PETITION OF THE

CENTER FOR THE STUDY OF CARBON DIOXIDE AND GLOBAL CHANGE

TO THE

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

FOR

REPEAL OF EPA'S 2009 ENDANGERMENT FINDING, 74 FR 66,496 (Dec. 15, 2009)

March 9, 2020

EPA MUST OVERTURN ITS ENDANGERMENT FINDING FOR GREENHOUSE GASES UNDER SECTION 202(A) OF THE CLEAN AIR ACT. A DECADE OF DATA COLLECTED SINCE THE 2009 ENDANGERMENT FINDING REVEAL RISING ATMOSPHERIC CO_2, THE CHIEF GREENHOUSE GAS, PRESENTS NO THREAT TO PUBLIC HEALTH AND WELFARE.

Table of Contents

I. INTRODUCTION

The Center for the Study of Carbon Dioxide and Global Change, a non-profit 501(c)(3) organization, incorporated in 1998 in the State of Arizona for the purpose of investigating and determining the climatic and biological consequences of the ongoing rise in the air's CO_2 content,[1] hereby petitions EPA to initiate a rulemaking proceeding on the subject of greenhouse gases and their impact on public health and welfare.

This petition is brought pursuant to 5 U.S.C. § 553(e), which grants any "interested person the right to petition for the issuance, amendment, or repeal of a rule." A rulemaking proceeding is appropriate when new developments demonstrate that an existing rule or finding rests on erroneous factual premises, and a rulemaking petition is a proper vehicle for asking an agency "to reexamine" the "continuing vitality" of a rule.[2]

In 2009, the EPA Administrator determined there was "compelling support for finding that greenhouse gas air pollution endangers the public welfare of both current and future generations."[3] Such finding, according to EPA, was based upon "both current observations and projected risks and impacts into the future,"[4] which risks and adverse impacts, they claimed, "are expected to *increase over time.*"[5]

Over ten years have elapsed since the Administrator made this judgment in its so-called CO_2 Endangerment Finding. During that time a considerable amount of scientific research has been conducted on the potential impacts of rising greenhouses gases on humanity and the natural world. The additional knowledge obtained from such research and observations reveal quite clearly that rising greenhouse gases do not represent what EPA identified in 2009 to be a current or future threat to public welfare. Multiple observations, discussed in the sections of this petition below, confirm that projected risks and adverse impacts of rising greenhouse gases accepted by EPA in the Endangerment Finding are failing to occur and are certainly not increasing with time. Moreover, a host of scientific studies reveal that CO_2 emissions and fossil fuel use have actually *enhanced* life and *improved* humanity's standard of living, and will continue to do so as more fossil fuels are used.

---

[1] http://www.co2science.org/about/mission.php.

[2] *Geller v. FCC*, 610 F.2d 973, 978–80 (D.C. Cir. 1979) (overturning agency's denial of petition for new rulemaking). An agency's "refusal to initiate a rulemaking naturally sets off a special alert when a petition has sought modification of a rule on the basis of a radical change in its factual premise." *American Horse Protection Ass'n v. Lyng*, 812 F.2d 1, 5 (D.C. Cir. 1987) (overturning agency's denial of petition for rulemaking in light of agency's failure to offer a satisfactory explanation). Alternatively, EPA may choose to treat our filing as a petition for reconsideration of its Endangerment Finding. The procedural basis for doing so is discussed in Concerned Household Electricity Consumers Council et al., *Petition for Reconsideration of "Endangerment and Cause or Contribute Findings for Greenhouse Gases Under Section 202(a) of the Clean Air Act"* (filed Jan. 20, 2017), at 1-5.

[3] Endangerment and Cause or Contribute Findings for Greenhouse Gases under the Clean Air Act, signed by the EPA Administrator on December 7, 2009. On December 15, 2009, the final findings were published in the Federal Register under Docket ID No. EPA-HQ-OAR-2009-0171. Hereafter, this document is referred to as the Endangerment Finding.

[4] Endangerment Finding p. 66,516.

[5] Endangerment Finding p. 66,499, emphasis added.

It is undeniable, for example, that fossil energy initiated (and continues to sustain) the Industrial Revolution and the many human and environmental benefits that have emerged therefrom. Without adequate supplies of low-cost centralized energy, few, if any, of the major technological and innovative advancements of the past two centuries that have enhanced and prolonged human life could have occurred. Additionally, without the increased CO_2 emissions from fossil fuel use over the past two centuries, Earth's terrestrial biosphere would be nowhere near as vigorous or productive as it is today. Rather, it would be devoid of the growth-enhancing, water-saving and stress-alleviating benefits it has reaped in managed and unmanaged ecosystems from rising levels of atmospheric CO_2 since the Industrial Revolution began.

Such demonstrable facts are examined in the pages below, providing clear evidence that EPA's 2009 Endangerment Finding is scientifically flawed. Furthermore, when considering and accounting for the many observed *positive* improvements of rising CO_2 on the human environment, it becomes morally indefensible to demonize fossil fuel use and declare CO_2 emissions a current (or long-term) threat to human health and welfare. Consequently, EPA must repeal and overturn its 2009 Endangerment Finding.

II. SCIENTIFIC OBSERVATIONS REVEAL RISING GREENHOUSE GASES PRESENT NO IMMINENT THREAT TO HUMAN HEALTH AND WELFARE

A. There is nothing unusual or unnatural about Earth's current warmth or rate of warming. Historic and modern records of atmospheric CO_2 and temperature violate established principles of causation. Model-based temperature projections since 1979 artificially inflate warming (compered to observations) by a factor of three, invalidating the models and all their ancillary claims associated with greenhouse gas-induced warming

There is no debate as to whether or not atmospheric carbon dioxide, or CO_2, is a so-called greenhouse gas. When present in the atmosphere, this one-carbon and two-oxygen molecule indeed has the capacity to absorb infrared radiation and warm the planet. There is also no debate as to whether or not the concentration of atmospheric CO_2 is rising; over the past two centuries it has increased from a meager 0.028% of the atmosphere by volume to a still-meager 0.041% today. Furthermore, there is no argument that global temperatures are warmer today than they were 50, 100 or even 200 years ago. The topic or question which *is* open to discussion, however, is whether or not the modern increase in atmospheric CO_2 has caused, or is presently causing, *dangerous* global warming, warming so severe that it is threatening life all across the planet.

At any given moment, Earth's temperature is a product of a multitude of forcing and feedback factors,[6] carbon dioxide being only one of them. And although the air's CO_2 content is indeed rising, this atmospheric trace gas is not nearly as capable of raising global temperatures or initiating threats to human health and welfare that the EPA Endangerment Finding claims.

Consider, for example, if CO_2 was indeed the all-important temperature control knob the Endangerment Finding claims it to be, then changes in atmospheric CO_2 should always *precede*

---

[6] See the many links under the headings *Feedback Factors* and *Forcing Factors* here: http://www.co2science.org/subject/f/subject_f.php

changes in temperature. And, because CO_2 is a so-called greenhouse gas, those changes should always be such that a rise in CO_2 should induce a corresponding rise in temperature, whereas a decline in CO_2 should induce a corresponding drop in temperature. Consistent observations to the contrary would prove that atmospheric CO_2 is nothing more than a bit player among the many factors that drive climate change. So, what *do* the records show in this regard?

Quite clearly, the historic temperature and atmospheric CO_2 records do indeed violate the aforementioned principles, and they do so more often than they maintain them. Multiple peer-reviewed scientific studies, for example, have demonstrated that, following the termination of each of the past several global ice ages, air temperatures have always *risen* well in *advance* of the increase in atmospheric CO_2.[7,8] In fact, during these glacial terminations, which represent the most dramatic warming events experienced on Earth over the past million years, the air's CO_2 content does not even *begin* to rise until some 400 to 2,800 years *after* planetary warming starts (see Figure II.A.1).[9,10,11,12,13]

Another violation of the principles of causation in the CO_2/temperature relationship is witnessed at the *onset* of Ice Ages. Here, scientists report that temperatures always *drop* first at the start of these glacial periods, and they do so well *before* the air's CO_2 concentration begins its *decline*.[14,15,16] And like glacial terminations, these data also indicate that the CO_2 decreases observed at the beginning of the Ice Ages lag behind the temperature decreases, often by several thousand years (see Figure II.A.1 for an example).[17]

Other equally problematic findings in the CO_2/temperature relationship have been discovered by scientists examining periods other than the onset or termination of the most recent Ice Ages, including (1) times when CO_2 rises and temperatures fall,[18,19,20,21,22] (2) times when CO_2 falls

---

[7] Caillon, N., Severinghaus, J.P., Jouzel, J., Barnola, J.-M., Kang, J. and Lipenkov, V.Y. 2003. Timing of atmospheric CO_2 and Antarctic temperature changes across Termination III. *Science* **299**: 1728-1731.

[8] Idso, S.B. 1989. *Carbon Dioxide and Global Change: Earth in Transition*. IBR Press, Tempe, AZ.

[9] Fischer, H., Wahlen, M., Smith, J., Mastroianni, D. and Deck B. 1999. Ice core records of atmospheric CO_2 around the last three glacial terminations. *Science* **283**: 1712-1714.

[10] Monnin, E., Indermühle, A., Dällenbach, A., Flückiger, J, Stauffer, B., Stocker, T.F., Raynaud, D. and Barnola, J.-M. 2001. Atmospheric CO_2 concentrations over the last glacial termination. *Science* **291**: 112-114.

[11] Siegenthaler, U., Stocker, T., Monnin, E., Luthi, D., Schwander, J., Stauffer, B., Raynaud, D., Barnola, J.-M., Fischer, H., Masson-Delmotte, V. and Jouzel, J. 2005. Stable carbon cycle-climate relationship during the late Pleistocene. *Science* **310**: 1313-1317.

[12] Stott, L., Timmermann, A. and Thunell, R. 2007. Southern Hemisphere and deep-sea warming led deglacial atmospheric CO_2 rise and tropical warming. *Science* **318**: 435-438.

[13] Tierney, J.E., Russell, J.M., Huang, Y., Sinninghe, J.S., Hopmans, E.C. and Cohen, A.S. 2008. Northern Hemisphere controls on tropical southeast African climate during the past 60,000 years. *Science* **322**: 252-255.

[14] Genthon, C., Barnola, J.M., Raynaud, D., Lorius, C., Jouzel, J., Barkov, N.I., Korotkevich, Y.S. and Kotlyakov, V.M. 1987. Vostok ice core: Climatic response to CO_2 and orbital forcing changes over the last climatic cycle. *Nature* **329**: 414-418.

[15] Idso, S.B. 1989. *Carbon Dioxide and Global Change: Earth in Transition*. IBR Press, Tempe, AZ.

[16] Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., and Stievenard, M. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399**: 429-436.

[17] Ibid.

[18] Indermuhle, A., Stocker, T.F., Joos, F., Fischer, H., Smith, H.J., Wahllen, M., Deck, B., Mastroianni, D., Tschumi, J., Blunier, T., Meyer, R. and Stauffer, B. 1999. Holocene carbon-cycle dynamics based on CO_2 trapped in ice at Taylor Dome, Antarctica. *Nature* **398**: 121-126.

[19] Steig, E.J. 1999. Mid-Holocene climate change. *Science* **286**: 1485-1487.

[20] Rothman, D.H. 2002. Atmospheric carbon dioxide levels for the last 500 million years. *Proceedings of the National Academy of Sciences USA* **99**: 4167-4171.

[21] Kouwenberg, L., Wagner, R., Kurschner, W. and Visscher, H. 2005. Atmospheric CO_2 fluctuations during the last millennium reconstructed by stomatal frequency analysis of *Tsuga heterophylla* needles. *Geology* **33**: 33-36.

[22] Davis, W.J. 2017. The relationship between atmospheric carbon dioxide concentration and global temperature for the last 425 million years. *Climate* **5**: 76; doi: 10.3390/cli5040076.

and temperatures rise,[23,24,25] or (3) times when a change in either of these two parameters evokes no change in the other.[26,27] And once again, such changes in CO_2 are typically observed to *follow* changes in temperature from hundreds to thousands of years.[28,29,3031]

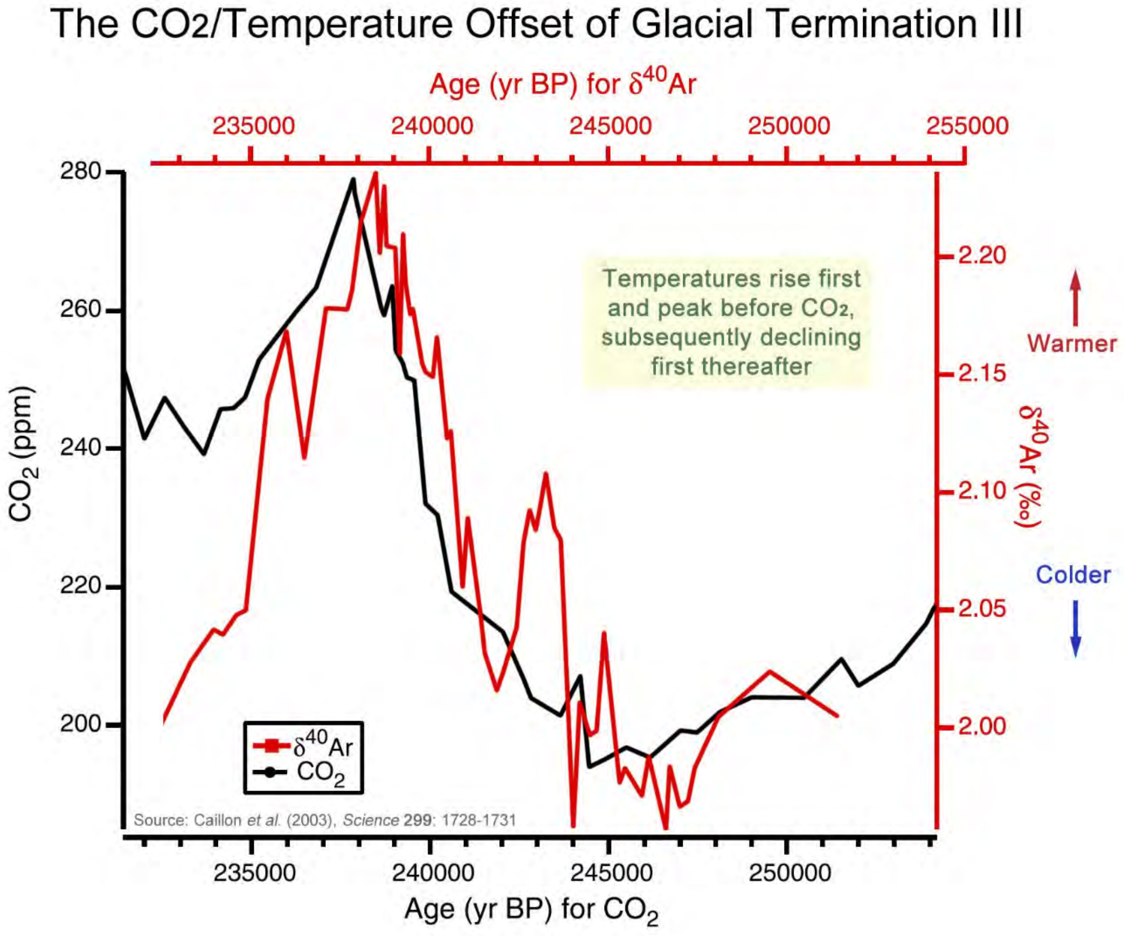


***Figure II.A.1**. The observed temporal lag in CO_2, as determined by Callion et al. (2003) for Glacial Termination III, approximately 245,000 years ago. In particular, note the temperature*

---

[23] Fischer, H., Wahlen, M., Smith, J., Mastroianni, D. and Deck, B. 1999. Ice core records of atmospheric CO_2 around the last three glacial terminations. *Science* **283**: 1712-1714.

[24] Barral, A., Gomez, B., Fourel, F., Daviero-Gomez, V. and Lécuyer, C. 2017. CO_2 and temperature decoupling at the million-year scale during the Cretaceous Greenhouse. *Scientific Reports* **7**: 8310, DOI: 10.1038/s41598-017-08234-0.

[25] Davis, W.J. 2017. The relationship between atmospheric carbon dioxide concentration and global temperature for the last 425 million years. *Climate* **5**: 76; doi: 10.3390/cli5040076.

[26] Fischer, H., Wahlen, M., Smith, J., Mastroianni, D. and Deck, B. 1999. Ice core records of atmospheric CO_2 around the last three glacial terminations. *Science* **283**: 1712-1714.

[27] Davis, W.J. 2017. The relationship between atmospheric carbon dioxide concentration and global temperature for the last 425 million years. *Climate* **5**: 76; doi: 10.3390/cli5040076.

[28] Staufer, B., Blunier, T., Dallenbach, A., Indermuhle, A., Schwander, J., Stocker, T.F., Tschumi, J., Chappellaz, J., Raynaud, D., Hammer, C.U. and Clausen, H.B. 1998. Atmospheric CO_2 concentration and millennial-scale climate change during the last glacial period. Nature 392: 59-62.

[29] Indermuhle, A., Monnin, E., Stauffer, B. and Stocker, T.F. 2000. Atmospheric CO_2 concentration from 60 to 20 kyr BP from the Taylor Dome ice core, Antarctica. *Geophysical Research Letters* **27**: 735-738.

[30] Mudelsee, M. 2001. The phase relations among atmospheric CO_2 content, temperature and global ice volume over the past 420 ka. *Quaternary Science Reviews* **20**: 583-589.

[31] Humlum, O., Stordahl, K. and Solheim, J.-E. 2013. The phase relation between atmospheric carbon dioxide and global temperature. *Global and Planetary Change* **100**: 51-69.

proxy shown in red, which precedes the rapid rise in atmospheric CO_2 (black line) by approximately 800 years. This leading rise in temperature and subsequent lag in CO_2 increase, which relationship is opposite expectations of the EPA Endangerment Finding, is a consistent and proven feature at the termination of all ice ages in Earth's recent geologic history.

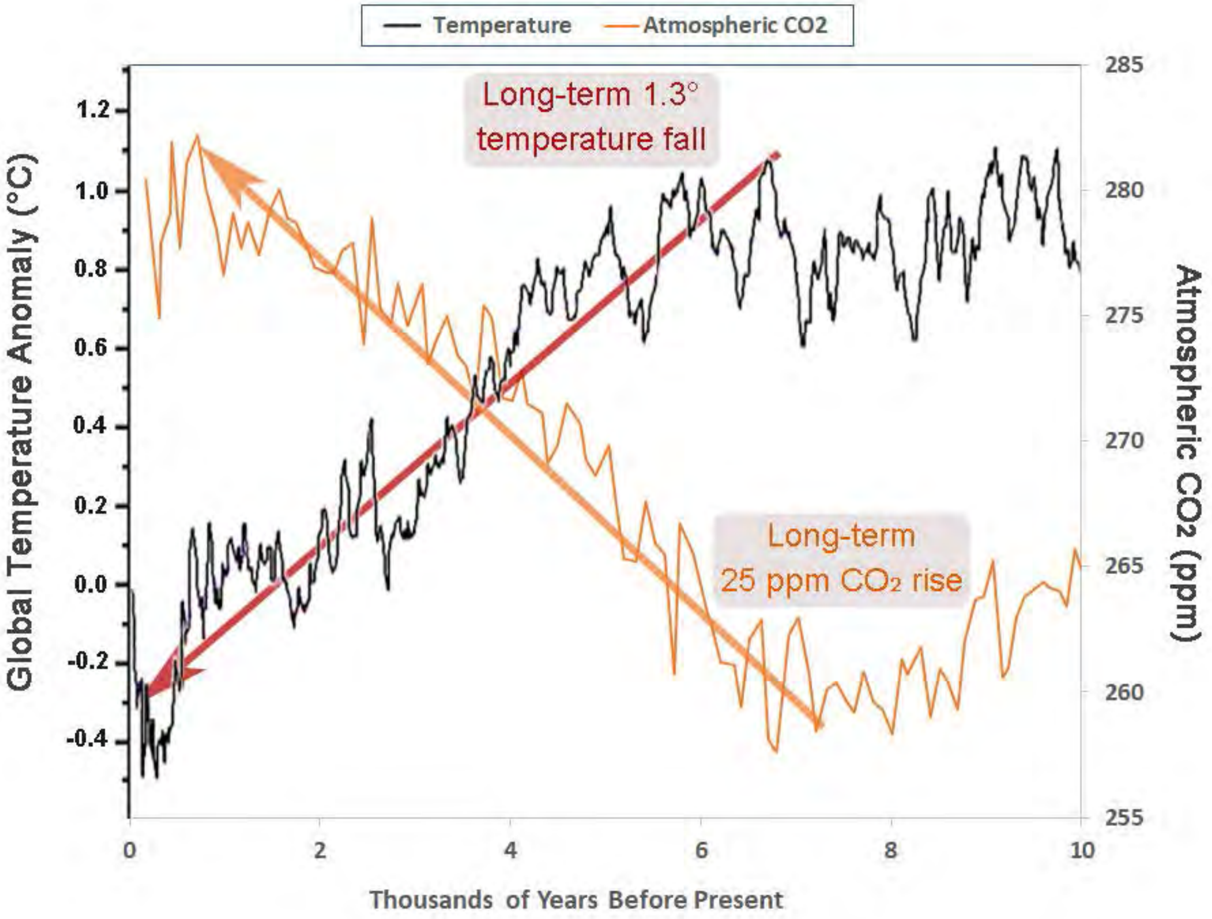


Figure II.A.2. *Sources: Holocene proxy records of global temperature (Marcott et al. 2013)*[32] *and atmospheric CO_2 (GRIP2 Dome C ice core).*

A more recent example of such contrary behavior is illustrated in the above plot of atmospheric CO_2 and temperature during the Holocene (Figure II.A.2), where it is seen that for 7,000 of the past 10,000 years atmospheric CO_2 concentrations rose while air temperatures declined. If CO_2 was indeed the potent, climate-controlling greenhouse gas the Endangerment Finding claims it to be, global temperatures would not have declined 1.3°C in response to the concomitant 25 ppm increase in atmospheric CO_2 that occurred over this period. Rather, this rise in CO_2 should have warmed planetary temperatures—*but it didn't!* That harsh reality, in conjunction with all the other conflicting and contrary observations regarding the historical relationship between atmospheric CO_2 and temperature, discussed previously, leaves little doubt that forces other than CO_2 play a much greater role in controlling and driving changes in global temperature.

---

[32] Marcott, S.A., Shakun, J.D., Clark, P.U. and Mix, A.C. 2013. A reconstruction of regional and global temperature for the past 11,300 years. *Science* **339**: 1198-1201.

While the historic record of the CO_2/temperature relationship over the past half million years certainly proves problematic to the conclusions of the Endangerment Finding, in actuality, one need only examine the most recent 150 years to recognize there is little or no rigorous evidence that rising concentrations of atmospheric CO_2 are causing dangerous global warming.

Over this period, it is estimated that carbon dioxide concentrations increased by around 40% (120 ppm) and global temperatures rose between 0.8-1.0°C. According to the EPA and others, some three-fourths to 100% of this observed temperature rise was of anthropogenic origin, most all of which warming they ascribe to the concomitant increase in atmospheric CO_2. This is because, notwithstanding the plethora of observational data that demonstrate otherwise, the only narrative the former EPA Administrator was willing to embrace in the Endangerment Finding regarding the CO_2/temperature relationship was the one in which atmospheric CO_2 is a powerful greenhouse gas whose increase always results in climate warming. And based upon that narrative, the Administrator relied upon multiple highly sophisticated, though imperfect, computer climate models, which not surprisingly projected dangerous global warming is already underway and growing worse in response to the modern and still-ongoing rise in the air's CO_2 content.

However, one red flag that immediately pops up when focusing on this time period is the observation that, despite a consistent and near-exponential rise in atmospheric CO_2 over the past 150 years, temperatures fluctuated between periods of *both* global warming and global *cooling* (see Figure II.A.3). In addition, it is difficult—if not impossible—for the EPA and others to adequately reconcile the fact that the two largest warming events that occurred in this record (the first between 1910 and 1945 and the second between 1975 and 2005), experienced nearly identical rates and magnitudes of warming, despite an atmospheric CO_2 increase in the latter event that was *five times that* which occurred during the former event (again, see Figure II.A.3). Nor is it easy for the EPA to adequately explain without abandoning their CO_2-induced global warming thesis how a three-decade-long cooling event can follow a three-and-a-half-decade-long warming event, when the CO_2 increase during the cooling event was *twice* that which occurred during the preceding warming event.

The only way to properly reconcile each of these contrary observations is for the EPA to admit they have overestimated the warming power of atmospheric CO_2.

Other evidences help to *further* prove this point.

Consider, for example, Figure II.A.4, which presents a record of historic temperatures over the past four ice age cycles. Note that the peak warmth of the preceding four interglacial periods was between 1 and 2°C *higher* than that observed during the current interglacial in which we now live, despite there being approximately 45 percent *more* CO_2 in the *present* atmosphere. Thus, even if temperatures were to warm another 1 or 2°C above their current values in the near future, there is no way such warming can definitively be attributed to the additional CO_2 humans have added to the atmosphere in the modern era, because the higher temperatures in each of the past four interglacial warm periods occurred under CO_2 concentrations that are about *half* the value that they are today. What is more, it is absurd to characterize *current* planetary temperatures as dangerous to human health and welfare as the EPA has done with its Endangerment Finding when all of the past four interglacial periods were 1-2°C warmer than it is now.

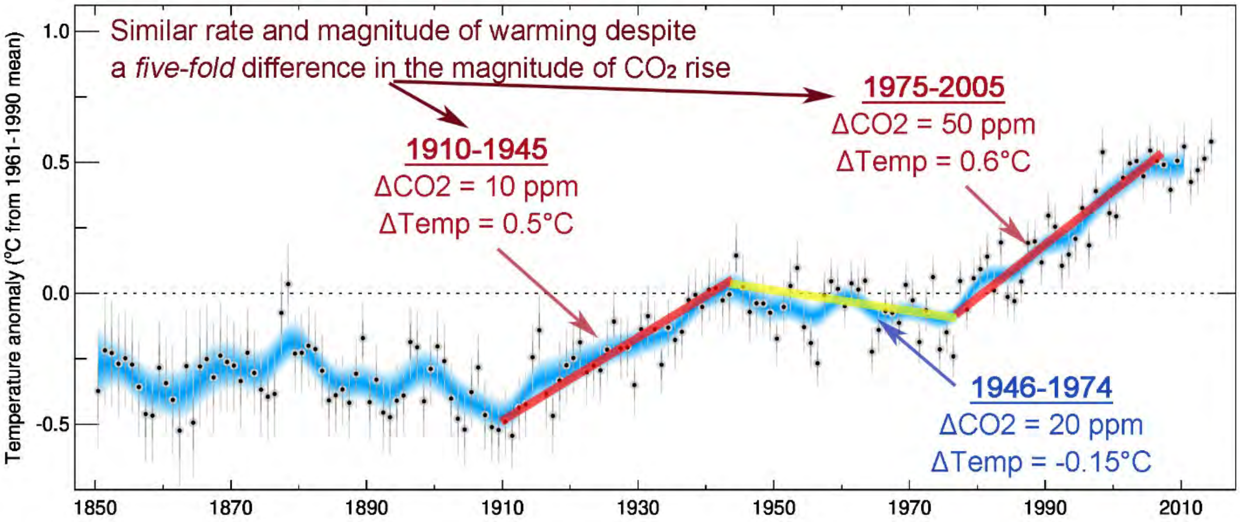


Figure II.A.3. *Global temperatures (HadCRUT4) since 1850 showing two periods of similar rates and magnitudes of warming despite a five-fold difference in the magnitude of observed CO_2 rise. Also shown is a cooling period despite a corresponding rise in CO_2.*

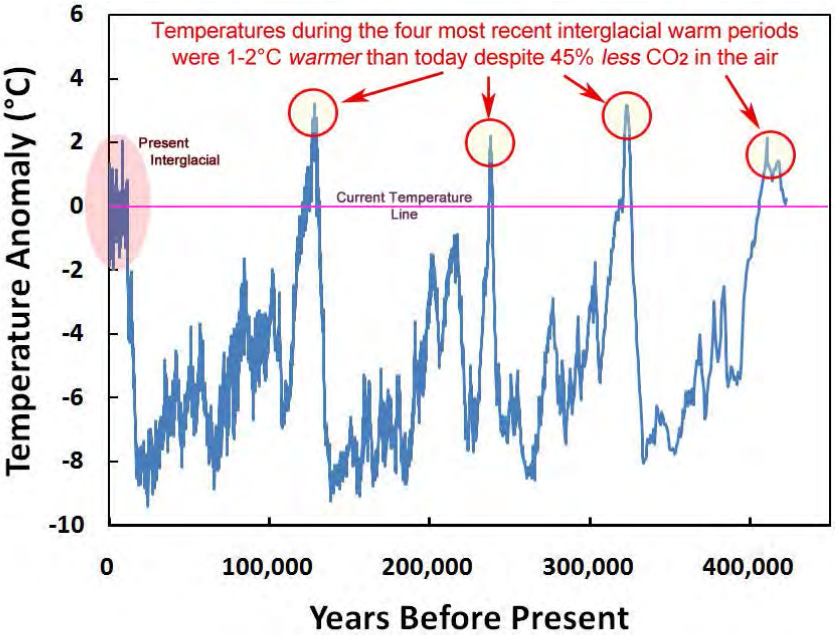


Figure II.A.4. *Historic temperatures of the past four glacial/interglacial cycles. Source: Petit et al. (1999).*[33]

---

[33] Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., and Stievenard, M. 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399**: 429-436.

Another problematic issue facing the Endangerment Finding is the recent global warming *pause* or temperature *hiatus*. As shown in Figure II.A.5, despite an 11% increase in atmospheric CO_2 over the recent two-decade period 1998-2018 (which CO_2 increase represents one-fourth of the total increase in CO_2 during the modern era), global temperatures experienced little, if any, warming. Not surprisingly, not one of the climate models predicted this temperature plateau. Expecting warming, they all failed to see it coming.

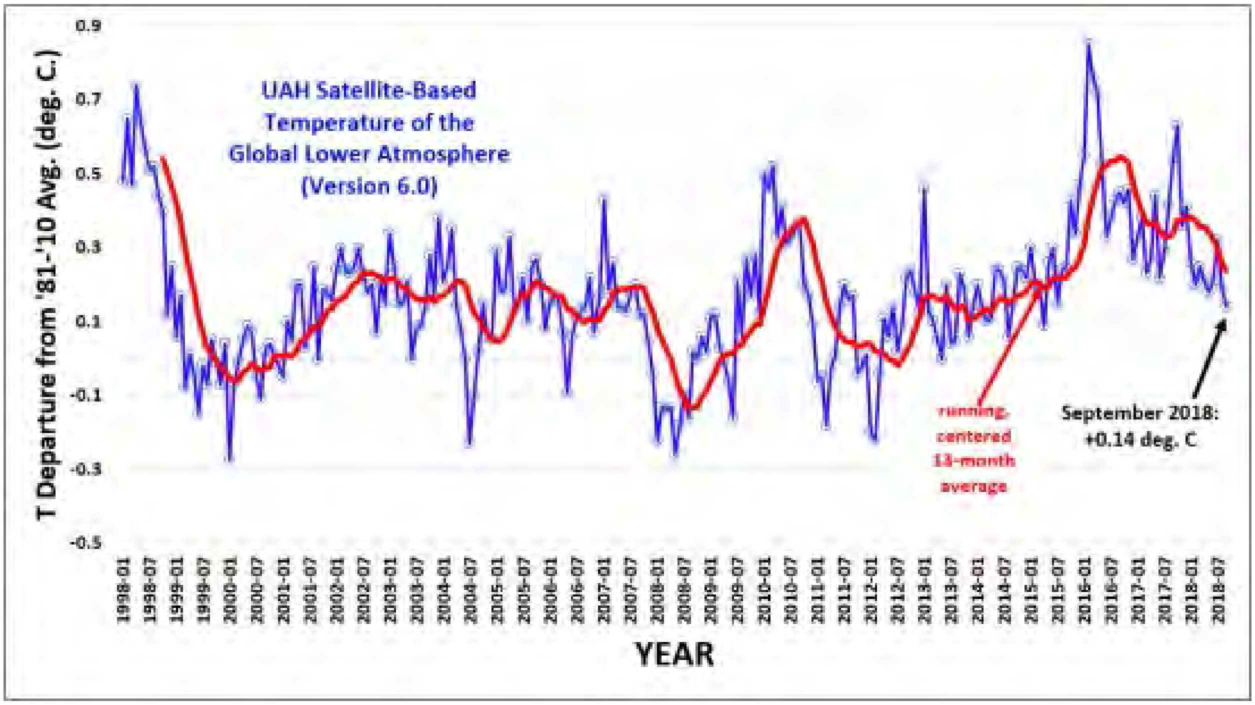


Figure II.A.5. *The great global warming "pause" of the early 21st century as witnessed in the UAH satellite-based temperature record of the lower atmosphere. Data Source: Version 6 of the UAH MSU/AMSU global satellite temperature dataset.*

And speaking of the models, according to theory inherent in all climate models, CO_2-induced global warming over the past 40 years should show a unique fingerprint in the form of a warming trend that increases with altitude in the tropical troposphere, as indicated by the red and orange colors presented in the center of Figure II.A.6 and outlined in blue. Climate changes due to solar variability or other known natural factors *do not yield this pattern*. However, as shown in Figure II.A.7, real-world observations do not match this model-expected theory.[34]

---

[34] Christy, J. and McKittrick, R . 2018. A Test of the Tropical 200- to 300-hPa Warming Rate in Climate Models. Earth and Space Science 5: https://doi.org/10.1029/2018EA000401.

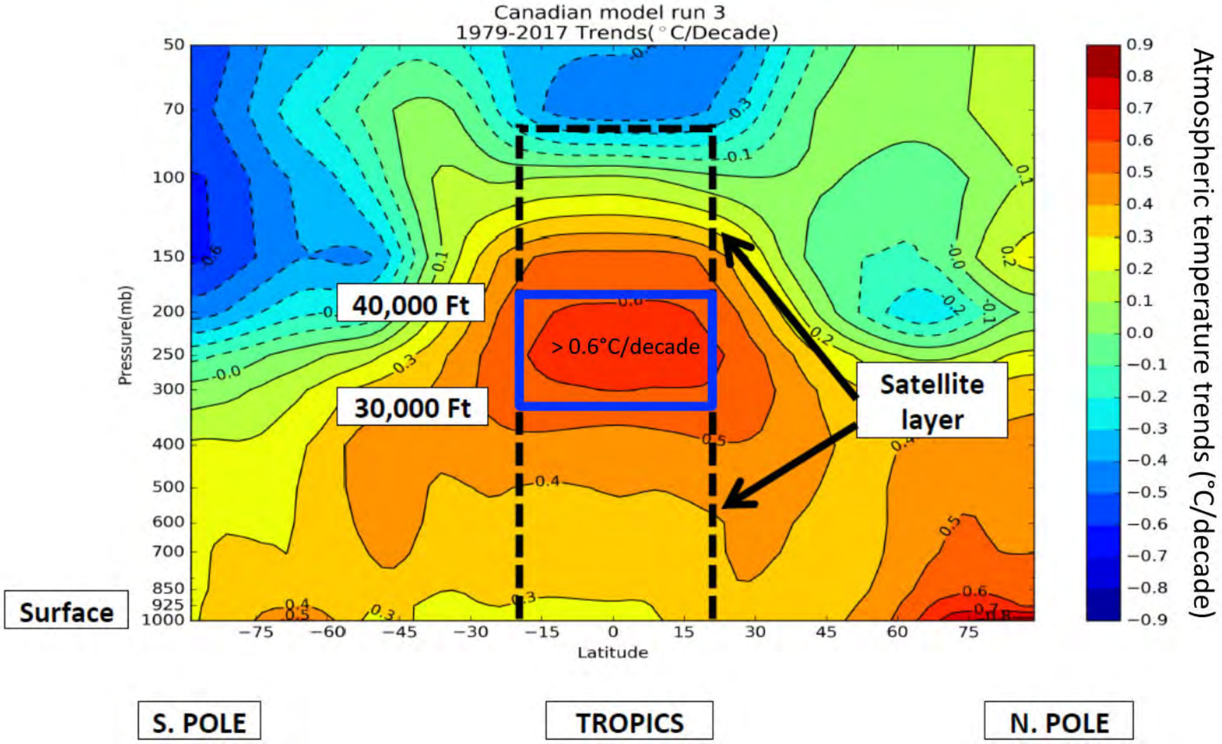


Figure II.A.6. *The supposed "fingerprint" of CO_2-induced global warming in the tropical upper troposphere (outlined by the blue rectangle) as depicted from Canadian model run 3 over the period 1979-2017.*[35]

Each of the red bars on Figure II.A.7 shows warming that *should* have occurred in the tropical upper troposphere over the period 1979-2017, as predicted by simulations from 102 different climate models. The average predicted warming rate over this nearly four-decade-long period, as shown by the black horizontal dashed line, is 0.44°C per decade. In contrast, radiosonde temperature measurements observed in this portion of the atmosphere, shown in blue, reveal that the *actual* warming rate is *three times smaller* than that predicted by the models.[36]

---

[35] Ibid.

[36] Ibid.

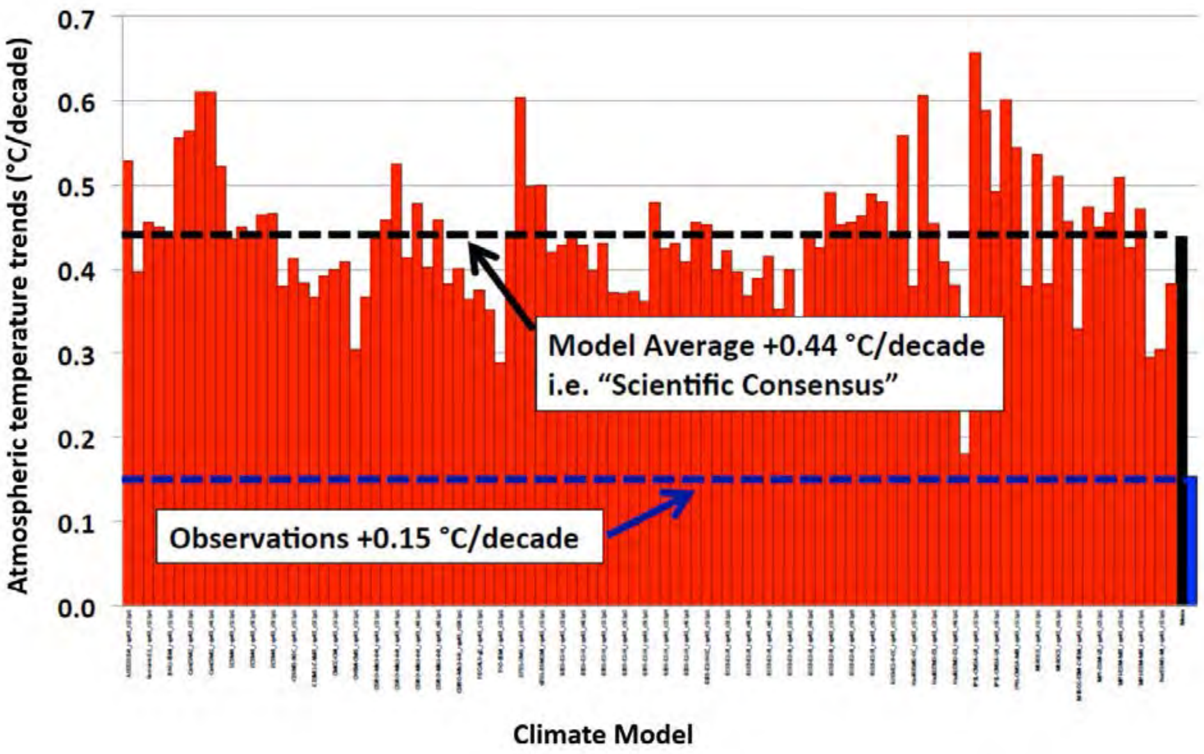


***Figure II.A.7**. Model-derived temperature trends of the tropical upper troposphere over the period 1979-2017 from 102 Climate Model Simulations (red bars). The average trend of the 102 models is 0.44°C and shown by the black bar and dashed black line. The blue bar and dashed line presents the observed temperature trend from radiosonde measurements.*

This divergence between model projections and observational data is even more evident in Figure II.A.8, which plots both predicted and observed temperature anomalies of the upper tropical troposphere. Once again observational data reveal that the model-derived projections of CO_2-induced warming are running far too hot, so much so, in fact, that mathematical analyses confirm a statistically significant difference between the two temperature series.[37] This key fact alone, is sufficient to provide more than enough of a credible, scientific basis for invalidating all of the climate models and their associated predictions.

---

[37] Ibid.

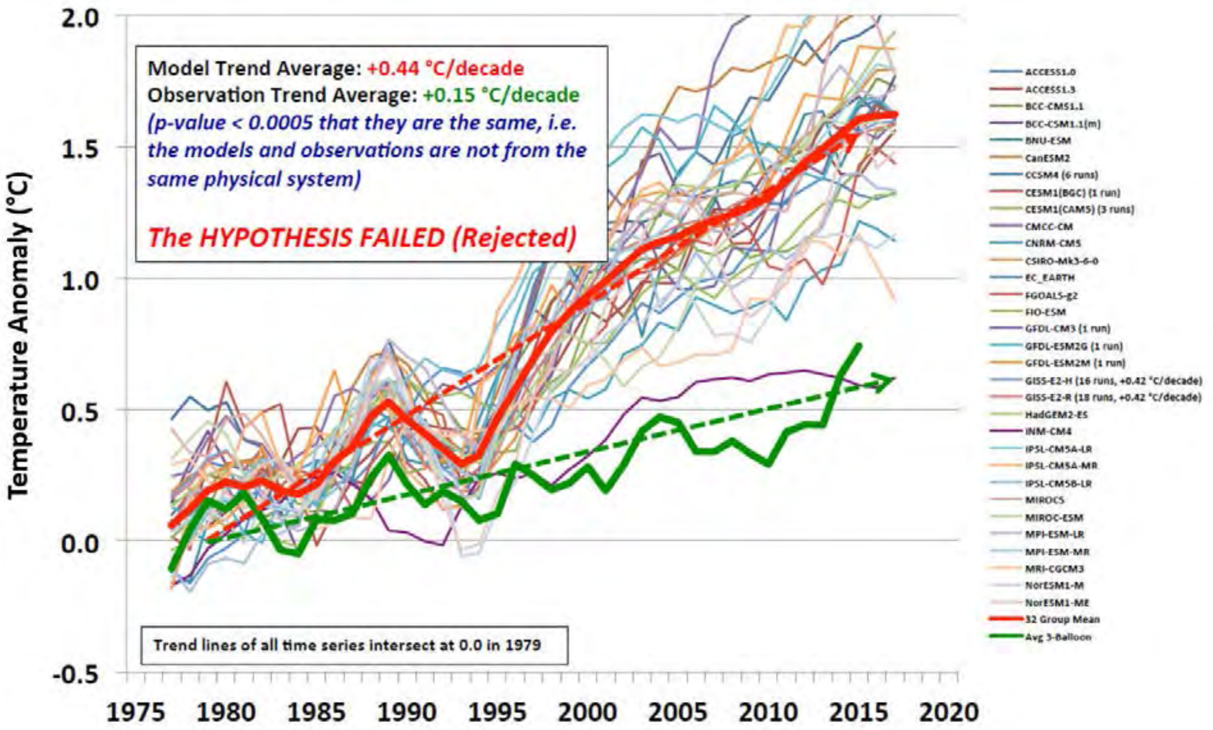


Figure II.A.8*. Plot of model versus observed temperature anomalies of the tropical upper troposphere, the supposed "fingerprint" of global warming, over the period 1979-2017. The model-based temperature trend of the tropical troposphere is significantly different from the observation-derived trend.*[38]

Additional evidence that the models are running too hot comes from the recent work of Huang *et al*. (2019).[39] In their study, the five researchers set out to examine how well model projections of Arctic temperatures (poleward of 60°N) compared with observations. More specifically, they used a statistical procedure suitable for nonlinear analysis (ensemble empirical mode decomposition) to examine secular Arctic warming over the period 1880-2017. Observational data utilized in the study were obtained from the HadCRUT4.6 temperature database, whereas model-based temperature projections were derived from simulations from 36 Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate models (GCMs). The key results are depicted in Figure II.A.9 below.

As indicated there, the model-estimated rate of secular warming (the solid red line) increased quite sharply across the 138-year period, rising from a value of around 0 °C per decade at the beginning of the record to a value of 0.35 °C per decade at the end. Observations, in contrast, started off with a higher warming rate than that of the models (a rate of 0.13 °C per decade; the solid black line), but dipped below the rate of warming predicted by the models around the middle of the record, thereafter experiencing a lower rate of warming relative to the models through the end of the record. By the end of the record, the model-predicted secular rate of

---

[38] Ibid.

[39] Huang, J., Ou, T., Chen, D., Lun, Y. and Zhao, Z. 2019. The amplified Arctic warming in the recent decades may have been overestimated by CMIP5 models. *Geophysical Research Letters* **46**: 13,338-12,345.

warming was 67% higher than that determined from observations (0.21 °C). Thus, the figure shows an *increasing disparity* between modelled and observed warming rates that starts around the middle of the record and grows to 0.14 °C per decade by the mid-2010s.

