damaging" or "nutrient-damaging" impacts, to the extent that these even exist. There is no "social cost of carbon," as is unfortunately and incorrectly claimed in numerous recent publications. In fact, there is a social benefit from more CO_2 in the air.

- Working in conjunction with the essential growth factors of H_2O and sunlight, CO_2 is the most important nutrient for plants and for all living organisms depending on food chains. For too long, inadequate atmospheric CO_2 has been the shortest stave of Liebig's barrel (see Fig. 4).

- Rising atmospheric concentrations of CO_2 have clearly been beneficial for the biosphere, agriculture, humanity, and particularly for global food security at very low additional cost. Still higher concentrations of CO_2 will bring additional benefits.

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About The CO_2 Coalition

The CO_2 Coalition was established in 2015 as a non-partisan educational foundation operating under Section 501(c)(3) of the IRS code for the purpose of educating thought leaders, policy makers and the public about the important contribution made by carbon dioxide to our lives and the economy. The Coalition seeks to engage in an informed and dispassionate discussion of climate change, humans' role in the climate system, the limitations of climate models and the consequences of mandated reductions in CO_2 emissions.

In carrying out our mission, we seek to strengthen the understanding of the role of science and the scientific process in addressing complex public policy issues like climate change. Science produces empirical, measurable, objective facts and provides a means for testing hypotheses that can be replicated and potentially disproven. Approaches to policy that do not adhere to the scientific process risk grave damage to the economy and to science.

The Coalition is comprised of more than 160 of the top experts in the world who are skeptical of a theoretical link between increasing CO_2 and a pending climate crisis while embracing the positive aspects of modest warming and increasing CO_2. They include physicists, chemists, meteorologists, geologists, biologists, ecologists, agronomists, engineers, economists and more. Within the Coalition, more than 70% of the members hold doctorates or commensurate degrees and include members of the National Academy of Sciences as well as a Nobel Laureate.

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