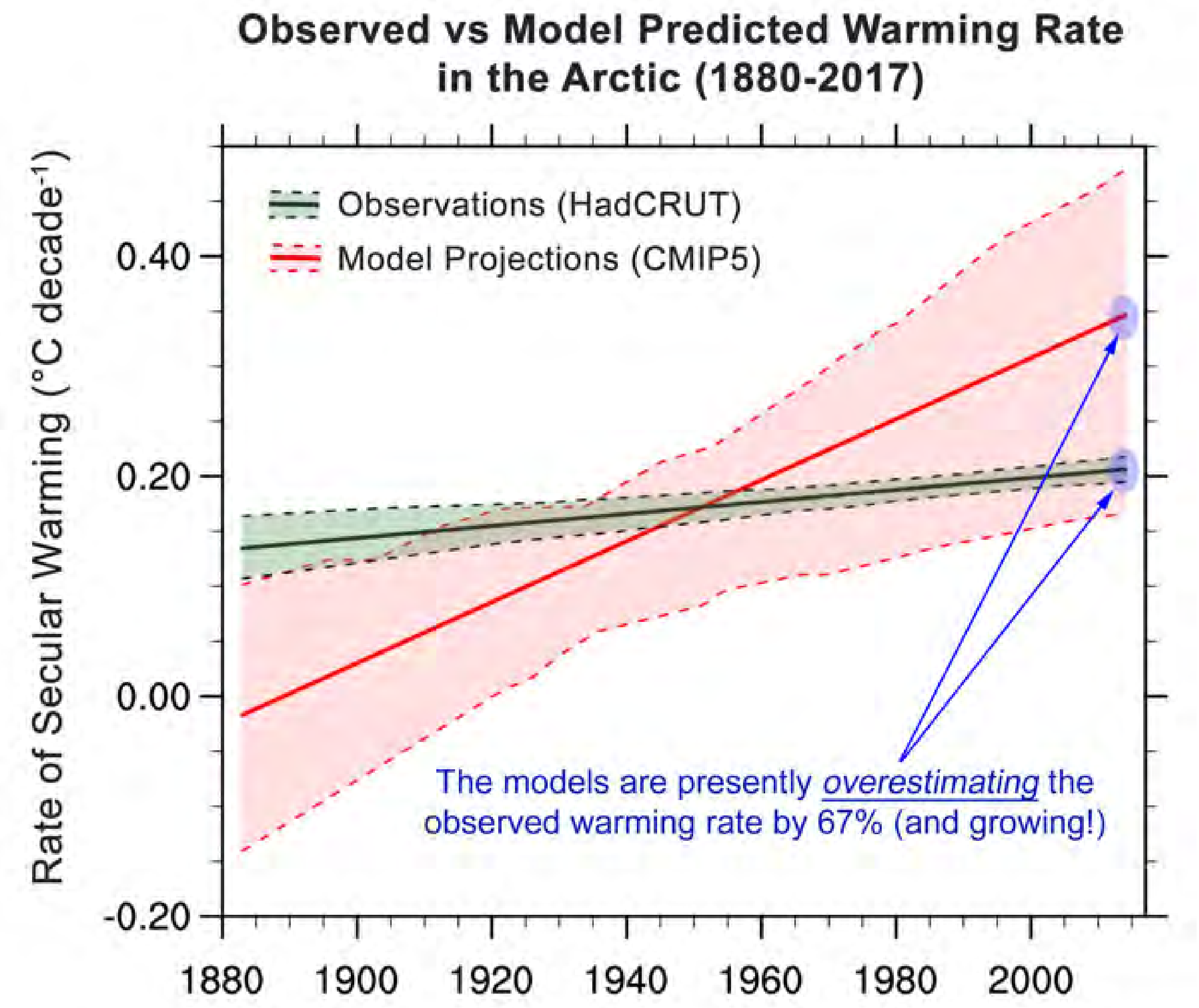


Figure II.A.9. *Observed and model-predicted rates of nonlinear, secular warming in the Arctic (60-90°N) over the period 1880-2017. The black and red dashed lines indicate the 10th and 90th percentiles for temperature means.*[40]

In commenting on these findings, Huang *et al*. state the obvious, that "anthropogenically induced secular warming has been overestimated by the CMIP5 GCMs during the most recent warming period, and the overestimation is aggravated with time." What is more, given the error bars shown on the figure, in the very near future the observed warming rate will likely soon fall outside the significance levels of the ensemble model mean, removing any remaining credibility left in the model projections of future Arctic warming.

---

[40] Ibid.

In considering each of the several evidences presented above, it is truly disingenuous for anyone—EPA included—to claim with any degree of certitude that the modern temperature increase bears a significant anthropogenic fingerprint or that rising atmospheric CO_2 is causing dangerous global warming. There exists far too much data to the contrary. Although atmospheric CO_2 is a greenhouse gas, it is certainly not the control knob that drives global temperature, nor will it ever be.

Sufficient proof is documented in the historic records. A control knob does not consistently lag several hundred to thousands of years behind changes in the parameter it is supposedly governing and a control knob most certainly does not produce multiple occurrences of a response that is *opposite* its expectation. The Endangerment Finding ignores such contrary empirical behaviors, even though they are far more characteristic of the historic relationship observed between atmospheric CO_2 and temperature than they are not.

Sufficient proof is also found in the missing fingerprint of CO_2-induced warming in the tropical upper troposphere that observations fail to capture. This fact alone, according to the scientific method, provides ample proof for invalidating all the model-based predictions of dangerous global warming. And because the models all fail in this regard, the Endangerment Finding should really be scrapped here, for pretty much *all* of the additional ancillary climate-related predictions in the Endangerment Finding listed as contributing factors harming human health and welfare rely on the unrealistic temperature rise predicted by now invalidated climate models. Nevertheless, the next section of this petition examines these ancillary warming-induced claims, finding there is sufficient proof to once again reject the Endangerment Finding's assessment that rising greenhouse gases are causing dangerous warming that is adversely impacting human health and welfare. Such proof come in the form of a vast array of real-world data that once again fail to match model projections over a host of subordinate temperature-related climate catastrophes.

B. Observations reveal key adverse effects of greenhouse gas-induced warming are not occurring despite EPA predictions they should be worsening.

The 2009 Endangerment Finding identifies a number of warming-related impacts to the climate system that it claims provide "compelling support for finding that greenhouse gas air pollution endangers the public welfare of both current and future generations," adding that "the risk and the severity of adverse impacts on public welfare are expected to increase over time."[41] More specifically, the Endangerment Finding alleges that unless the atmospheric CO_2 concentration is slowed or even reduced, dangerous global warming will ensue, producing all sorts of undesirable consequences with little to no positive effects, including more frequent and severe floods and droughts, more numerous and stronger hurricanes, dangerous sea level rise, more frequent and severe storms, increased human mortality, widespread plant and animal extinctions, declining vegetative productivity and still *other* negative impacts.

---

[41] Endangerment Finding p. 66,535.

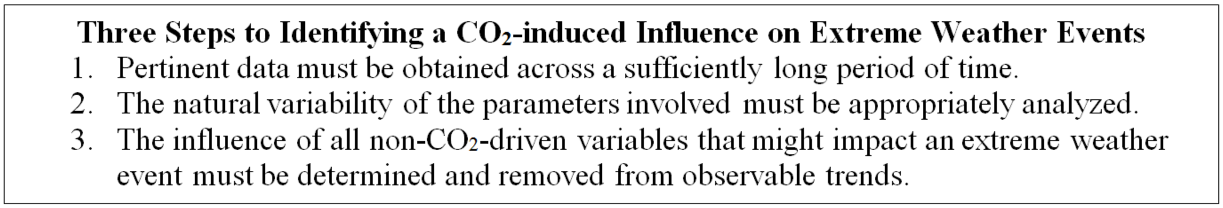
The only way to validate model projections of CO_2-induced climate change is to wait a sufficient period of time before the projections can be compared with observations. Because climate, by definition, is the long-term average of day-to-day weather fluctuations, literally decades can be required before enough observations are collected to enable a proper evaluation of the model projections using the scientific method. However, given that the Endangerment Finding claims rising CO_2 will increase the frequency and severity of extreme weather events, EPA can be held accountable *now* for this assertion; for empirical analyses can be readily performed to test the correctness of this thesis by examining how extreme weather events have changed (or not changed) in response to the approximate 45% rise in atmospheric CO_2 since the Industrial Revolution.

The present section conducts just such an analysis, examining trends in extreme weather events over the historical past using instrumental observations and paleoclimate proxies. It is prefaced by a discussion of three fundamental principles that must be followed in order to properly deduce a scientific link between rising CO_2 and extreme weather, principles the EPA ignored in their attribution of recent extreme weather events to CO_2-induced climate change. Thereafter, the work provides a summary analysis of trends in key categories of extreme weather events, finding no compelling evidence to support the claim of a CO_2-indcuded influence. Scientific analysis and observation prove otherwise. Rising atmospheric carbon dioxide is not making extreme weather worse and reducing the air's CO_2 content will not cause the frequency or intensity of such events to diminish.

1. How to Properly Test for a CO_2-induced Influence on Extreme Weather

The scientific method is a tried and true means by which hypotheses can be formulated, tested, and evaluated. The first step in the method is to observe and conduct background research on a particular topic or scientific question. Next, based on initial observations and research, an hypothesis is created to supposedly explain the phenomenon under examination. Then, it is tested via a series of properly designed and controlled experiments, after which the information gleaned from the experiments is studied and evaluated, leading to a conclusion that either supports or refutes the original hypothesis.

For centuries this method has provided the physical and natural sciences with the means to critically gather information and expand knowledge. The scientific method is also highly applicable in investigations of the potential causes and consequences of climate change. However, it is frequently misapplied in attributing extreme weather events to CO_2-induced global warming. This section examines three critical principles that are often overlooked in reaching that attribution (see Figure II.B.1.1). Failure to observe any one of these principles generally invalidates all CO_2-related attribution claims. When properly applied, in most (if not all) instances, claims that extreme weather events are increasing in frequency and severity because of rising CO_2 fail to be substantiated.



Three Steps to Identifying a CO_2-induced Influence on Extreme Weather Events

1. Pertinent data must be obtained across a sufficiently long period of time.
2. The natural variability of the parameters involved must be appropriately analyzed.
3. The influence of all non-CO_2-driven variables that might impact an extreme weather event must be determined and removed from observable trends.

Figure II.B.1.1. *A list of three principles that must be followed in order to ascertain a CO_2-induced global warming effect on extreme weather events. Failure to follow any of these principles effectively invalidates claims of a CO_2 link.*

As shown in Figure II.B.1.1, the first step in properly attributing a given extreme weather event to CO_2-induced global warming is to obtain real, measurable data on that event over a sufficiently long time period. This rule may seem rather obvious, yet time and again many scientists, politicians and members of the media violate this principle and publically intimate there exists a CO_2-induced global warming influence on extreme weather simply because climate models *project* an influence. These individuals fail to recognize the basic truth that climate model projections are not of the same standard as real world observations. In fact, model output is unquestionably *far inferior*.

Still, climate models are important tools utilized to advance our understanding of current and past climate. They also provide both qualitative and quantitative information about potential future climate. But despite of their sophistication, they remain just that—models. They are nothing more than simulations of the real world, constrained in their ability to correctly capture and portray each of the important processes that operate across multiple spatial and temporal domains to affect climate. By their very nature, climate models deal in the *hypothetical*. Their output amounts to nothing more than projections of future *possibilities*; and as such, model output can never substitute for real-world observations, especially when attempting to discern a CO_2-induced influence on extreme weather.

It is also worth pointing out another weakness of climate models. The average person has little to no knowledge concerning the inner workings and limitations that exist in present-day state-of-the-art climate models. Few people are aware that although the models are quite sophisticated, they are also replete with numerous inadequacies and biases. And although such shortcomings are frequently documented in the peer-reviewed scientific literature, these imperfections rarely find their way into public discourse (including the Endangerment Finding).

A partial assessment of model inadequacies has been conducted and published in a major report of the Nongovernmental International Panel on Climate Change (NIPCC). Notwithstanding their admirable complexities, the NIPCC scientists found the models to be deficient in many aspects of their portrayal of climate, leading them to strongly question their ability to provide reliable simulations of the future.[42]

---

[42] Idso, C.D., Carter, R.M. and Singer, S.F. (Eds.) 2013. *Climate Change Reconsidered II: Physical Science*. The Heartland Institute, Chicago, Illinois.

One example of such deficiencies was presented in Figure II.A.8 of the previous section, where simulated global temperatures from 102 models are plotted against mid-tropospheric observed temperatures over the past four decades. The universal failure of the models to correctly project global temperature over this time period is shocking, especially since global temperature is the single most important variable examined in all the models because of its expectation to rise as the air's CO_2 content increases. No other variable receives as much attention. Yet, the models failed to correctly project *global* temperature over the past four decades. So how in the world can they be expected to produce reliable simulations of *extreme weather events* decades to *centuries* into the future? Simply put, they cannot. It is intrinsically much more difficult to simulate extreme weather events-which operate within much smaller spatial and temporal domains-than it is to simulate average global temperature.

Confidence in a model is based on the careful evaluation of its performance against actual observations. Because models fail to accurately simulate what is arguably supposed to be the *simplest* of all climatic variables-global temperature-confidence in their ability to simulate more complex events, such as is required with extreme weather, must be greatly tempered.

Recognizing that climate model output is no substitute for real-world data, scientists must turn to *observations* in their efforts to prove or disprove any CO_2-induced influence on extreme weather events. And that requires datasets that have been in existence for long periods of time, datasets which are of sufficient length to adequately discern whether or not recent changes in extreme weather parameters have stretched beyond their known realm of natural variability. And this leads to the second principle presented in Figure II.B.1.1: *The natural variability of the parameter must be studied and known*.

Aside from model projections of the *future*, multiple scientific organizations and government agencies, including the U.S. EPA, contend that CO_2-induced global warming is causing an increase in the frequency and/or magnitude of extreme weather events *now*. Far too often these groups point to the occurrence of a recent extreme weather event and claim it was either directly or indirectly caused by rising temperatures that result from rising atmospheric CO_2.

The correctness of such claims can be evaluated rather simply by analyzing trends in extreme weather events over the historic past. If the observational data show *no trend*, or if they *decline* over time toward the present, the hypothesis that rising CO_2 is increasing the frequency and/or magnitude of the events can be falsified. For under such circumstances, it cannot be concluded that rising CO_2 is having any measurable effect on the extreme weather event under examination. Yet it is a bit more complicated than that.

Figure II.B.1.2 presents a flow chart of the many questions that must be asked, and the steps that must be followed, before one is able to properly test the CO_2-induced increase in extreme weather hypothesis. A critical step in this process centers on obtaining datasets of sufficient length to conduct proper statistical analyses. False signals can be obtained if a dataset is too short. Determining what constitutes a sufficiently long dataset begins with an understanding of how atmospheric CO_2 and global temperature have changed over time.

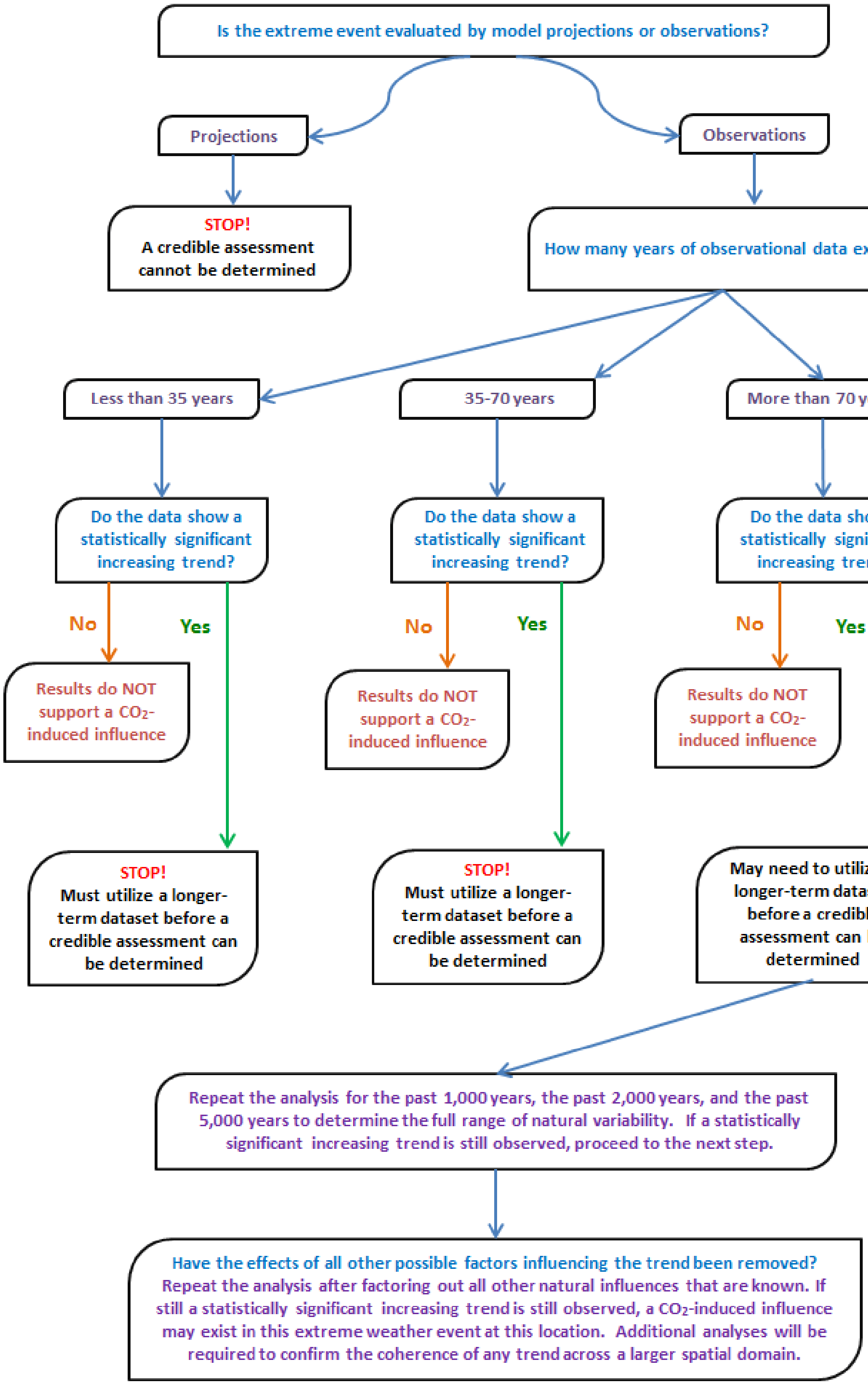


***Figure II.B.1.2**. Flow chart detailing questions that must be addressed and steps that must be taken to perform a proper analysis to test the model-based hypothesis that rising CO_2 concentrations are increasing the frequency and severity of extreme weather events.*

Atmospheric carbon dioxide concentrations have been rising since the dawn of the Industrial Revolution. Driven by gaseous emissions from the burning of fossil fuels such as coal, gas and oil, the air's CO_2 content has risen from a mean concentration of about 280 parts per million (ppm) in 1800 to a value of approximately 415 ppm today. This historic rise in CO_2, however, has not been uniform. Half of the increase has occurred since 1980 and three-fourths has occurred since the end of World War II (WWII). Therefore, if rising CO_2 is having an effect on extreme weather, testing for such requires examination of extreme weather events that have occurred over a period of time in which a large fraction of the modern buildup of CO_2 has occurred. Though it is perhaps somewhat subjective to designate at what point in time the rise in CO_2 constitutes a "large fraction" of the modern increase, a good starting point would be since the end of WWII (~75 yrs), as three-fourths of its modern increase occurred since that time. However, because many extreme weather datasets do not extend back in time 75 years, a secondary starting option would be some interval of time between the end of WWII and 1979, as around half of the modern increase in atmospheric CO_2 has occurred during the past 40 years. If no trend or a declining trend in the data is observed over either of these two periods, the hypothesis that a given extreme weather event is affected by the rise in CO_2 cannot be verified, and is more likely falsified.

But what if a *rising* trend were observed in the data, would that be proof of a CO_2-induced influence? In a word, no. As shown in Figure II.B.1.2, additional analyses must be performed.

It has already been established that, at a minimum, trends in extreme weather events must be evaluated over the period of majority buildup of CO_2, which logically could be interpreted as the three-fourths increase that has occurred since the end of WWII or the one-half increase since 1979. If a *rising* trend is observed over this period, the parameter must further be examined over a much longer time period from which the full expression of its natural variability can be observed. And because the Endangerment Finding projects extreme weather events to increase with time in consequence of CO_2-induced global *warming*, the only way to obtain an untainted view of their natural variability is to examine how these events responded to changes in climate over similar warm periods prior to the modern buildup of anthropogenic CO_2. In most cases, this requires extending datasets back in time approximately 1,000 years to a climatic period known as the Medieval Warm Period, which was the last time global temperatures reached levels as warm as-or warmer than-they are today. Nevertheless, shorter datasets may still be used to *falsify* the CO_2-induced extreme weather hypothesis, they just can't be used to prove it. Though a record may only extend back in time 200, 300, or 500 years, if it shows no trend or a declining trend, the hypothesis of a CO_2-induced influence can be rejected.

The example below illustrates the importance of tempering attribution claims of a CO_2-induced influence on extreme weather events of the modern era and the need to study and evaluate their occurrence over a much longer period where the full expression of natural variability can be observed.

According to John Hooper's 14 August 2002 article in *The Guardian*,[43] in the midst of that year's massive flooding in Europe, Gallus Cadonau (the managing director of the Swiss Greina

---

[43] See http://www.co2science.org//articles/V6/N41/C2.php

Foundation) called for a punitive tariff on U.S. imports to force cooperation on greenhouse gas emissions, claiming that the flooding "definitely ha[d] to do with global warming" and stating that "we must change something now." He was joined in this sentiment by Germany's environment minister, Jurgen Trittin, who implied much the same thing when he said "if we don't want this development to get worse, then we must continue with the consistent reduction of environmentally harmful greenhouse gasses." A thorough analysis of historical flood accounts and more recent river-flow data by Mudelsee *et al*. (2003),[44] however, revealed something very different.

What this team of German researchers did was to analyze historical documents stretching from the 11th century to 1850 and subsequent water stage and daily runoff records from then until 2002 pertaining to two of the largest rivers in central Europe, the Elbe and Oder rivers, seeking to determine trends in flood occurrence over the past thousand years. In so doing, the scientists report that "for the past 80 to 150 years"—which climate alarmists typically describe as a period of unprecedented CO_2-induced global warming—"we find a decrease in winter flood occurrence in both rivers, while summer floods show no trend, consistent with trends in extreme precipitation occurrence." Thus, the strident claims of Cadonau and Trittin that global warming had caused the 2002 flooding failed to stand up to scrutiny when compared with historical observations. As the world recovered and warmed from the global chill of the Little Ice Age, flooding of the Elbe and Oder rivers did *not* materially change in summer and actually *decreased* in winter.

Blaming anthropogenic CO_2 emissions for the European flooding of 2002 was obviously incorrect and not a reasoned deduction based on scientific evidence. If Cadonau and Trittin had properly followed the steps outlined in Figure II.B.1.2, they would not have gotten things so wrong.

The dilemma and difficulty in most analyses of extreme weather events, however, is that modern records do not extend back that far in time. Indeed, most datasets only go back a few decades, rarely eclipsing a century in length. Thus, proxy records of extreme weather events must be collected and studied. And that is not easy to do. They take time and effort, and they are costly to produce. Nevertheless, they are necessary for those desiring to conduct proper scientifically-based analyses of extreme weather events.

At this point, as illustrated in Figure II.B.1.2, it should also be noted that even if a location yields a positive trend in an extreme weather event across a time period of over 1,000 years or more, such a finding is still not sufficient to validate the model-based claims; for the mere existence of a positive trend does not prove it was caused by CO_2-induced influences. And that brings up the third and final step required to properly establish a CO_2 effect on extreme weather events: *The influence of all other (non CO_2-driven) variables that impact a given extreme weather event must be studied and factored out of observable trends*.

Anyone with limited knowledge of statistics knows that correlation among variables does not prove causation, and anyone with a limited understanding of weather and climate knows there

---

[44] Mudelsee, M., Borngen, M., Tetzlaff, G. and Grunewald, U. 2003. No upward trends in the occurrence of extreme floods in central Europe. *Nature* **425**: 166-169.

are many factors that can cause extreme weather events. Natural forcings and factors operate across multiple timescales and varying spatial domains to cause extreme weather; and they have been doing it independent of the air's CO_2 concentration for eons.

Consider, for example, the following analysis of extreme river levels and flows of the Nile River by Kondrashov *et al*. (2005).[45] For their analysis, they applied advanced spectral methods to fill in data gaps and locate interannual and interdecadal periodicities in historical records of annual low- and high-water levels of the Nile River over the 1,300-year period A.D. 622 to 1922. In doing so, they found several statistically significant periodicities in the record, including cycles of 256, 64, 19, 12, 7, 4.2, and 2.2 years. With respect to the *causes* of these cycles, Kondrashov *et al*. say the 4.2- and 2.2-year oscillations are likely the product of El Niño-Southern Oscillation variations. The 7-year cycle, on the other hand, is possibly related to North Atlantic influences, according to them, while the longer-period oscillations may be due to astronomical forcings.

In addition to revealing the stated periodicities, the results of Kondrashov *et al*.'s analysis and annual-scale resolution provide what they refer to as a "sharper and more reliable determination of climatic-regime transitions" for tropical east Africa, including documentation of fairly abrupt shifts in river flow at the beginning and end of the Medieval Warm Period, as well as for other periods throughout the record. These "fairly sharp shifts in the amplitude and period of the interannual and interdecadal modes over the last millennium-and-a-half," according to the researchers, "support concerns about the possible effect of climate shifts in the not-so-distant future."

Thus, those living near the Nile and who are dependent on it for their sustenance should be particularly concerned, for abrupt changes in flow rates and river levels have punctuated the river system for 1,300 years or more; and there is no reason why similar changes will not continue in the future, independent of any change in atmospheric CO_2 concentration.

If and when the situation does change and the Nile flow rates and river levels experience extreme events, these natural periodicities would have to be accounted for and subtracted out before any attribution could properly be ascribed to rising CO_2. The same is true for all indices of extreme weather. The burden of proof remains with those claiming a CO_2 effect, who must demonstrate that the influence of all other potential factors have been removed and ruled out as possible cause(s) of an extreme weather event increase before they can ascribe its rise to CO_2. Unfortunately, many are not content to do this required work (including EPA in its Endangerment Finding); and they therefore have no business making attribution claims that have not been properly vetted.

Furthermore, it is also important to note that results from one analysis in one location do not a *global* conclusion make. Similar trends from *multiple* locations around the globe are needed before a true assessment of the extreme weather hypothesis can be made. Fortunately, numerous such studies have been conducted according to the principles and steps outlined above; and they have been published in the peer-reviewed scientific literature, providing a fairly complete assessment of the entirety of the climate-alarmist hypothesis set forth in EPA's Endangerment

---

[45] Kondrashov, D., Feliks, Y. and Ghil, M. 2005. Oscillatory modes of extended Nile River records (A.D. 622-1922). *Geophysical Research Letters* **32**: doi:10.1029/2004GL022156.

Finding. The following section highlights that literature and provides links to detailed analyses of it, presenting a compelling refutation of the claim that CO_2-induced global warming is increasing the frequency and severity of key extreme weather phenomena.

2. Extreme Weather Observations and Trends

Numerous studies have been conducted over the past decade or so that allow evaluation of the Endangerment Finding's claim that CO_2-induced global warming is increasing both the frequency and intensity of various types of extreme weather events. This subsection highlights only a small portion of that work. However, links to hundreds of additional peer-reviewed scientific articles supporting the general conclusions depicted here are provided for further study and proof. In addition, we cite a major report by the Nongovernmental International Panel on Climate Change (Idso *et al*., 2013; located online at https://www.heartland.org/_template-assets/documents/CCR/CCR-II/Chapter-7-Extreme-Weather.pdf), which highlights the findings of over 1,000 scientific papers that have examined this topic prior to 2013. Similar to what is conveyed here, that report concluded there is nothing unusual, unnatural, or unprecedented about extreme weather events of the past few decades, and that the ongoing rise in the atmosphere's CO_2 concentration is having no measurable influence on these phenomena.

For brevity, the material in the following subsections references only a handful of examples of each category of extreme weather event discussed below. However, information on additional peer-reviewed studies pertaining to each subtopic can be found by following the Internet links provided at the end of each subsection.

(i) Hurricanes

The Endangerment Finding accepted the premise established by climate models in operation prior to 2009 that the intensity and frequency of hurricanes or *tropical cyclones* (TCs) are increasing in response to CO_2-induced global warming. However, the accuracy of those models has been called into question.

Writing in the *Journal of Climate*, Roberts *et al*. (2015)[46] say "there is an increasing need for skillful climate information at regional and local scales, particularly for considering variability and extremes," but they note that the "current phase 5 of the Coupled Model Intercomparison Project (CMIP5)-class models[47] generally fall short of being able to provide information on these small space and time scales[48]." And, hence, they proceed to report the results of the models' then-current "objective, resolution-independent feature-tracking methodology," which they used to identify and track tropical cyclone (TC)-like features in several of the CMIP5 models that they then compared with real-world observations.

---

[46] Roberts, M.J., Vidale, P.L., Mizielinski, M.S., Demory, M.-E., Schiemann, R., Strachan, J., Hodges, K., Bell, R. and Camp, J. 2015. Tropical cyclones in the UPSCALE ensemble of high-resolution global climate models. *Journal of Climate* **28**: 574-596.

[47] Taylor, K.E., Stouffer, R.J. and Meehl, G.A. 2012. An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society* **93**: 485-498.

[48] Christensen, J.H. *et al*. 2014. Climate phenomena and their relevance for future regional climate change. *Climate Change 2013: The Physical Science Basis*. Cambridge University Press, pp. 1217-1308.

This work revealed, in the words of the nine UK researchers, that (1) “all model storms are weak compared to observations, particularly with regard to 10-m wind speed ... but also applying to wind at other levels,” that (2) “the models produce typically too few TCs in the NA [North Atlantic],” as well as (3) “too many in the EP [Eastern Pacific],” that (4) “the models also generate storms in the South Atlantic [SA], where hurricanes are observed to be rare,” that (5) “increased model resolution enhances an error in the CP [Central Pacific], where the density becomes too high compared to observations,” along with (6) “tracks that are too zonal,” together with (7) “fewer storms being generated nearer to the equator in the western Pacific than seen in the observations,” that (8) “an additional model bias lies in the Gulf of Mexico/EP region, where the track density is again too high,” that (9) “in the Southern Hemisphere, the main error in distribution is found in the SWI [Southwestern Indian Ocean] basin, where the track density is strongly enhanced to the west near Madagascar,” that (10) “in the NA [North Atlantic] the season starts too early,” that (11) it “does not increase strongly through July-September, as seen in the observations,” that (12) “the EP has too many storms in the higher-resolution models,” that (13) there are “too many easterly waves propagating into this region” with (14) “a dip in September that is not seen in observations,” that (15) there is “poor simulation of the Indian monsoon,” that (16) “in general, the Southern Hemisphere has too many storms,” and that (17) the mean ACE [accumulated cyclone energy] in the models “is much smaller than observed, typically by 3-10 times.”

Such shortcomings and model failures are not exactly a ringing endorsement of sound judgment by the EPA to place so much weight upon the models in their evaluation of future trends in tropical cyclone frequency and intensity as reported in the Endangerment Finding. Furthermore, the EPA should have placed more weight in an evaluation of real-world *observations* of tropical cyclone trends, which also fail to match expectations outlined in the Endangerment Finding.

In this regard, consider the work of Klotzbach and Landsea (2015),[49] who analyzed trends in category 4 and 5 hurricanes for the conglomerate of all global ocean basins over the period 1970 to 2004. The two researchers report that “when restricted to the most recent 25 years (1990-2014) with the most reliable and homogeneous records, the following conclusions are reached and illustrated in the [Figure II.B.2.i.1]:” (1) “small, insignificant decreasing trends are present in category 4-5 hurricane frequency in the Northern Hemisphere and globally, while there is virtually no trend in Southern Hemisphere frequency,” that (2) “small, insignificant upward trends are present in category 4-5 hurricane percentages in the Northern Hemisphere, the Southern Hemisphere, and globally,” and, last of all, that (3) “large, significant downward trends are present in accumulated cyclone energy (ACE) in the Northern Hemisphere, the Southern Hemisphere, and globally.”

---

[49] Klotzbach, P.J. and Landsea, C.W. 2015. Extremely intense hurricanes: Revisiting Webster et al. (2005) after 10 years. *Journal of Climate* **28**: 7621-7629.

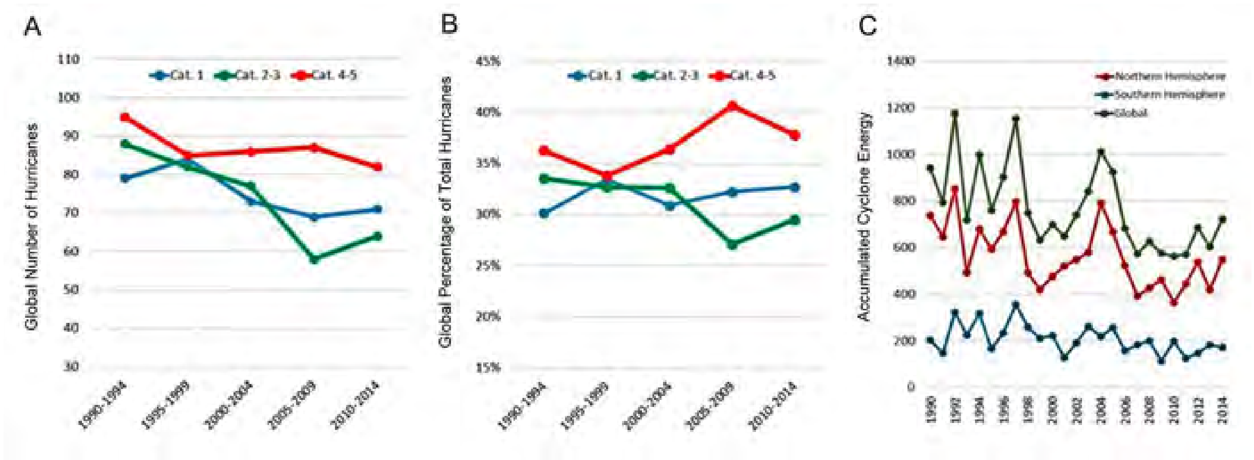


***Figure II.B.2.i.1**. (A) Pentad total of the number of hurricanes that achieved a maximum intensity of each category grouping as delineated by the Saffir–Simpson scale. (B) As in (A), but for the percentage of total hurricanes achieving each category grouping.(C) Global and hemispheric ACE values (10^4 kt^2).*

In light of these diverse findings, Klotzbach and Landsea conclude their paper by noting that prior to 1990, pertinent records are "incomplete and lead to a distorted view of the actual activity that occurred before that time," while as for the *future*, they suggest that "given the large natural variability driven by ENSO and other natural phenomena, it is likely to be challenging to confidently ascribe an anthropogenic signal to changes in the most intense tropical cyclones for the next several decades."

More examples of global hurricane data are presented in the next two figures. Figure II.B.2.i.2 depicts global tropical storm and tropical cyclone frequencies since 1971. Although there is considerable interannual and decadal variability in these records, there is no evidence tropical storms or tropical cyclones are increasing in response to supposed CO_2-induced global warming. If anything, a linear trend in these data reveals that these extreme weather events have *declined* over this five decade period.

A similar assessment can be made for tropical cyclone intensity trends. As shown in Figure II.B.2.i.3, measurements of accumulated cyclone energy, which is representative of hurricane intensity, reveal interannual and decadal fluctuations, but no definitive evidence of an increasing trend due to rising atmospheric CO_2.

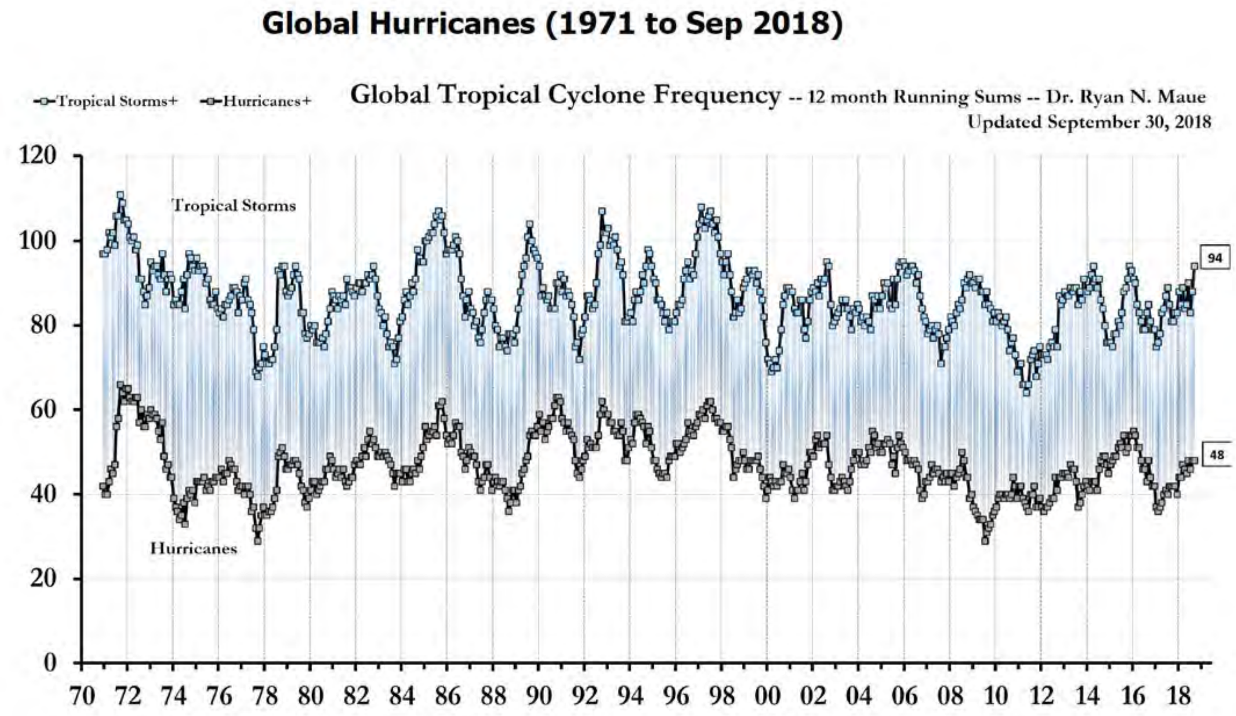


Figure II.B.2.i.2. *Global tropical storm and tropical cyclone frequencies over the period 1971-2018.*

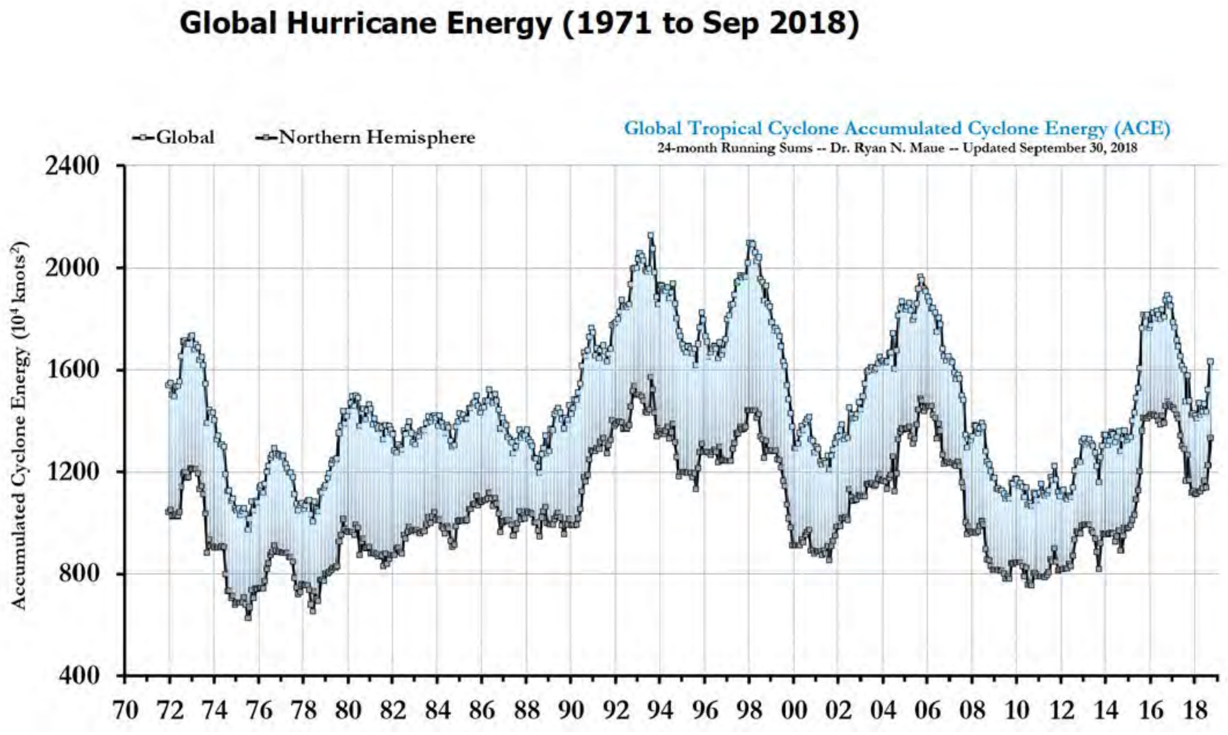


Figure II.B.2.i.3. *Global and Northern Hemispheric tropical cyclone intensity (i.e., accumulated cyclone energy) over the period 1971-2018.*

Focusing in on the United States, Truchelut and Staehling (2017) introduced and examined an extended record of U.S. tropical cyclone activity based on accumulated cyclone energy (ACE, which accounts for hurricane intensity) over the period 1900 to 2017. Key findings of their study are presented in the three-panel graphic of Figure II.B.2.i.4.

Perhaps the most significant observation noted in their ACE times series (see panel b) is the *lack* of any statistically significant trend across the 118 year record, albeit there are fluctuations on various time scales. Such *absence* of a long-term upward trend in the data is contrary to claims that rising levels of atmospheric carbon dioxide are causing more frequent or more severe storms. This point is further supported by the data presented in panel a, which depicts the number of days between U.S. hurricane landfalls since 1900. As seen there, the average return period of major hurricanes with wind speeds of 100 kt or greater (i.e, Category 3) is approximately 700 days. Interestingly, prior to the passing of Hurricane Harvey in 2017, there was a record 4,324 days where no Category 3 or higher hurricane made landfall in the U.S., which time period the authors say "is almost double the length of the next-longest gap in major hurricane landfalls." Thus, if anything, these data suggest that CO_2-induced global warming is *reducing* the number and strength of landfalling U.S. hurricanes.

In one final data demonstration to show that the Endangerment Finding has got it wrong (and possibly backwards), Truchelut and Staehling prepared a plot of the percent of each Atlantic hurricane season's observed basin-wide ACE that occurred over or within a 0.5° buffer of the continental U.S. over the period 1950-2017. Analysis of these data revealed that "the 2006-2015 average is the lowest on record, with just under 3% of the total ACE in the period occurring over the continental U.S." Such drought of hurricane activity in later years contributed to an overall downward trend in the record that the authors report was statistically significant at the 99% confidence level.

Clearly, based on the data presented above and in many other papers (see the links below), there is no compelling evidence to support the contention that rising levels of atmospheric CO_2 are increasing the frequency or magnitude of hurricanes hitting the U.S. or the globe. If anything, the data suggest rising CO_2 is having no effect or may even be reducing them.

Information on additional peer-reviewed scientific studies on this topic can be accessed by clicking on the links below, or from under the heading of Hurricanes here: http://www.co2science.org/subject/h/subject_h.php.

Hurricanes
 Atlantic Ocean
  El Niño Effect
  Global Warming Effects
   Frequency
   Past Century
   Past Few Centuries
   Past Few Millennia
   Intensity

[Miscellaneous](#)
[Global](#)
[Indian Ocean](#)
[Pacific Ocean](#)

(ii) Storms

Among the predicted changes expected by the Endangerment Finding to attend CO_2-induced global warming are increases in the frequency and severity of various types of storms. Storms are a concern of the residents of any coastal city, as high winds, water surges and high-energy waves carry the potential for damage via flooding and erosion. The prior subsection revealed that this claim is unsupported by data on hurricanes. And although fewer data exist to cover the many types of extratropical storms, those data also fail to support the model-based claims on the frequency and severity of storms.

This section discusses only three such research papers. Nevertheless, links at the end of the section present reviews of multiple other studies on the topic, which also fail to support the model-based claims on storms championed by the EPA.

Taking advantage of the fact, as they describe it, that "systematic observations of wind speed and direction have been collected at Skagen Fyr (Skagen Lighthouse), northern Denmark from December 1860 to August 2012," Clemmensen *et al*. (2014)[50] employed these data to develop a concomitant history of wind-induced storminess over this period of time, when the Earth transited from the extreme *cold* of the Little Ice Age to the less debilitating *heat* of the Current Warm Period, while noting that "the chosen site is considered to be representative for the wind climate of the central North Sea and SW Scandinavia."

As illustrated in Figure II.B.2.ii.1 below, this work revealed, in their words, that "between 1860 and 1875 storminess (wind events exceeding Beaufort 8) is extremely high, but since then storminess decreases." And they note that, concomitantly, around 1870 the annual *drift potential* (DP) of coastal dunes was "also extremely high and reaches up to 9600 vector units (VU, knots)." But they say that "since 1980 DP levels are below 3000 VU and decreasing," which significant "shift in wind climate towards less storminess is seen at a number of stations in NW Europe." Thus, in this study, global warming, which was an historical reality over the period examined in Clemmensen *et al*.'s work, *decreased* storminess.

---

[50] Clemmensen, L.B., Hansen, K.W.T and Kroon, A. 2014. Storminess variation at Skagen, northern Denmark since AD 1860: Relations to climate change and implications for coastal dunes. *Aeolian Research* **15**: 101-112.

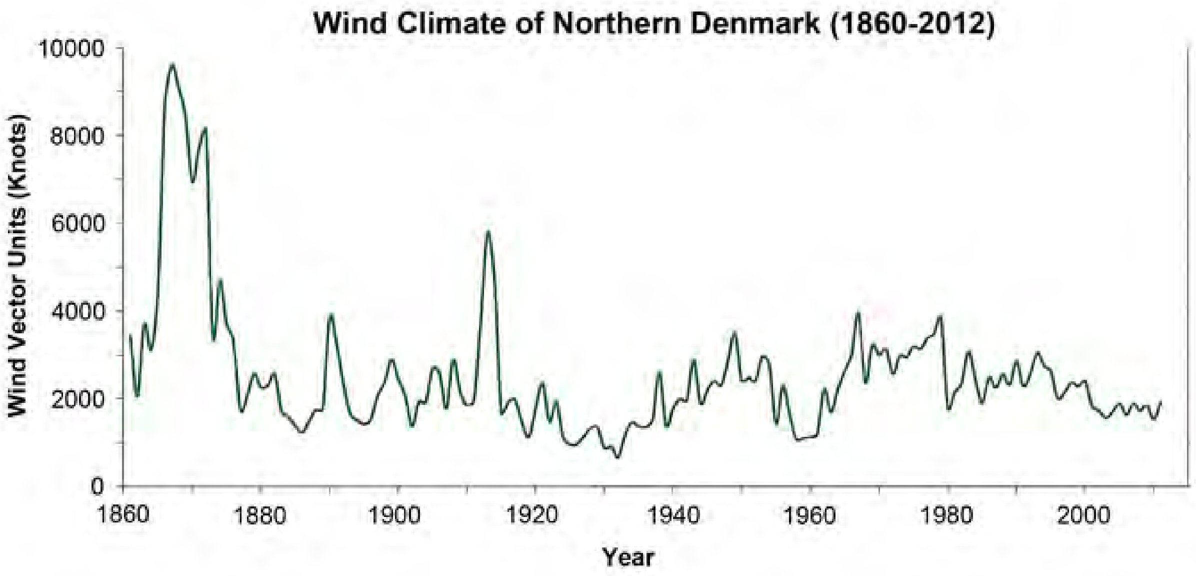


Figure II.B.2.ii.1. *Wind climate for northern Denmark over the period 1860-2012, expressed as annual drift potential (a measure of wind power).*

In setting the rationale for their work, Zou *et al*. (2018)[51] say that "there is increasing concern that local severe storm occurrence may be changing as a result of climate change," which thesis they set out to examine for severe storm and hail events in the Tibetan Plateau.

Starting off their analysis, the four scientists note that the Tibetan Plateau (TP) is considered to be "one of the most sensitive areas to climate change." Over the second half of the 20th century it warmed at an average rate of 0.16 °C per decade. What is more, the region of the TP experiences the most frequent occurrence of hail and thunderstorms in all of China. Thus, if there ever was a location to test the hypothesis that global warming increases the frequency of severe storms and hail events, *this is that place!* So, that is exactly what the researchers set out to do. And what did they find?

As displayed in Figure II.B.2.ii.2, despite considerable warming over the period 1960-2012, Zou *et al*. determined that there has been a statistically significant *decline* of 3.1 storms days per decade across the TP. Hail days, on the other hand, showed a slight increasing trend of 5.8% per decade from 1955-1980, but thereafter declined by a much larger 18.3% per decade over the period 1980-2012.

With respect to the cause of the observed declines, Zou *et al*. analyzed a series of meteorological soundings of the atmosphere, as well as reanalysis data and found that a drying of the mid-troposphere, likely caused by surface warming, was "the primary reason for the decrease of warm-season storm days in the TP." And, they add that weaker wind shear combined with an increase in the height of the atmospheric melting level, mainly after 1980, led to the decline in

---

[51] Zou, T., Zhang, Q., Li, W. and Li, J. 2018. Responses of hail and storm days to climate change in the Tibetan Plateau. *Geophysical Research Letters* **45**: 4485-4493.

the number of hail days. Consequently, they conclude that their results "imply that global warming is likely to cause a decrease in the conditions required for severe thunderstorm and hail formation in the TP over the next century," just the opposite from what the models suggest!

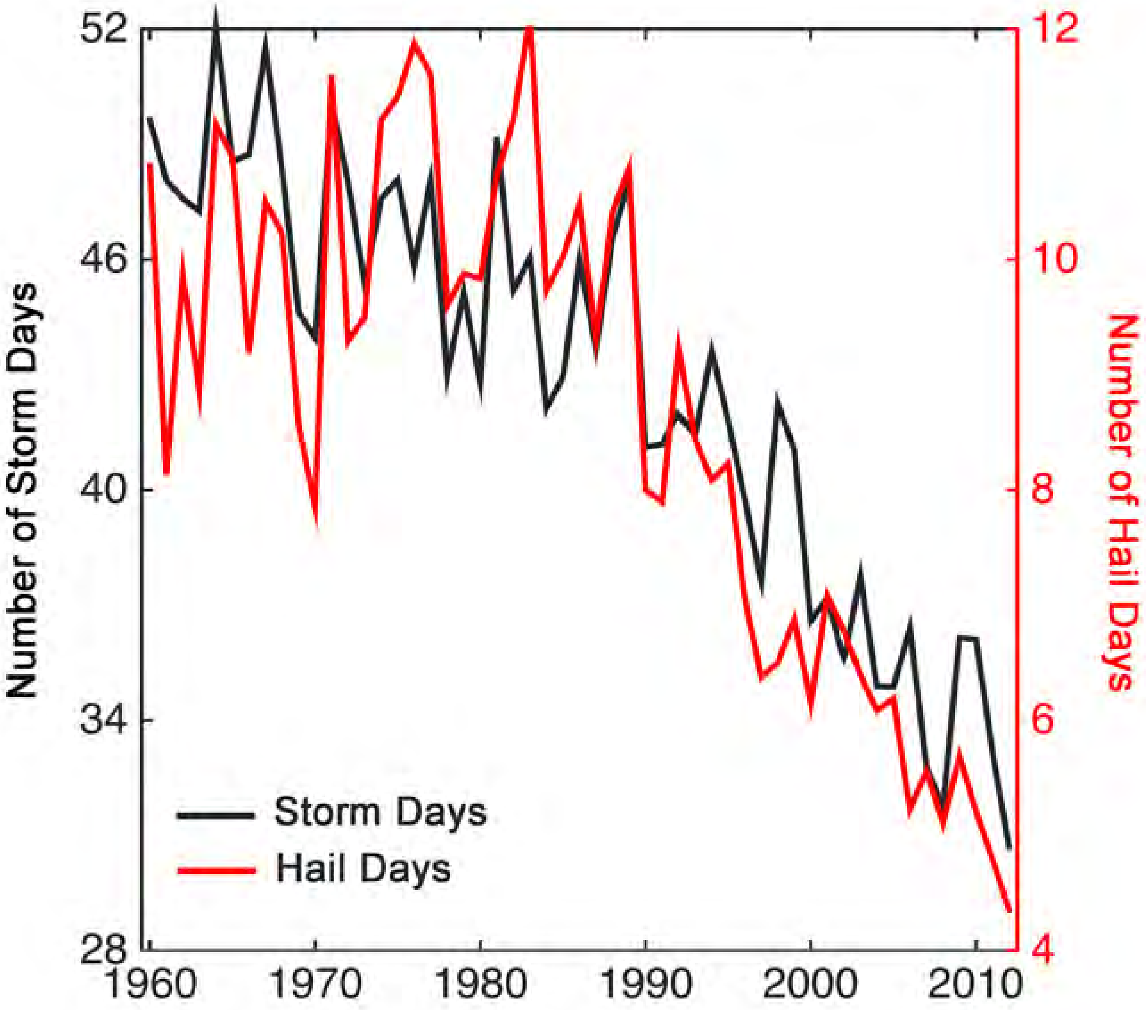


***Figure II.B.2.ii.2**. Historic time series of warm season mean storm days (black line) and hail days (red line) averaged over the Tibetan Plateau over the period 1960-2012.*

In another study Rangel-Buitrago *et al*. (2016)[52] examined wave-buoy data recorded at Turbot Bank buoy near the western edge of the Bristol Channel, Wales, UK (51.6°N, 4.58°W), over the period 1998-2013. More specifically, they analyzed average annual and monthly significant wave (H_s) and maximum wave (H_{smax}) heights to characterize trends in "wave climate, wave energy, and the definition and description of storms." In doing so the researchers report that small decreases in monthly H_s and H_{smax} values were observed over the length of the record as

---

[52] Rangel-Buitrago, N.G., Thomas, T., Phillips, M.R., Anfuso, G. and Williams, A.T. 2016. Wave climate, storminess, and Northern Hemisphere teleconnection patterns influences: The Outer Bristol Channel, South Wales, U.K. *Journal of Coastal Research* **32**: 1262-1276.

shown in Figure II.B.2.ii.3. Similarly, there were nonsignificant decreasing trends in wave energy and the frequency, duration and intensity of storms throughout the record (also shown in Figure II.B.2.ii.3). These findings, in the words of the authors, are "contradicting [of] the forecasted general increase, attributed to climatic change, in the number and intensity of storms in many oceans around the world and, more closely, in the northern hemisphere."

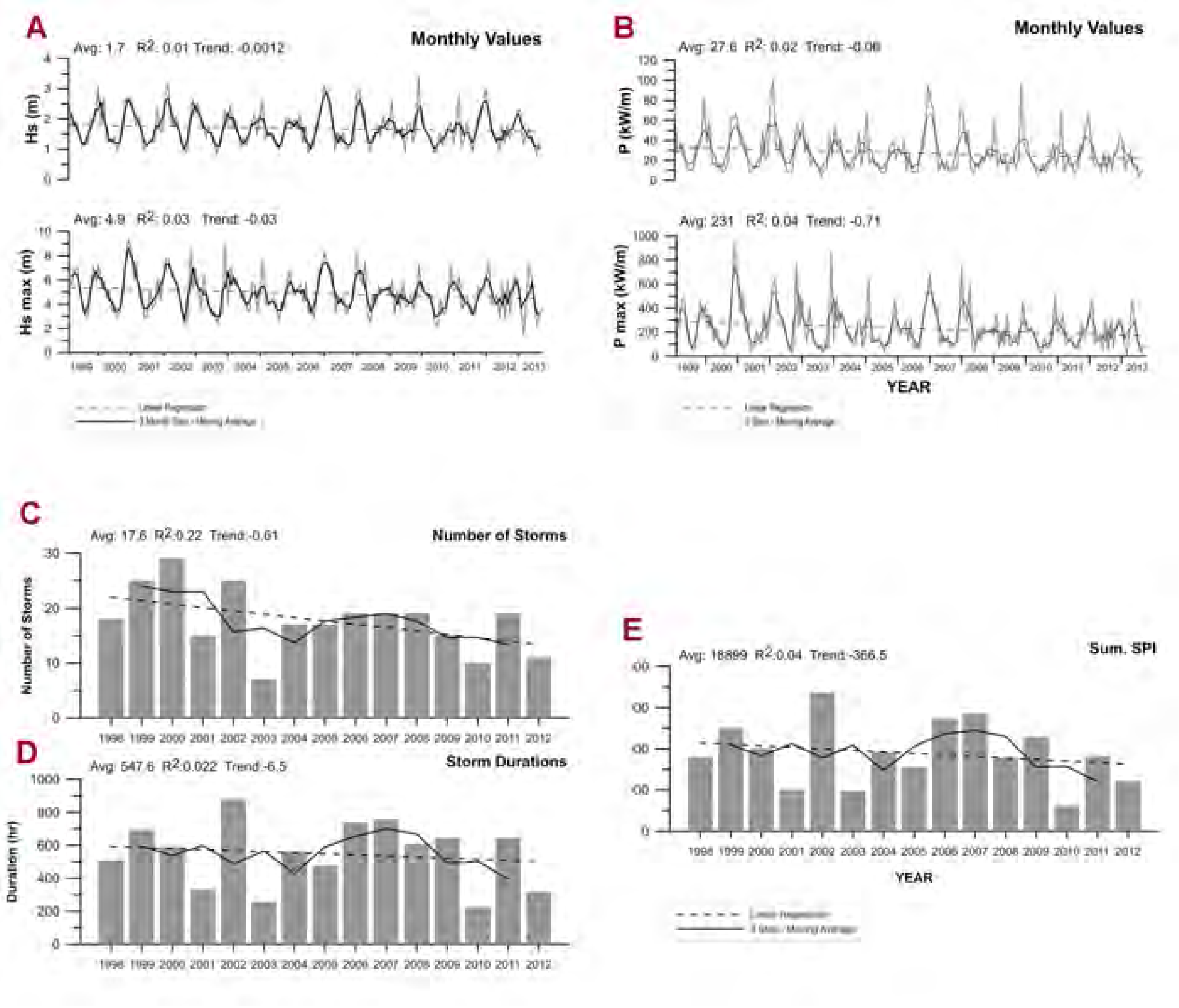


Figure II.B.2.ii.3. *Panel A: Monthly average values of significant wave height (Hs) and maximum wave height (Hsmax). Panel B: Monthly average values of wave power and maximum wave power. Panels C, D and E: Distribution of the number of storms (C), duration (D), and sum of storm power (E) per year.*

Finally, several researchers have examined trends in tornadoes, one the most destructive phenomena of severe storms.[53,54,55,56,57] In this regard, it has been observed that the number of the most severe tornadoes have declined in recent years as temperatures have warmed, which decline is evidence in the plot below (Figure II.B.2.ii.4). Once again, the observed behavior of nature (tornado frequency) has failed to confirm model-based claims of a CO_2-induced influence that is supposed to increase tornado events.

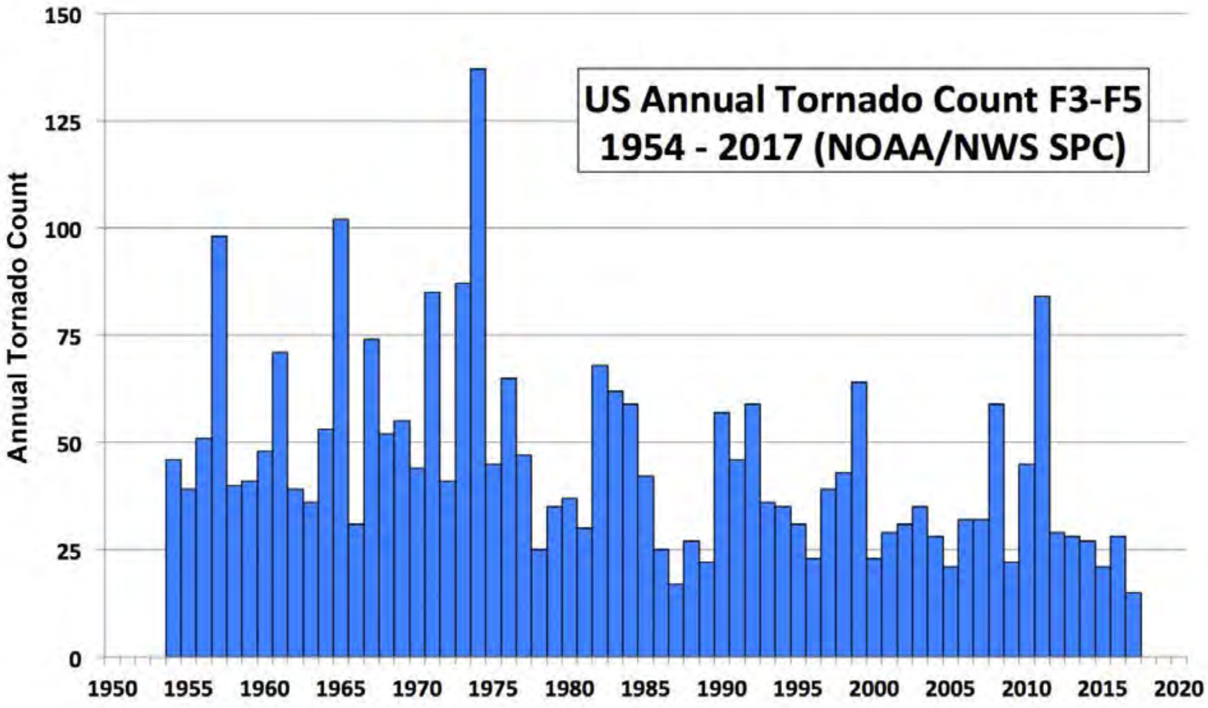


Figure II.B.2.ii.4. *Annual number of severe tornadoes (F3 to F5) in the United States over the period 1954-2017, revealing there has been a marked decline in the frequency of such events over the past half-century.*

Information on additional peer-reviewed scientific studies on this topic can be accessed by clicking on the links below, or from under the heading of Storms here: http://www.co2science.org/subject/s/subject_s.php.

---

[53] Balling Jr., R.C. and Cerveny, R.S. 2003. Compilation and discussion of trends in severe storms in the United States: Popular perception vs. climate reality. *Natural Hazards* **29**: 103-112.

[54] Changnon, S.A. 2003. Shifting economic impacts from weather extremes in the United States: A result of societal changes, not global warming. *Natural Hazards* **29**: 273-290.

[55] Daoust, M. 2003. An analysis of tornado days in Missouri for the period 1950-2002. *Physical Geography* **24**: 467-487.

[56] Diffenbaugh, N.S., Trapp, R.J. and Brooks, H. 2008. Does global warming influence tornado activity? *EOS, Transactions, American Geophysical Union* **89**: 553-554.

[57] Brooks, H.E., Carbin,G.W. and Marsh, P.T. 2014. Increased variability of tornado occurrence in the United States. *Science* **346**: 349-352.

Storms

- Asia
- Australia/New Zealand
- Dust Storms
- Europe
  - France
  - Other Regions
  - United Kingdom
- Global
- Hail
- Model Inadequacies
- North America
- North Atlantic Ocean
- Northern Hemisphere
- South America
- Southern Hemisphere
- Tornadoes

(iii) Floods

Climate models predict that floods will increase in the future in response to CO_2-induced global warming. This section reveals that observations across the globe do not support this claim.

Model projections of future increases in precipitation from anthropogenic global warming have led to concerns that there will be corresponding increases in river flooding. Consequently, many researchers have begun to search for evidence of more frequent and/or severe flooding over the past several decades. One example of a team of scientists conducting such an investigation is that of Hodgkins *et al*. (2017),[58] who examined trends in the occurrence of major floods across North America and Europe over the past eight decades.

In preparing for their analysis, the twelve researchers first made sure to build a proper database free of contaminating influences. This was accomplished by their using only those hydrologic stations that were located in minimally altered catchments. Such catchments, for example, had to contain (1) less than 10 percent urban area, (2) have no substantial flow alteration or changes in land cover, (3) less than 10 years of missing data and (4) good quality gauges capable of providing accurate peak-flow data. By sticking to these criteria, the authors were confident that any trends they found in the data would most likely be the result of climate-driven influences (either human-induced or natural in origin). This winnowing process led the authors to select 1204 hydrologic stations, which they utilized to examine for changes in major flood events over the period 1961-2010. They then repeated their analysis on a smaller subset of 322 stations over the longer time period of 1931-2010. And what did their results reveal?

---

[58] Hodgkins, G.A., Whitfield, P.H., Burn, D.H., Hannaford, J., Renard, B., Stahl, K., Fleig, A.K., Madsen, H., Mediero, L., Korhonen, J., Murphy, C. and Wilson, D. 2017. Climate-driven variability in the occurrence of major floods across North America and Europe. *Journal of Hydrology* **552**: 704-717.

Hodgkins *et al*. report that "there was no compelling evidence for consistent changes over time in major-flood occurrence during the 80 years through 2010," adding that "the number of significant trends in major-flood occurrence across North America and Europe was approximately [equal to] the number expected due to chance alone." Consequently, they conclude that "compelling evidence for increased flooding at a global scale is lacking." And this *lack of evidence* disproves any attempt by the EPA to claim that major floods are currently increasing due to anthropogenic-induced climate change, at least over this large portion of the globe.

In a separate study, Schedel and Schedel (2018)[59] write that "the mainstream media report regularly that storm events in the United States, especially on the East Coast, are becoming more severe and more frequent," with the blame almost always being placed upon CO_2-induced global warming. In an effort to determine the validity of these claims, the two U.S. Naval Academy researchers performed a series of statistical analyses on sea level data from thirteen locations along the U.S. East Coast, which stations were selected due to their long length (75 years or more) and completeness (87% or greater) of record. And what did the tide gauge data from each of these thirteen locations reveal with respect to the frequency and severity of coastal flood events? Have they indeed changed over time?

As stated by the authors, their analysis showed that "flood events on the U.S. East Coast are not more severe or frequent than in the past." They only *appear* to be greater if one fails to account for (and remove) the long-term influence of sea level rise, which rise has increased the baseline height of such events over the course of the past century. Yet, despite this baseline increase in sea level, the frequency and severity of coastal flood events have not changed over the past century.

In one final example, Taricco *et al*. (2015)[60] write when introducing their study that "a deep understanding of natural decadal variability is pivotal to discuss recently observed climate trends." Indeed, such comprehension is *necessary* before claims of an anthropogenic influence on climate-related parameters can be validated. And it is with this fact in mind that the eight Italian researchers determined to study the hydrologic variability of the Po River, a major freshwater river whose catchment encompasses a large area of Northern Italy. More specifically, they examined a high-resolution foraminiferal $\delta^{18}O$ record from a sediment core retrieved from the Ionian Sea to reconstruct a 2,200-year history of hydrological variability. And what did the reconstruction show?

In discussing their findings, Taricco *et al*. report that spectral analysis of the core "reveals a highly significant decadal cycle with modulated amplitude throughout the whole 2,200-yr-long $\delta^{18}O$ record" (see Figure II.B.2.iii.1). During some periods, the amplitude of the decadal fluctuations was found to be exceptionally high, including the periods AD 300-600, 900-1100

---

[59] Schedel, J.R., Jr. and Schedel, A.L. 2018. Analysis of variance of flood events on the U.S. East Coast: The impact of sea level rise on flood event severity and frequency. *Journal of Coastal Research* **34**: 50-57.

[60] Taricco, C., Alessio, S., Rubinetti, S., Zanchettin, D., Cosoli, S., Gačić, M., Mancuso, S. and Rubino, A. 2015. Marine sediments remotely unveil long-term climatic variability over Northern Italy. *Scientific Reports* **5**: 12111, doi:10.1038/srep12111.

and 1400-1800, the latter of which witnessed the *highest* level of hydrologic variability and coincided with "the coldest phase of the Little Ice Age." In contrast, the reconstructed amplitude was found to be weakest around AD 200, 800, 1200 and 1400. These findings were bolstered by a comparison between Taricco's reconstructed amplitude and archived reports of floods in the Po River basin over the past two millennia, which revealed widespread coherence among the two records.

Given the above findings, it would appear that the modern rise in atmospheric CO_2 has had no measureable impact on the hydrologic variability of Northern Italy. Rather, such trends have waxed and waned naturally for two millennia or more and will likely continue to do so in the future, changes in atmospheric CO_2 concentrations notwithstanding.

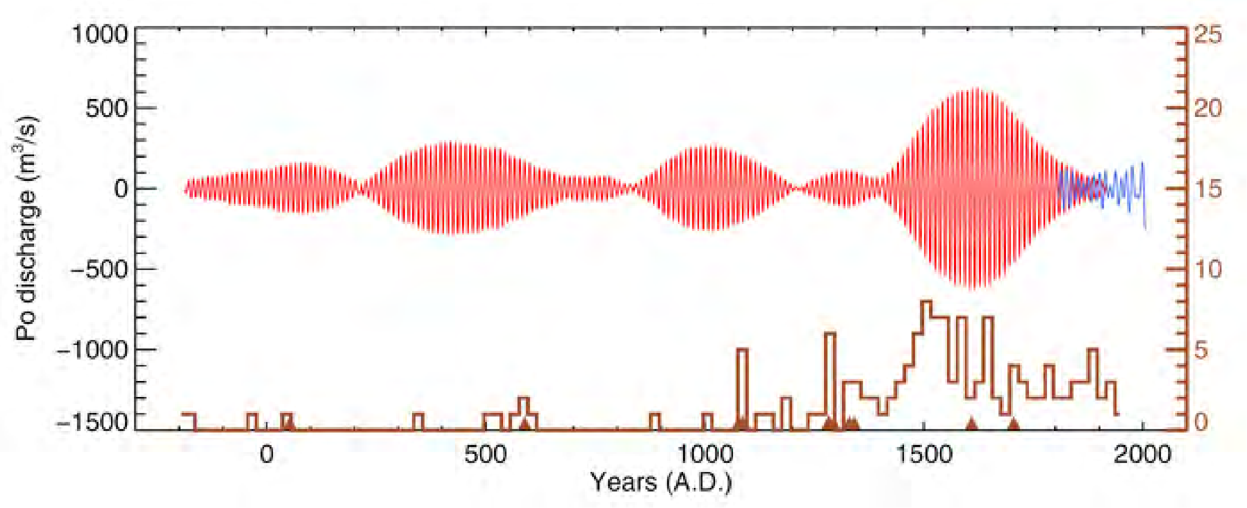


Figure II.B.2.iii.1. *Extrapolation of the Po River discharge before 1917 to the last 2 millennia (red curve). As a reference for the modern era, the Po discharge decadal component is superimposed (blue curve). Known major floods in the Po plain from 200 BC are represented by the histogram, with major events demarked by brown triangles along the edge of the x-axis. The same weight is attributed to each flooding event, since documental description is only qualitative.*

Information on additional peer-reviewed scientific studies on floods can be accessed by clicking on the links below, or from under the heading of Floods here: http://www.co2science.org/subject/f/subject_f.php.

Floods
Africa
Asia
Europe
General
North America
Solar Influence
South America

(iv) Drought

Climate models predict that drought will increase in the future in response to CO_2-induced global warming. This section reveals that observations across the globe do not support this claim.

Publishing their work in the *Journal of Hydrometeorology,* Mo and Lettenmaier (2018)[61] examined historical drought in the United States. In citing the rationale for their study, the two scientists referenced a widespread and severe drought in 2012 that covered more than 62% of the country and caused some $40 billion in damages. And as their contribution to the subject, they set out to investigate this drought event in the context of the past century, seeking to determine if such events are becoming more frequent or more severe. To do so, they used "gridded observed precipitation and reconstructed total moisture percentiles and runoff from four land surface models" to develop an *integrated drought index* (IDI) for defining drought in the continental USA over the period 1916-2013. Using this resulting index, drought periods were then defined as having an IDI value less than 0.3.

A time series showing the percent of the country meeting the above drought criteria is presented in Figure II.B.2.iv.1. As illustrated there, it is clear that the frequency and magnitude of droughts are *not* increasing. In fact, they have *decreased* over the past century.

Taking their findings a step further, Mo and Lettenmaier next filtered the data presented in Figure II.B.2.iv.1 to examine *severe* drought events that covered 50% of the continental USA for a period of six months or longer. Analyses of these data revealed that (1) severe drought events were chiefly located in the central USA, (2) "the 2012 drought event was not unique," considering that there were "16 great drought events in the 98 years of record [they] analyzed," (3) "great droughts occurred less often, and events were less severe as time progressed" and (4) all but two of the 16 great drought events occurred in the first half of the record.

With respect to the potential cause(s) of the 16 great drought events, Mo and Lettenmaier detected a relationship between the Atlantic Multidecadal Oscillation (AMO) and drought (there was a higher percentage of drought when the AMO was in a positive phase) and between ENSO and drought (12 of the 16 great drought events occurred during cold La Niña years). However, droughts did not always occur when the AMO was in a positive phase or when La Niña conditions existed.

Such findings make it abundantly clear that climate model projections of more frequent and more severe drought events are not holding true for the conterminous United States. In contrast, the data reveal a decline in these two parameters over the course of the past half-century.

---

[61] Mo, K.C. and Lettenmaier, D.P. 2018. Drought variability and trends over the central United States in the instrumental record. *Journal of Hydrometeorology* **19**: 1149-1166.

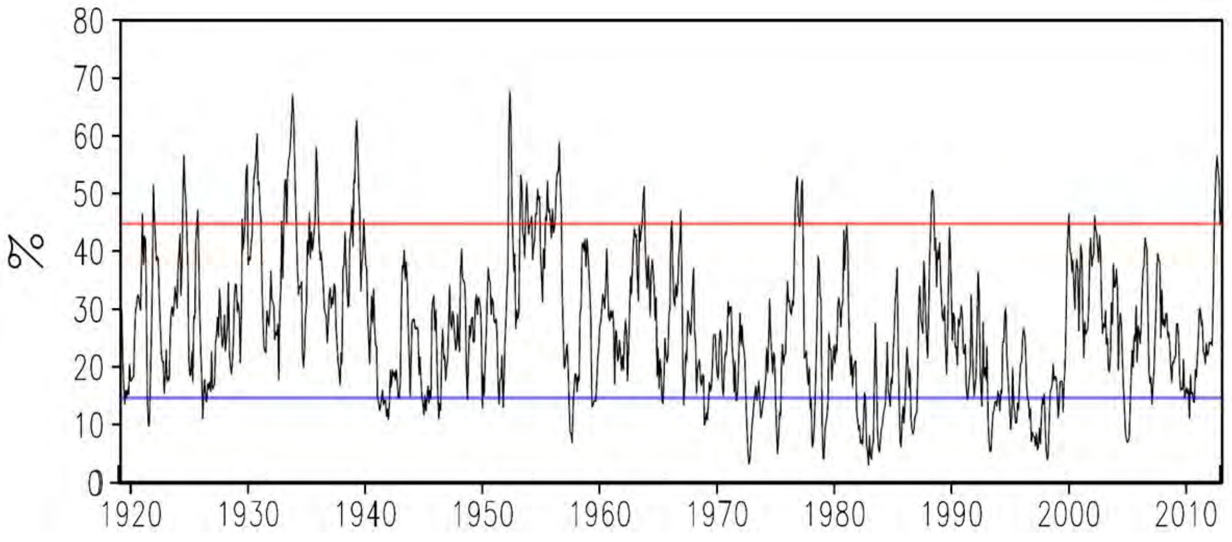


Figure II.B.2.iv.1*. Time series of the percentage of the conterminous United States experiencing drought (IDI index of < 0.3).*

Introducing their study, Benitez and Domecq (2014)[62] write that "droughts are the world's costliest natural disasters, causing an average US$ 6 - US$ 8 billion in global damages annually and collectively affecting more people than any other form of natural disaster," citing Wilhite (2000).[63] And in light of these facts, the Paraguay researchers set out to conduct a study "to determine if the frequency and/or severity of droughts has increased or decreased in the last years, in response to climate change" within their own country. So using the Standardized Precipitation Index, they did just that for the period stretching from 1964 to 2011.

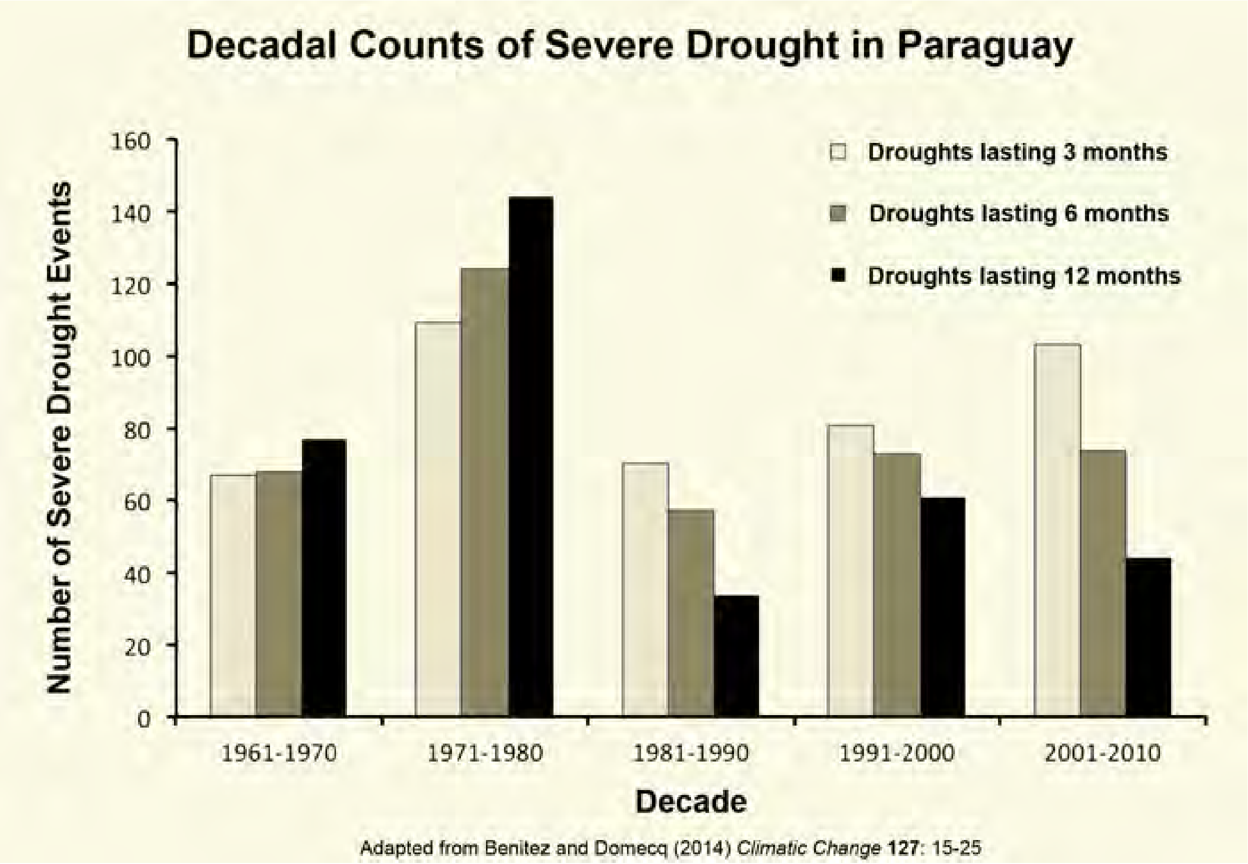
Results indicated, in the words of the two scientists, that "no undeniable increasing trend in drought frequency/severity was detected" (see Figure II.B.2.iv.2 below), despite the fact they report that according to projections of a CMIP5 multi-model ensemble, "during the 21st century drought frequency and severity is expected to increase in Southern South America as well as in Paraguay," as reported by Penalba and Rivera (2013).[64] In fact, they found initial telling signs of just the *opposite* coming to pass, reporting that "during the first years of the records, from 1964 to 1978, the frequency of drought was high when compared with the period 1976-1999."

---

[62] Benitez, J.B. and Domecq, R.M. 2014. Analysis of meteorological drought episodes in Paraguay. *Climatic Change* **127**: 15-25.

[63] Wilhite, D.A. 2000. Drought as a natural hazard: concepts and definitions. In: Wilhite, D.A. (Ed). *Drought: A Global Assessment*," Evanston, pp. 3-18.

[64] Penalba, O.C. and Rivera,J.A. 2013. Future changes in drought characteristics over Southern South America projected by a CMIP5 multi-model ensemble. *American Journal of Climate Change* **2**: 173-182.



Adapted from Benitez and Domecq (2014) *Climatic Change* **127**: 15-25

Figure II.B.2.iv.2. *Decadal counts of severe drought lasting either 12, 6, or 3 months in duration obtained from 20 meteorological stations in Paraguay. Severe drought events were classified as a Standard Precipitation Index (SPI) value ≤ -1.50.*

Damberg and AghaKouchak (2014)[65] note that "numerous studies argue that the Earth's climate is changing rapidly, especially during the second half of the twentieth century," citing Trenberth (2001)[66] as a prime example of this point of view, as well as Trenberth (1999)[67] as an example of this viewpoint as it applies to the planet's hydrologic cycle. Not convinced of the extreme nature of these contentions, however, they decided to analyze "changes in areas under droughts over the past three decades." However, they say that "unlike most previous global-scale studies that have been based on climate models," their study was "based on satellite gauge-adjusted precipitation observations." So what did the two U.S. researchers thereby learn?

As they write near the end of their paper, "several areas, such as the southwestern United States, Texas and the Gulf of Mexico region, parts of the Amazon, the Horn of Africa, northern India, and parts of the Mediterranean region, are among areas showing significant drying trends over the past three decades." *On the other hand*, they say that "central Africa, Thailand, Taiwan,

---

[65] Damberg, L. and AghaKouchak, A. 2014. Global trends and patterns of drought from space. *Theoretical and Applied Climatology* **117**: 441-448.

[66] Trenberth, K. 2001. Climate variability and global warming. *Science* **293**: 48-49.

[67] Trenberth, K. 1999. Conceptual framework for changes of extremes of the hydrological cycle with climate change. *Climatic Change* **42**: 327-339.

Central America, northern Australia, and parts of eastern Europe show a wetting trend during the same time span." And, last of all, they report that a Mann-Kendall test of the satellite data reveal that "the area of global land under drought conditions does not show a significant trend over the past three decades."

In further commenting on what they learned, Damberg and AghaKouchak state that the results of their satellite-based study "disagree with several model-based studies (e.g., Dai, 2012)[68] that indicate droughts have been increasing over land." However, as they state in the concluding paragraph of their paper, their findings *concur* with those of several observation-based studies, such as those of Sheffield *et al*. (2012).

Information on additional peer-reviewed scientific studies on drought can be accessed by clicking on the links below, or from under the heading of Drought here: http://www.co2science.org/subject/d/subject_d.php.

Drought
- Africa
- Asia
- Australia/New Zealand
- Central America
- Europe
- General
- Global
- North America
  - Canada
  - Mexico
  - United States
    - Central
    - Eastern
    - Entire
    - Southern
    - Western
- Solar Influence
- South America

(v) Fires

According to model-based predictions, larger and more intense wildfires will increase as a result of CO_2-induced global warming; and as a result, many have begun to search for a link between fire and climate, with some purporting to find it in the recent severe fire season observed in Australia of 2019/2020. But would that assumption be correct?

---

[68] Dai, A. 2012. Increasing drought under global warming in observations and models. *Nature Climate Change* **2**: 52-58.

Not according to multiple data-based studies on the subject.[69]

Consider, for example, the important work of Earl and Simmonds (2017),[70] who examined the spatial and temporal patterns of fire activity for Australia over the period 2001-2015. Their time period of selection allowed them to utilize satellite data from the MODerate resolution Imaging Spectroradiometer (MODIS) sensors on the Terra and Aqua satellites, which they say allows for "a more consistent and comprehensive evaluation" of fire trends. Using such data, fire count numbers were derived from an active fire algorithm, which fire detection scheme was judged by the authors to be superior to other methods and which allowed them to calculate seasonal and annual fire activity on a 0.1° x 0.1° grid box scale (~1000 km^2).

Results for the country as a whole are presented in Figure II.B.2.v.1 below. As shown there, annual fire numbers for Australia have decreased across the past 15 years of study, albeit the decrease is not statistically significant. Seasonally, the most abundant fire season was in the spring (48% of all fires), followed by winter (21%), summer (16%) and fall (15%). Summer was the only season found to exhibit a statistically significant trend ($p < 0.05$), showing a decline over the period of record.

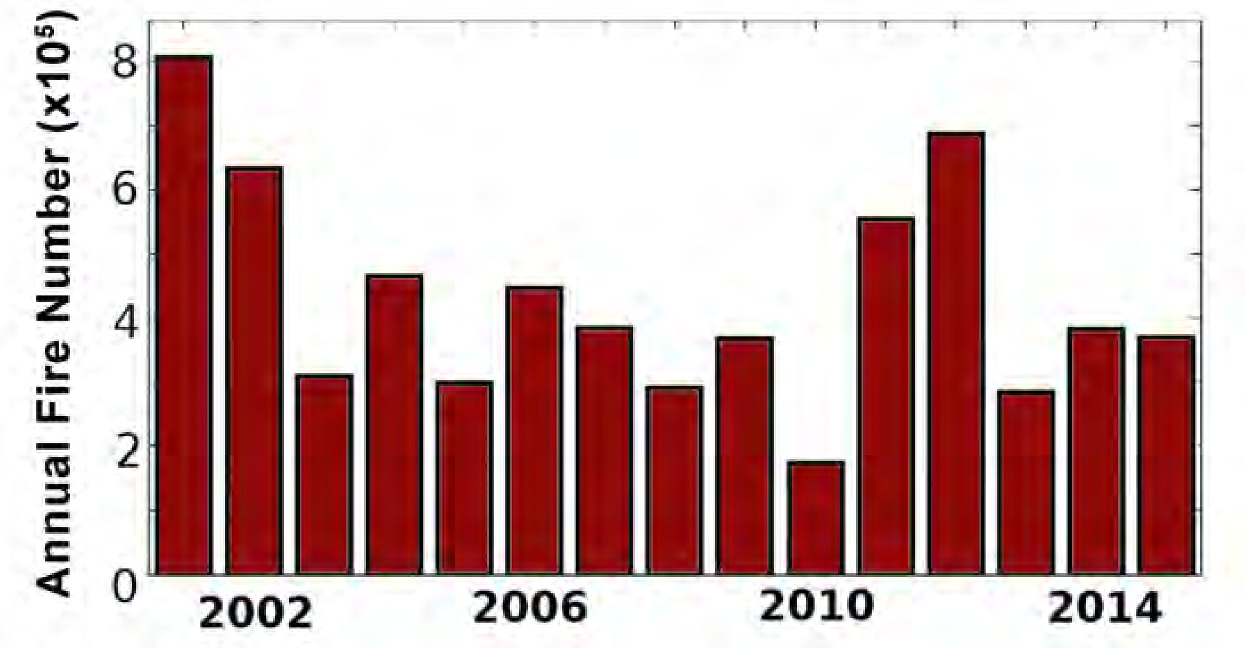


Figure II.B.2.v.1*. Annual number of Australian fires over the period 2001-2015. Adapted from Earl and Simmonds (2017).*

With respect to possible climatic drivers of annual fire number statistics, Earl and Simmonds conducted a series of analyses to explore their relationship with large-scale climate indices, including ENSO, the Indian Ocean Dipole and a precipitation dataset covering the continent.

---

[69] See the many studies referenced in the links on this page, http://www.co2science.org/subject/f/firegw.php.

[70] Earl, N. and Simmonds, I. 2017. Variability, trends, and drivers of regional fluctuations in Australian fire activity. *Journal of Geophysical Research: Atmospheres* **122**: 7445-7460.

Their results revealed some significant relationships across both space and time. Surprisingly, however, the authors did *not* conduct an analysis between the fire records and temperature, which omission is remedied in Figure II.B.2.v.2 below. As illustrated there, a statistically significant relationship exists between Australian temperature and annual fire counts, such that a 1°C temperature increase results in a 2.39 x 10^5 *decline* in annual fire count. Consequently, these data would appear to contradict model-based claims that rising temperatures will increase fire frequency.

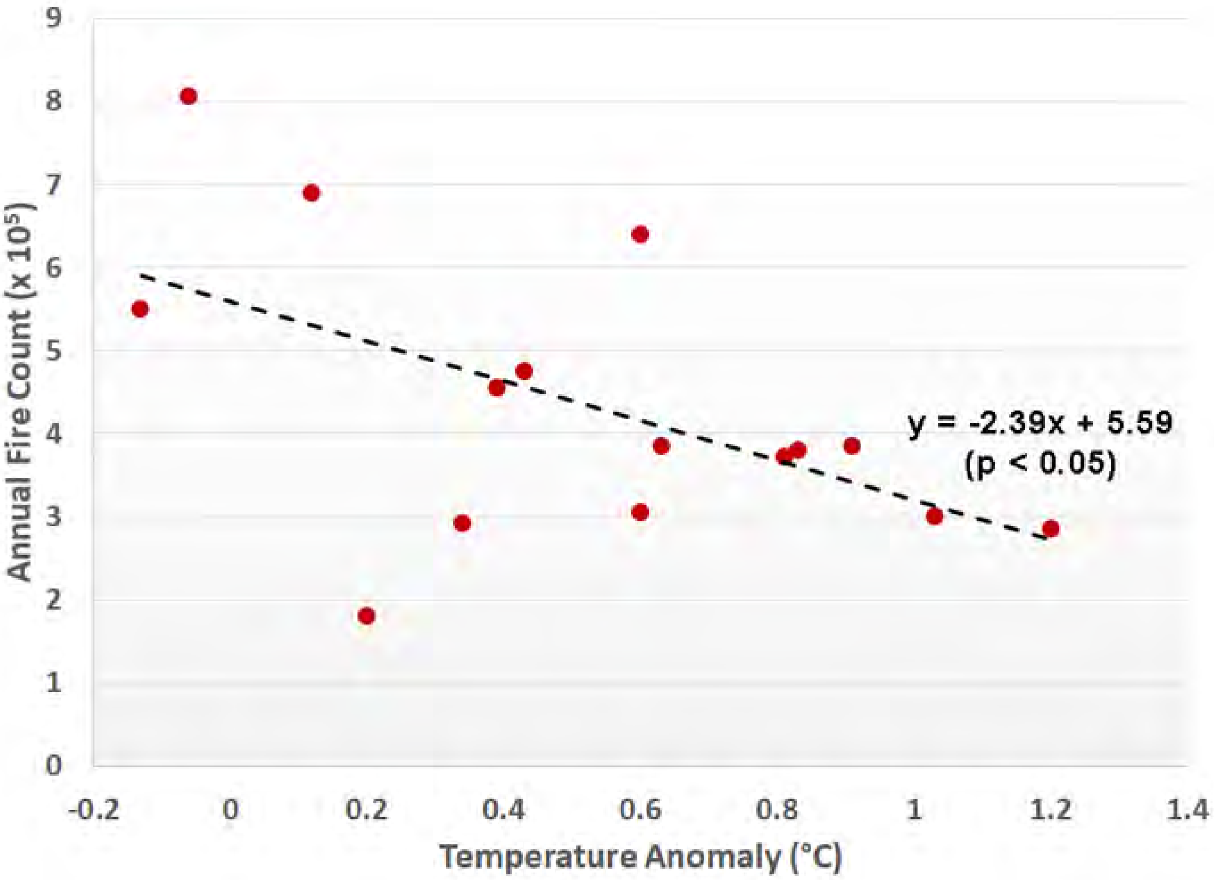


Figure II.B.2.v.2. *The relationship between the annual number of Australian fires and Australian temperature anomalies over the period 2001-2015. Adapted from Earl and Simmonds (2017).*

In another study, this time from Europe, Turco *et al*. (2016)[71] write that "quantitative assessment of recent trends in fire statistics is important for assessing the possible shifts induced by climate and other environmental/socioeconomic changes in this area." And, therefore, they go on to describe how they analyzed "recent fire trends in Portugal, Spain, southern France, Italy and Greece, building on a homogenized fire database integrating official fire statistics provided by several national/EU agencies."

---

[71] Turco, M., Bedia, J., Di Liberto, F., Fiorucci, P., von Hardenberg, J., Koutsias, N., Llasat, M.-C., Xystrakis, F. and Provenzale, A. 2016. Decreasing Fires in Mediterranean Europe. *PLoS ONE*: **11**(3): e0150663.

In discussing their findings, the nine researchers from Greece, Italy and Spain report that (1) "during the period 1985-2011, the total annual burned area (BA) displayed a general decreasing trend" (see Figure II.B.2.v.3), that (2) "BA decreased by about 3020 km^2 over the 27-year-long study period (i.e. about -66% of the mean historical value)," that (3) "these results are consistent with those obtained on longer time scales when data were available," and that (4) "similar overall results were found for the annual number of fires (NF), which globally decreased by about 12,600 in the study period (about -59%)."

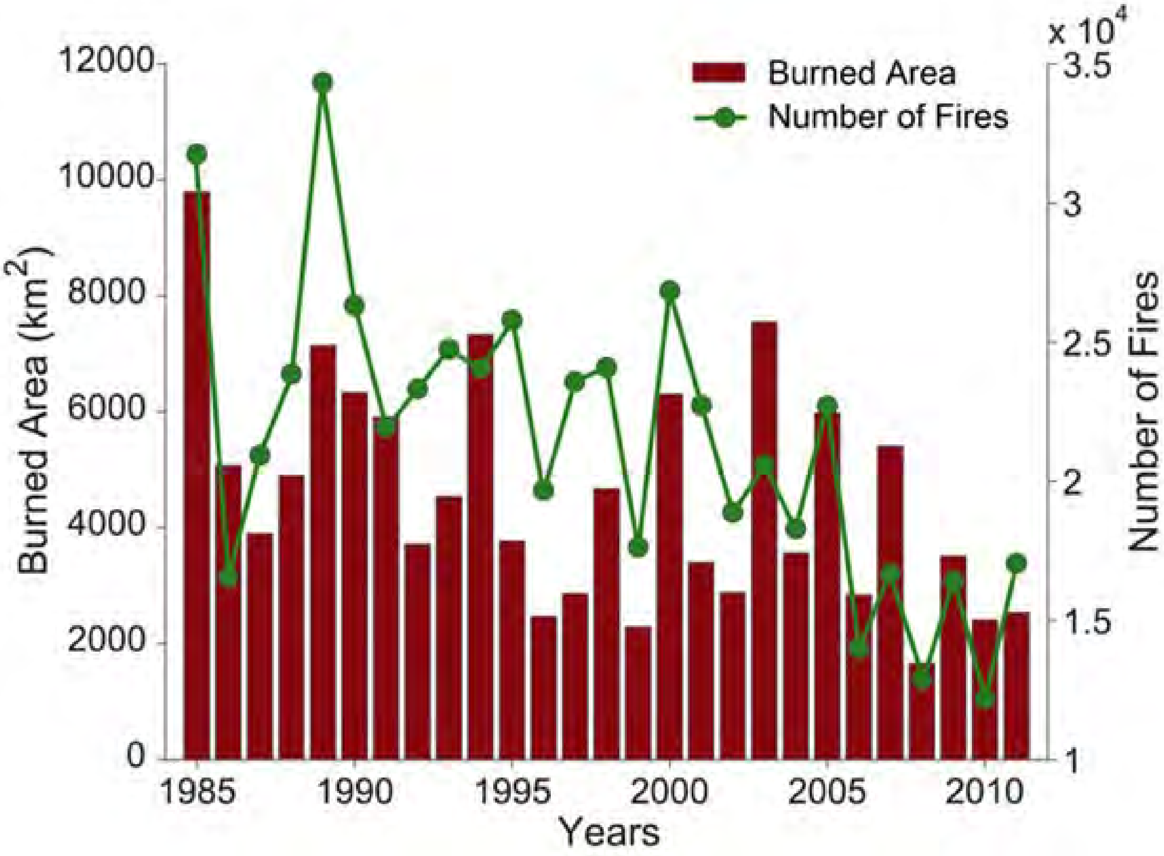


Figure II.B.2.v.3. *Annual series of the total annual burned area (BA) and number of fires (NF) in Mediterranean Europe for the period 1985-2011.*

In examining fire trends on a global-scale perspective, Yang *et al*. (2014)[72] write that fire is a critical component of the biosphere that "substantially influences land surface, climate change and ecosystem dynamics." And, therefore, they say that to accurately predict fire regimes in the 21st century, "it is essential to understand the historical fire patterns and recognize the interactions among fire, human and environmental factors." But until *now*, they indicate that few

---

[72] Yang, J., Tian, H., Tao, B., Ren, W., Kush, J., Liu, Y. and Wang, Y. 2014. Spatial and temporal patterns of global burned area in response to anthropogenic and environmental factors: Reconstructing global fire history for the 20th and early 21st centuries. *Journal of Geophysical Research: Biogeosciences* **119**: 249-263.

efforts have been directed to studying long-term fire histories and the roles played by anthropogenic and environmental factors on a global scale.

In an attempt to provide what had previously been lacking in this regard, Yang *et al*., as they describe it, "developed a 0.5° x 0.5° data set of global burned area from 1901 to 2007 by coupling the Global Fire Emission Database version 3 with a process-based fire model and conducted factorial simulation experiments to evaluate the impacts of human, climate and atmospheric components." In describing their findings, the seven scientists say they found (1) "the average global burned area was about 442 x 10^4 km^2/yr during 1901-2007," with (2) "a notable declining rate of burned area globally (1.28 x 10^4 km^2/yr)" (see Figure II.B.2.v.4) that (3) "burned area in the tropics and extra-tropics exhibited a significant declining trend, with no significant trend detected at high latitudes," that (4) "factorial experiments indicated that human activities were the dominant factor in determining the declining trend of burned area in the tropics and extra-tropics," that (5) "climate variation was the primary factor controlling the decadal variation of burned area at high latitudes," that elevated CO_2 and nitrogen deposition (6) "enhanced burned area in the tropics and southern extra-tropics," but that (7) they "suppressed fire occurrence at high latitudes."

All things considered, Yang *et al*.'s study makes it quite clear that society's various activities constitute *by far* the most important single factor among the many that have resulted in a net century-long history of *ever-decreasing global burned area*.

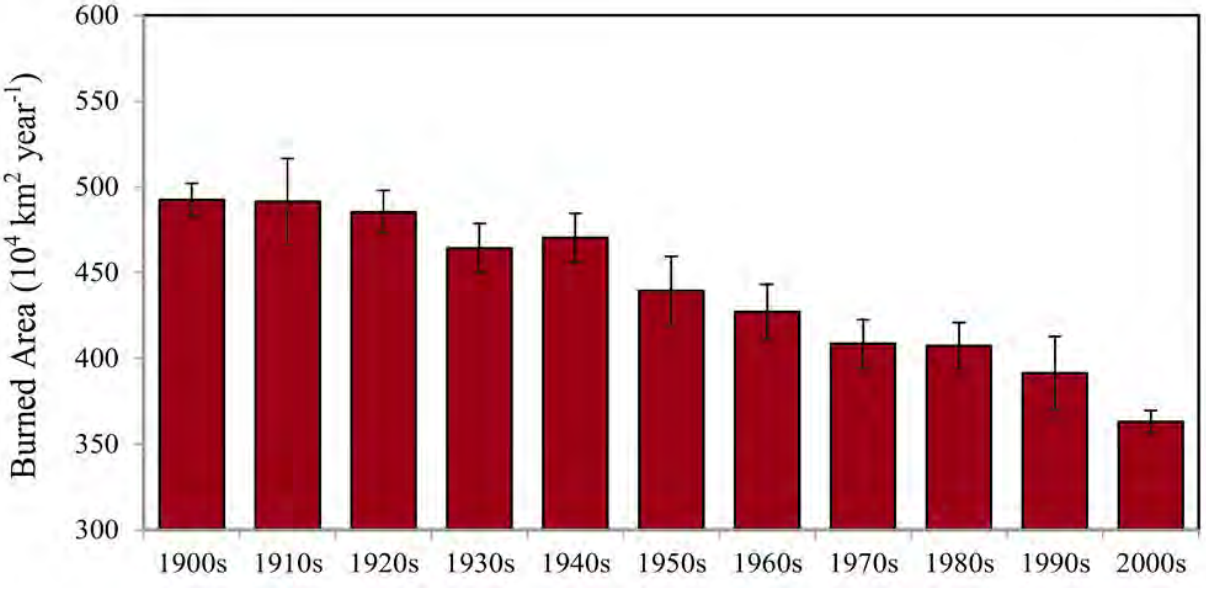


Figure II.B.2.v.4. *Decadal variation of global burned area.*

In light of all of the above findings, coupled with those listed in the linked pages below, it is becoming ever more clear that there is little support for the model-based contention that future CO_2-induced *global* warming (if it occurs at all) will have any significant effect on *global* fire trends, except maybe to *reduce* them.

Information on additional peer-reviewed scientific studies on fires can be accessed by clicking on the links below, or from under the heading of Fire here: http://www.co2science.org/subject/f/subject_f.php.

Fire
General
Relationship to Global Warming

3. Temperature-induced Mortality

According to the quotes below, taken from the 2009 Endangerment Finding, the EPA expects human mortality and morbidity to increase in the future in response to rising temperatures caused by increasing atmospheric CO_2 concentrations. However, observational data demonstrate that global cooling, as opposed to global warming, poses the most significant temperature-related threat to human health and that global warming would likely result in a net saving of human lives.

Key Mortality-related Quotes from the EPA's 2009 Endangerment Finding

- "After review of public comments, the Administrator continues to believe that climate change can increase the risk of morbidity and mortality and that these public health impacts can and should be considered when determining endangerment to public health under CAA section 202(a)." Endangerment Finding p. 66,524

- "The impact on mortality and morbidity associated with increases in average temperatures which increase the likelihood of heat waves also provides support for a public health endangerment finding. There are uncertainties over the net health impacts of a temperature increase due to decreases in cold-related mortality, but there is some recent evidence that suggests that the net impact on mortality is more likely to be adverse, in a context where heat is already the leading cause of weather-related deaths in the United States." Endangerment Finding p. 66,526

Relationships between human morbidity and mortality have been observed at both the high and low end of the temperature spectrum. According to the models, the number of heat-related deaths should be increasing because of CO_2-induced global warming. But are they?

In prefacing their investigation into this topic, Bobb *et al*. (2014)[73] write that "increasing temperatures are anticipated to have profound health impacts," but they say "little is known about the extent to which the population may be adapting." And, therefore, they decided to examine "the hypothesis that if adaptation is occurring, then heat-related mortality would be deceasing over time."

---

[73] Bobb, J.F., Peng, R.D., Bell, M.L. and Dominici, F. 2014. Heat-related mortality and adaptation to heat in the United States. *Environmental Health Perspectives* **122**: 811-816.

To accomplish this objective, Bobb *et al*. used “a national database of daily weather, air pollution, and age-stratified mortality rates for 105 U.S. cities (covering 106 million people) during the summers of 1987-2005,” employing “time-varying coefficient regression models and Bayesian hierarchical models” to estimate “city-specific, regional, and national temporal trends in heat-related mortality and to identify factors that might explain variation across cities.”

With respect to their findings, Bobb *et al*. state that “on average across cities, the number of deaths (per 1,000 deaths) attributable to each 10°F increase in same-day temperature decreased from 51 in 1987 to 19 in 2005” (see Figure II.B.3.1). Furthermore, they report that “this decline was largest among those ≥ 75 years of age, in northern regions, and in cities with cooler climates.” In addition, they write that “although central air conditioning (AC) prevalence has increased, we did not find statistically significant evidence of larger temporal declines among cities with larger increases in AC prevalence.”

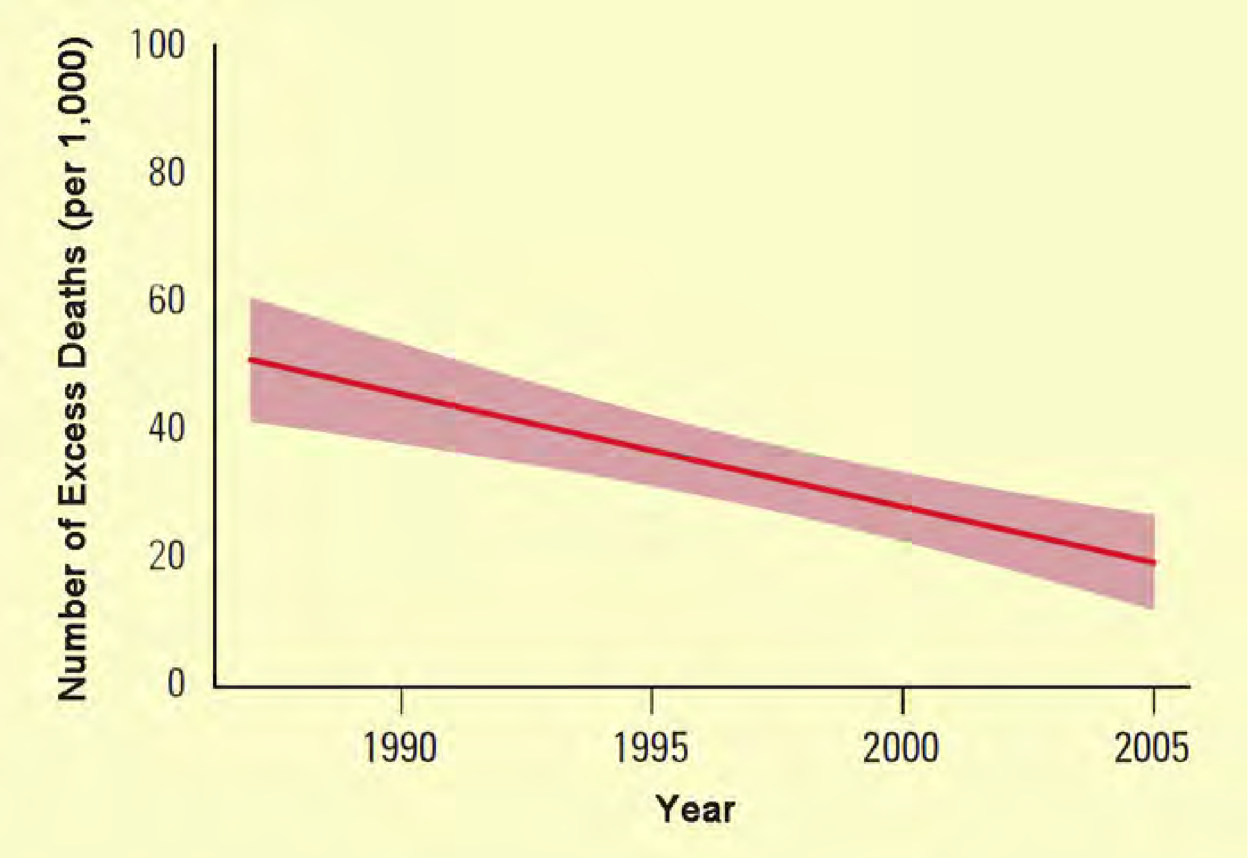


Figure II.B.3.1. *The number of excess U.S. deaths (per 1,000) attributable to each 10°F increase in the same day’s summer temperature over the period 1987 to 2005.*

Based on these findings, Bobb *et al*. conclude that the U.S. population has, “become more resilient to heat over time”—in this case from 1987 to 2005—led by the country’s astute senior citizens. This discovery, coupled with many other similar findings from all across the world,[74] indicate the model predictions of increased heat related mortality in response to the so-called unprecedented warming of the past few decades are not occurring.

In another study, Zhang *et al*. (2019).[75] used climate and mortality data from 106 urban communities located across the continental United States to calculate the attributable fraction of cardiorespiratory mortality due to ambient temperature over the period 1987-2000. This was accomplished by applying a quasi-Poisson regression with a distributed lag nonlinear model to the data to estimate locational-specific temperature/cardiorespiratory mortality associations. Then, the authors pooled these associations into seven regional and one national estimate via multivariate meta-analysis.

The results revealed that, "for all communities, cold weather accounted for the most majority (89-99%) of the total temperature-attributable [mortality] burden." Nationally, the fraction of cardiorespiratory deaths caused by cold weather was 7.15%, whereas for warm weather it was only a paltry 0.43%. Thus, the mortality effects of cold weather were *more than 16 times higher* than that due to warm weather. The regional attributable fraction percentages were similar to that observed for the national average and are shown in Figure II.B.3.2 below.

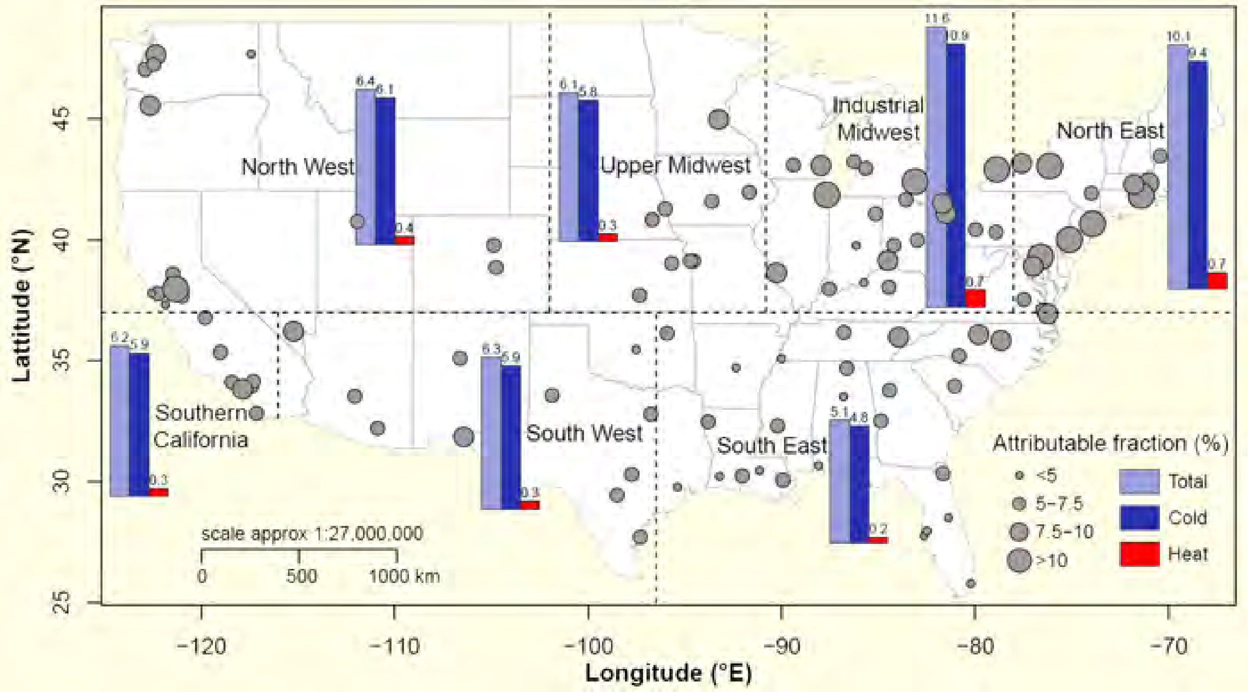


Figure II.B.3.2. *Fractions of cardiovascular mortality attributable to ambient temperatures by communities and regions over the period 1987-2000.*

---

[74] Idso, C.D, Idso, S.B., Carter, R.M. and Singer, S.F. (Eds.) 2014. *Climate Change Reconsidered II: Biological Impacts*. Chicago, IL: The Heartland Institute.

[75] Zhang, Y., Xiang, Q., Yu, Y., Zhan, Z., Hu, K. and Ding, Z. 2019. Socio-geographic disparity in cardiorespiratory mortality burden attributable to ambient temperature in the United States. *Environmental Science and Pollution Research* **26**: 694-705.

Summing up their findings, Zhang *et al*. conclude that, “despite some regional differences in estimates of attributable fraction, cold weather was consistently found to be responsible for the most majority of temperature-related mortality burden.” And, thus, their research confirms that it is *cold* temperatures about which society should be most concerned. A little global warming would likely go a long way in producing a net *saving* of human lives!

In a study with global implications, Gasparrini *et al.* (2015)[76] analyzed data from 384 locations scattered around the world, including the countries of Australia, Brazil, Canada, China, Italy, Japan, South Korea, Spain, Sweden, Taiwan, Thailand, the United Kingdom and the United States of America. And by fitting a standard time-series Poisson model to the data obtained for each location, while controlling for trends and day of the week, they estimated temperature-mortality associations with a distributed lag non-linear model with 21 days of lag, after which they pooled the results they obtained in a multivariate meta-regression that included country indicators and temperature averages and ranges.

This work allowed them to calculate the number of human deaths attributable to heat and cold—defined as temperatures above and below the optimum (minimum mortality) temperature—for both moderate and extreme temperatures, the latter being defined “using cutoffs at the 2.5th and 97.5th temperature percentiles.” And what did they thereby learn?

Based on data pertaining to a total of 74,225,200 human deaths that occurred between 1985 and 2012, the 23 researchers determined that 7.71% of the lives lost were caused by non-optimum temperatures; and among this group they found that “more temperature-attributable deaths were caused by cold (7.29%) than by heat (0.42%)” (see Figure II.B.3.3), which makes *cold* in excess of *seventeen times more deadly* than *heat*. And they add, in this regard, that *moderate* “hot and cold temperatures represented most of the total health burden.” Consequently, it seems pretty clear that any successful attempt to reverse or slow any potential increase in Earth’s mean global temperature would likely come at a net *cost* of many human lives the world over, not a savings as the EPA believes.

---

[76] Gasparrini, A., Guo, Y., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., Tobias, A., Tong, S., RocklÖv, J., Forsberg, B., Leone, M, De Sario, M., Bell, M.L., Guo, Y.L.L., Wu, C.F., Kan, H., Yi, S.M., de Sousa, Z., Coelho, S. M., Saldiva, P.H., Honda, Y., Kim, H. and Armstrong, B. 2015. Mortality risk attributable to high and low ambient temperature: a multi-country observational study. *The Lancet*: 10.1016/S0140-6736(14)62114-0.

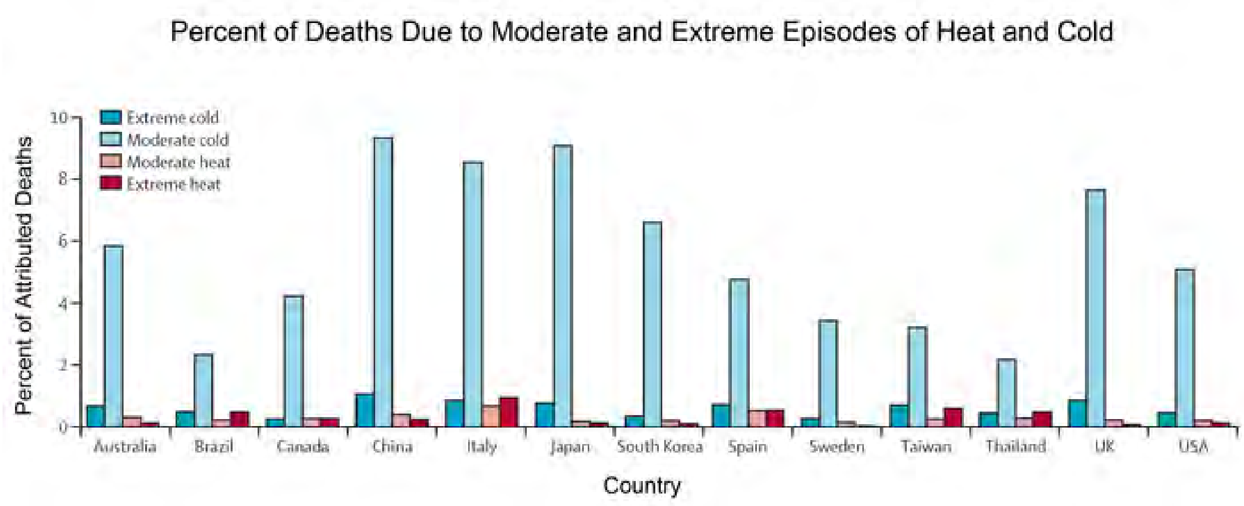


Figure II.B.3.3. *Fraction of all-cause mortality attributable to moderate and extreme hot and cold temperature by country. Extreme and moderate high and low temperatures were defined with the minimum mortality temperature and the 2.5 and 97.5th percentiles of temperature distribution as cutoffs.*

Information on additional peer-reviewed scientific studies on temperature-induced mortality can be accessed by clicking on the links below, or from under the heading of Mortality here: http://www.co2science.org/subject/m/subject_m.php.

Mortality
Cardiovascular
Cholera
Dengue Fever
General
Hot vs. Cold Weather
  Asia
  Australia
  Europe
  Global
  Miscellaneous
  North America
  South America
Malaria
Respiratory
Stroke
Temperature (Other)
Tick-Borne Diseases
Yellow Fever

4. Sea Level Rise

According to the following quotes below taken from the 2009 Endangerment Finding, potential negative effects of future sea level rise on coastal areas represent what the EPA considers to be among the most significant (and sure) impacts of rising atmospheric CO_2, providing the strongest rationale for the Endangerment Finding. However, observational data clearly show the EPA has once again reached an erroneous conclusion by not adequately considering sea level measurements from the observational record.

Key Sea Level Quotes from the EPA's 2009 Endangerment Finding

- "The most serious potential adverse effects are the increased risk of storm surge and flooding in coastal areas from sea level rise and more intense storms. Observed sea level rise is already increasing the risk of storm surge and flooding in some coastal areas." EF p. 66,498

- "There is strong evidence that global sea level gradually rose in the 20th century and is currently rising at an increased rate." EF p. 66,518

- "Overall, the evidence on risk of adverse impacts for coastal areas from sea level rise provides clear support for finding that greenhouse gas air pollution endangers the welfare of current and future generations." EF p. 66,533

- "The most serious potential adverse effects are the increased risk of storm surge and flooding in coastal areas from sea level rise and more intense storms." EF p. 66,535

Multiple peer-reviewed scientific studies reveal that real-world sea level rise has been far less dramatic over the course of the Industrial Revolution than what is often portrayed or estimated by climate models.[77] As one example, Boretti (2012)[78] began the report of his contribution to the subject by noting that in its report of 2007, the IPCC had projected global sea level was likely to rise somewhere between 18 and 59 cm by 2100, while further noting that certain "model-based analyses performed recently have predicted much higher sea level rise [SLR] for the twenty-first century," even "exceeding 100 cm if greenhouse gas emissions continue to escalate," citing most pointedly in this regard the studies of Rahmstorf (2007, 2010)[79,80]. However, he noted that studies reaching just the *opposite* conclusion had also been published, referencing those of

---

[77] See http://www.co2science.org/subject/s/summaries/sealevelglobal.php for brief summaries of twenty five such papers.

[78] Boretti, A.A. 2012. Short term comparison of climate model predictions and satellite altimeter measurements of sea levels. *Coastal Engineering* **60**: 319-322.

[79] Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea-level rise. *Science* **315**: 368-370.

[80] Rahmstorf, S. 2010. A new view on sea level rise: has the IPCC underestimated the risk of sea level rise. *Nature Reports Climate Change:* 10.1038/climate.2010.29.

Holgate (2007),[81] Wunsch *et al.* (2007),[82] Wenzel and Schroter (2010)[83] and Houston and Dean (2011).[84] And so the scientist set out to utilize what he called "the best source of global sea level data," which he identified as the TOPEX and Jason series of satellite radar altimeter data, to investigate trends in seal level for himself. In doing so, Boretti applied simple statistics to the two decades of information contained in the sea level data in order to "better understand if the sea level rise (SLR) is accelerating, stable or decelerating." And what did he thereby learn?

The Australian scientist reported that the average rate of SLR over the almost 20-year period of satellite radar altimeter observations was 3.1640 mm/year, which if held steady over a century would yield a mean global SLR of 31.64 cm, which is just a little above the low-end projection of the IPCC for the year 2100. However, he also found that the rate of SLR had been *reducing* over the measurement period at a rate of -0.11637 mm/year^2, and that this *de*celeration was *also* "reducing" at a rate of -0.078792 mm/year^3, as may be seen in the following figure from his paper (Figure II.B.4.1).

Boretti writes that the huge deceleration of SLR over the last 10 years "is clearly the opposite of what is being predicted by the models," and that "the SLR's reduction is even more pronounced during the last 5 years." To illustrate the importance of his findings, he notes that "in order for the prediction of a 100-cm increase in sea level by 2100 to be correct, the SLR must be almost 11 mm/year every year for the next 89 years," but he notes that "since the SLR is dropping, the predictions become increasingly unlikely," especially in view of the facts that (1) "not once in the past 20 years has the SLR of 11 mm/year ever been achieved," and that (2) "the average SLR of 3.1640 mm/year is only 20% of the SLR needed for the prediction of a one meter rise to be correct."

Additional evidence the models are over-predicting future sea level rise is noted in the work of Watson (2018).[85] Writing in the *Journal of Marine Science and Engineering*, Watson says that "despite the increasing complexity and resolution of [climate] models, their utility for future projections will always be conditional on their ability to replicate historical and recent observational global and regional data trends of importance (such as temperature, sea level, CO_2 trends, etc.)."

---

[81] Holgate, S.J. 2007. On the decadal rates of sea level change during the twentieth century. *Geophysical Research Letters* **34**: 10.1029/2006GL028492.

[82] Wunsch, C., Ponte, R. and heimbach, P. 2007. Decadal trends in sea level patterns: 1993-2004. *Journal of Climate* **20**: 5889-5911.

[83] Wenzel, M. and Schroter, J. 2010. Reconstruction of regional mean sea level anomalies from tide gauges using neural networks. *Journal of Geophysical Research* **115**: 10.1029/2009JC005630.

[84] Houston, J.R. and Dean, R.G. 2011. Sea-level acceleration based on U.S. tide gauges and extensions of previous global-gauge analyses. *Journal of Coastal Research* **27**: 409-417.

[85] Watson, P.J. 2018. How well do AR5 sea surface-height model projections match observational rates of sea-level rise at the regional scale? *Journal of Marine Science and Engineering* **6**: 11, doi:10.3390/jmse6010011.

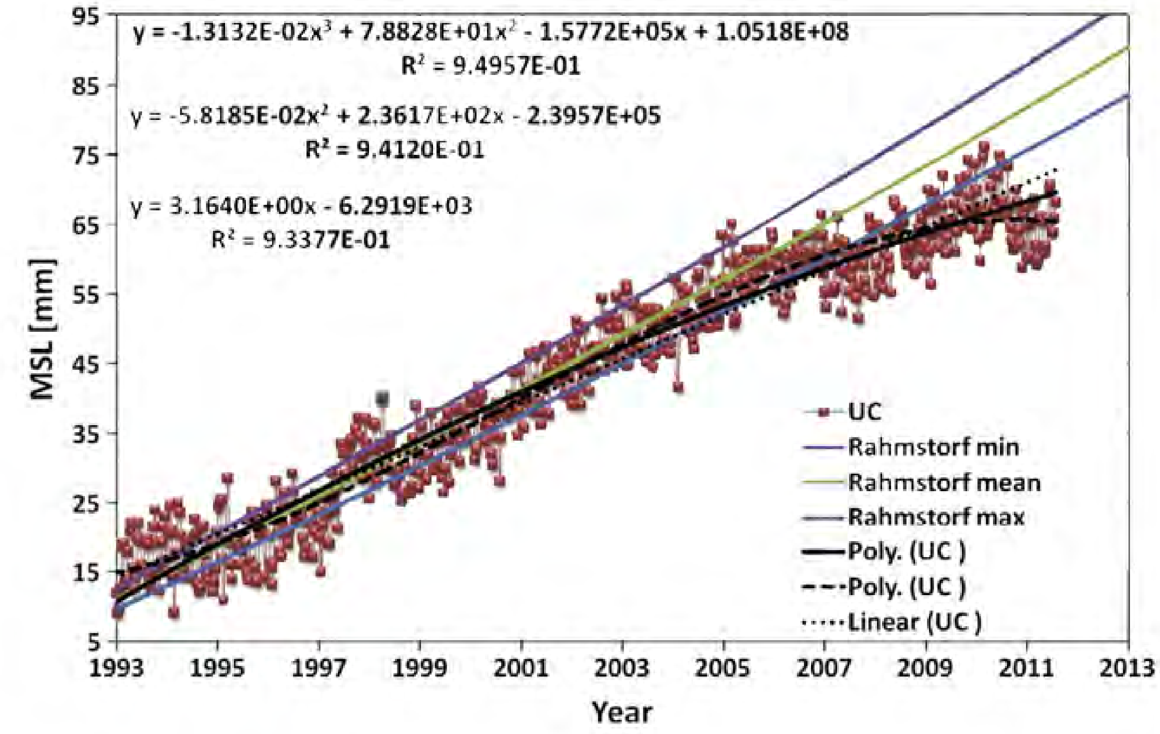


Figure II.B.4.1. *Comparison of Mean Sea Level (MSL) predictions from Rahmstorf (2007) with measurements from the TOPEX and Jason series. Adapted from Boretti (2012), who states in the figure caption that "the model predictions [of Rahmstorf (2007)] clearly do not agree with the experimental evidence in the short term."*

Indeed, model projections must *always* be evaluated by *observations*, regardless of their assumed complexities and abilities. Without such validation, and a thorough understanding of a model's predictive limitations, its output should never be utilized in the formation of policy as in the case of the EPA's Endangerment Finding. And so it is a welcomed exercise that Watson set out to compare model predictions versus observations for one of the key parameters in the climate change debate, *sea level rise*.

In his words, Watson's work "provides a snapshot of how closely current rates of sea-level rise from observational data records (tide gauges) are represented by the ensemble mean of the [IPCC's] AR5 model-projection products at the regional scale, considering 19 sites across the global ocean over the period of common coverage (2007-2016)." And to accomplish this comparison, Watson applied singular spectrum analysis to "efficiently isolate the externally (or climate-change) forced signal from all other contaminating dynamic influences (including internal climate modes)" for both types of data, i.e., model projections and observations. The results can be summarized in the figure below.

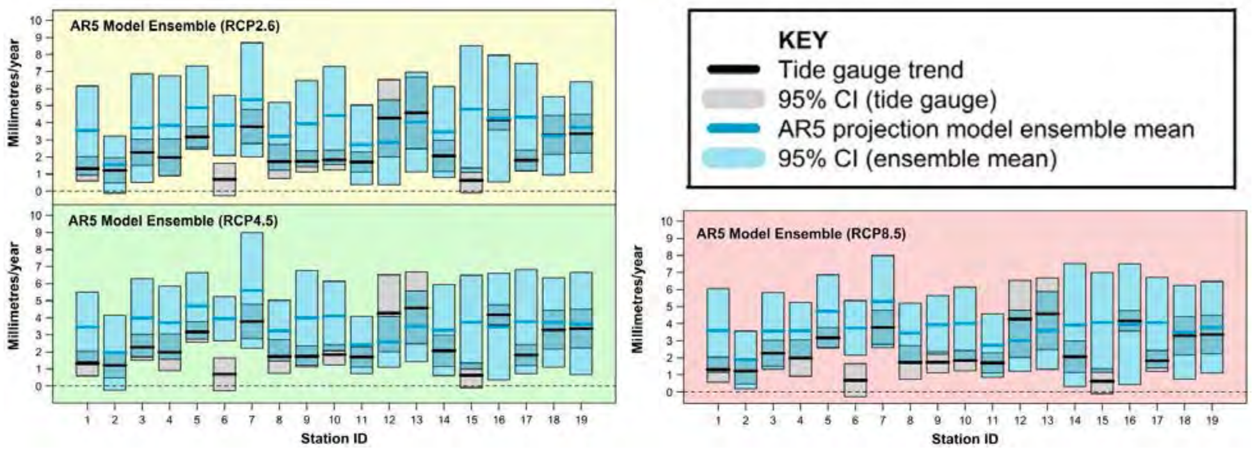


***Figure II.B.4.2**. Average rates of sea level rise over the period 2007-2016 for nineteen globally-dispersed locations. The charts directly compare the observational record (tide-gauge analysis) and corresponding AR5 ensemble-model projections for three model scenarios (RCP2.6, RCP4.5 and RCP8.5).*

Figure II.B.4.2 presents the average rates of sea level rise over the period 2007-2016 for each of the 19 globally-distributed stations with associated error bars in the upper, middle and lower panel. It also displays the AR5 ensemble model-predicted average rates of sea level rise for three different greenhouse gas emission and future temperature scenarios (RCP2.6, RCP4.5 and RCP 8.5 in the upper, middle and lower panel, respectively). Two important points can be summarized from this image: (1) the error margins of the IPCC's model predictions of future sea level rise are quite large and (2) those wide margins "[mask] the fact that the mean velocity for the model-projection products exceed observational records for nearly all stations and Representative Concentration Pathway (RCP) [scenarios]." And with respect to how great in magnitude the model projections of sea-level rise are from reality, Watson reports that when all station records are considered across all RCP experiments the average gap is between 1.6-2.5 mm/year. To put this difference in perspective, over the past decade the ensemble model-mean projections of future sea level rise are approximately *twice the magnitude* of that which is observed in the tide gauge observations.

Commenting on these important findings, Watson understates the obvious by writing "evidence suggests the AR5 projection-model outputs for sea surface height appear to be rising at a faster rate than the observational (tide gauge) records over the decade of common coverage," adding that his work provides "an early warning sign that the evaluation of ocean model components with respect to projected mean sea level could be relevantly improved." Or, in plain English, this work demonstrates that the model projections of future sea level rise that EPA utilized in its Endangerment Finding are garbage, invalidated by real-world observations despite their large error bars.

Another example demonstrating the futility of the models in properly predicting sea level rise is noted in research examining atoll islands. Projections suggest these low-lying islands are most vulnerable to sea level rise. Consequently, they are expected to be washed away in the near future due indirect consequences of CO_2-induced global warming. But is this correct?

Over the past few years, multiple research teams have examined this topic, including Duvat *et al*. (2017),[86] Duvat and Pillet (2017),[87] Purkis *et al*. (2016),[88] Testut *et al*. (2016),[89] Ford and Kench (2016),[90] Ford and Kench (2015),[91] Kench *et al*. (2015),[92] Biribo and Woodroffe (2013),[93] Ford (2013),[94] Rankey (2011),[95] Dunne *et al*. (2012),[96] Ford (2012)[97] and Webb and Kench (2010),[98] consistently finding little support (if any) for the model-based predictions. The latest group to do so was that of Duvat (2019),[99] who conducted a review of the existing literature to compile the largest single database assessing atoll island stability over the past several decades. And what did the new review reveal?

In all, 35 atolls and 852 islands were examined in the study, allowing for a quantitative analysis of land area change for a subset of 30 atolls and 709 islands. That analysis revealed a global trend of island land area *persistence*. More specifically, Duvat reports that "29 atolls exhibited a stable land area, while one (South Tarawa, Kiribati) increased in size." Of the 709 islands in these 30 atolls, 518 (73.1%) were stable, 110 (15.5%) increased in size, and 81 (11.4%) decreased in area. Thus, a total of 88.6% of all islands examined were either *stable* or *increased* in size.

Other key information presented by Duvat was the finding that island behavior correlates with island size. In this regard, the author reports that the smallest islands (< 5 ha) exhibited the

---

[86] Duvat, V.K.E., Salvar, B. and Salmon, C. 2017. Drivers of shoreline change in atoll reef islands of the Tuamotu Archipelago, French Polynesia. *Global and Planetary Change* **158**: 134-154.

[87] Duvat, V.K.E. and Pillet, V. 2017. Shoreline changes in reef islands of the Central Pacific: Takapoto Atoll, Norther Tuamotu, French Polynesia. *Geomorphology* **282**: 96-118.

[88] Purkis, S.J., Gardiner, R., Johnston, M.W. and Sheppard, C.R.C. 2016. A half-century of coastline change in Diego Garcia - The largest atoll island in the Chagos. *Geomorphology* **261**: 282-298.

[89] Testut, L., Duvat, V., Ballu, V., Fernandes, R.M.S., Pouget, F., Salmon, C. and Dyment, J. 2016. Shoreline changes in a rising sea level context: The example of Grande Glorieuse, Scattered Islands, Western Indian Ocean. *Acta Oecologica* **72**: 110-119.

[90] Ford, M.R. and Kench, P.S. 2016. Spatiotemporal variability of typhoon impacts and relaxation intervals on Jaluit Atoll, Marshall Islands. *Geology* **44**: 159-162.

[91] Ford, M.R. and Kench, P.S. 2015. Multi-decadal shoreline changes in response to sea level rise in the Marshall Islands. *Anthropocene* **11**: 14-24.

[92] Kench, P.S., Thompson, D., Ford, M.R., Ogawa, H. and McLean, R.F. 2015. Coral islands defy sea-level rise over the past century: Records from a central Pacific atoll. *Geology* **43**: 515-518.

[93] Biribo, N. and Woodroffe, C.D. 2013. Historical area and shoreline change of reef islands around Tarawa Atoll, Kiribati. *Sustainability Science* **8**: 345-362.

[94] Ford, M. 2013. Shoreline changes interpreted from multi-temporal aerial photographs and high resolution satellite images: Wotje Atoll, Marshall Islands. *Remote Sensing of Environment* **135**: 130-140.

[95] Rankey, E.C. 2011. Nature and stability of atoll island shorelines: Gilbert Island chain, Kiribaati, Equatorial Pacific. *Sedimentology* **58**: 1831-1859.

[96] Dunne, R.P., Barbosa, S.M. and Woodworth, P.L. 2012. Contemporary sea level in the Chagos Archipelago, central Indian Ocean. *Global and Planetary Change* **82-83**: 25-37.

[97] Ford, M. 2012. Shoreline changes on an urban atoll in the central Pacific Ocean: Majuro Atoll, Marshall Islands. *Journal of Coastal Research* **28**: 11-22.

[98] Webb, A.P. and Kench, P.S. 2010. The dynamic response of reef islands to sea-level rise: Evidence from multi-decadal analysis of island change in the Central Pacific. *Global and Planetary Change* **72**: 234-246.

[99] Duvat, V.K.E. 2019. A global assessment of atoll island platform changes over the past decades. *WIREs Climate Change* **10**: e557.

highest variability in land area change. Larger islands were more stable (see Figure II.B.4.3), as Duvat notes that “all of the islands larger than 10 ha experienced either stability (209/234 islands, that is, 89.32%) or expansion (25/234 islands, that is, 10.68%).” For islands under 10 ha in size, 65% experienced stability (no change), 17.9% expanded and 17.1% contracted.

In concluding her review, Duvat writes that her work “confirms that over the past decades to century, atoll islands exhibited no widespread sign of physical destabilization by sea-level rise,” adding that, “importantly, islands located in ocean regions affected by rapid sea-level rise showed neither contraction nor marked shoreline retreat.” Taken together, therefore, it seems obvious that model-based predictions of rapidly rising sea levels due to anthropogenic global warming are not presently having, nor will they likely have in the future, any negative impact on atoll island stability.

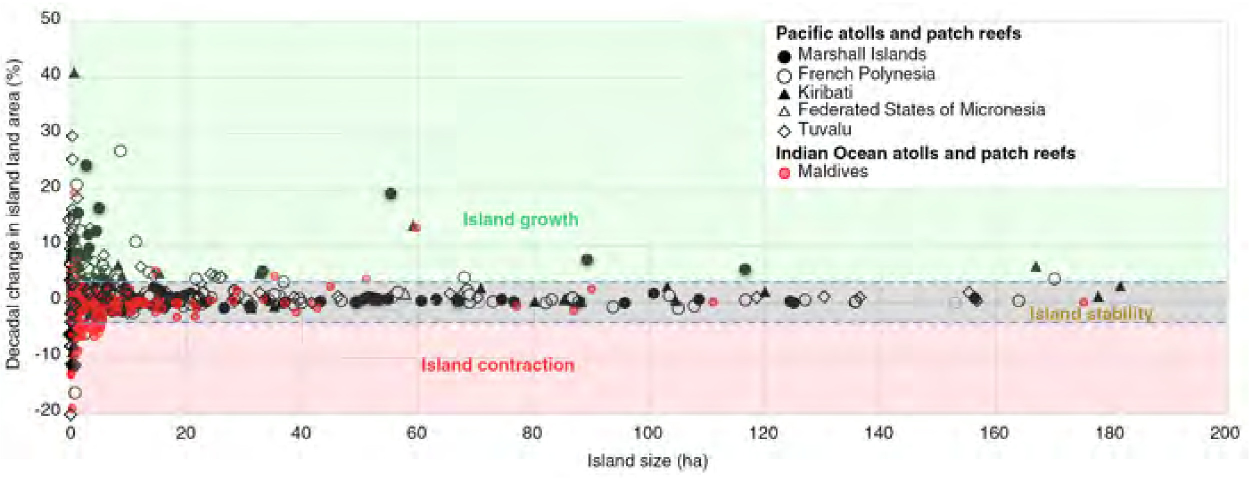


Figure II.B.4.3. *Decadal change in island land area for 709 Pacific and Indian Ocean islands.*

Information on additional peer-reviewed scientific studies on sea level can be accessed by clicking on the links below, or from under the heading of Sea Level here: http://www.co2science.org/subject/s/subject_s.php.

Sea Level
Asian Measurements
Difficulties Predicting Change
Effects on Carbon Sequestration
European Measurements
Global Measurements
North American Measurements
The Role of Antarctica
The Role of Greenland
Small Island States
Southern Hemisphere Measurements

III. CO_2 EMISSIONS AND FOSSIL ENERGY USE INITIATED, AND CONTINUE TO SUSTAIN, THE INDUSTRIAL REVOLUTION AND THE MANY HUMAN AND ENVIRONMENTAL BENEFITS THAT HAVE EMERGED THEREFROM, WHICH BENEFITS HAVE ENHANCED HUMAN HEALTH AND WELFARE

As discussed in Section III above, EPA has erroneously concluded that dangerous climate change, caused by rising levels of atmospheric CO_2, is presently occurring to the detriment and peril of humanity and the natural world. And because the combustion of fossil fuels is the principal source behind the CO_2 rise, their Endangerment Finding presupposes that society must abandon all use of fossil fuels to avoid human peril. Consequently, the Endangerment Finding is utilized by those who seek to enforce government and private sector efforts as justification to restrict fossil fuel use via tax, caps or fiat limits on CO_2 emissions.

Reality, however, paints a much different picture. The *real* story is that there is no upcoming climate catastrophe and CO_2 emissions and fossil energy should be *celebrated* for enhancing life and improving the standard of living for humanity and the natural world, and they will continue to do so as more fossil fuels are used in the future.

In regard to this latter point, it is undeniable that fossil energy initiated (and continues to sustain) the Industrial Revolution and the many human and environmental benefits that have emerged therefrom. Without adequate supplies of low-cost centralized energy, few, if any, of the major technological and innovative advancements of the past two centuries that have spurred economic growth, reduced poverty, increased literacy and enhanced and prolonged human life could have occurred. Furthermore, without the increased CO_2 emissions from fossil fuel use over the past two centuries, Earth's terrestrial biosphere would be nowhere near as vigorous or productive as it is today. Rather, it would be devoid of the growth-enhancing, water-saving and stress-alleviating benefits it has reaped in managed and unmanaged ecosystems from rising levels of atmospheric CO_2 since the Industrial Revolution began.

This section examines the major benefits of fossil fuel use—and the CO_2 emissions that are derived therefrom—on humanity and the natural world, beginning with a discussion on key environmental benefits that are derived from what has come to be known as the *aerial fertilization effect of atmospheric* CO_2.

A. Environmental Benefits

1. Plant Productivity

Atmospheric carbon dioxide: you can't see, hear, smell or taste it. But it's there—all around us—and it's *crucial* for life. Composed of one carbon and two oxygen atoms, this simple molecule serves as the primary raw material out of which plants construct their tissues, which in turn provide the materials out of which animals construct theirs. Knowledge of the key life giving and life sustaining role played by carbon dioxide, or CO_2, is so well established, in fact, that humans—and all the rest of the biosphere—are described in the most basic of terms as *carbon-based lifeforms*. We simply could not and would not exist without it.

Ironically, EPA's Endangerment Finding falsely labels this important atmospheric trace gas a pollutant. Nothing could be further from the truth. Far from being a pollutant, this colorless, odorless, tasteless and invisible gas is better than the best fertilizer ever invented. Essentially, it is the "food" that sustains all plants on the face of the earth. And the more of it they "eat" (or take in from the air during the process of photosynthesis), the bigger and better they grow.

Figure III.A.1.1 presents a visual demonstration of this truly amazing benefit, as observed for the common house plant known as Golden Pothos. Both plants in the figure were grown under identical conditions, with the exception of atmospheric CO_2 content. The plant on the left, which was grown at about ¼ the CO_2 concentration of that to which the plant on the right was exposed, is clearly deficient in the amount of leaf, stem and root biomass it was able to produce.

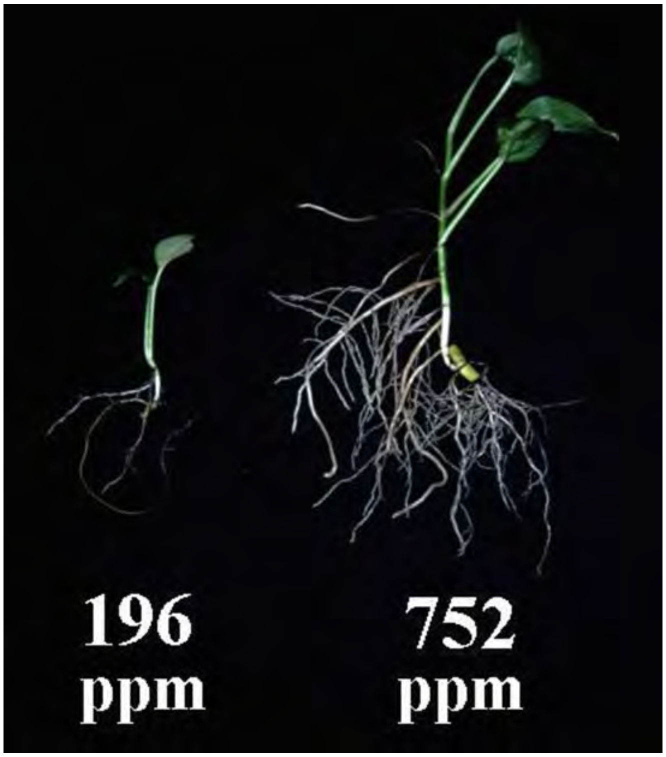
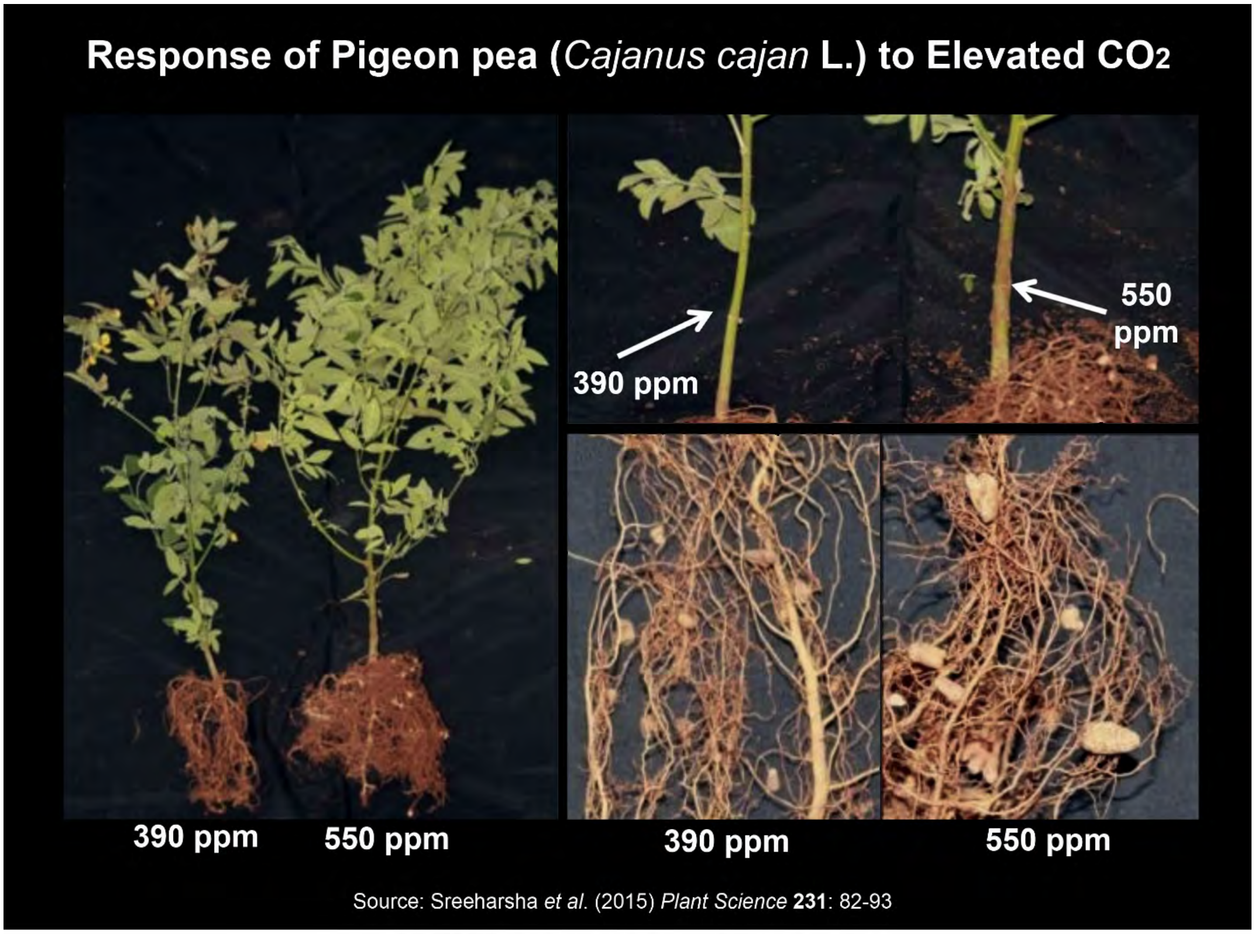


***Figure III.A.1.1**. Depiction of two Golden Pothos plants grown under identical conditions except atmospheric CO_2 concentration, one at 196 ppm and the other at 752 ppm.*

Similar results are seen for pigeon pea in Figure III.A.1.2, where the growth-enhancing effects of CO_2 fertilization are once again readily apparent in the plants' leaf, stem and root biomass.


Response of Pigeon pea (*Cajanus cajan* L.) to Elevated CO_2

Source: Sreeharsha *et al.* (2015) *Plant Science* **231**: 82-93

Figure III.A.1.2*. Response of pigeon pea to ambient (390 ppm) or elevated (550 ppm) concentrations of atmospheric CO_2, demonstrating an enhancement of leaf, stem and root biomass of the plant growing under elevated CO_2 conditions.*[100]

Our organization, the *Center for the Study of Carbon Dioxide and Global Change*,[101] has been studying the effects of atmospheric CO_2 on plants for decades and maintains a Plant Growth database archiving the results of literally *thousands* of laboratory and field CO_2 enrichment studies (freely accessible at http://www.co2science.org/data/plant_growth/plantgrowth.php). The information contained in that database data confirms beyond any doubt that rising atmospheric CO_2 is greatly enhancing the productivity of Earth's plants. A 300 ppm increase in the air's CO_2 content, for example, typically raises the productivity of most herbaceous plants by about one-third and is generally manifested by an increase in the number of branches and tillers, more and thicker leaves, more extensive root systems, and more flowers and fruit.[102] On average, a 300 ppm increase in atmospheric CO_2 enrichment leads to yield increases of 15% for CAM crops,

---

[100] Sreeharsha, R.V., Sekhar, K.M. and Reddy, A.R. 2015. Delayed flowering is associated with lack of photosynthetic acclimation in Pigeon pea (*Cajanus cajan* L.) grown under elevated CO_2. *Plant Science* **231**: 82-93.
[101] http://www.co2science.org/index.php
[102] Idso, C.D., Idso, S.B., Carter, R.M. and Singer, S.F. (Eds.) 2014. *Climate Change Reconsidered II: Biological Impacts*. The Heartland Institute, Chicago, Illinois.

49% for C_3 cereals, 20% for C_4 cereals, 24% for fruits and melons, 44% for legumes, 48% for roots and tubers and 37% for vegetables.[103]

The growth response of woody plants to atmospheric CO_2 enrichment has also been extensively studied.[104] Reviews of numerous individual woody plant experiments have revealed a mean growth enhancement on the order of 50% *or more* for an approximate doubling of the air's CO_2 content,[105] which is about one and a half times as much as the response of non-woody herbaceous plants. Figure III.A.1.3 illustrates this phenomenon in pine trees grown in normal air and air enriched with an extra 150, 300 and 450 ppm of CO_2. Taken approximately three decades ago, the person in the figure is our organization's emeritus President, Dr. Sherwood Idso, who worked for many years at the U.S. Water Conservation Laboratory in Phoenix, AZ, demonstrating the beneficial effects of atmospheric CO_2 enrichment on plants.

Figure III.A.1.3*. Growth response of Eldarica pine trees to ambient CO_2 air (amb) and air enriched with an extra 150, 300 or 450 ppm CO_2. The trees were grown in open-top chambers at the US. Water Conservation Laboratory of the Department of Agriculture in Phoenix, AZ, in 1989.*[106]

In one of his more famous experiments, Dr. Idso grew sour orange trees in ambient and CO_2-enriched air in the Phoenix desert for nearly 19 years. In that study, which at the time was the longest such experiment ever to be conducted anywhere in the world, trees exposed to a CO_2

---

[103] Idso, C.D. and Idso, K.E. 2000. Forecasting world food supplies: The impact of rising atmospheric CO_2 concentration. *Technology* **7** (suppl.): 33-56.

[104] Idso, C.D., Idso, S.B., Carter, R.M. and Singer, S.F. (Eds.) 2014. *Climate Change Reconsidered II: Biological Impacts*. The Heartland Institute, Chicago, Illinois.

[105] See http://www.co2science.org/subject/f/forests.php for a list of papers discussing the growth response of CO_2 to trees.

[106] Photo courtesy of Dr. Craig D. Idso

concentration 75% greater than normal annually produced 80% more biomass and 80% more fruit.[107] And as icing on the cake, so to speak, the vitamin C concentration of the juice of the CO_2-enriched oranges was between 5 and 15% *greater* than that of the juice of the oranges produced on the trees growing in ambient air.[108]

Although much less studied than terrestrial plants, many aquatic plants are also known to be responsive to atmospheric CO_2 enrichment, including unicellular phytoplankton and bottom-rooted macrophytes, for both freshwater[109] and saltwater[110] species. Hence, there is probably no category of photosynthesizing plant that does not respond in a positive manner to atmospheric CO_2 enrichment and that is not likely to be benefited by the ongoing rise in the air's CO_2 content.

Perhaps the obvious question to ask at this point is what do such growth-enhancing benefits of atmospheric CO_2 enrichment portend for the biosphere?

One answer is greater crop productivity, and many researchers have acknowledged the yield-enhancing benefits of the historical and still-ongoing rise in the air's CO_2 content on past, present and future crop yields. [111] In this regard, studies have shown that the benefits of CO_2 on agriculture are so important that without them, world food supply will fall short of world food demand by mid-century.[112]

Direct monetary benefits of atmospheric CO_2 enrichment on both historic and future global crop production have also been calculated.[113] Over the 50-year time period from 1961-2011, such benefits amount to over $3.2 trillion. And projecting the monetary value of this positive externality forward in time reveals that it will bestow an additional $9.8 trillion on crop production by 2050. And, as amazing as this estimate sounds, it may very well be vastly *undervalued*.

Consider, for example, the fact that rice is the third most important global food crop, accounting for 9.4% of global food production. Based upon data presented in our *CO_2 Science* Plant Growth Database, the average growth response of rice to a 300-ppm increase in the air's CO_2 concentration is approximately 35%.[114] However, as illustrated in Figure III.A.1.4, a team of researchers who studied the growth responses of 16 different rice genotypes, reported CO_2-induced productivity increases in those genotypes that ranged from near zero to a whopping

---

[107] Idso, S.B. and Kimball, B.A. 2001. CO_2 enrichment of sour orange trees: 13 years and counting. *Environmental and Experimental Botany* **46**: 147-153.

[108] Idso, S.B., Kimball, B.A., Shaw, P.E., Widmer, W., Vanderslice, J.T., Higgs, D.J., Montanari, A. and Clark, W.D. 2002. The effect of elevated atmospheric CO_2 on the vitamin C concentration of (sour) orange juice. *Agriculture, Ecosystems and Environment* **90**: 1-7.

[109] See http://www.co2science.org/subject/a/aquaticmacrophytes.php and http://www.co2science.org/subject/a/aquaticplants.php

[110] See http://www.co2science.org/subject/o/acidmacroalgae.php, http://www.co2science.org/subject/o/acidificationdiatoms.php and http://www.co2science.org/subject/o/acidificationcocco.php

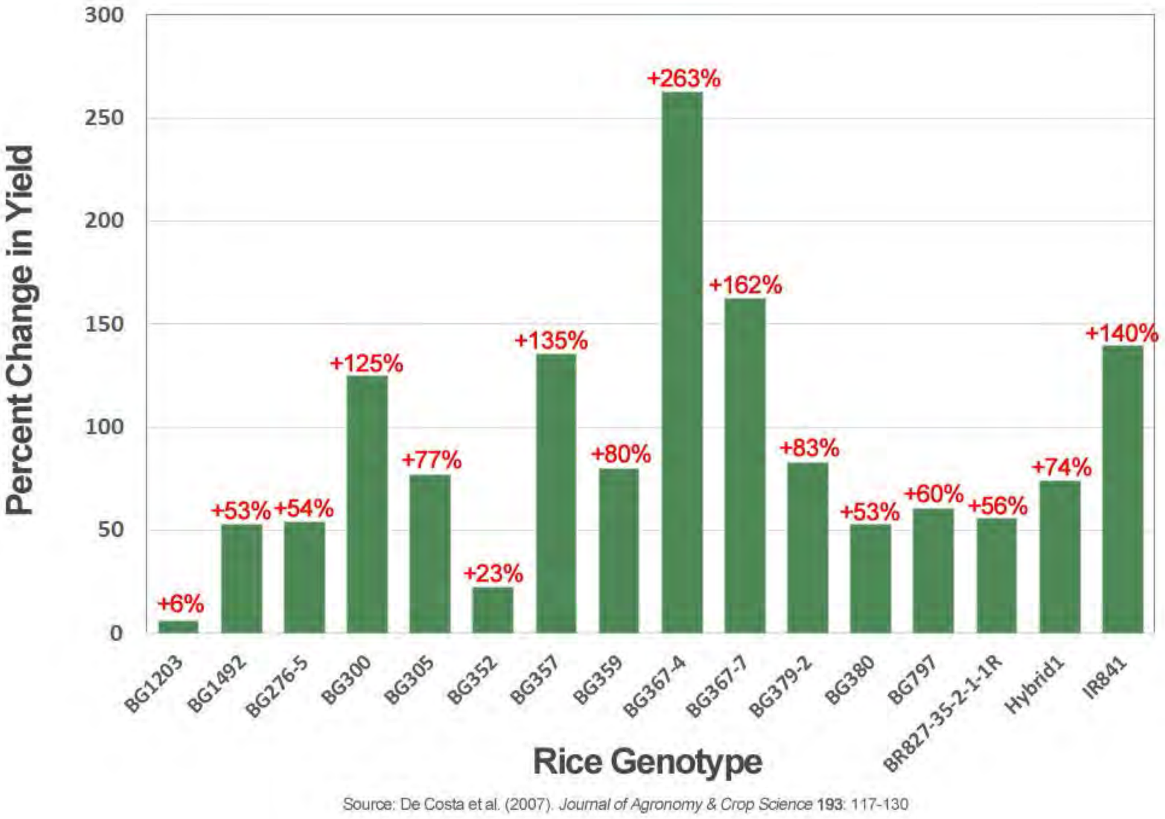
[111] See the numerous reviews posted at http://www.co2science.org/subject/a/agfeedworld.php.

[112] See http://www.co2science.org/education/reports/foodsecurity/GlobalFoodProductionEstimates2050.pdf

[113] See http://www.co2science.org/education/reports/co2benefits/MonetaryBenefitsofRisingCO2onGlobalFoodProduction.pdf

[114] See http://www.co2science.org/data/plant_growth/dry/o/oryzas.php

+263%.[115] Therefore, if countries learned to identify which genotypes provided the largest yield increases per unit of CO_2 rise, and then grew those genotypes, it is quite possible that the world could collectively produce enough food to supply the needs of all of its inhabitants, staving off the crippling food shortages that are projected to result in just a few short decades from now in consequence of the planet's ever increasing human population. Unfortunately, research has progressed but little on this front because the far too many view CO_2 as a pollutant instead of a valuable aerial fertilizer.



Source: De Costa et al. (2007). *Journal of Agronomy & Crop Science* **193**: 117-130

Figure III.A.1.4. *Percent change in grain yield for 16 rice genotypes due to a 300 ppm increase in atmospheric* CO_2.[116]

In conclusion, when considering all the productivity-related benefits rising atmospheric CO_2 offers global agriculture, it should come as no surprise that the father of modern research in this area – Dr. Sylvan H. Wittwer – has stated that "it should be considered good fortune that we are living in a world of gradually increasing levels of atmospheric CO_2," and that "the rising level of atmospheric CO_2 is a universally free premium, gaining in magnitude with time, on which we

---

[115] De Costa, W.A.J.M., Weerakoon, W.M.W., Chinthaka, K.G.R., Herath, H.M.L.K. and Abeywardena, R.M.I. 2007. Genotypic variation in the response of rice (*Oryza sativa* L.) to increased atmospheric carbon dioxide and its physiological basis. *Journal of Agronomy & Crop Science* **193**: 117-130.

[116] ibid

can all reckon for the future."[117] Dr. Wittwer could not have been more correct or insightful. Atmospheric CO_2—it's *necessary* for life.

2. Water Use Efficiency

The previous subsection examined how rising levels of atmospheric CO_2 enhance nature by stimulating the growth and development of plants. A *second* major benefit elevated CO_2 offers nature is the improvement of plant *water use efficiency*.

In basic terms, plant water use efficiency is the amount of biomass produced by a plant per unit of water lost via transpiration. At higher CO_2 levels plants generally do not open their leaf stomatal pores through which they give off water vapor as wide as they do at lower CO_2 concentrations. The smaller pore openings make it more difficult for water within the sub-stomatal cavities of the leaves to escape to the air. Consequently, elevated CO_2 not only enhances plant photosynthesis and growth, it also reduces plant water loss by transpiration, which combination of factors improves plant *water use efficiency*.

The magnitude of this incredible benefit varies by plant and growing conditions. Nevertheless, most plants experience water use efficiency gains on the order of 70 to 100%--*or more*—for a doubling of atmospheric CO_2.[118]

As an example of this phenomenon, Figure III.A.2.1 shows the effects of elevated CO_2 and plant water supply on the water use efficiency of soybeans.[119] The plants were grown in controlled-environment greenhouses for 40 days under ambient or twice ambient CO_2 concentrations and one of three water treatments: well-watered, moderate drought or severe drought. Regardless of watering treatment, the scientists who conducted this study found that a doubling of CO_2 significantly increased the water use efficiency of these plants by a whopping 217 to 247%!

Gratefully, nature does not have to wait another century or so for the air's CO_2 concentration to double before reaping benefits from enhanced water use efficiency. It has already begun to profit in this regard from the approximate 45% increase in atmospheric CO_2 that has occurred since the Industrial Revolution began.

Evidence of this fact is frequently noted in scientific studies utilizing dendrochronological methods and stable isotope analyses on long-lived tree species from all across the globe. Figure III.A.2.2, for example, depicts the change in atmospheric CO_2 and water use efficiency for an evergreen coniferous species in China. Since 1880, the rise in atmospheric CO_2 has helped boost the water use efficiency of these trees by an incredible 60%.[120]

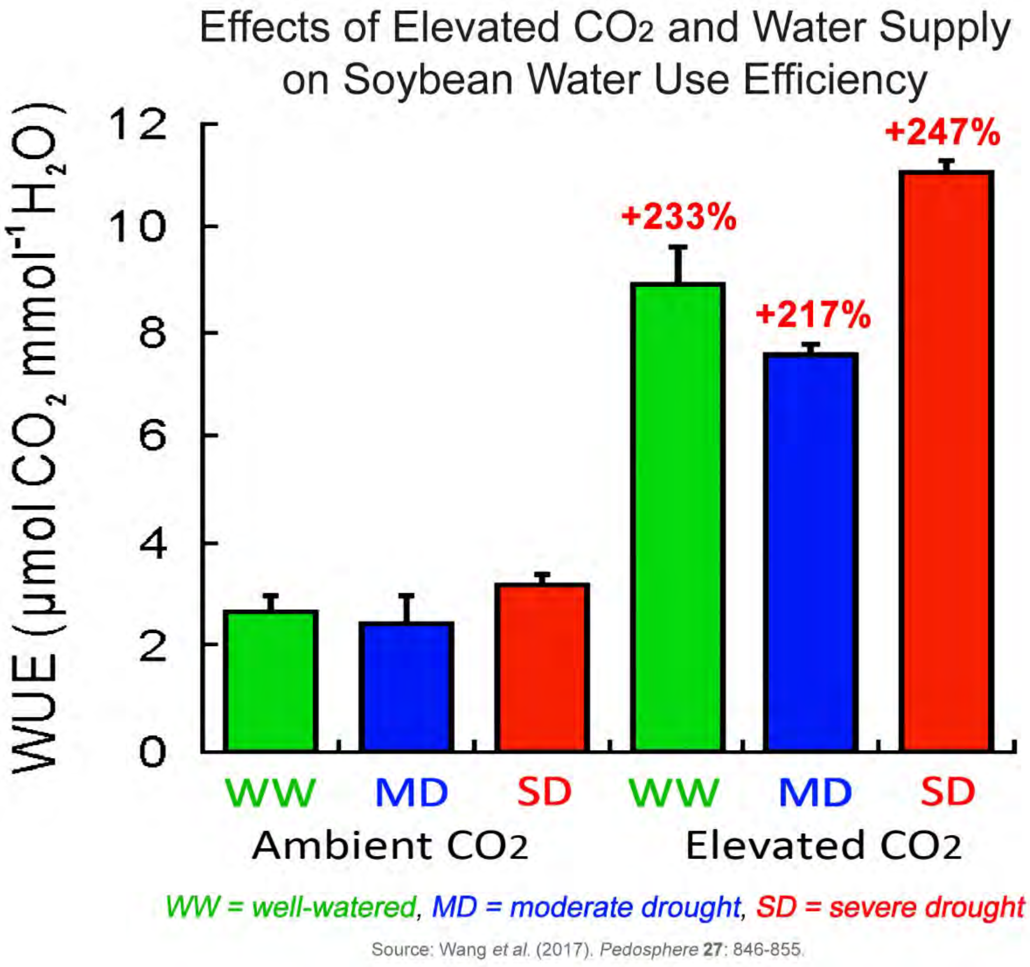
---

[117] Wittwer, S.H. 1995. Food, Climate, and Carbon Dioxide: The Global Environment and World Food Production. CRC Press, Boca Raton, FL.

[118] Idso, C.D., Idso, S.B., Carter, R.M. and Singer, S.F. (Eds.) 2014. *Climate Change Reconsidered II: Biological Impacts*. The Heartland Institute, Chicago, Illinois.

[119] Wang, Y., Yan, D., Wang, J., Sing, Y. and Song, X. 2017. Effects of elevated CO_2 and drought on plant physiology, soil carbon and soil enzyme activities. *Pedosphere* **27**: 846-855.

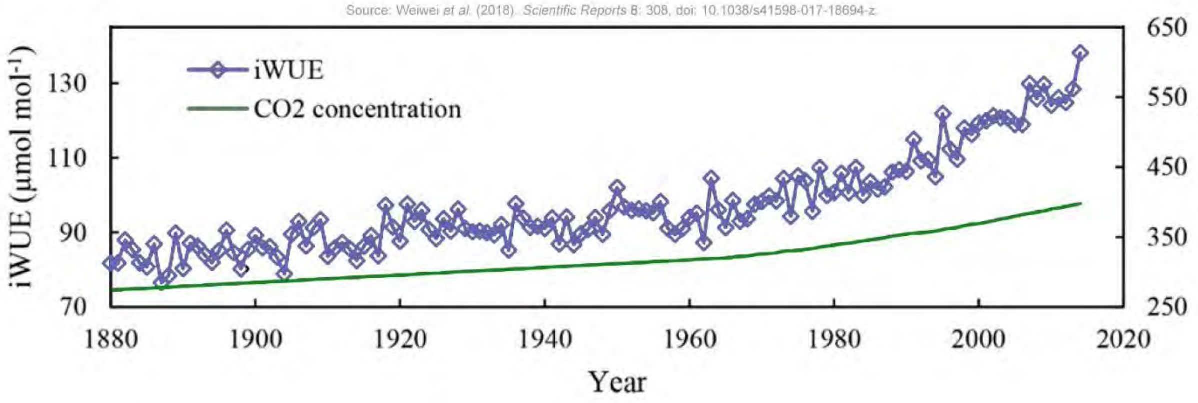
[120] Weiwei, L.U., Xinxiao, Y.U., Guodong, J.I.A., Hanzhi, L.I. and Ziqiang, L.I.U. 2018. Responses of intrinsic water-use efficiency and tree growth to climate change in semi-arid areas of north China. *Scientific Reports* **8**: 308, doi: 10.1038/s41598-017-18694-z.



Effects of Elevated CO2 and Water Supply on Soybean Water Use Efficiency

Source: Wang *et al.* (2017). *Pedosphere* **27**: 846-855.

Figure III.A.2.1. *Water use efficiency (WUE) of soybean plants grown for 40 days under various treatments of drought (WW = well-watered; MD = moderate drought; SD = severe drought) and atmospheric CO_2 (ambient and elevated, elevated = twice ambient).*



Source: Weiwei *et al.* (2018). *Scientific Reports* 8: 308, doi: 10.1038/s41598-017-18694-z.

Figure III.A.2.2. *Annual variations in intrinsic water use efficiency (iWUE) and atmospheric CO_2 concentrations (Ca) between 1880 and 2014 for P. orientalis.*

Similar-magnitude increases in water use efficiency have also been noted in Douglas fir and Ponderosa pine from the United States (Figure III.A.2.3),[121] in Norway spruce in Italy and Germany (Figure III.A.2.4),[122] cypress trees in southern Chile (Figure III.A.2.5),[123] Juniper, Acacia and Aleppo Pines in northern Africa (Figure III.A.2.6),[124,125] as well as a host of other trees from numerous other locations.[126] But perhaps the best evidence of a modern increase in water use efficiency due to rising levels of atmospheric CO_2 comes from a key study published in the scientific journal *Nature Communications* by Cheng *et al*. (2017).[127]

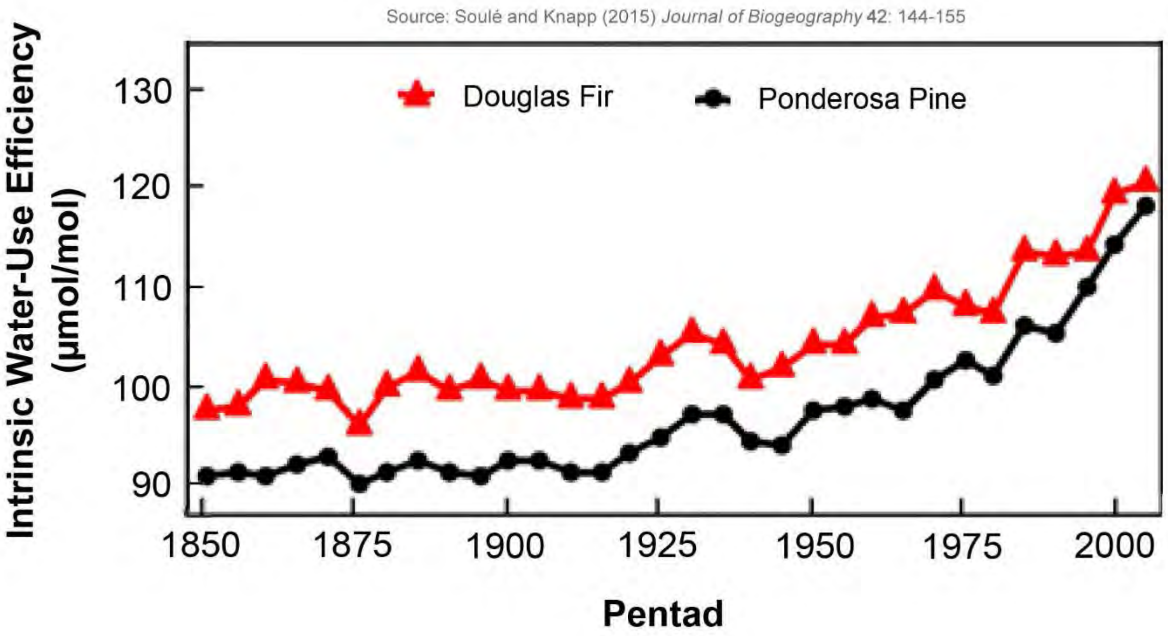


Figure III.A.2.3. *Mean tree-ring* δ^{13}*C-derived iWUE values over the period 1850-2005 for Douglas fir and Ponderosa Pine trees located in the U.S. Forest Service's Northern Rockies Region.*

---

[121] Soulé, P.T. and Knapp, P.A. 2015. Analyses of intrinsic water-use efficiency indicate performance differences of ponderosa pine and Douglas-fir in response to CO_2 enrichment. *Journal of Biogeography* **42**: 144-155.

[122] Giammarchi, F., Cherubini, P., Pretzsch, H. and Tonon, G. 2017. The increase of atmospheric CO_2 affects growth potential and intrinsic water-use efficiency of Norway spruce forests: insights from a multi-stable isotope analysis in tree rings of two Alpine chronosequences. *Trees* **31**: 503-515.

[123] Urrutia-Jalabert, R., Malhi, Y., Barichivich, J., Lara, A., Delgado-Huertas, A., Rodríguez, C.G. and Cuq, E. 2015. Increased water use efficiency but contrasting tree growth patterns in *Fitzroya cupressoides* forests of southern Chile during recent decades. *Journal of Geophysical Research, Biogeosciences* **120**: 2505-2524.

[124] Wils, T.H.G., Robertson, I., Woodborne, S., Hall, G., Koprowski, M. and Eshetu, Z. 2016. Anthropogenic forcing increases the water-use efficiency of African trees. *Journal of Quaternary Science* **31**: 386-390.

[125] Choury, Z., Shestakova, T.A., Himrane, H., Touchan, R., Kherchouche, D., Camarero, J.J. and Voltas, J. 2017. Quarantining the Sahara desert: growth and water-use efficiency of Aleppo pine in the Algerian Green Barrier. *European Journal of Forest Research* **136**: 139-152.

[126] See the multiple papers referenced in the links here, http://www.co2science.org/subject/w/waterusetrees.php

[127] Cheng, L., Zhang, L., Wang, Y.-P., Canadell, J.G., Chiew, F.H.S., Beringer, J., Li, L., Miralles, D.G., Piao, S. and Zhang, Y. 2017. Recent increases in terrestrial carbon uptake at little cost to the water cycle. *Nature Communications* **8**: 110, DOI:10.1038/s41467-017-00114-5.

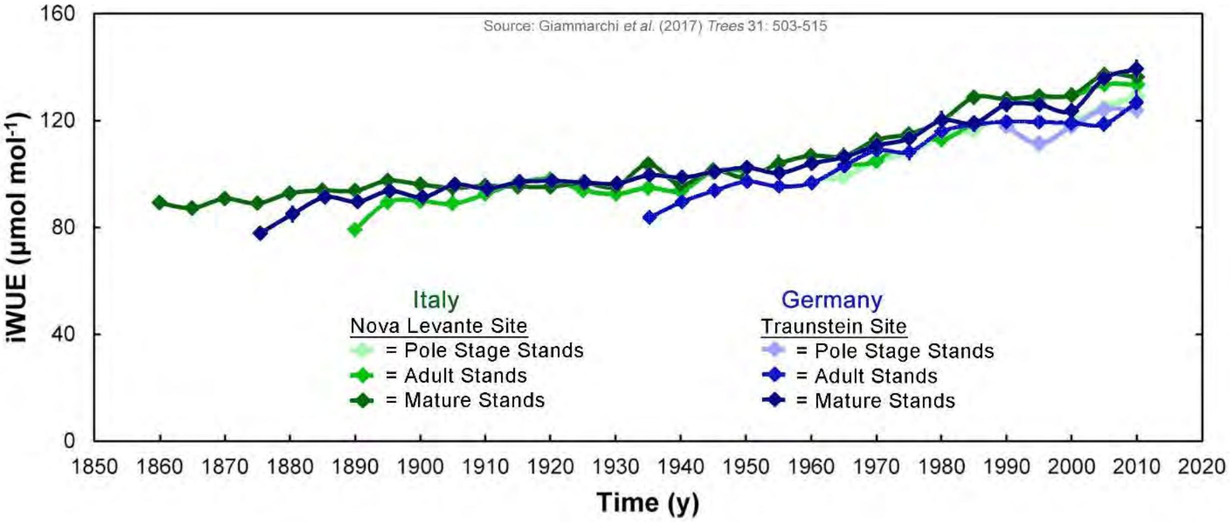
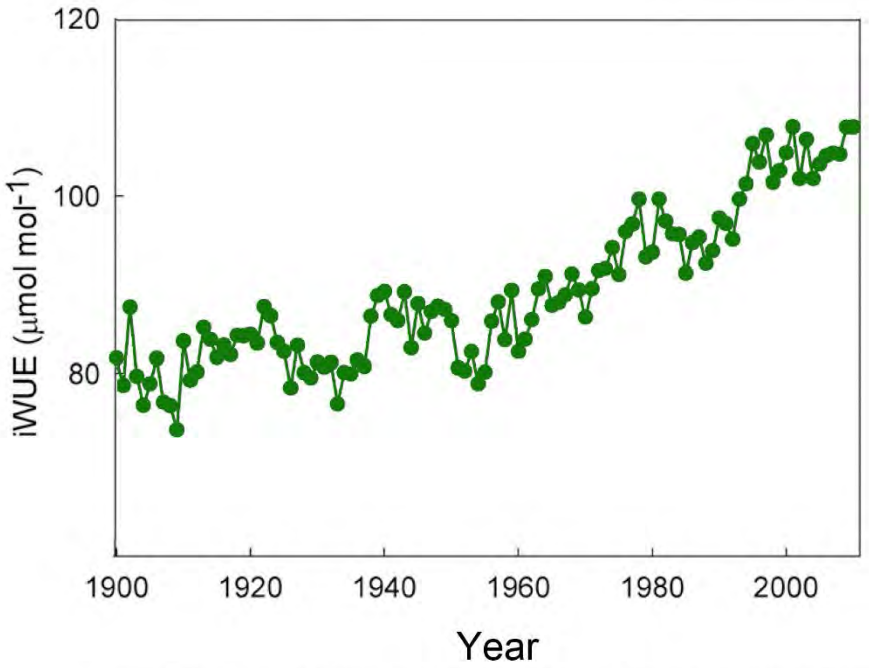
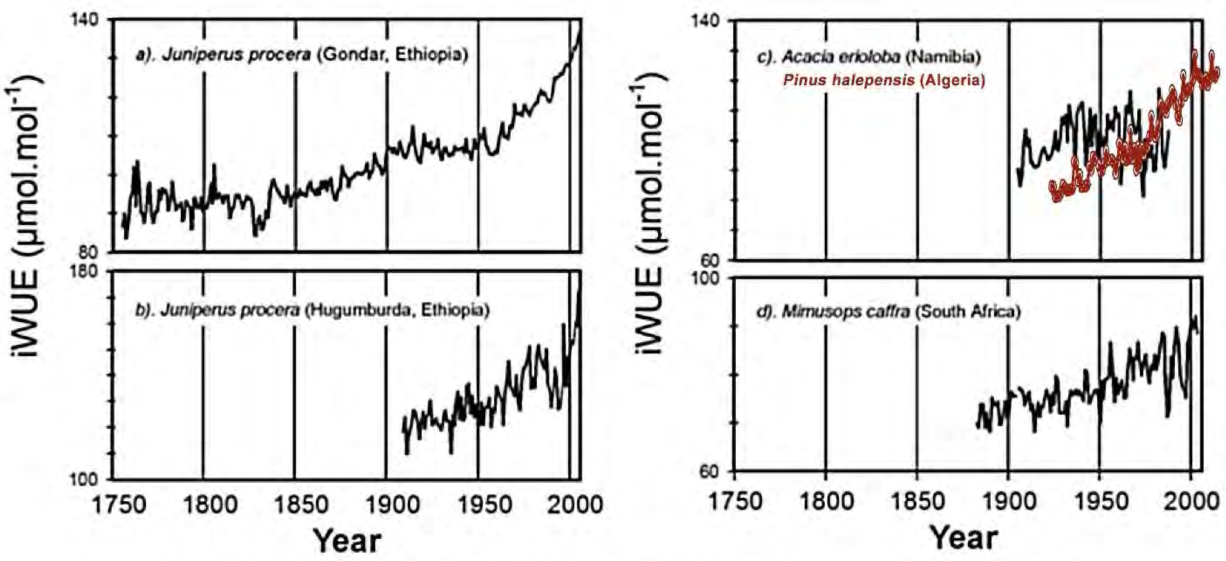

Source: Giammarchi *et al.* (2017) *Trees* 31: 503-515

Figure III.A.2.4. *δ^{13}C-inferred iWUE of three different aged stands of Norway spruce at Nova Levante (South Tyrol, Italy) and Traunstein (Bavaria, Germany).*



Source: Urrutia-Jalabert *et al.* (2015) *Journal of Geophysical Research, Biogeosciences* 120: 2505-2524

Figure III.A.2.5. *Intrinsic water use efficiency (AD 1900-2010) of long-lived Fitzroya cupressoides trees in the Andean Cordilleras of southern Chile.*



Sources: Wils *et al.* (2016) *Journal of Quaternary Science* 31: 386-390; Choury *et al.* (2017) *European Journal of Forest Research* 136: 139-152

Figure III.A.2.6. *Annual intrinsic water-use efficiency (iWUE) of (a) Juniperus procera trees growing in the north-western Ethiopian Highlands, (b) Juniperus procera growing at Hugumburda on the northwestern escarpment of the Ethiopian Rift Valley, (c) Acacia erioloba growing in the Koichab Valley in Namibia and from trees in the Djelfa forest of Algeria, and (d) Mimusops caffra growing in KwaZulu-Natal in South Africa.*

Using a combination of ground-based and remotely sensed land and atmospheric observations, the authors of this seminal work performed a series of calculations to estimate changes in global water use efficiency over the period 1982 to 2011. Results of their work, as shown in Figure III.A.2.7, reveal that global water use efficiency increased at a mean rate of 13.7 milligrams of carbon per millimeter of water per year, experiencing a phenomenal 21.6% enhancement over this three-decade-long period, almost all of which was attributed to rising atmospheric CO_2. What is more, the authors report that this increase did ***not*** come at a cost of enhanced global terrestrial water use. Instead, rising atmospheric CO_2 improved the global carbon uptake per unit of water used, meaning that plants today are larger and produce significantly more biomass than 30 years ago without needing any more water to do so, which finding holds extremely important ramifications for the future growth and survival of both plant and animal species.

Figure III.A.2.8 presents a spatial view of the global water use efficiency trends reported in Figure III.A.2.7. As is clearly evident by the various degrees of green shading, a full 90 percent of the global vegetated land area show *positive*, increasing trends in water use efficiency, which finding is actually quite impressive considering there were large-scale disturbances such as heat waves and droughts over the study period that should have adversely impacted water use efficiency in many regions. So why didn't they?

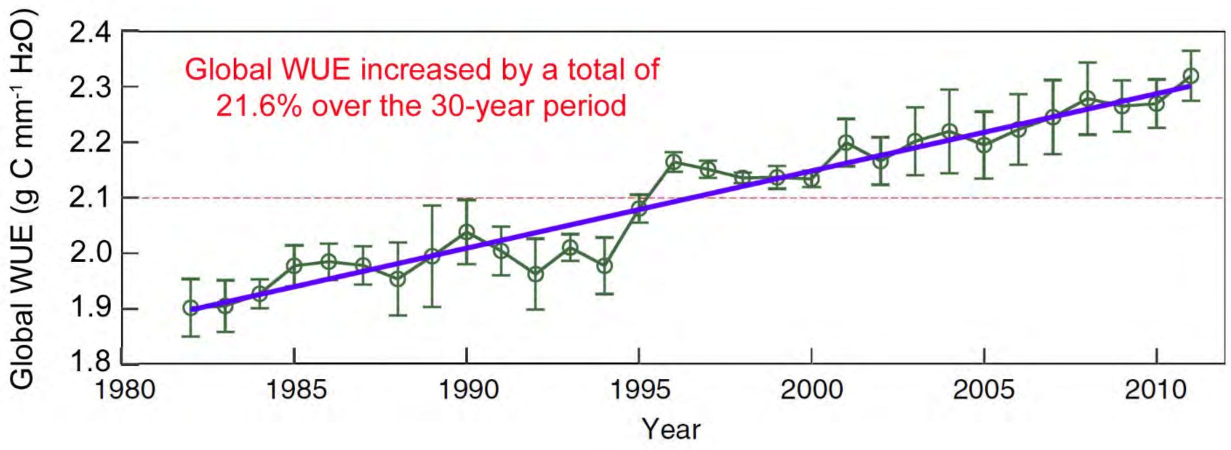


Figure III.A.2.7. *Estimated trends in global water use efficiency (WUE) over the period 1982-2011. Annual mean anomalies and associated standard deviations are plotted in green with a linear trend line shown in blue.*

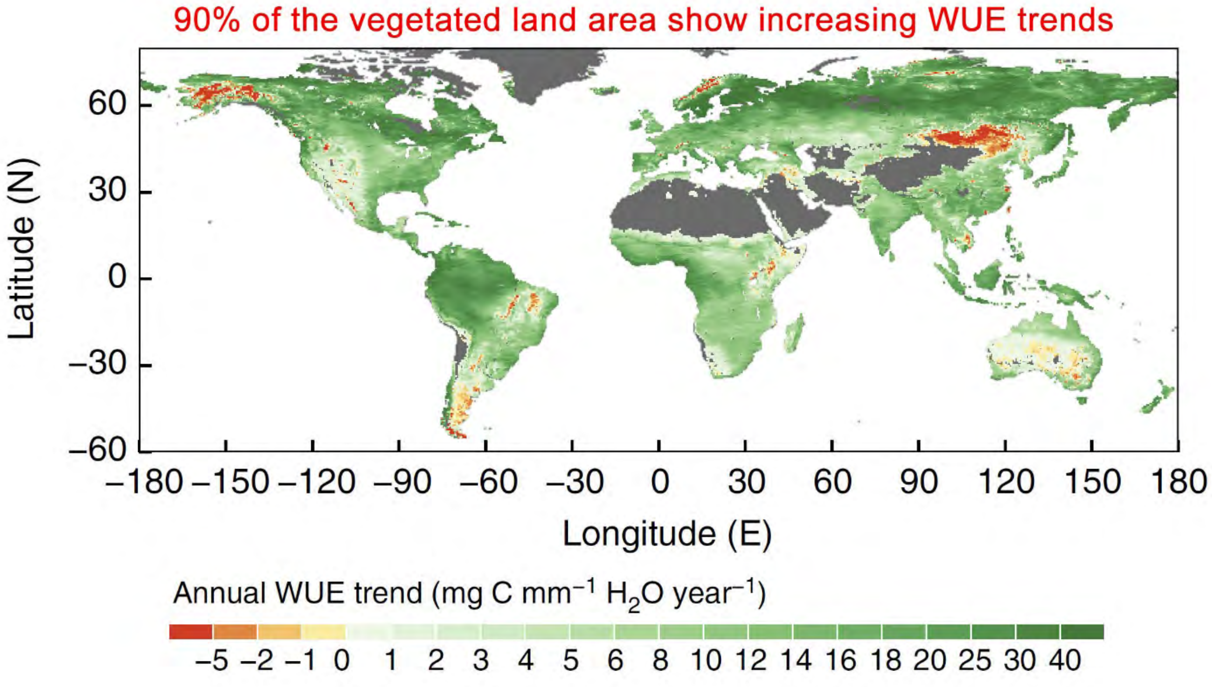


Figure III.A.2.8. *Estimated spatial variations of the contributions to trends of ecosystem water use efficiency (WUE) from atmospheric CO_2 concentration over 1982-2011. Source: Cheng et al. (2017).*

The reason is *because* of CO_2. Thanks to rising levels of this key atmospheric trace gas, the world's vegetation has met and largely overcome a host of debilitating influences that should have reduced plant water use efficiency in more locations than shown on the preceding map. And as CO_2 emissions from fossil fuel use *continue* to increase in the years and decades ahead, the observed positive enhancements to plant water use efficiency will increase even more, as Cheng *et al*. further report a 10% increase in atmospheric CO_2 induces a 14% increase in global water use efficiency.

So it is that nature's plants truly benefit from enhanced water use efficiency resulting from rising levels of atmospheric carbon dioxide. Far from being the pollutant EPA claims in its Endangerment Finding, atmospheric CO_2 is benefitting life.

3. Amelioration of Soil Nutrient Limitations

A third expected key benefit of rising atmospheric CO_2 is *the amelioration of resource limitations and environmental stresses*.

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

Many agricultural lands are nutrient-poor. The modern application of fertilizers—particularly nitrogen (N), phosphorus (P) and potassium (K)—however, has helped to significantly counter nutrient limitations and boost crop yields.[128,129] Yet, in many regions, agricultural use of fertilizers remains low or non-existent, especially across large areas of Africa, South Asia or Oceania, where new lands (typically nutrient-poor) continue to be brought into cultivation at the expense of wild nature.[130] 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. And, once again, rising concentrations of atmospheric CO_2 are helping in this regard, particularly so for crops grown on nutrient-poor soils.

As a good example of this phenomenon, Sultana *et al*. (2017)[131] examined the interactive effects of elevated CO_2 and nitrogen application on wheat under both rainfed and irrigated conditions. As shown in Figure III.A.3.1, elevated CO_2 stimulated the grain biomass in each of the N and water supply treatments from 17 to 37 percent. Perhaps more importantly, however, the percentage growth enhancements due to CO_2 were *greater* in the no N-added vs. N-added treatments.

---

[128] Smil, V. 2002. Nitrogen and food production: proteins for human diets. *Ambio* **31**: 126-131, 2002.

[129] Erisman, J.W., Sutton, M.A., Galloway, J., Klimont, Z. and Winiwarter, W. 2008. How a century of ammonia synthesis changed the world. *Nature Geoscience* **1**: 636-639.

[130] Lu, C. and Tian, H. 2017. Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: shifted hot spots and nutrient imbalance. *Earth System Science Data* **9**: 181-192.

[131] Sultana, H., Armstrong, R., Suter, H., Chen, D. and Nicolas, M.E. 2017. A short-term study of wheat grain protein response to post-anthesis foliar nitrogen application under elevated CO_2 and supplementary irrigation. *Journal of Cereal Science* **75**: 135-137.

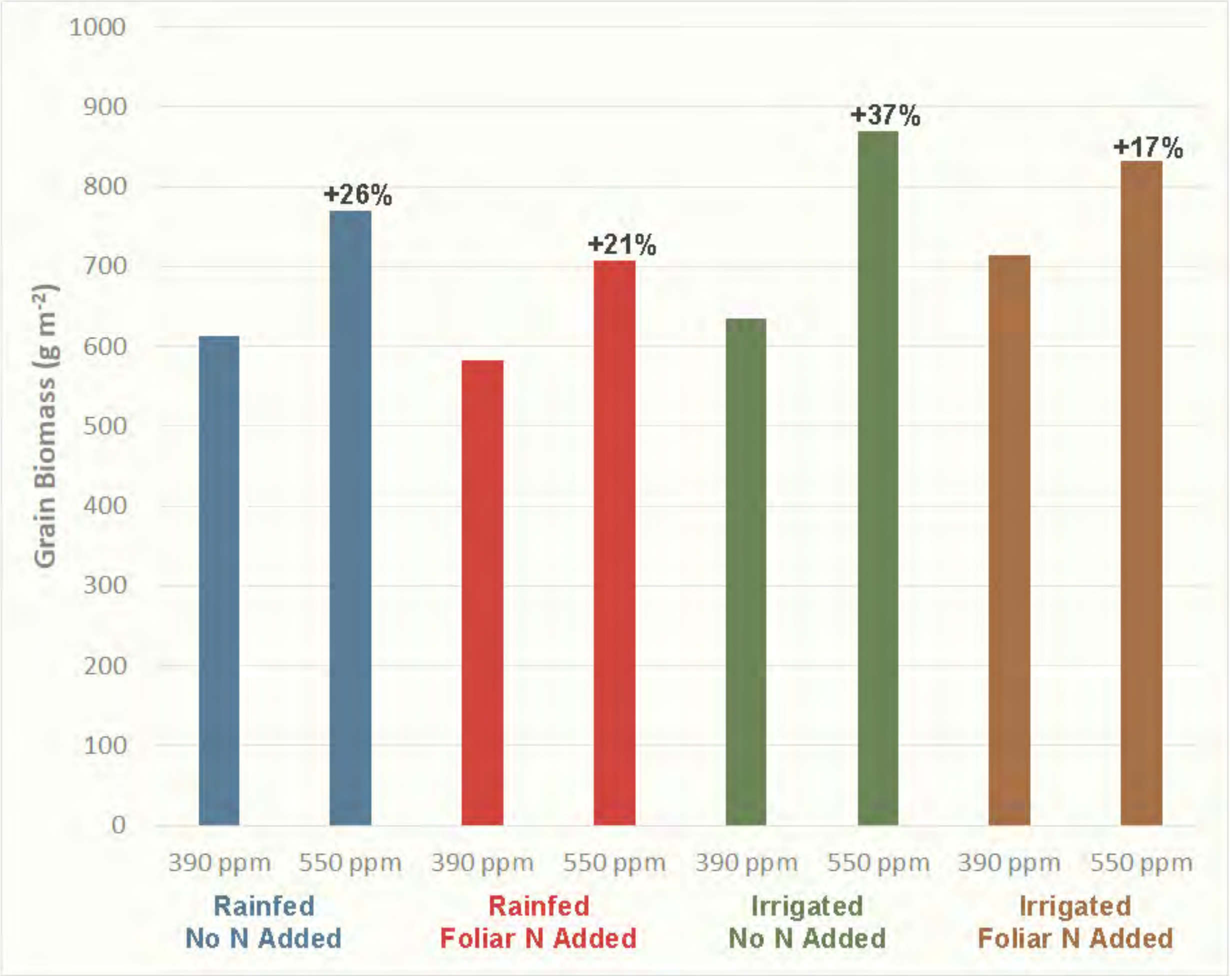


Figure III.A.3.1. *Grain biomass of spring wheat (Triticum aestivum, cv. Yitpi) grown for 190 days under various combinations of CO_2 (390 or 550 ppm), N treatment (no N or foliar added N), and water supply (rainfed or irrigated). The percentage difference in biomass due to CO_2 is listed in black above each treatment.*

Sultana *et al*. also examined the grain N content and concentration, finding that there was no statistically significant difference between the grain N *concentrations* (i.e., grain protein) at ambient or elevated CO_2 levels under any of the N or water supply treatments. In contrast, elevated CO_2 increased the total N *contents* in the grains, from 14 to 33 percent, depending on N and water supply conditions. The significance of such findings is that grain protein concentration is often assessed as an indicator of grain *quality*. Consequently, Sultana *et al*.'s work demonstrated the ability of elevated CO_2 to increase the *quantity* of wheat grain yields without sacrificing their *quality*, even under conditions of reduced nitrogen availability.

Other crops have also been shown to benefit from atmospheric CO_2 enrichment when nitrogen is limiting. Under elevated CO_2 conditions, increases in plant nitrogen fixation and/or nitrogen use efficiency (the amount of carbon fixed in plant tissues per unit of N available or supplied) have been reported for cacao,[132] cowpea,[133] garden bean,[134] garden pea,[135,136] maize,[137] papaya,[138] peanut,[139] rice,[140,141,142,143] soybean,[144,145,146] strawberry,[147] sugar beet[148,149] and sunflower.[150,151] But nitrogen is not the only limiting nutrient affecting plant growth that can be ameliorated by rising CO_2.

Although it is a less significant component of plant tissues than carbon and nitrogen, phosphorus is still required for successful life-cycle completion in many plant species. Of the few studies that have investigated aspects of plant phosphorus acquisition and biomass production in response to

---

[132] Lahive, F., Hadley, P. and Daymond, A.J. 2018. The impact of elevated CO_2 and water deficit stress on growth and photosynthesis of juvenile cacao (*Theobroma cacao* L.). *Photosynthetica* **56**: 911-920.

[133] Dey, S.K., Chakrabarti, B., Prasanna, R., Pratap, D., Singh, S.D., Purakayastha, T.J. and Pathak, H. 2017. Elevated carbon dioxide level along with phosphorus application and cyanobacterial inoculation enhances nitrogen fixation and uptake in cowpea crop. *Archives of Agronomy and Soil Science* **63**: 1927-1937.

[134] Haase, S., Neumann, G., Kania, A., Kuzyakov, Y., Romheld, V. and Kandeler, E. 2007. Elevation of atmospheric CO_2 and N-nutritional status modify nodulation, nodule-carbon supply, and root exudation of *Phaseolus vulgaris*. L. *Soil Biology & Biochemistry* **39**: 2208-2221.

[135] Butterly, C.R., Armstrong, R., Chen, D. and Tang, C. 2016. Free-air CO_2 enrichment (FACE) reduces the inhibitory effect of soil nitrate on N_2 fixation of *Pisum sativum. Annals of Botany* **117**: 177-185.

[136] Parvin, S., Uddin, S., Fitzgerald, G.J., Tausz-Posch, S., Armstrong, R. and Tausz, M. 2019. Free air CO2 enrichment (FACE) improves water use efficiency and moderates drought effect on N2 fixation of *Pisum sativum* L. *Plant Soil* **436**: 587-606.

[137] Zong, Y. and Shangguan, Z. 2014. CO_2 enrichment improves recovery of growth and photosynthesis from drought and nitrogen stress in maize. *Pakistan Journal of Botany* **46**: 407-415.

[138] Cruz, J.L., Alves, A.A.C., LeCain, D.R., Ellis, D.D. and Morgan, J.A. 2016. Interactive effects between nitrogen fertilization and elevated CO_2 on growth and gas exchange of papaya seedlings. *Scientia Horticulturae* **202**: 32-40.

[139] Tu, C., Booker, F.L., Burkey, K.O. and Hu, S. 2009. Elevated atmospheric carbon dioxide and O_3 differentially alter nitrogen acquisition in peanut. *Crop Science* **49**: 1827-1836.

[140] Weerakoon, W.M., Olszyk, D.M. and Moss, D.N. 1999. Effects of nitrogen nutrition on responses of rice seedlings to carbon dioxide. *Agriculture, Ecosystems and Environment* **72**: 1-8.

[141] Weerakoon, W.M.W., Ingram, K.T. and Moss, D.D. 2000. Atmospheric carbon dioxide and fertilizer nitrogen effects on radiation interception by rice. *Plant and Soil* **220**: 99-106.

[142] Kim, H.Y., Lieffering, M., Miura, S., Kobayashi, K. and Okada, M. 2001. Growth and nitrogen uptake of CO_2-enriched rice under field conditions. *New Phytologist* **150**: 223-229.

[143] Kim, H.-Y., Lieffering, M., Kobayashi, K., Okada, M., Mitchell, M.W. and Gumpertz, M. 2003. Effects of free-air CO_2 enrichment and nitrogen supply on the yield of temperate paddy rice crops. *Field Crops Research* **83**: 261-270.

[144] Lam, S.K., Hao, X., Lin, E., Han, X., Norton, R., Mosier, AR.., Seneweera, S. and Chen, D. 2012. Effect of elevated carbon dioxide on growth and nitrogen fixation of two soybean cultivars in northern China. *Biology and Fertility of Soils* **48**: 603-606.

[145] Prevost, D., Bertrand, A., Juge, C. and Chalifour, F.P. 2010. Elevated CO_2 induces differences in nodulation of soybean depending on bradyrhizobial strain and method of inoculation. *Plant and Soil* **331**: 115-127.

[146] Li, Y., Yu, Z., Liu, X., Mathesius, U., Wang, G., Tang, C., Wu, J., Liu, J., Zhang, S. and Jin, J. 2017. Elevated CO_2 increases nitrogen fixation at the reproductive phase contributing to various yield responses of soybean cultivars. *Frontiers in Plant Science* **8**: 1546, doi: 10.3389/fpls.2017.01546.

[147] Deng, X. and Woodward, F.I. 1998. The growth and yield responses of *Fragaria ananassa* to elevated CO_2 and N supply. A*nnals of Botany* **81**: 67-71.

[148] Demmers-Derks, H., Mitchell, R.A.G., Mitchell, V.J. and Lawlor, D.W. 1998. Response of sugar beet (*Beta vulgaris* L.) yield and biochemical composition to elevated CO_2 and temperature at two nitrogen applications. *Plant, Cell and Environment* **21**: 829-836.

[149] Romanova, A.K., Mudrik, V.A., Novichkova, N.S., Demidova, R.N. and Polyakova, V.A. 2002. Physiological and biochemical characteristics of sugar beet plants grown at an increased carbon dioxide concentration and at various nitrate doses. *Russian Journal of Plant Physiology* **49**: 204-210.

[150] Zerihun, A., Gutschick, V.P. and BassiriRad, H. 2000. Compensatory roles of nitrogen uptake and photosynthetic N-use efficiency in determining plant growth response to elevated CO_2: Evaluation using a functional balance model. *Annals of Botany* **86**: 723-730.

[151] Lakshmi, N.J., Vanaja, M., Yadav, S.K., Maheswari, M., Archana, G., Patil, A and Srinivasarao, C. 2017. Effect of CO_2 on growth, seed yield and nitrogen uptake in sunflower. *Journal of Agrometeorology* **19**: 195-199.

atmospheric CO_2 enrichment, when phosphorus concentrations in soils are less than optimal, the future looks promising.

In an early study of the subject, Barrett *et al*. (1998)[152] demonstrated that a doubling of the air's CO_2 content under continuous phosphorus deficiency increased wheat root phosphatase activity by 30 to 40%, thus increasing the inorganic phosphorus supply for plant utilization. As phosphatase is the primary enzyme responsible for the mineralization of organic phosphate, which thereby makes phosphorus available for plant use, an increase in its activity with elevated CO_2 could facilitate sustained plant growth responses to the ongoing rise in the air's CO_2 content, even in areas where growth is currently limited by phosphorous deficiencies. Furthermore, because these increases in phosphatase activity were also observed under sterile growing conditions, this observation indicates that this response can be mediated directly by plant roots without involving soil microorganisms, which are already known to aid in phosphorus mineralization.

As the air's CO_2 content thus continues to rise, it would be expected that phosphatase activity in wheat roots will increase, thereby converting organic phosphorus into inorganic forms that can be used to support the increased plant growth and development that is stimulated by higher CO_2 concentrations. And because a similar increase in phosphatase activity at elevated CO_2 has already been reported for a native Australian pasture grass, these results may be applicable to most of Earth's vegetation. If this is indeed the case, then plants that are currently phosphorus limited in their growth might increase their phosphorous acquisition from soil organic supplies as the atmospheric CO_2 concentration increases; and this phenomenon, in turn, may allow them to sequester even greater amounts of carbon from the air as the atmosphere's CO_2 concentration climbs ever higher. The end result of these several occurrences, of course, is improved agricultural yields under phosphorus-limited conditions, which observation has been confirmed in several studies subsequent to Barrett *et al*. In general, these additional works demonstrate that P deficiency results in plant photosynthetic and growth-related reductions, which reductions are ameliorated under atmospheric CO_2 enrichment.[153]

Another important element that can negatively impact plant growth at insufficient levels is potassium (K). According to Singh and Reddy (2017),[154] K 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 growth limitations are also likely to be lessened—and potentially overcome—in the future under atmospheric CO_2 enrichment.

Working in controlled-environment growth chambers, for example, Singh and Reddy demonstrated experimentally by exposing soybean plants to two CO_2 treatment levels and three levels of K. Their results indicated that K deficiency significantly reduced soybean growth-related parameters regardless of CO_2 concentration. However, as illustrated in Figure III.A.3.2,

---

[152] Barrett, D.J., Richardson, A.E. and Gifford, R.M. 1998. Elevated atmospheric CO_2 concentrations increase wheat root phosphatase activity when growth is limited by phosphorus. *Australian Journal of Plant Physiology* **25**: 87-93.

[153] See the many studies on this topic listed here: http://www.co2science.org/subject/p/phosphorus.php.

[154] Singh, S.K. and Reddy, V.R. 2017. Potassium starvation limits soybean growth more than the photosynthetic processes across CO_2 levels. *Frontiers in Plant Science* **8**: 991, doi: 10.3389/fpls.2017.00991.

elevated CO_2 compensated and partially ameliorated the K deficiency-induced growth reductions in total plant dry matter such that the percentage growth enhancement due to elevated CO_2 was greater (+63% and +28%) under the two levels of K deficiency (0.50 and 0.02 mM K) than when K was not a growth-limiting factor (+23% CO_2-induced enhancement at 5.00 mM K level). Averaged across potassium treatments, elevated CO_2 increased the leaf, stem, root and pod weights by 28, 68, 23 and 33 percent, respectively, at maturity.

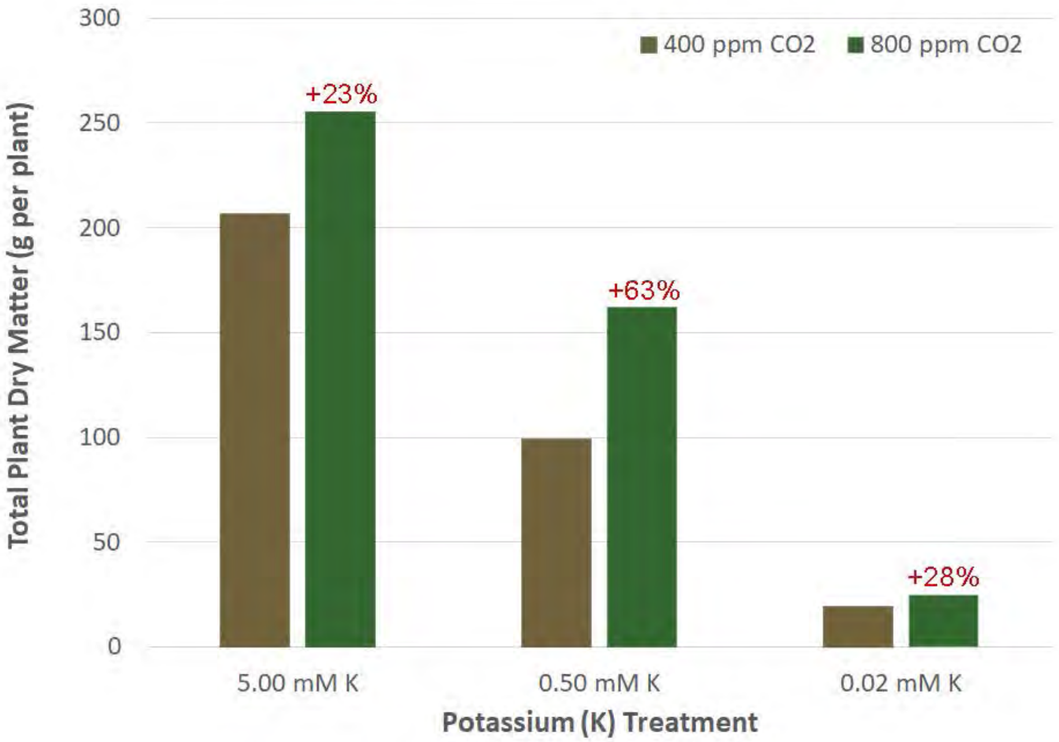


Figure III.A.3.2. *Effects of elevated CO_2 and potassium treatment on the total plant dry matter of soybean.*

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

In another study Asif *et al*. (2018)[155] examined the impact of elevated CO_2 on bread wheat (*Triticum asesivum*, cv. Tahirova) plants subjected to adequate or deficient K fertilization. As expected, elevated CO_2 *positively* impacted plant yield parameters at full maturity, whereas K-deficiency *negatively* impacted them. More specifically, elevated CO_2 significantly increase grain yield by 22 and 69 percent in adequate and deficient potassium plants, respectively (see Figure III.A.3.3). Plant thousand-grain weight, straw yield and spikes per plant were also higher

---

[155] Asif, M., Tune, C.E. and Ozturk, L. 2018. Changes in yield attributes and K allocation in wheat as affected by K deficiency and elevated CO_2. *Plant Soil* **426**: 153-162.

under elevated CO_2 regardless of K treatment level. And although the absolute values of these parameters were reduced in the K-deficient treatment, the relative percent increase or stimulation due to atmospheric CO_2 enrichment was higher under K-deficit conditions than K-adequate conditions, indicating elevated CO_2 was able to partially ameliorate the negative growth impacts of K deficiency. Asif *et al*. also found that elevated CO_2 enhanced the allocation of potassium into plant grains, particularly so in the K-deficient treatment.

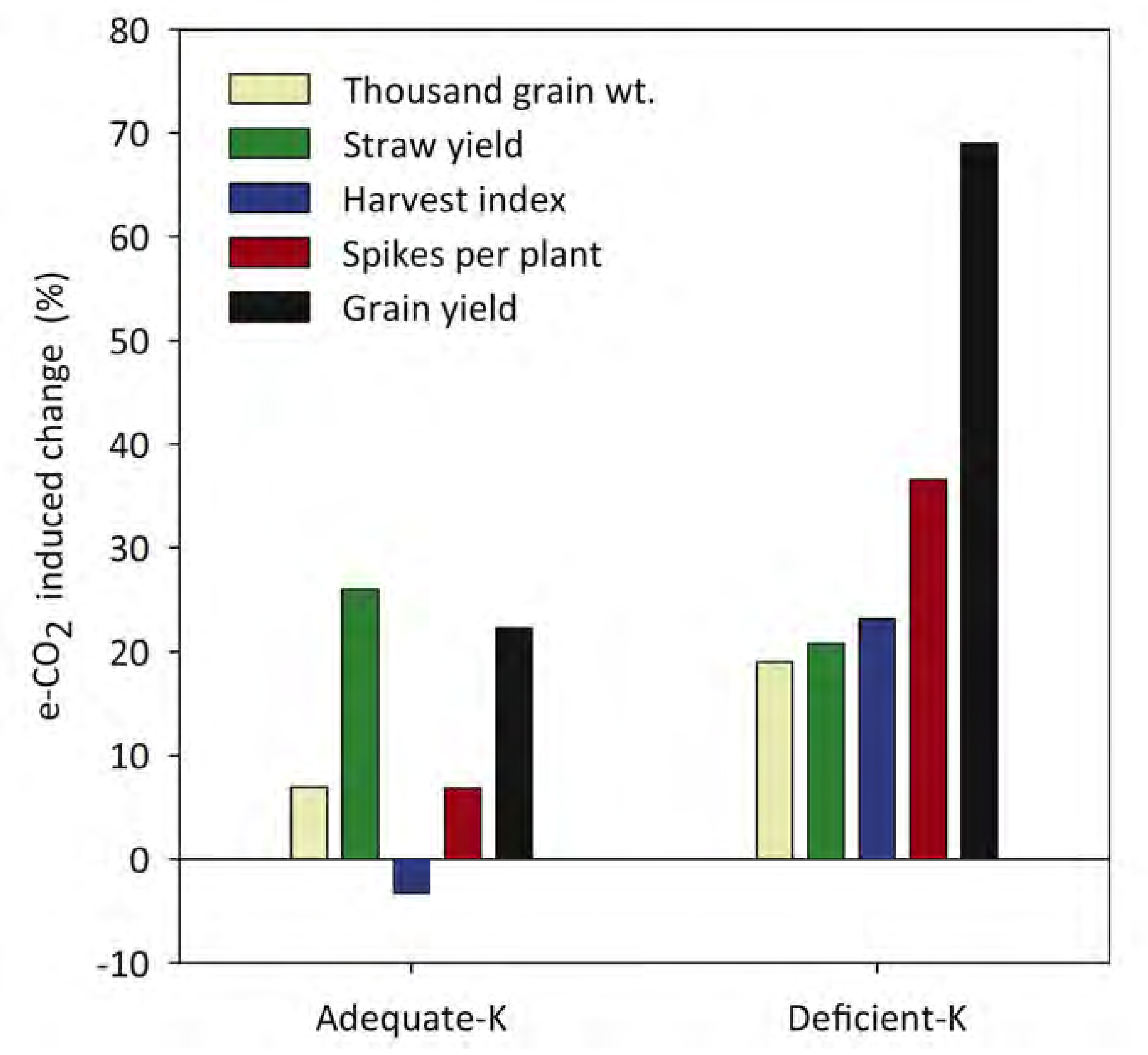


Figure III.A.3.3. *Changes in bread wheat (Triticum aestivum, cv. Tahirova) yield attributes in response to elevated atmospheric CO_2 (e-CO_2: 700 ppm, relative to ambient, 420 ppm) under adequate-K (250 mg K kg^{-1}) and deficient-K (50 mg K kg^{-1}) treatments.*

Dabu *et al*. (2019)[156] have also reported positive effects of elevated CO_2 under potassium-limited conditions. Working with cucumber (*Cucumis sativus* cv. Zhongnong 20), they found that elevated CO_2 increased total biomass by 73% under potassium-limited conditions and by 33% when potassium was not limited (see Figure III.A.3.4). In this regard, higher potassium concentrations positively impacted biomass by helping to increase the transport of photosynthetic products from the leaves into other plant organs (e.g., stems, roots).

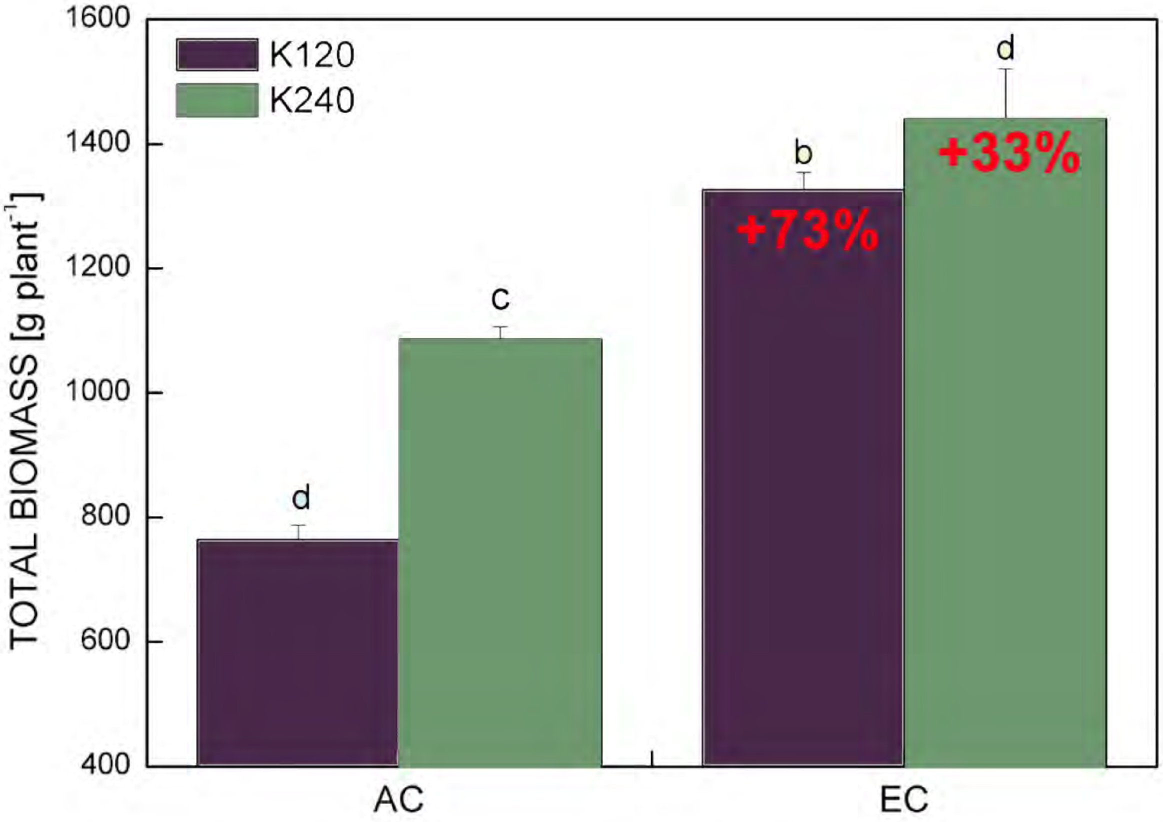


Figure III.A.3.4. *Effects of elevated CO_2 concentrations and increasing potassium concentrations on the total biomass on cucumber plants grown hydroponically in a greenhouse. AC = ambient CO_2 concentration of 380 ppm; EC = elevated CO_2 concentration of 1,000 ppm; K120 = potassium application of 120 mg L^{-1}; K240 = potassium application of 240 mg L^{-1}. The percentages in red text indicate the total biomass enhancement due to elevated CO_2 at a given potassium treatment.*

Clearly, therefore, in light of the several findings presented above, future agricultural production will benefit greatly from CO_2-induced enhancements in plant nutrient-use efficiency. When crops are grown on nutrient-deficient soils without the addition of fertilizers, elevated CO_2 will improve crop utilization of the existing low-level supply of nutrients. When fertilizers *are* added and nutrients are non-limiting, elevated CO_2 will raise yields even more. Consequently, this

---

[156] Dabu, X., Li, S., Cai, Z., Ge, T. and Hai, M. 2019. The effect of potassium on photosynthetic acclimation in cucumber during CO_2 enrichment. *Photosynthetica* **57**: 640-645.

unique characteristic of atmospheric CO_2 enrichment—increasing crop yields per unit of available nutrients—will help society to meet its future food needs without taking and converting more land from wild nature into agricultural production.

4. Amelioration of Other Environmental Stresses

In addition to soil nutrient deficiencies, there are several other environmental stresses that can negatively impact plant growth. Yet, once again, a vast array of research shows that elevated concentrations of atmospheric CO_2 tend to help plants better cope with, or *fully overcome*, these growth-retarding effects. In this regard, CO_2 fertilization has been shown to counteract the deleterious effects of high soil salinity, high/low air temperature, high/low light intensity, oxidative stress, UVB stress, pathogen attack, micronutrient deficiencies, and the stress of herbivory. For brevity, the material in the following subsections references only two examples of the CO_2 benefits in each of the afore-mentioned environmental stresses. However, information on additional peer-reviewed studies conducted on each subtopic can be found by following the Internet links provided at the end of each subsection.

(i) High Soil Salinity

In agricultural enterprises the buildup of soil salinity from repeated irrigations can reduce crop yields. Similarly, in unmanaged ecosystems where exposure to brackish or salty water is commonplace, saline soils can induce growth stresses in plants that are not naturally adapted to coping with this problem. Consequently, it is important to understand how rising atmospheric CO_2 concentrations may interact with soil salinity to affect plant growth; and when the pertinent literature is analyzed, it becomes clear that most plants growing in such conditions will continue to respond positively to continued increases in the air's CO_2 content.

Example 1

Salicornia ramosissima is an edible halophyte capable of growing in hostile environments of high salinity and/or water deficit. According to Pérez-Romero *et al*. (2018),[157] it has been recognized as a multifunctional cash crop, having been utilized as a gourmet food ingredient, feed for cattle, and as a tool for phytoremediation. However, little is known about how this plant might respond to future changes in climate that could alter its growing conditions. Consequently, Pérez-Romero *et al*. set out to examine the combined impacts of elevated CO_2 and salinity on this crop species.

Work was conducted under controlled-environment conditions in Lisbon, Portugal, where 3-month-old *S. ramosissima* seedlings were exposed to one of three salinity treatments (0, 171 or 513 mM NaCl) under either normal (400 ppm) or elevated (700 ppm) atmospheric CO_2 concentrations for a period of 30 days. At the end of this period, the authors conducted a number of measurements in an effort to assess the impacts of elevated CO_2 on various growth-related parameters of this species.

---

[157] Pérez-Romero, J.A., Idaszkin, Y.L., Barcia-Piedras, J.-M., Duarte, B., Redondo-Gómez, S., Cacador, I. and Mateos-Naranjo, E. 2018. Disentangling the effect of atmospheric CO_2 enrichment on the halophyte *Salicornia ramosissima* J. Woods physiological performance under optimal and suboptimal saline conditions. *Plant Physiology and Biochemistry* **127**: 617-629.

Results of the analysis revealed, in the words of the authors, that "atmospheric CO_2 enrichment would increase the tolerance of the halophyte *S. ramosisima* to suboptimal salinity concentration (NaCl excess)." As indicated in Figure III.A.4.i.1 below, plants growing under elevated CO_2 were able to maintain similar values of net photosynthesis, regardless of salinity level. This positive effect, according to Pérez-Romero *et al*., was linked to "a reduction of mesophyll conductance and biochemical limitation imposed [by] salt excess." In contrast, at ambient CO_2 net photosynthesis declined as the salinity content rose.

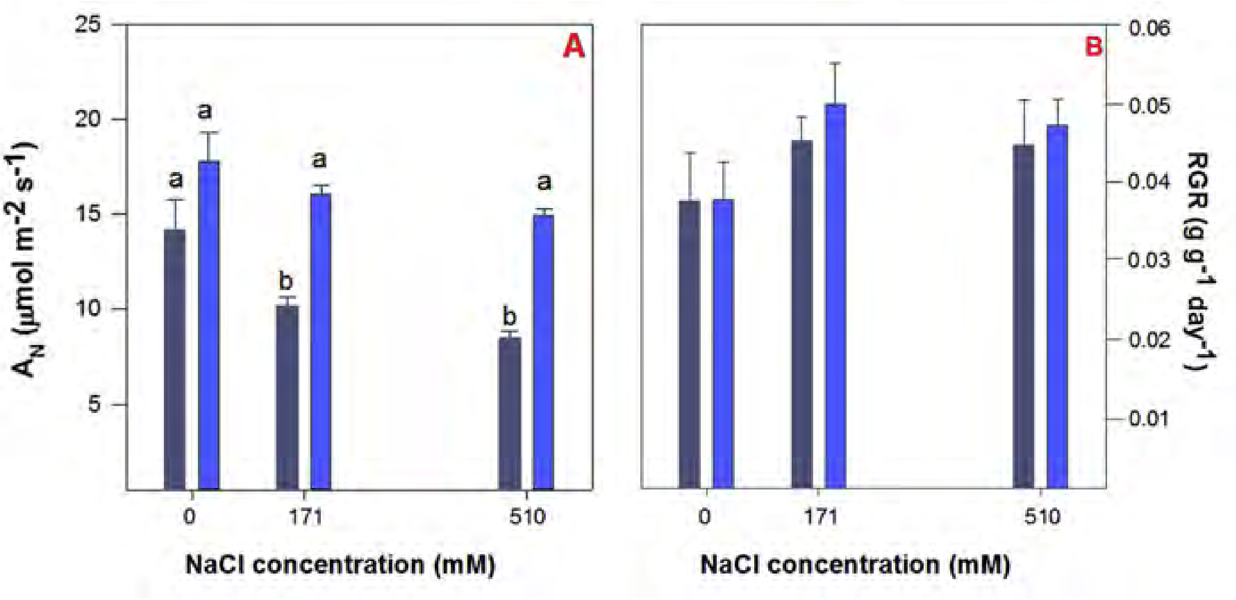


Figure III.A.4.i.1. *Net photosynthesis (AN) and relative growth rate (RGR) of S. ramosissima after 30 days of growth under normal (400 ppm, dark blue bars) or enriched (700 ppm, light blue bars) atmospheric CO_2 and three different soil salinity concentrations (0, 171 or 510 mM NaCl). Different letters indicate means that are significantly different from each other ($P < 0.05$).*

Other noted benefits of CO_2 enrichment on this edible halophyte included an improved water balance resulting from a reduction in stomatal conductance and a reduction in the risk of reactive oxygen species production, indicated by an improvement of the electron flux and a rise of energy dissipation. Lastly, Pérez-Romero *et al*. report that "the positive effect of the CO_2 was also supported by the modulation of pigments profiles (mainly zeaxhantin and violaxhantin) concentrations and anti-oxidative stress enzymes, such as superoxide dismutase and ascorbate peroxidase." And in light of *all* of the above findings, the scientists conclude that "this multifunctional cash crop specie could be an interesting suitable natural resource to be cultivated in a future climate change scenario, where an increment of soil salinity concentration is expected together with the atmospheric CO_2 enrichment."

Example 2

The excessive accumulation of sodium in soils (i.e., salinity stress) is harmful to plants and induces physiological damages. Elevated levels of atmospheric CO_2, in contrast, have been shown to promote plant growth and alleviate stresses. Thus, it was the design of authors Zhuang *et al*. (2019)[158] to study the *combined* effects of elevated CO_2 and salinity stress on Kentucky bluegrass (*Poa pratensis* cv. Kenblue).

The work was conducted in growth chambers under controlled environments over a period of 42 days. Treatments included control (ambient CO_2 concentration of 400 ppm and 250 mL of salt-free irrigation water daily), elevated CO_2 (elevated CO_2 concentration of 800 ppm and 250 mL of salt-free irrigation daily), salt stress (ambient CO_2 and 250 mL of daily irrigation water containing 200 mM NaCl solution to induce salt stress) and combined elevated CO_2 and salt stress (800 ppm and 250 mL of daily irrigation water containing 200 mM NaCl solution). During each week of the experiment the researchers measured a number of plant growth and physiological indices to evaluate the impact of the two variables. Then, at the end of the 42 day study period they sampled fresh leaves and roots to determine leaf ion contents and to extract and quantify various metabolites, hoping to discern the mechanisms behind the physiological changes observed in their study.

In terms of growth, elevated CO_2 had a *positive* effect while salinity stress had a *negative* effect, evidenced by the relative growth rate and net photosynthesis data presented in Figure III.A.4.i.2. With respect to the *combined* elevated CO_2 and salinity stress treatment, Zhuang *et al*. report that "elevated CO_2 effectively ameliorated plant growth and physiological damages due to salt stress, as shown by the increase in turf quality, relative water content, leaf chlorophyll content, shoot growth rate, net photosynthetic rate, and K^+ content, as well as by the reduction in electrolyte leakage and Na^+ content in both leaves and roots." What is more, they add that elevated CO_2 "altered metabolic profiles of leaves and roots exposed to salt stress, with enhanced accumulation of organic acids (quinic acid, mucic acid, pyruvic acid, citric acid, lactic acid, malic acid, fumaric acid, and shikimic acid in leaves; citric acid, fumaric acid, gluconic acid, galacturonic acid, isocitric acid, glyceric acid, succinic acid, and malonic acid in roots), sugars (glucose, fructose, hexopyranose, gulose, tagatose, mannose, sucrose, trehalose, cellobiose in leaves; glucose, galactose, hexopyranose, sucrose, trehalose, lactose, turanose in roots), sugar alcohols (galactinol, glycerol in leaves and galactinol, glycerol, mannitol in roots), sterols (B-sitosterol in leaves and stigmasterol, B-sitosterol, campesterol in roots), and fatty acids (linolenic acid and palmitic acid in both leaves and roots)." Such CO_2-induced metabolite changes, according to the authors, are likely the reason why elevated CO_2 improved the salt tolerance of this perennial grass species. And these findings are great news for plants that are growing in areas subjected to salt stress. In the future, they will grow better *because* of rising CO_2.

---

[158] Zhuang, L., Yang, Z., Fan, N., Yu, J. and Huang, B. 2019. Metabolomic changes associated with elevated CO_2-regulation of salt tolerance in Kentucky bluegrass. *Environmental and Experimental Botany* **165**: 129-138.

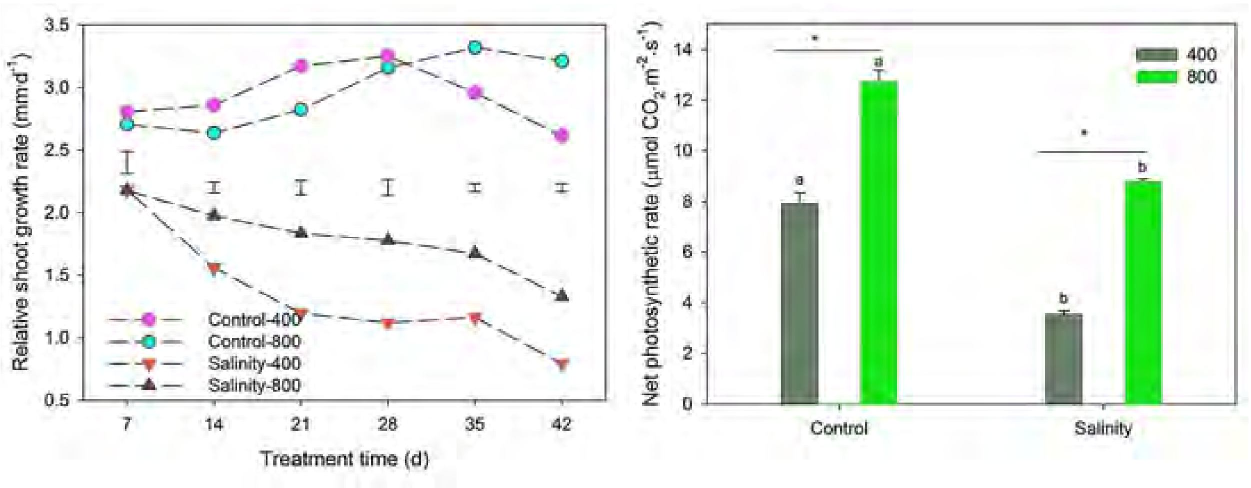


Figure III.A.4.i.2. *Effects of CO_2 concentration on relative shoot growth (left panel) and net photosynthetic (right panel) rates of Kentucky bluegrass exposed to salt stress. The 400 and 800 refer to ambient (400 ppm) and elevated (800 ppm) CO_2 concentrations, respectively. Vertical bars in the left panel represent significant difference between different treatments based on LSD values ($P \leq 0.05$). Vertical bars in the right panel indicate standard errors of the mean for each treatment. Columns marked with small letters and * represent the salt-induced significant differences at a given CO_2 concentration and the elevated CO_2-induced significant differences at either control or salt stressed condition, respectively, based on LSD values ($P \leq 0.05$).*

Information on additional peer-reviewed scientific studies on this topic can be accessed at http://www.co2science.org/subject/s/salinitystress.php under the heading *Interactive Effects of CO_2 and Salinity Stress on Plant Growth*.

(ii) Heat Stress

Climate models predict that heat waves will become more frequent and more severe in the future because of CO_2-induced global warming. Heat waves, depending on length and severity, can cause serious harm to plant development and growth. Consequently, the EPA and others are concerned about the future impact of heat waves on managed and unmanaged natural ecosystems. Regardless of whether or not model predictions of heat waves come true, one thing is for sure, in the future plants will be better equipped to deal with heat stress *because* of rising atmospheric CO_2.

Example 1

Introducing their work, Chavan *et al*. (2019)[159] write that “developing wheat varieties ready for future climates calls for improved understanding of how elevated CO_2 and heat stress interactively impact wheat yields.” And thus they went on to explain how they had examined the

---

[159] Chavan, S.G., Duursma, R.A., Tausz, M. and Channoum, O. 2019. Elevated CO_2 alleviates the negative impact of heat stress on wheat physiology but not on grain yield. *Journal of Experimental Botany* **70**: 6447-6459.

interactive effects of elevated CO_2 and heat stress on the photosynthesis, biomass and grain yield of wheat.

The experiment was conducted in controlled-environment glasshouses at the Hawkesbury campus of Western Sydney University, Richmond, New South Wales, Australia. The authors utilized a commercial wheat cultivar, Scout, which they describe as a "high yielding variety with very good grain quality [that] contains a putative high transpiration efficiency gene which can increase water use efficiency." The CO_2 concentrations examined in the study included ambient (419 ppm) and elevated (654 ppm). Temperatures were maintained at 22/15 °C (day/night) in the control treatment. Then, thirteen weeks after planting heat stress was enacted on half the plants in each CO_2 treatment by raising the day/night temperatures to 40/24 °C for five days. Thereafter, the heat-stressed plants were returned to the control temperatures. Adequate water was supplied to all treatments throughout the experiment so as to avoid confounding effects of water stress.

In discussing their findings, Chavan *et al*. report that elevated CO_2 enhanced net photosynthesis by 36% in non-heat stressed plants, whereas high temperature stress reduced this parameter by 42%. In the combined elevated CO_2 and heat stress treatment, net photosynthesis was not reduced because, in the words of the authors, "elevated CO_2 protected photosynthesis by increasing ribulose biphosphate regeneration capacity and reducing photochemical damage [caused by] heat stress."

With respect to biomass and yield, as shown in the figure below, elevated CO_2 stimulated these two parameters by 36% and 31%, respectively, in the control treatment. Heat stress alone, in contrast, induced a small non-significant reduction in total biomass and a 44% reduction in grain yield. When elevated CO_2 and heat stress were combined, total biomass increased by 46% over the control treatment (ambient CO_2 and non-heat stress) and by 58% relative to the heat stress treatment under ambient CO_2. Grain yield, on the other hand, experienced a 23% decline in the combined elevated CO_2 and heat stress treatment relative to control conditions, but a positive 37% increase relative to heat stress alone at ambient CO_2. Thus, in the future, elevated CO_2 may well be able to ameliorate a large portion of the negative impact of high temperature stress on grain yield.

Commenting on their findings, Chavan *et al*. state that "heat stress caused irreversible photosynthetic damage at ambient CO_2, while growth at elevated CO_2 mitigated the negative impact of heat stress on photosynthesis." Additionally, they say that "plant biomass completely recovered from heat stress under both CO_2 treatments due to the development of additional late tillers and ears; yet these did not fully develop and fill grains," which explains the drop in grain yield observed under heat stress. Consequently, they advocate for more research and breeding programs designed to improve grain filling and translocation of plant resources to the grain at high temperatures and elevated CO_2 to protect future food production. In the meantime, as demonstrated in Figure III.A.4.ii.2 below, the air's rising CO_2 content will help ameliorate the negative influence of high temperature stress on wheat grain yields.

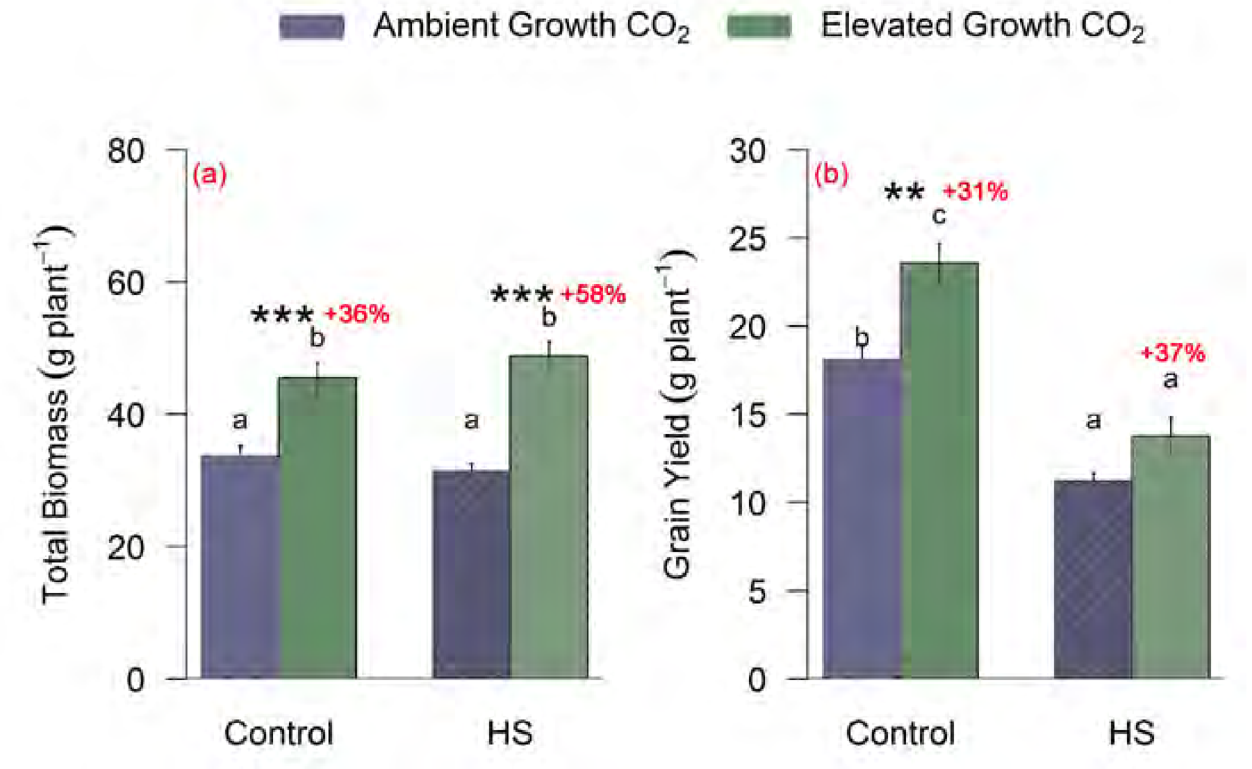


Figure III.A.4.ii.2. *Total biomass (a) and grain yield (b) of wheat plants at harvest in response to elevated CO_2 and heat stress (HS). Values represent means ± SE using two-way ANOVA. Means sharing the same letter in the individual panels are not significantly different according to Tukey's HSD test at the 5% level. Statistical significance levels (t-test) for eCO_2 effect are shown as follows: ** $P < 0.01$: *** $P < 0.001$. The percentages in red text indicate the change in biomass or grain yield due to elevated CO_2 under control or heat stress conditions.*

<u>Example 2</u>

High temperature stress can negatively impact the quantity and quality of crop yields by impairing photosynthetic activity, disrupting plasma membrane integrity, inducing oxidative stress and/or causing protein denaturation. Consequently, in light of model-based predictions of rising temperatures in response to increasing levels of atmospheric CO_2, many are concerned that global food and nutritional security will be compromised in the near future. But how likely is this scenario?

It is well-known that to cope with heat stress, plants have evolved several mechanisms to minimize high temperature-induced damage, including the activation of antioxidants to scavenge excessive reactive oxygen species and the production of heat shock proteins (HSPs) to maintain normal protein conformation and ensure plant thermotolerance. What is more, a number of studies to date have shown that these thermotolerance mechanisms are often *enhanced* under elevated CO_2 conditions, including the recent work of Pan *et al*. (2019).[160]

---

[160] Pan, C., Zhang, H., Ma, Q., Fan, F., Fu, R., Ahammed, G.J., Yu, J. and Shi, K. 2019. Role of ethylene biosynthesis and signaling in elevated CO_2-induced heat stress response in tomato. *Planta* **250**: 563-572.

Working with tomato plants (*Solanum lycopersicum* cv. Ailsa Craig) that they grew in controlled-environment chambers under either ambient (400 ppm) or elevated (800 ppm) CO_2, the eight researchers investigated the heat stress response of this key agricultural crop. At the five-leaf stage, the authors transferred the seedlings into the study chambers under the two CO_2 concentrations. Then, after two days of acclimation, they subjected half the plants to heat stress (42°C day/night temperature versus a control 25°C day/night temperature) for one day, after which time they conducted a series of tests to determine the ability of elevated CO_2 to alleviate the stress.

In discussing their findings, Pan *et al*. report that elevated CO_2 "attenuated high temperature-induced damages [in the photosynthetic apparatus and membrane integrity] as evidenced by a significant increase in the maximum photochemical efficiency of photosystem II (Fv/Fm) and a drastic decrease in relative electrical conductivity (REC)" relative to plants exposed to heat stress under ambient CO_2 conditions (see Figure III.A.4.ii.3). Furthermore, by analyzing the response of key genes known to enhance plant tolerance to heat stress (notably ethylene and heat shock proteins), the authors obtained "convincing evidence" that both ethylene and heat shock proteins were significantly induced by elevated CO_2 and helped to ameliorate heat stress.

In highlighting this key stress-alleviating thermotolerance benefit of atmospheric CO_2 enrichment, the above findings suggest that the plants of tomorrow will be better equipped to withstand high temperatures so as to help ensure greater crop yields in the years and decades ahead.

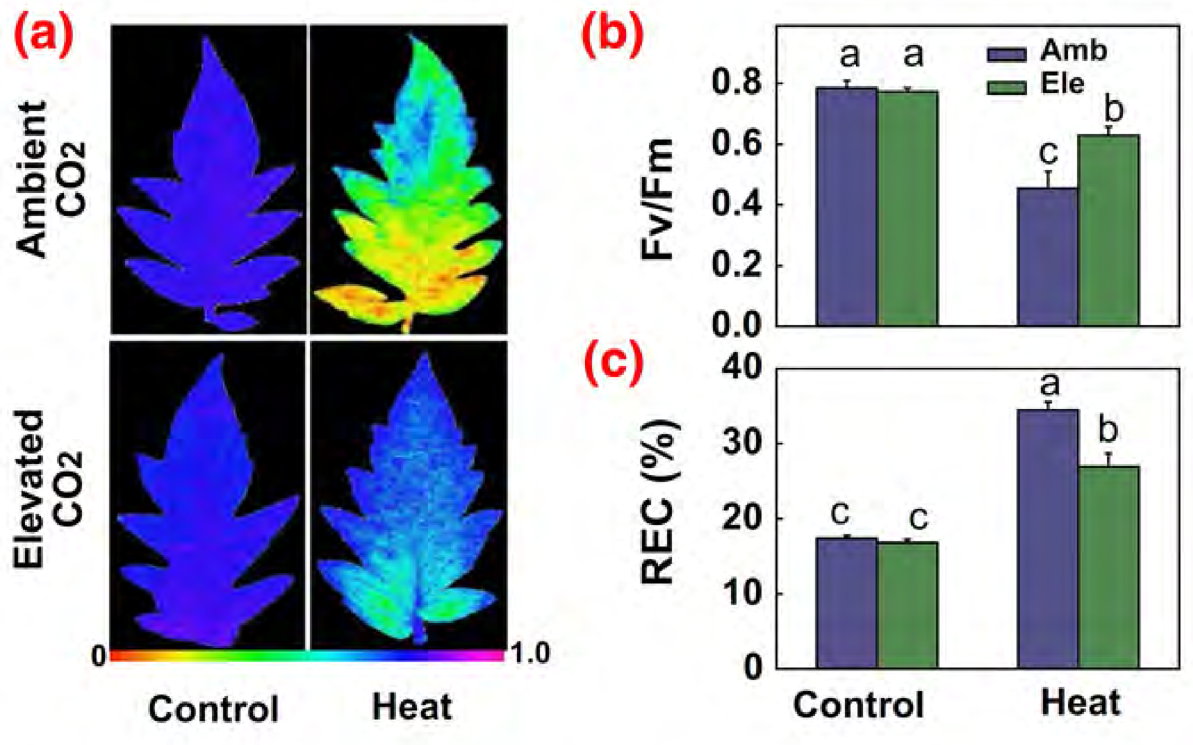


Figure III.A.4.ii.3. *Effects of elevated CO_2 on tomato plant responses to heat stress. Tomato plants were acclimated in ambient (400 ppm) or elevated (800 ppm) CO_2 conditions for 2 days before exposure to heat stress (42°C) or control temperature (25°C). Panel a displays images of maximum photochemical efficiency of photosystem II (Fv/Fm) and Panel b presents their quantitative values measured after 1 day of heat stress treatment. The color gradient scale at the bottom indicates the magnitude of the fluorescence signal represented by each color. Panel c displays the relative electrical conductivity (REC) in tomato leaves after 1 day of heat stress treatment in ambient or elevated CO_2 conditions. The results in b and c are presented as mean values and error bars indicate standard deviation (SD), in which n = 6 and 3, respectively. One-way ANOVA test followed by Tukey's post hoc test was performed, and different letters indicate significant differences between treatments ($P < 0.05$) according to Tukey's test.*

Information on additional peer-reviewed scientific studies on this topic can be accessed under the following links: ***Growth Response to CO_2 with Other Variables** (Temperature: Agricultural Crops)*, ***Growth Response to CO_2 with Other Variables** (Temperature: Grassland Species)*, ***Growth Response to CO_2 with Other Variables** (Temperature: Woody Plants)* and ***Growth Response to CO_2 with Other Variables** (Temperature: General)*.

(iii) Inadequate Lighting

Many plants experience growth-limiting conditions caused by inadequate lighting. In both managed and unmanaged ecosystems, for example, leaves further down the plant canopy are shaded by plant stems and leaves from further up the canopy, which canopy-induced shading reduces photosynthetic rates and restricts plant growth. However, elevated levels of atmospheric CO_2 help plants mitigate this limitation by stimulating photosynthetic rates to a greater extent under light-limiting than under non-light-limiting conditions. In fact, twice-ambient CO_2 concentrations have been shown to increase net photosynthesis rates in wheat by approximately 100% in upper-canopy leaves and by *several hundred percent* further down in the canopy, where light intensity often amounts to 60% less than that observed in the upper canopy.[161]

In the years and decades ahead, it is thus expected that plants will exhibit enhanced rates of photosynthesis in leaves deep within crop canopies where irradiance is severely reduced due to shading by upper-canopy leaves *because* of rising atmospheric CO_2. The greater pigment contents of CO_2-enrichment will allow plants to significantly enhance their radiation-use efficiency and maintain significantly greater rates of photosynthesis throughout their entire canopies. Hence, farmers of the future in a world of higher atmospheric CO_2 concentration should be able to remove much heftier grain harvests from their fields than they do currently.

Such CO_2-induced benefits under low light intensities are not limited to farm land. Unmanaged ecosystems will be rewarded too. Kerstiens (1998)[162] provided proof that elevated atmospheric

---

[161] Harnos, N., Tuba, Z. and Szente, K. 2002. Modelling net photosynthetic rate of winter wheat in elevated air CO_2 concentrations. *Photosynthetica* **40**: 293-300.

[162] Kerstiens, G. 1998. Shade-tolerance as a predictor of responses to elevated CO_2 in trees. *Physiologia Plantarum* **102**: 472-480.

CO_2 helps to ameliorate the stress of low light intensities in trees. By analyzing the results of 15 previously published studies of trees having differing degrees of shade tolerance, Kerstiens found that elevated CO_2 caused greater relative biomass increases in shade-tolerant species than in shade-intolerant or sun-loving species. In fact, in more than half of the studies analyzed, shade-tolerant species experienced CO_2-induced relative growth increases that were two to three times *greater* than those of less shade-tolerant species.

In an extended follow-up review analyzing 74 observations from 24 studies, Kerstiens (2001)[163] reported that twice-ambient CO_2 concentrations increased the relative growth response of shade-tolerant and shade-intolerant woody species by an average of 51 and 18%, respectively. Moreover, similar results were reported by Poorter and Perez-Soba (2001),[164] who performed a detailed meta-analysis of research results pertaining to this topic, and by Kubiske *et al*. (2002),[165] who measured photosynthetic acclimation in aspen and sugar maple trees. Low light intensity, therefore, is by no means a roadblock to the benefits that come to plants as a consequence of an increase in the air's CO_2 content.

Finally, elevated CO_2 has also been shown to help ameliorate plant stress caused by high light intensity.[166] So, whether light intensity is high or low, or leaves are shaded or sunlit, when the CO_2 content of the air is increased, so too are the various biological processes that lead to plant robustness increased. Less than optimal light intensities, therefore, clearly do *not* negate the beneficial effects of atmospheric CO_2 enrichment.

Example 1

Winter greenhouse crop cultivation is becoming increasingly popular in places like northwestern China. However, compared to the summer season, the quality and quantity of such production is often much lower due to reduced levels of light intensity experienced during the winter months. Desiring to assist farmers to optimize yields during this less productive time, Li *et al*. (2017)[167] set out to investigate the interactive effect of elevated CO_2 and supplemental light intensity on hot pepper (cv Meite). In doing so, they grew peppers from seed to maturity in plastic pots in a climate-controlled phytotron under two light intensities (normal and supplemental, the latter *doubling* the intensity of the former) and four CO_2 concentrations (400, 550, 700 and 900 ppm). And what did their experiment reveal?

Both elevated CO_2 and supplemental light improved the growth and yield of the peppers. With respect to the impact of CO_2, at elevated concentrations it increased leaf net photosynthetic rates in normal winter light by 37, 68 and 99 percent in the 550, 700 and 900 ppm treatments (relative

---

[163] Kerstiens, G. 2001. Meta-analysis of the interaction between shade-tolerance, light environment and growth response of woody species to elevated CO_2. *Acta Oecologica* **22**: 61-69.

[164] Poorter, H. and Perez-Soba, M. 2001. The growth response of plants to elevated CO_2 under non-optimal environmental conditions. *Oecologia* **129**: 1-20.

[165] Kubiske, M.E., Zak, D.R., Pregitzer, K.S. and Takeuchi, Y. 2002. Photosynthetic acclimation of overstory *Populus tremuloides* and understory *Acer saccharum* to elevated atmospheric CO_2 concentration: interactions with shade and soil nitrogen. *Tree Physiology* **22**: 321-329.

[166] Pardos, M., Puertolas, J., Aranda, I. and Pardos, J.A. 2006. Can CO_2 enrichment modify the effect of water and high light stress on biomass allocation and relative growth rate of cork oak seedlings? *Trees* **20**: 713-724.

[167] Li, X., Kang, S., Li, F., Zhang, X., Huo, Z., Ding, R., Tong, L., Du, T. and Li, S. 2017. Light supplement and carbon dioxide enrichment affect yield and quality of off-season pepper. *Agronomy Journal* **109**: 2107-2118.

to the ambient 400 ppm treatment, see Figure III.A.4.iii.1). Slightly smaller enhancements were noted in plants growing in the supplemental light treatment, where leaf net photosynthetic rates rose by 28, 44 and 72 percent (compared to ambient, see figure below) in the 550, 700 and 900 ppm CO_2 treatments, respectively.

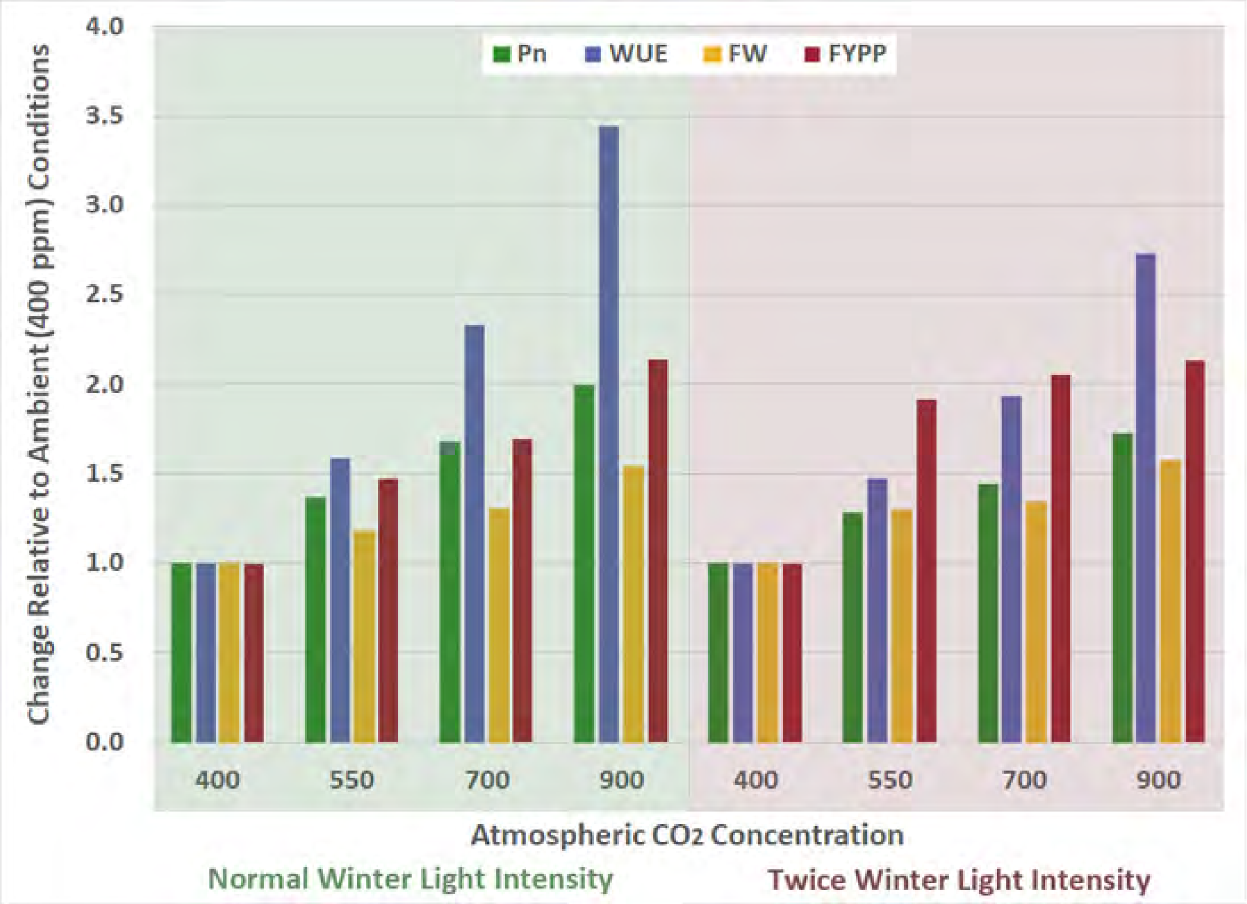


Figure III.A.4.iii.1. *Impact of elevated CO_2 on leaf net photosynthetic rate (Pn), water use efficiency (WUE), individual fruit weight (FW) and fruit yield per plant (FYPP) of hot peppers growing under normal winter light intensity and supplemental light that was twice the amount of normal winter values.*

Other benefits of CO_2 enrichment included significant increases in plant water use efficiency (from 59-244% under normal winter light and from 47-173% under supplemental light, see figure below), individual fruit weight (from 18-54% under normal winter light and from 29-57% under supplemental light, see figure below) and the total fruit yield per plant (from 47-114% under normal winter light and from 92-113% under supplemental light, see Figure III.A.4.iii.1), as was the fruit number per plant (from 58-81% under normal winter light and from 45-58% under supplemental light) and fruit volume (from 2-30% under normal winter light and from 49-51% under supplemental light).

Given these several findings, it would appear that rising atmospheric CO_2 concentrations will lead to important yield and water use efficiency increases in hot pepper, even under low light intensities.

Example 2

Enhancing crop nutritional value has long been a goal of the agricultural industry. Growing plants under less than optimal conditions for a short period of time generally increases their oxidative stress. To counter such stress, plants will usually increase their antioxidant metabolism which, in turn, elevates the presence of various antioxidant compounds in their tissues, compounds that are of great nutritional value from a human point of view.

However, stress-induced nutritional benefits often come at a price, including a reduction in plant growth and yield, making it unproductive and costly to implement these practices in the real world. But what if there was a way to harness such benefits without sacrificing crop biomass? What if there was a way for society to have its proverbial cake and eat it too? An intriguing paper published in the journal *Scientia Horticulturae* explains just how this incredible objective can be accomplished, involving lettuce, light stress, and atmospheric CO_2.

According to Pérez-López *et al*. (2015),[168] the authors of this work, "few studies have utilized light and elevated CO_2 levels in combination to enhance a crop's nutraceutical value." Thus, the team of four Spanish researchers set out to conduct just such an experiment involving two lettuce cultivars, Blonde of Paris Badavia (a green-leaf lettuce) and Oak Leaf (a red-leaf lettuce). In so doing, they grew the lettuce cultivars from seed in controlled environment chambers at either ambient (400 ppm) or enriched (700 ppm) CO_2 for a period of 35 days, after which they supplied a subset of the two treatments with either normal (400 µmol photons m^{-2} s^{-1}) or high light (700 µmol photons m^{-2} s^{-1}) conditions for 4 days to simulate high-light stress. Thereafter they conducted a series of analyses to report growth and nutritional characteristics of the cultivars under these varying growth conditions. And what did those analyses reveal?

As shown in Figure III.A.4.iii.2, high light intensity treatment had no effect upon the dry weight of red lettuce, whereas it actually *increased* the growth of the green-leaf cultivar. Additionally, Pérez-López *et al*. report that *both* cultivars experienced increased growth in the high light intensity treatment under elevated CO_2 conditions as compared with the ambient light and CO_2 treatment. Specifically, there was a 68 percent enhancement in the dry weight of Oak leaf lettuce and a 91 percent increase for Blonde of Paris Badavia.

---

[168] Pérez-López, U., Miranda-Apodaca, J., Muñoz-Rueda, A. and Mena-Petite, A. 2015. Interacting effects of high light and elevated CO_2 on the nutraceutical quality of two differently pigmented *Lactuca sativa* cultivars (Blonde of Paris Batavia and Oak Leaf). *Scientia Horticulturae* 191: 38-48.

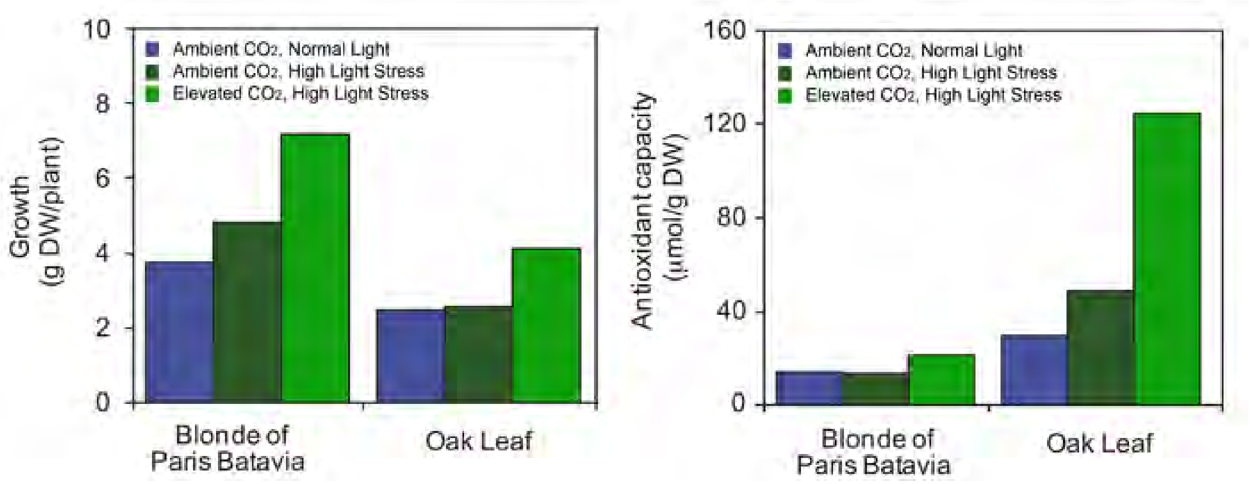


Figure III.A.4.iii.2*. Effects of high light stress (normal = 400 µmol photons m^{-2} s^{-1}, stressed = 700 µmol photons m^{-2} s^{-1}) and CO^{2} (ambient = 400 ppm, elevated = 700 ppm) on the growth (left panel) and antioxidant capacity (right panel) of Blonde of Paris Batavia green-leaf lettuce and Oak Leaf red-lettuce.*

With respect to antioxidant capacity, under ambient CO_2 conditions, high light stress increased this parameter in red lettuce by 65 percent, whereas it remained unchanged in green lettuce compared to control conditions. Under elevated CO_2 conditions, however, the antioxidant capacity was increased by 54 percent in the green lettuce cultivar and a whopping 302 percent in the red cultivar compared to control. Pérez-López *et al*. also report that "the concentrations of minerals (except Fe and Mg), glutathione and ascorbate remained constant compared with the high light and ambient CO_2 conditions, which indicated that these components and biomass accumulated at comparable rates." They also found evidence suggesting "a relief of oxidative stress" at elevated CO_2 levels. And in consideration of *all* of the above, the team of five researchers conclude that "the nutritional quality of lettuce can be improved in practice: however, the choice of the best cultivation practice depends on the cultivar of lettuce and the attributes that are targeted for improvement."

Information on additional peer-reviewed scientific studies on this topic can be accessed at http://www.co2science.org/subject/g/lightinteraction.php under the heading ***Growth Response to CO$_2$ with Other Variables*** *(Light)*.

(iv) Oxidative Stress

Tropospheric ozone (O_3) is a gaseous air pollutant that results from incomplete combustion of fossil fuels. It negatively affects plant growth, gaining entry through stomatal openings where it dismutates and generates reactive oxygen species that damage cell components and disturb metabolic processes.

In the future, the concentration of O_3 is projected to increase significantly, resulting in more frequent and severe cell damage and in extreme cases, plant death. However, the atmospheric concentration of carbon dioxide (CO_2) is also expected to rise in consequence of increased fossil fuel combustion. And because elevated CO_2 *enhances* plant growth, there has been much interest in how these two opposing forces will play out; and when this is done, CO_2 is found to be the perfect antidote for countering the negative effects of increasing levels of ozone pollution. Typically, CO_2 enrichment reduces the negative effects of ozone on carbon assimilation, leading to far less foliar injury while maintaining significantly greater leaf chlorophyll contents than control plants at ambient CO_2 concentrations.

Example 1

A team of the three Canadian researchers[169] from the Department of Horticultural Science at the University of Guelph grew wheat (*Triticum aestivum* L. cv Roblin) from seed in controlled environment chambers for five weeks at two O_3 concentrations (4 ppb for ambient and 120 ppb for elevated) and two CO_2 concentrations (390 ppm for ambient and 800 ppm for elevated). O_3 exposure was provided for 8 hours per day during the photoperiod and CO_2 concentrations were maintained constant throughout both the day and night. And what did this study reveal?

As expected, elevated CO_2 resulted in “substantial increases in the shoot biomass of plants” (approximately 36% under ambient O_3 conditions, see Figure III.A.4.iv.1), whereas elevated O_3 resulted in a significant decline (approximately 34% under ambient CO_2 conditions). Grown in combination, the shoot biomass of the wheat plants under elevated CO_2 and elevated O_3 conditions was “almost the same” as that of plants grown under high CO_2 and ambient O_3 conditions. In other words, the beneficial effects of elevated CO_2 not only fully compensated for the dry weight loss due to elevated ozone, it *completely overcame it as if this stress was never present!* And driving this point home, the authors of this study write “we did not observe an adverse impact of O_3 on the shoot biomass of wheat plants grown under high CO_2.”

---

[169] Rao, M.V., Hale, B.A. and Ormrod, D.P. 1995. Amelioration of ozone-induced oxidative damage in wheat plants grown under high carbon dioxide. *Plant Physiology* **109**: 421-432.

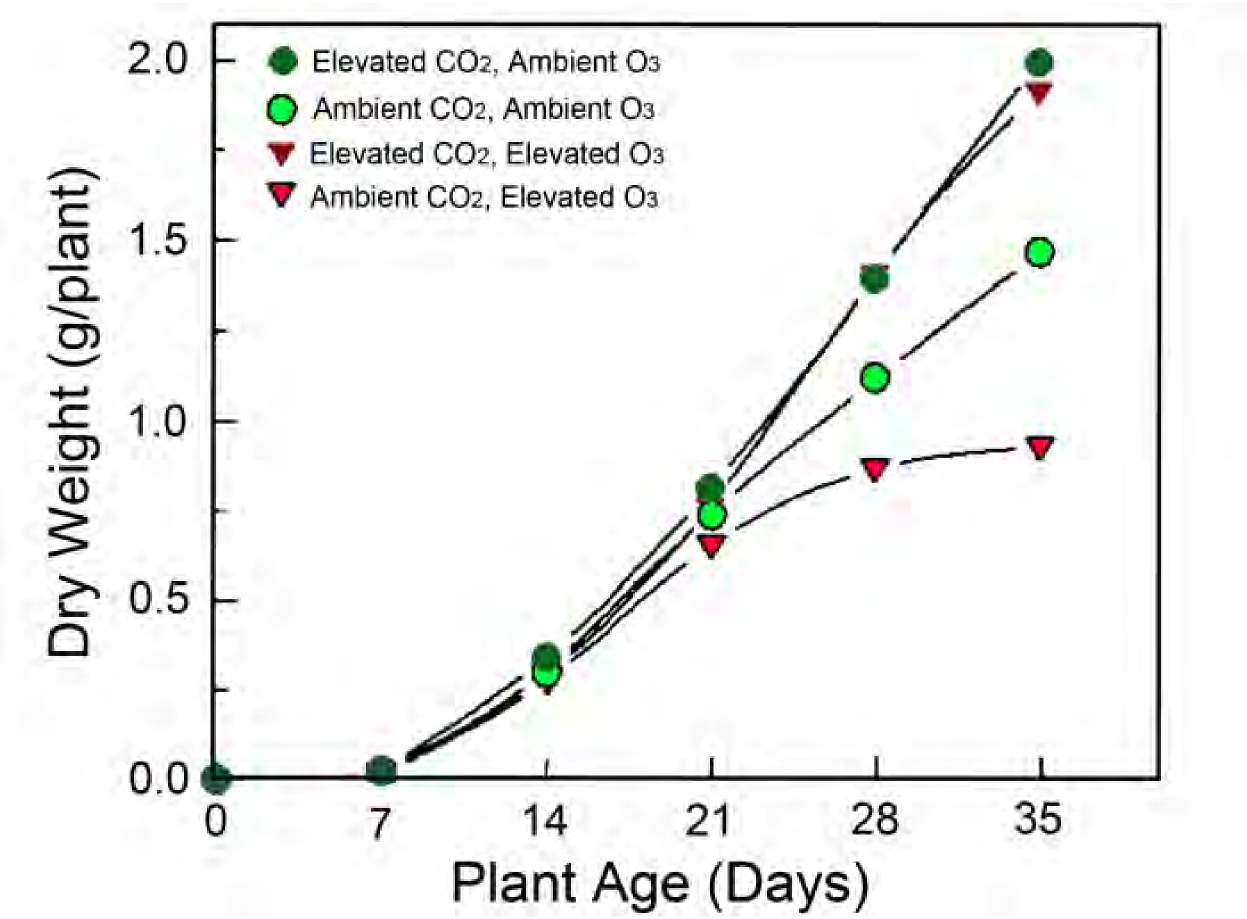


***Figure III.A.4.iv.1**. Weekly measurements of shoot dry weight of wheat (Triticum aestivum L. cv Roblin) grown under various combinations of CO_2 (390 or 800 ppm) and O_3 (4 or 120 ppb) concentrations.*

In an attempt to discern *why* such benefits were conferred, the team of researchers also investigated the impact of these two variables on various enzymes and proteins. Such examination revealed that "prolonged O_3 exposure in ambient CO_2 inactivated antioxidant enzymes, whereas the activities were maintained in plants exposed to O_3 in high CO_2." And in consequence of these findings, the scientists conclude that their study provides "evidence for the role of high CO_2 in maintaining an efficient antioxidant defense system upon receiving oxidative stress," which defense system, they note, may also operate in the presence of other environmental stresses, including heat shock, water deficit, UV radiation and pathogens.

Example 2

Japanese cedar (*Cryptomeria japonica*) is a key silviculture species in Japan, making up approximately 44 percent of the country's plantation area. Given such prominence, Hiraoka *et al*. (2017)[170] write that "in order to adapt to future environments, tree improvement programs will need to consider rising O_3 and CO_2 concentrations, as well as other changes in climate" that may

---

[170] Hiraoka, Y., Mine Nose, T.I., Tobita, H., Yazaki, K., Watanabe, A., Fujisawa, Y. and Kitao, M. 2017. Species characteristics and intraspecific variation in growth and photosynthesis of *Cryptomeria japonica* under elevated O_3 and CO_2. *Tree Physiology* **37**: 733-743.

occur. Therefore, as their contribution to this effort, the team of seven Japanese researchers investigated the individual and combined impacts of CO_2 and O_3 on the growth of Japanese cedar.

To accomplish their goal, they planted 1-year-old cuttings from twelve *C. japonica* clones in a free-air CO_2 enrichment (FACE) facility at the Forestry and Forest Products Research Institute in Tsukuba, Japan. The trees were grown for two years under one of four treatment conditions during the growing season: (1) ambient air, (2) twice-ambient O_3 (approximately +30 ppb), (3) elevated CO_2 (~550 ppm during daylight hours) and (4) twice-ambient O_3 and elevated CO_2. During the experiment, as well as at its end, the scientists made a number of measurements to discern the impacts of the different treatments on the growth of the young trees.

Results of their analysis revealed that *C. japonica* had a low sensitivity to the negative (growth-retarding) effects of O_3. In fact, as illustrated in the figure below, trees growing in the elevated O_3 environment had higher plant dry mass than their ambient counterparts, though the difference were not statistically significant. With respect to elevated CO_2, it induced a statistically significant increase in stem, shoot, root and total plant biomass (see figure below), the latter of which parameter increased by some 60 percent in response to a relatively small CO_2 stimulation of approximately 175 ppm. Tree dry mass was also improved in the combined elevated O_3 and elevated CO_2 treatment, though not quite to the extent as it was in the CO_2 treatment alone. Consequently, in light of all of the above, it is expected that Japanese cedar growth will experience enhancements in the years and decades to come as both the CO_2 and O_3 contents of the atmosphere increase. And that is *great news* for the silviculture industry in Japan.

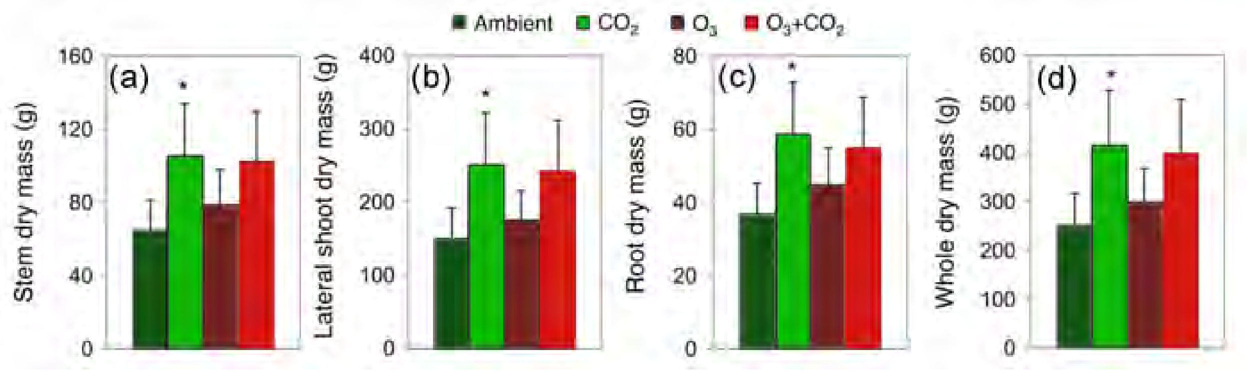


Figure III.A.4.iv.2. *Average stem (a), lateral shoot (b), root (c) and whole plant dry mass (d) of 3-yr-old Cryptomeria japonica trees at the end of a 2-year CO_2 and O_3 experiment. Shaded colors indicate the treatment regime. Asterisks indicate significant differences between ambient and other treatments by Dunnett's test; $P < 0.05$. Error bars represent the 95% confidence interval.*

Information on additional peer-reviewed scientific studies on this topic can be accessed under the following links: ***Ozone*** *(Effects on Plants: Agricultural Species, Wheat)*, ***Ozone*** *(Effects on Plants: Agricultural Species, Soybean)*, ***Ozone*** *(Effects on Plants: Agricultural Species, Other)*, ***Ozone*** *(Effects on Plants -- Tree Species: Aspen)*, ***Ozone*** *(Effects on Plants -- Tree Species:*

Beech), ***Ozone** (Effects on Plants: Tree Species: Birch)*, ***Ozone** (Effects on Plants -- Tree Species: Yellow-Poplar)*, ***Ozone** (Effects on Plants -- Tree Species: Miscellaneous)*, and ***Ozone** (Effects on Plants: General)*.

(v) UVB Stress

It has been postulated that UV-B radiation (280-320 nm) may increase in the future due to stratospheric ozone depletion. Because increased levels of UV-B radiation are known to negatively impact plant growth, development and other physiological processes, whether by inhibiting photosynthesis, degradation of protein and DNA, or increased oxidative stress, it is only natural to wonder how the ongoing rise in the air's CO_2 content might impact Earth's vegetation. And in this regard, multiple studies have shown that the ongoing rise in the air's CO_2 content is a powerful antidote for the deleterious biological impacts that might be caused by an increase in the flux of UV-B radiation at the surface of the Earth due to any further depletion of the planet's stratospheric ozone layer.

Example 1

Qaderi and Reid (2005)[171] grew well-watered and fertilized canola (*Brassica napus*) plants from seed to maturity in pots within controlled environment chambers maintained at either 370 or 740 ppm CO_2 with and without a daily dose of UV-B radiation in the amount of 4.2 kJ m^{-2}, while a number of plant parameters were measured at various times throughout the growing season.

With respect to the bottom-line result of *final seed yield*, this parameter was determined to be 0.98 g/plant in the control treatment (ambient CO_2, with UV-B). Doubling the CO_2 concentration increased yield by 25.5% to 1.23 g/plant. Alternatively, removing the UV-B radiation flux increased yield by 91.8% to 1.88 g/plant. Doing both (doubling the CO_2 concentration while simultaneously removing the UV-B flux) increased final seed yield most of all, by 175.5% to 2.7 g/plant. Viewed from a different perspective, doubling the air's CO_2 concentration in the *presence* of the UV-B radiation flux enhanced final seed yield by 25.5%, while doubling CO_2 in the *absence* of the UV-B radiation flux increased seed yield by 43.6% (see Figure III.A.v.1).

---

[171] Qaderi, M.M. and Reid, D.M. 2005. Growth and physiological responses of canola (*Brassica napus*) to UV-B and CO_2 under controlled environment conditions. *Physiologia Plantarum* **125**: 247-259.

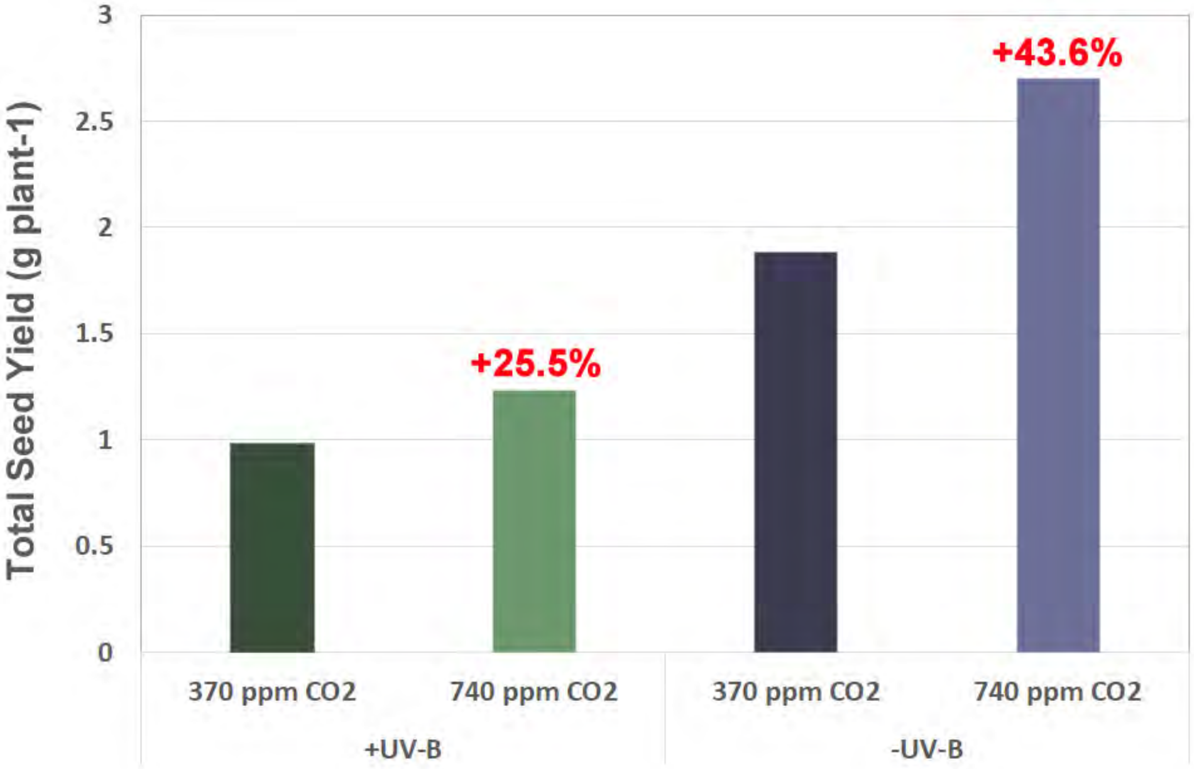


Figure III.A.4.v.1. *Total seed yield of soybean plants grown under ambient (370 ppm) or elevated (740 ppm) atmospheric* CO_2 *concentration and with (daily dose of 4.2 kJ* m^{-2}*) or without UV-B stress. The percentages in red text indicate the change in seed yield due to elevated* CO_2 *at a given UV-B treatment.*

Example 2

Brand *et al*. (2016)[172] examined the interactive effects of CO_2, UV-B radiation and low temperature on the root morphology and early seedling vigor of four cotton cultivars. The work was conducted at the Rodney Foil Plant Science Research facility located at Mississippi State University, where they grew the four cotton cultivars in controlled sunlit growth chambers for 20 days following seedling emergence. In all, eight treatments were utilized to examine the interactive growth effects, including two CO_2 concentrations (400 or 750 ppm), two temperatures (28/20°C or 21/12°C) and two UV-B levels (0 or 10 kJ m^{-2} d^{-1} between 0800 and 1600 hours each day). The control treatment was set at 400 ppm CO_2, 28/20°C day/night temperature (which was the *higher* of the two temperature treatments) and 0 kJ m^{-2} d^{-1} UV-B.

In describing their findings, Brand *et al*. report that the "vegetative growth of all cotton cultivars including root morphology traits was negatively influenced by low temperature and increased UV-B treatment, but it was positively influenced by elevated CO_2," which elevation "increased the total biomass production significantly in all four cotton cultivars tested." Elevated CO_2 also

---

[172] Brand, D., Wijewardana, C., Gao, W. and Reddy, K.R. 2016. Interactive effects of carbon dioxide, low temperature, and ultraviolet-B radiation on cotton seedling root and shoot morphology and growth. *Frontiers in Earth Science* **10**: 607-620.

"stimulated root growth," producing longer, thicker and highly branched roots, while low temperature and elevated UV-B "either individually or in combination, suppressed most root traits" (see Figure III.A.4.v.2). Consequently, it is likely that cotton plants will benefit from rising atmospheric CO_2 concentrations, and those benefits will help to reduce the deleterious impacts of growth-related stresses caused by low temperature and elevated UV-B radiation.

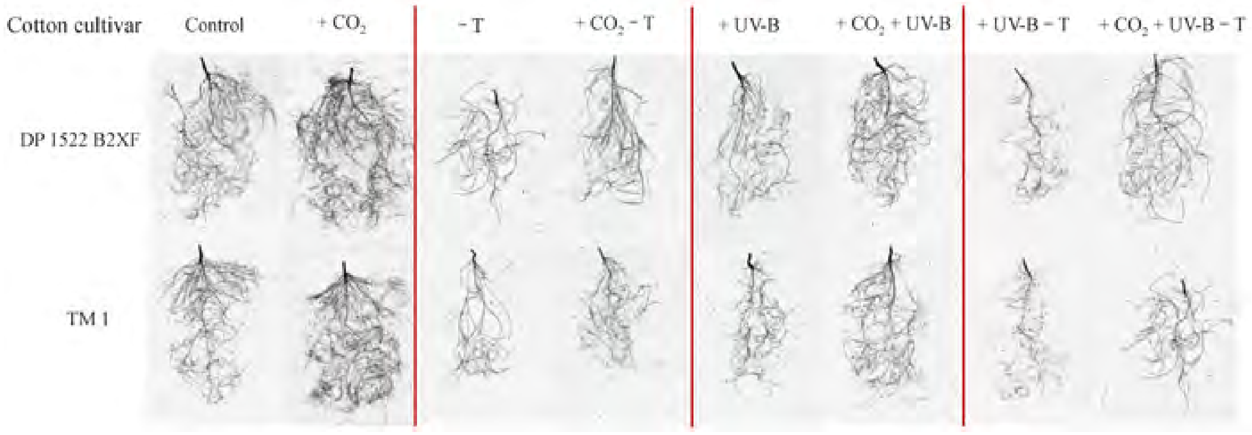


Figure III.A.4.v.2. *Representative scanned root images from single and combined stress treatments for two cotton cultivars (DP1522B2XF and TM-1) harvested at 20 d after planting. Treatment legend: +CO_2 = elevated CO_2, -T = low temperature, +UV-B = elevated UV-B.*

Information on additional peer-reviewed scientific studies on this topic can be accessed at http://www.co2science.org/subject/u/uvbradiation.php under the heading ***UV-B Radiation*** *(Terrestrial Ecosystems)*.

(vi) Pathogen Attack

Plant pathogens have long been a thorn in the side of the agricultural industry, reducing crop production between 10-16 percent annually and costing an estimated $220 billion in economic losses.[173] Most such viruses are transmitted via insects, who feed on infected plants and then pass viruses on to uninfected ones. As the air's CO_2 content continues to rise, nearly all of Earth's plants should continue to exhibit increasing rates of photosynthesis and, as a result, increased biomass production. But what about plants that are suffering from various pathogenic diseases? Will they be able to reap the benefits of the many positive effects of atmospheric CO_2 enrichment?

---

[173] Chakraborty, S. and Newton, A.C. 2011. Climate change, plant diseases and food security: an overview. *Plant Pathology* **60**: 2-14.

According to Chakraborty and Datta (2003),[174] there are a number of CO_2-induced changes in plant physiology, anatomy and morphology that have been implicated in increased plant resistance to disease that "can potentially enhance host resistance at elevated CO_2," among which phenomena they list "increased net photosynthesis allowing mobilization of resources into host resistance;[175] reduced stomatal density and conductance;[176] greater accumulation of carbohydrates in leaves; more waxes, extra layers of epidermal cells and increased fiber content;[177] production of papillae and accumulation of silicon at penetration sites;[178] greater number of mesophyll cells;[179] and increased biosynthesis of phenolics,[180] among others."

In a plant disease CO_2-enrichment study conducted on paper birch and sugar maple saplings, Parsons *et al*. (2003)[181] concluded that "the higher condensed tannin concentrations that were present in the birch fine roots may [have offered] these tissues greater protection against soil-borne pathogens and herbivores." In another intriguing study, Gamper *et al*. (2004)[182] begin by noting that *arbuscular mycorrhizal fungi* (AMF) are expected to modulate plant responses to elevated CO_2 by "increasing resistance/tolerance of plants against an array of environmental stressors (Smith and Read, 1997)[183]." In investigating this subject in a set of experiments conducted over a seven-year period of free-air CO_2-enrichment on two of the world's most extensively grown cool-season forage crops (*Lolium perenne* and *Trifolium repens*), they determined that "at elevated CO_2 and under [two] N treatments, AMF root colonization of both host plant species was increased," and that "colonization levels of all three measured intraradical AMF structures (hyphae, arbuscules and vesicles) tended to be higher." Hence, they concluded that these CO_2-induced benefits may lead to "increased protection against pathogens and/or herbivores."

Whatever the mechanism for increasing plant resistance to pathogen attack, several studies have provided proof that plants often gain the advantage as the air's CO_2 content rises. Two examples of such are provide below, followed by links to many more studies offering similar results.

---

[174] Chakraborty, S. and Datta, S. 2003. How will plant pathogens adapt to host plant resistance at elevated CO_2 under a changing climate? *New Phytologist* **159**: 733-742.

[175] Hibberd, J.M., Whitbread, R. and Farrar, J.F. 1996. Effect of elevated concentrations of CO_2 on infection of barley by *Erysiphe graminis*. *Physiological and Molecular Plant Pathology* **48**: 37-53.

[176] Hibberd, J.M., Whitbread, R. and Farrar, J.F. 1996b. Effect of 700 µmol per mol CO_2 and infection of powdery mildew on the growth and partitioning of barley. *New Phytologist* **134**: 309-345.

[177] Owensby, C.E. 1994. Climate change and grasslands: ecosystem-level responses to elevated carbon dioxide. *Proceedings of the XVII International Grassland Congress*. Palmerston North, New Zealand: New Zealand Grassland Association, pp. 1119-1124.

[178] Hibberd, J.M., Whitbread, R. and Farrar, J.F. 1996a. Effect of elevated concentrations of CO_2 on infection of barley by *Erysiphe graminis*. *Physiological and Molecular Plant Pathology* **48**: 37-53.

[179] Bowes, G. 1993. Facing the inevitable: Plants and increasing atmospheric CO_2. *Annual Review of Plant Physiology and Plant Molecular Biology* **44**: 309-332.

[180] Hartley, S.E., Jones, C.G. and Couper, G.C. 2000. Biosynthesis of plant phenolic compounds in elevated atmospheric CO_2. *Global Change Biology* **6**: 497-506.

[181] Parsons, W.F.J., Kopper, B.J. and Lindroth, R.L. 2003. Altered growth and fine root chemistry of *Betula papyrifera* and *Acer saccharum* under elevated CO_2. *Canadian Journal of Forest Research* **33**: 842-846.

[182] Gamper, H., Peter, M., Jansa, J., Luscher, A., Hartwig, U.A. and Leuchtmann, A. 2004. Arbuscular mycorrhizal fungi benefit from 7 years of free air CO_2 enrichment in well-fertilized grass and legume monocultures. *Global Change Biology* **10**: 189-199.

[183] Smith, S.E. and Read, D.J. 1997. *Mycorrhizal Symbioses*. Academic Press, London, UK.

Example 1

Writing as background for their work, Souza Araújo *et al*. (2019)[184] say that powdery mildew, commonly caused by the fungus *Podosphaera xanthiii*, is one of the main diseases impacting the melon crop in Brazil. Each year it is responsible for causing great economic damage via production losses. Given projections of possible future changes in temperature and CO_2, Souza Araújo *et al*. set out to investigate how those changes might impact the severity of powdery mildew disease on eight melon cultivars commonly grown in Brazil.

To accomplish this objective, the three Brazilian researchers grew the cultivars (Araguaia, Awton, Eldorado, Gladial, Gold, Hibix, Juazeiro, Natal and Sancho) in environment-controlled growth chambers under ambient (410 ppm) or elevated (770 ppm) CO_2 and ambient or elevated (ambient +4°C) temperatures. The melon seedlings were inoculated with powdery mildew in a full-factorial design with the temperature and CO_2 treatments and the severity of the disease was examined nine days after inoculation. And what did the experiment reveal?

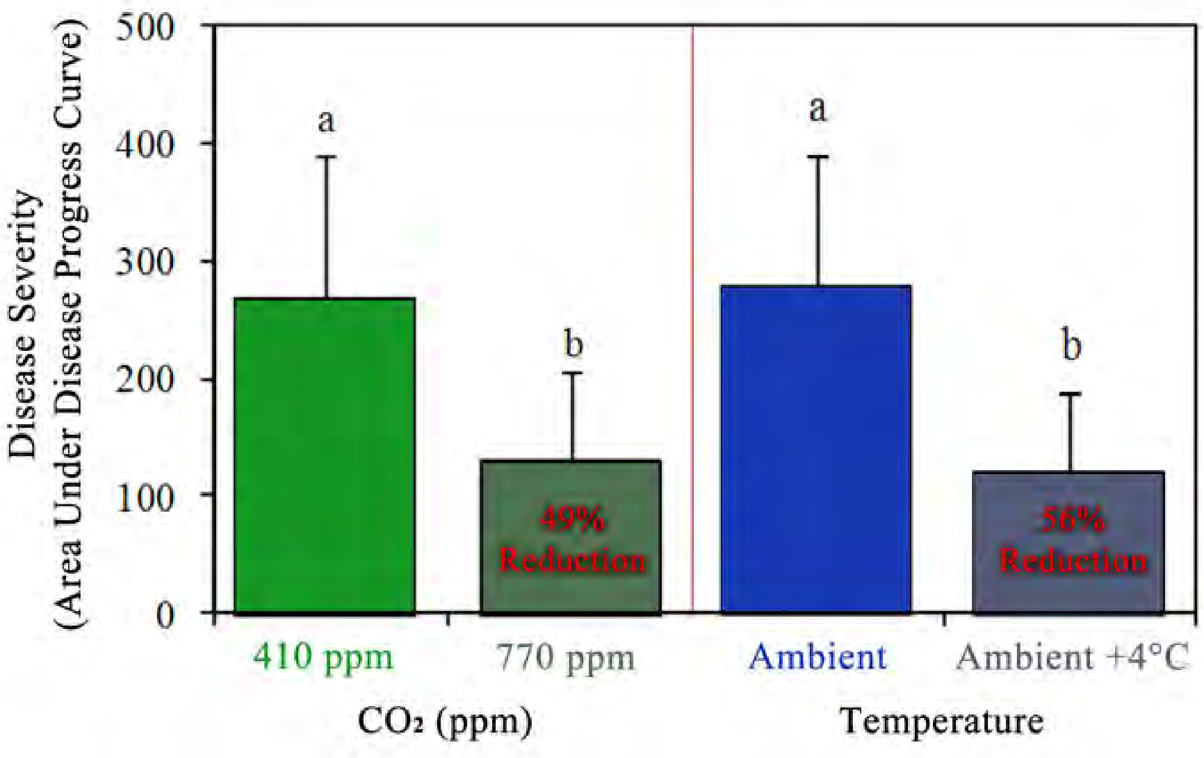


Figure III.A.4.vi.1. *Severity of powdery mildew in melon seedlings (pooled for 8 different cultivars) at different CO_2 concentrations (left panel) and temperatures (right panel). The red text indicates the reduction in disease severity relative to ambient conditions at elevated CO_2 and elevated temperature conditions.*

---

[184] Souza Araújo, A., Angelotti, F. and Ribeiro Junior, P.M. 2019. Severity of melon powdery mildew as a function of increasing temperature and carbon dioxide concentration. *Revista Brasileira de Coemcoas Agrárias* **14**: e6916, 2019, doi: 10.5039/agrarian.v14i4a6916.

As shown in Figure III.A.4.vi.1 (above), with the data pooled for all cultivars both elevated CO_2 alone and elevated temperature alone reduced disease severity. Specifically, relative to ambient conditions, disease severity was reduced by 49% under elevated CO_2 and by 56% under elevated temperature.

Figure III.A.4.vi.2 displays the results of each melon cultivar under the various treatment conditions, where it is seen that the effects of elevated CO_2 and elevated temperature, in combination, were *additive*; disease severity declined in the eight cultivars from 62% to 89% compared to ambient CO_2 and ambient temperature conditions.

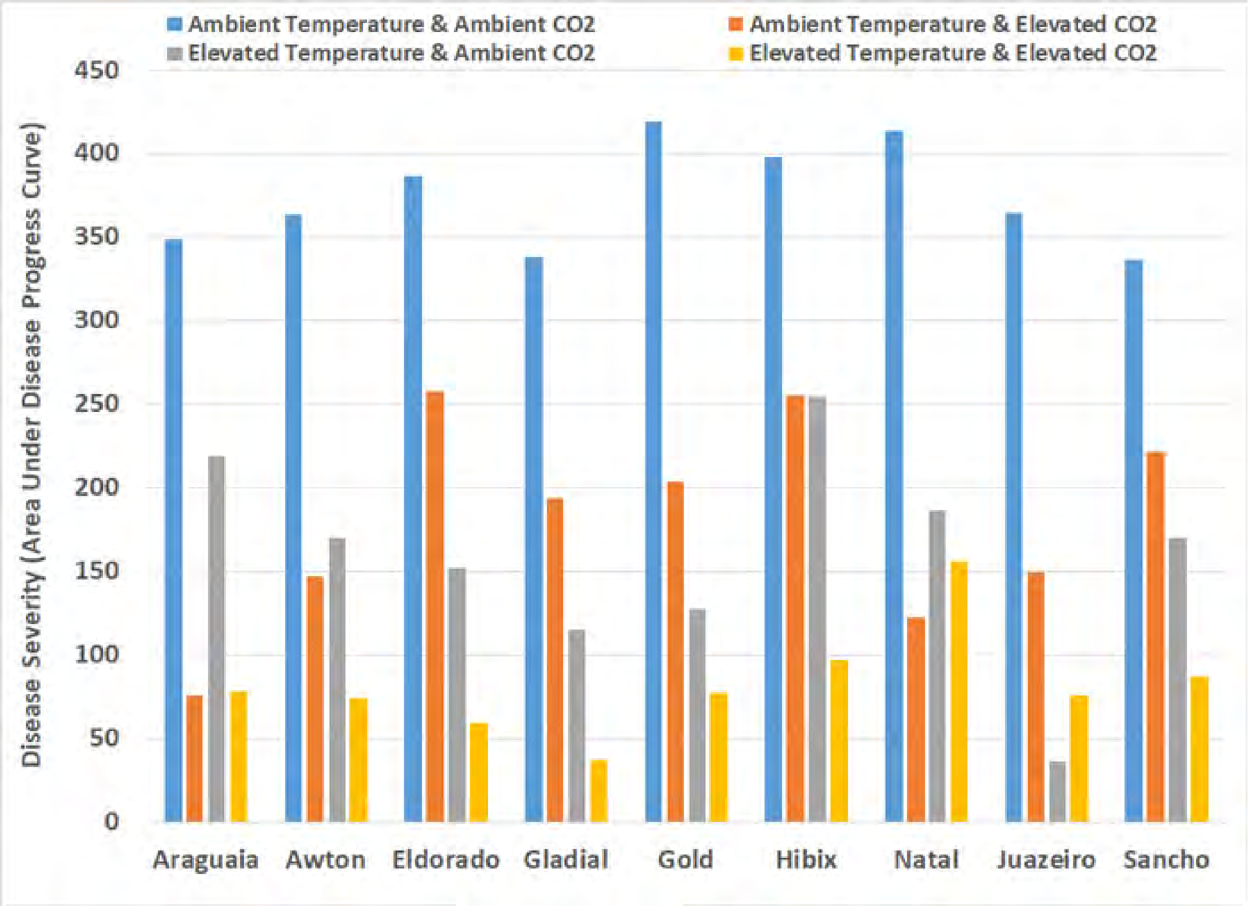


Figure III.A.4.vi.2. *Interactive effects of temperature and CO_2 on powdery mildew disease severity of eight melon cultivars.*

Clearly, therefore, in light of the findings presented above, a warmer environment that is enriched with atmospheric CO_2 will be a healthier environment for melon production. And that is great news for farmers who are losing large quantities of this favored crop to powdery mildew disease across Brazil and elsewhere!

Example 2

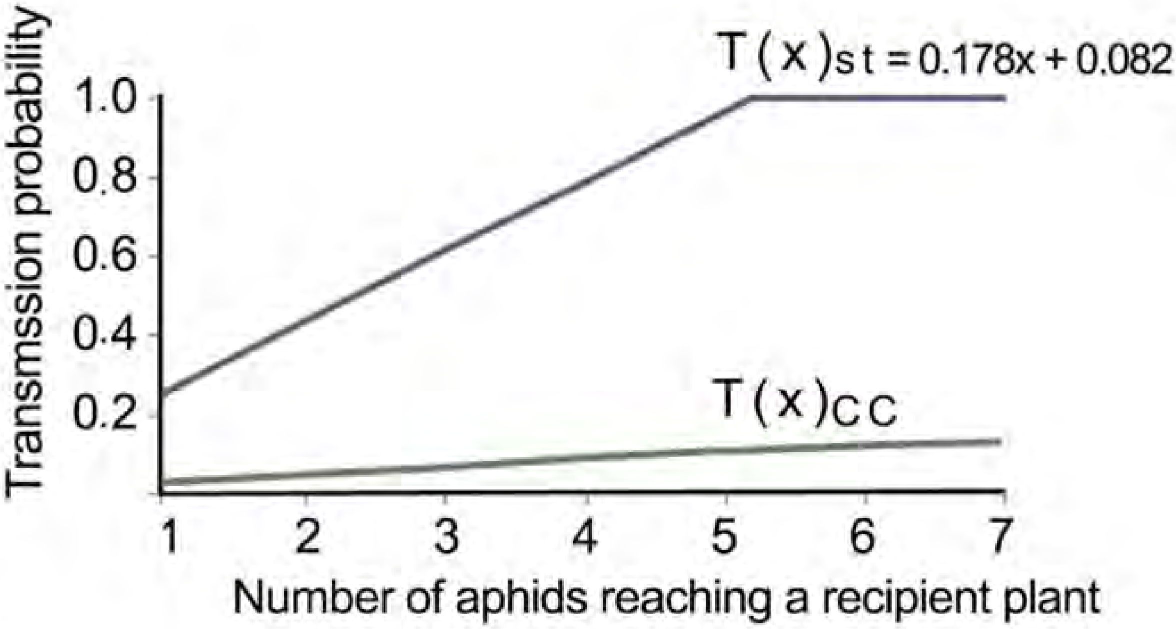
Del Toro *et al*. (2019)[185] examined the probability of transmission of potato virus Y by the peach aphid (*Myzus persicae*) to *Nicotiana benthamiana* plants subjected to either (1) *present-day* temperatures (25°C) and atmospheric CO_2 levels (405 ppm), referred to as the standard treatment (ST) or (2) *future-projected* temperatures (30°C) and CO_2 levels (970 ppm), referred to as the climate change (CC) treatment.

Results indicated that when the experimental environment included 3 virus-infected aphids, transmission frequencies were *88% lower* in the CC treatment (6.3% transmission rate) compared to the ST treatment (52.5% transmission rate). Similar findings were observed using fewer (1 or 2) or more (4) aphids per recipient plantlet, where virus transmission rates in the ST treatment were always significantly higher than those in the CC treatment. But this was not all the authors reported.

Using the data obtained in the first stage of their experiment as described above, del Toro *et al*. next sought to "calculate transmission probabilities from either ST or CC donor [infected] leaves for different numbers of aphids probing on [uninfected] recipient plantlets." The resultant probabilities are shown in Figure III.A.4.vi.3 below. As revealed there, the probability of a single aphid transmitting the virus after feeding on an infected plant in the ST treatment is 26% (0.260), whereas in the CC treatment it is a much lower 2.9% (0.029). These probabilities rise as more aphids are introduced into the equation such that when there are five aphids having the potato virus Y probing on a plant, the probability of virus transmission to the uninfected plant reaches 100% in the ST treatment. However, in the CC treatment, 100% infection probability is not reached until the number of infected aphid events on a given plant reaches a whopping 34, a value far off the graph!

---

[185] del Toro, F.J., Choi, K.S., Rakhshandehroo, F., Aguilar, E., Tenllado, F. and Canto, T. 2019. Ambient conditions of elevated temperature and CO_2 levels are detrimental to the probabilities of transmission by insects of a *Potato Virus Y* isolate and to its stimulated prevalence in the environment. *Virology* **530**: 1-10.

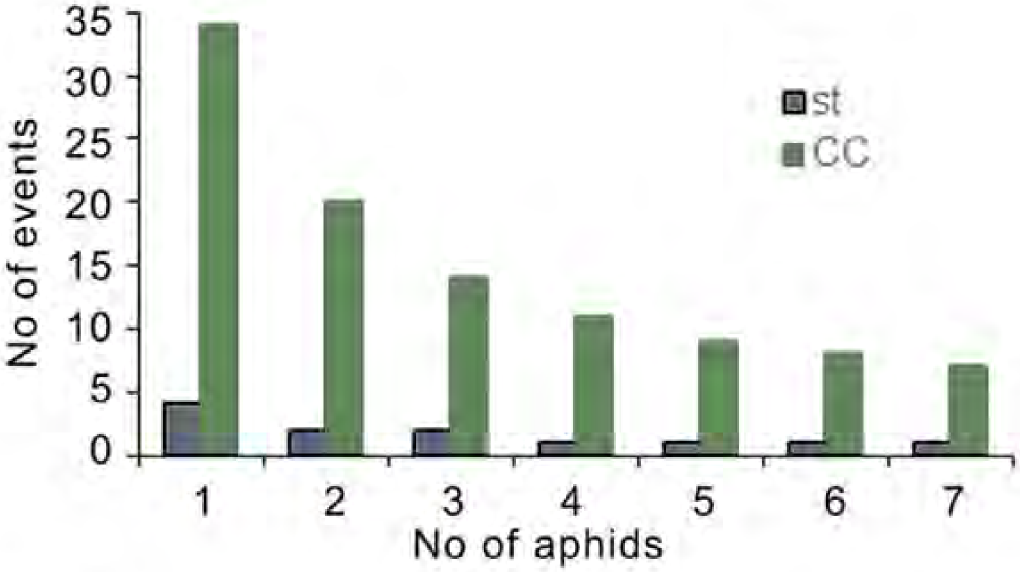


Number of aphids	1	2	3	4	5	6	7
ST condition	0.260	0.438	0.616	0.794	0.972	1.000	1.000
CC condition	0.029	0.050	0.070	0.090	0.110	0.130	0.150

$$T(x)_{CC} = T(x)_{st} * 0.1132$$

***Figure III.A.4.vi.3**. The observed proportion of non-persistent transmission of viral infection by a given number (x) of aphids that fed on donor leaves from Nicotiana benthamiana plants infected by a potato virus Y isolate kept under ST or CC conditions, relative to the number of aphids that reached and probed on each recipient plantlet.*

Figure III.A.4.vi.4 presents a graph of the average number of first-time probings by aphids on recipient plants after having fed on leaves of infected plants in the two temperature and CO_2 treatments that are required to contaminate the uninfected plant, relative to the number of aphids that reach each recipient plant. Using the data presented in this figure, del Toro *et al*. determined that in the ST treatment a visitation rate of 1.10 aphids per plant in a week was “sufficient to maintain potato virus Y in a simulated environment,” whereas a visit of 4 aphids per plant per week was enough to ensure maximum transmission/plant infection. In contrast, the researchers determined that “the virus disappeared from the environment when less than 10 aphids (9.881) visited each plant in a week” in the CC treatment, and they note that “only with values equal to or greater than 10 visiting aphids/plant/week infection became endemic, although with percentages of infection much lower than under ST conditions.”



Event: No. of aphids arriving at a plant	1	2	3	4	5	6	7
No. of events to infect a plant:							
ST conditions	4	2	2	1	1	1	1
CC conditions	34	20	14	11	9	8	7

Figure III.A.4.vi.4. *The average number of events (first-time probings by aphids on recipient plantlets after having fed from leaves of infected plants kept under ST or under CC conditions) required to infect a Nicotiana benthamiana plantlet relative to the number of aphids that reach each recipient plantlet.*

Thus, given the above calculations and findings, the authors conclude that "conditions of elevated ambient temperature and CO_2 levels decreased probabilities of transmission of viral infection by aphids," which suggests that "extended warm episodes and permanent elevated levels of CO_2 associated [with] climate change could challenge the prevalence of infections by some populations of non-persistently transmitted potyviruses." And that is wonderful news for plants routinely subjected to such.

Information on additional peer-reviewed scientific studies on this topic can be accessed under the following links: ***Pathogens** (Agriculture: Legumes)*, ***Pathogens** (Agriculture: Other)*, and ***Pathogens** (Trees)*.

(vii) Heavy Metal Contamination

Soil contamination by heavy metals is a significant issue in many parts of the world, where millions of ha of land are presently contaminated.[186] Such contamination significantly impairs plant growth by reducing photosynthesis and altering soil biogeochemical processes. Some plants, however, are more tolerant than others in coping with metal toxicity and are thus frequently utilized for their *phytoremediation* potential to clean up contaminated soils. Fortunately, CO_2 fertilization helps ameliorate the stress of heavy metal toxicity.

Example 1
Writing as background for their study, Zhang *et al*. (2015)[187] state that lead (Pb) is one of the most toxic heavy metal contaminants in soils, causing "a wide range of adverse effects on plant growth and physiology." Yet, in contrast, they note that elevated CO_2 has been shown to alleviate its detrimental effects by "increasing antioxidant enzyme activity and photosynthesis, which increases biomass accumulation," citing the works of Wu *et al*. (2009),[188] Jia *et al*. (2010)[189] and Ju *et al*. (2011).[190] Against this backdrop, Zhang *et al*. set out to examine how elevated CO_2 might impact the growth characteristics and phytoremediation abilities of *Phragmites australis*, a plant known for its natural ability to mitigate Pb contamination, particularly in polluted wetland soils. In doing so, the team of ten Chinese researchers grew two-month-old *P. australis* seedlings under five Pb concentrations (0, 500, 1000, 1500 and 3000 mg kg-1) and two CO_2 levels (380 or 760 ppm) for a period of 50 days in a controlled laboratory environment, after which they performed a series of measurements to determine the interactive effects of these two conditions.

Based upon an analysis of those measurements, Zhang *et al*. found that elevated CO_2 enhanced net photosynthesis (See Figure III.A.4.vii.1, panel a, below), which resulted in an increase in overall plant biomass across all Pb treatment levels (Figure III.A.4.vii.1, panel b). In addition, they report elevated CO_2 improved plant water use efficiency (Figure III.A.4.vii.1, panel c), "triggered a vast amount of Pb accumulation in the root systems" (Figure III.A.4.vii.1, panel d) and stimulated a remarkable increase in the number of buds and daughter shoots per plant, the latter of which two increases led to an overall enhancement in "the clonal propagative ability of *P. australis* growing in Pb contaminated soils." In light of such findings, the authors rightly

---

[186] Huang, Y.Z., Hu, Y. and Liu, Y.X. 2009. Combined toxicity of copper and cadmium to six rice genotypes (*Oryza sativa* L.). *Journal of Environmental Sciences* **21**: 647-653.

[187] Zhang, N., Lin, J., Yang, Y., Li, Z., Wang, Y., Cheng, L., Shi, Y., Zhang, Y., Wang, J. and Mu, C. 2015. The tolerance of growth and clonal propagation of *Phragmites australis* (common reeds) subjected to lead contamination under elevated CO_2 conditions. *RCS Advances* **5**: 55,527-55,535.

[188] Wu, H.B., Tang, S.R., Zhang, X.M., Guo, J.K., Song, Z.G., Tian, S. and Smith, D.L. 2009. Using elevated CO_2 to increase the biomass of a *Sorghum vulgare × Sorghum vulgare var. sudanense* hybrid and *Trifolium pratense L.* and to trigger hyperaccumulation of cesium. *Journal of Hazardous Materials* **170**: 861-870.

[189] Jia, Y., Tang, S., Wang, R.G., Ju, X.H., Ding, Y.Z., Tu, S.X. and Smith, D.L. 2010. Effects of elevated CO_2 on growth, photosynthesis, elemental composition, antioxidant level, and phytochelatin concentration in *Lolium mutiforum* and *Lolium perenne* under Cd stress. *Journal of Hazardous Materials* **180**: 384-394.

[190] Ju, X.H., Tang, S., Jia, Y., Guo, J.K., Ding, Y.Z., Song, Z.G. and Zhao, Y.J. 2011. Determination and characterization of cysteine, glutathione and phytochelatins (PC^{2-6}) in *Lolium perenne L*. exposed to Cd stress under ambient and elevated carbon dioxide using HPLC with fluorescence detection. *Journal of Chromatography B* **879**: 1717-1724.

conclude that "elevated CO_2 could ameliorate Pb toxicity and improve resistance capacity of *P. australis* to Pb contamination."

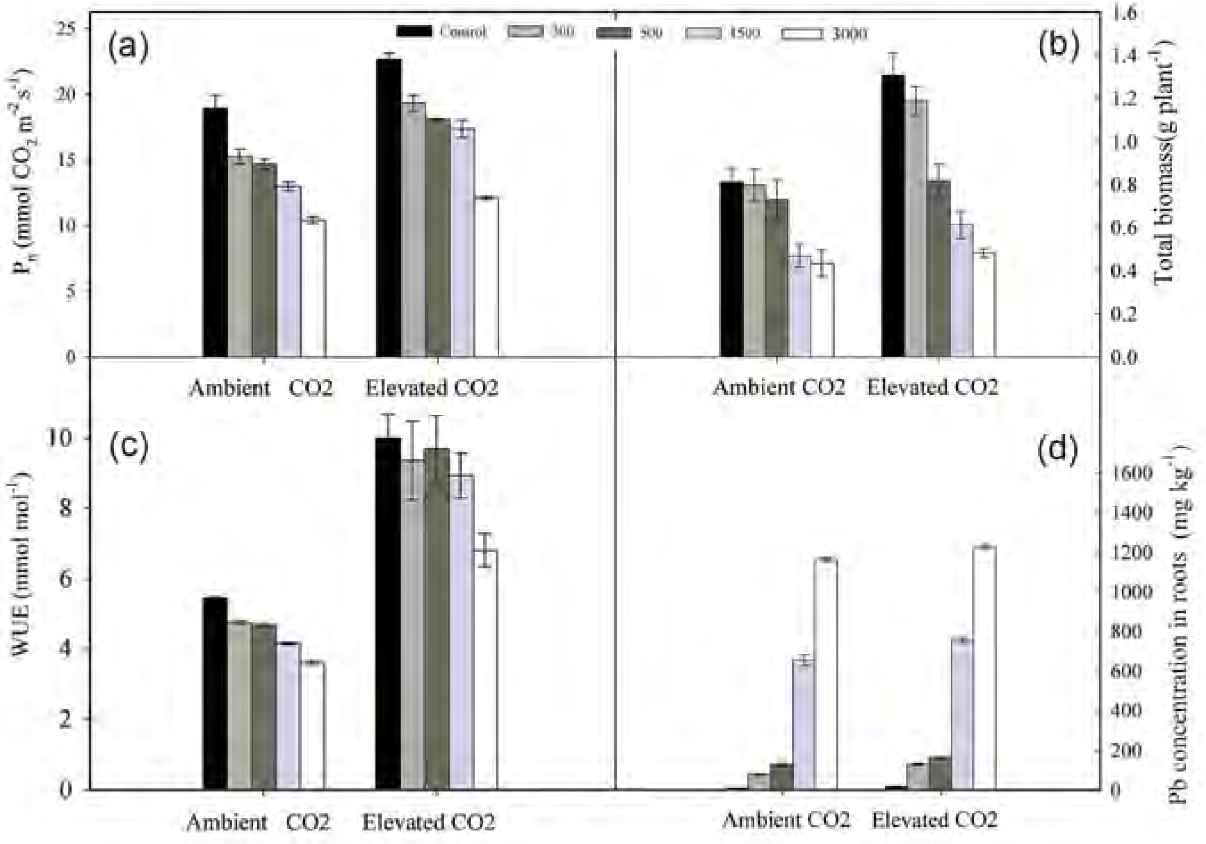


***Figure III.A.4.vii.1**. Effects of elevated CO_2 (ambient = 380 ppm, elevated = 760 ppm) and Pb contamination (in mg kg^{-1} as indicated in the legend at the top of the figure) on (a) net photosynthetic rate, (b) total biomass, (c) water use efficiency, and (d) total Pb concentration of Phragmites australis.*

<u>Example 2</u>

Setting the stage for their study, Zhu *et al*. (2017)[191] note that aluminum (Al) is the most abundant metal on Earth. When present in significant quantities in the soil, it can be detrimental to plant growth, disrupting physiological and molecular properties. In many instances, aluminum toxicity inhibits root elongation, even at very low concentrations, making it difficult for plants to acquire nutrients, thus leading to a reduction in both the magnitude and quality of their growth.

To date, there has been surprisingly little research conducted on the response of plants to aluminum stress under elevated atmospheric CO_2 conditions. Therefore, Zhu *et al*. set out to

---

[191] Zhu, X.F., Zhao, X.S., Wang, B., Wu, Q. and Shen, R.F. 2017. Elevated carbon dioxide alleviates aluminum toxicity by decreasing cell wall hemicellulose in rice (*Oryza sativa*). *Frontiers in Physiology* **8**: 512, doi: 10.3389/fphys.2017.00512.

investigate the interactive effects of elevated CO_2 and aluminum toxicity on one of the most important global food crops—rice (*Oryza sativa*).

Working with two subspecies cultivars (ssp. *indica*, cv Kasalath and ssp. *japonica*, cv Nipponbare), the five Chinese scientists subjected 3-day-old seedlings to 24-hour treatments of one of two CO_2 concentrations (400 or 600 ppm) and one of two aluminum solutions (no added aluminum or 50 µM aluminum added) in a controlled environment chamber, measuring a number of physiological and molecular parameters before and after the treatments to discern the impacts of these two growth-competing variables. And what did their experiment reveal?

As shown in the left and center panels of Figure III.A.4.vii.2 below, acting alone, aluminum toxicity inhibited root growth in both cultivars, relative to control conditions, by 69 percent in Kasalath and 52 percent in Nipponbare. Elevated CO_2, in contrast, stimulated root growth in Kasalath, but had no impact on Nipponbare. In the combined treatment, elevated CO_2 ameliorated the negative impacts of aluminum toxicity on root growth, causing a smaller 49 and 32 percent reduction in root growth relative to control in the Kasalath and Nipponbare cultivars, respectively.

Searching for the potential mechanism responsible for the reduction in aluminum toxicity by elevated CO_2, Zhu *et al*.'s additional analyses revealed that "elevated CO_2 significantly reduced aluminum retention in the [root] cell wall (see Figure III.A.4.vii.2, panel c), which in turn increased aluminum resistance in rice, indicating the operation of the cell-wall-based aluminum exclusion mechanism." And, therefore, the authors conclude that "elevated CO_2 can alleviate aluminum toxicity in rice," which is an important phenomenon for them to have observed.

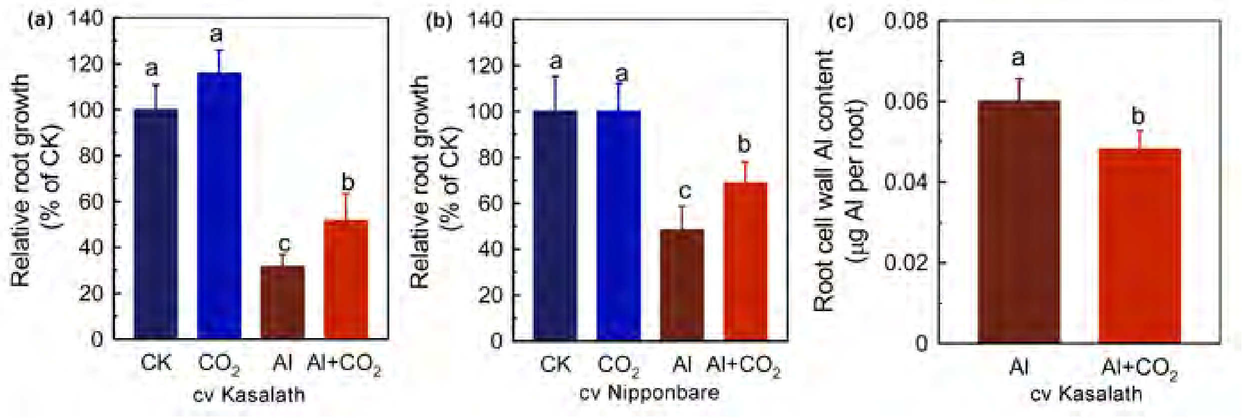


Figure III.A.4.vii.2. *Effects of elevated* CO_2 *on the relative root growth of cultivars Kasalath (Panel A) and Nipponbare (Panel B) on three-day-old rice seedlings that were treated with 0.5 mM* $CaCl_2$ *solution with or without 50 µM Al under ambient (400 ppm; CK) or elevated (600 ppm;* CO_2*)* CO_2 *for 24 h (pH 4.5). Root length was measured before and after treatment. Panel C shows the effects of elevated* CO_2 *treatment on root cell wall Al accumulation in Kasalath under the same treatment conditions. Columns with different letters are significantly different at* $P < 0.05$.

Information on additional peer-reviewed scientific studies on this topic can be accessed at http://www.co2science.org/subject/h/heavymetaltoxicity.php under the heading ***Heavy Metal Toxicity***.

(viii) Herbivory

There exists a significant body of research demonstrating that rising atmospheric CO_2 helps plants better cope with, and respond to, herbivore threats.[192] Given that herbivore attacks are responsible for millions of hectares of agricultural losses annually, future increases in CO_2 will likely reduce the percentage of such losses.

Example 1

Climate alarmists are quick to claim that the increased growth and biomass of plants due to CO_2 enrichment will be met with even greater plant loss due to increased insect consumption, hypothesizing that insects will consume more plant tissue in order to obtain sufficient nitrogen in response to the sometimes-observed decline in plant tissue nitrogen concentration under elevated CO_2. But is this claim correct?

Xu *et al*. (2019)[193] provide an answer with respect to maize and the Asian corn borer (*Ostrinia furnacalis*), which insect pest is responsible to 10-30% yield losses annually throughout China. In doing so, the five Chinese scientists conducted an experiment to investigate combined the effects of elevated CO_2 and increased nitrogen (N) fertilization on maize-*O. furnacalis* interactions. The experiment was performed in controlled-environment chambers; the CO_2 treatment included ambient (380 ppm) or elevated (750 ppm) and the N treatment included low (100 mg N/kg soil mixture), medium (200 mg N/kg soil mixture) or high (300 mg N/kg soil mixture).

Results of the study indicated the following: (1) "both elevated CO_2 and increased N fertilization increased starch content, while increased N fertilization promoted the N content in maize," (2) the combined effects of elevated CO_2 and N fertilization "did not influence the total non-structural carbohydrates:N ratio in maize," (3) the total phenolics content and defensive enzyme activities of maize increased under elevated CO_2, increased N fertilization and *O. furnacalis* infestation." Additionally, the authors report that "relative to ambient CO_2, elevated CO_2 extended the duration of the [4] larval and [5] pupal stage by 3.99 and 7.13%, respectively; [6] reduced larval body mass by 5.64%; and decreased [7] mean relative growth rate, [8] efficiency of conversion of ingested food and [9] efficiency of conversion of digested diet by 4.15, 18.89 and 19.23%, respectively."

Consequently, the results of this study demonstrate that the resistance-related secondary metabolites in maize were *enhanced* by elevated CO_2 and increased N fertilization (with or without *O. furnacalis* being present), which increased the plant's overall defensive response to

---

[192] See reviews of multiple research papers on this topic under the heading **Herbivory** at this link: http://www.co2science.org/subject/h/subject_h.php.

[193] Xu, H., Xie, H., Wu, S., Wang, Z. and He, K. 2019. Effects of elevated CO_2 and increased N fertilization on plant secondary metabolites and chewing insect fitness. *Frontiers in Plant Science* **10**: 739, doi: 10.3389/fpls.2019.00739.

combat *O. furnacalis*. Furthermore, elevated CO_2 slowed the growth of the Asian corn borer and decreased its food digestibility and utilization. Consequently, in the *Conclusion* section of their paper, Xu *et al*. write that as the air's CO_2 concentration rises in the years and decades ahead, farmers who utilize N fertilization in the production of maize will promote its resistance to the Asian corn borer. And that will translate to greater yields to be consumed by an ever-increasing planetary population.

Example 2

Writing by way of introduction to their work, Reineke and Selim (2019)[194] note that grapevine (*Vitis* spp.) is an important commodity crop cultivated in temperate regions around the world. And while many scientists have examined the effects of possible climate change on grapevine growth, very little is known about its potential *combined* response with insect herbivory under various future climate change scenarios. Thus, seeking to provide more information in this regard, the two German researchers set out to investigate the transcriptomic response of grapevine plants to insect herbivory from the European grapevine moth (*Lobesia botrana*).

The work was conducted at the Geisenheim Vineyard FACE facility at Geisenheim University, Germany. Two *Vitis vinifera* cultivars were used in the study (Riesling and Cabernet Sauvignon) and grown under ambient or elevated CO_2 concentrations, the latter of which only amounted to a meager +58 ppm above ambient during daylight hours. At the "development of fruits" and "ripening of berries" stages, a subset of plants growing in the two CO_2 treatments was subjected to herbivory by *L. botrana*. In this instance, five larvae were placed per grape bunch and were allowed to feed for four days. To prevent herbivore escape, nylon mesh bags were used to cover the grape bunches. Control plants also received nylon mesh bags, but without larvae infestation. Leaf samples were thereafter collected from both herbivore infected and non-infected leaves and subjected to transcriptome sequencing in order to assess if grapevine plants would show a differential transcriptomic response to herbivory based on CO_2 concentration.

Results of the analysis revealed, in the words of the authors, that "grapevine transcriptional response to herbivory was clearly dependent on phenological stage, with a higher number of differentially expressed genes identified at fruit development compared to berry ripening." More specifically, they note that more transcripts were differentially expressed at fruit development as a response to herbivory under elevated compared to ambient CO_2 concentrations. Furthermore, they report that "classification of the respective transcripts revealed that in particular genes involved in metabolic pathways, biosynthesis of secondary metabolites and plant-pathogen interactions were significantly enriched," adding that "most of these genes had similar expression patterns under both CO_2 concentrations, with a higher fold-change under elevated CO_2 concentrations."

Fortunately, many of the gene expression patterns observed at elevated CO_2 were associated with improvements in biotic stimuli or defense responses to *L. botrana* herbivory. Identified changes in the grapevine's transcriptome included those involved in defense signaling of herbivore attack and were associated with the production of reactive oxygen species and phytohormones (such as

---

[194] Reineke, A. and Selim, M. 2019. Elevated atmospheric CO_2 concentrations alter grapevine (*Vitis vinifera*) systemic transcriptional response to European grapevine moth (*Lobesia botrana*) herbivory. *Scientific Reports* **9**: 2995, DOI:10.1038/s41598-019-39979-5.

ethylene, jasmonate and salicylic acid stress hormones), as well as disease resistance proteins, which *combination of factors* play a critical role in conferring resistance against *L. botrana* attack.

In light of these encouraging findings, it should come as no surprise that Reineke and Selim conclude by saying their study "indicates that future elevated CO_2 concentrations will affect interactions between grapevine plants and one of its key insect pests, with consequences for future relevance of *L. botrana* in worldwide viticulture." And, gratefully, that relevance will likely be greatly diminished, leading to more robust growth and grape harvests in the years and decades to come as the air's CO_2 concentration continues to rise.

Information on additional peer-reviewed scientific studies on this topic can be accessed under the following links: ***Herbivory** (Herbaceous Plants)*, ***Herbivory** (Woody Plants: Maple)*, ***Herbivory** (Woody Plants: Oak)*, ***Herbivory** (Woody Plants: Miscellaneous)*, and ***Herbivory** (General)*.

5. A Continued Greening of Planet Earth

Based largely on computer model projections, the EPA's Endangerment Finding claims that CO_2-induced global warming will wreak havoc on Earth's natural and agro-ecosystems by reducing plant growth and development, potentially leading to the *extinction* of many species. The previous four subsections of this petition refute such a negative view of the future, presenting a very large and significant body of evidence to the contrary that is based on a multitude of laboratory and field-based observations.

The reality is, the world's vegetation possesses an *ideal mix of abilities* to reap a *tremendous* benefit in the years and decades to come thanks to the ongoing rise in the air's CO_2 content, via its (a) *aerial fertilization effect* that induces incredible plant productivity gains, (b) its *transpiration-reducing effect* that boosts plant water use efficiency, (c) its *stress-alleviating effect* that lessens the negative growth impacts of resource limitations and environmental constraints. And based on a multitude of *additional* real-world observations *that future is* ***now*** -- as evidence from all across the globe indicates that the terrestrial biosphere is already experiencing an incredible stimulation of growth, due in large measure to the approximate 45% increase in atmospheric CO_2 that has occurred since the beginning of the Industrial Revolution.

Consider, for example, Figure III.A.5.1, which shows that prior to around 1940, Earth's land surfaces were a net source of CO_2-carbon to the atmosphere. From 1940 onward, however, the terrestrial biosphere has become, in the mean, an increasingly greater *sink* for CO_2-carbon.[195]

---

[195] Tans, P. 2009. An accounting of the observed increase in oceanic and atmospheric CO_2 and an outlook for the future. *Oceanography* **22**: 26-35.

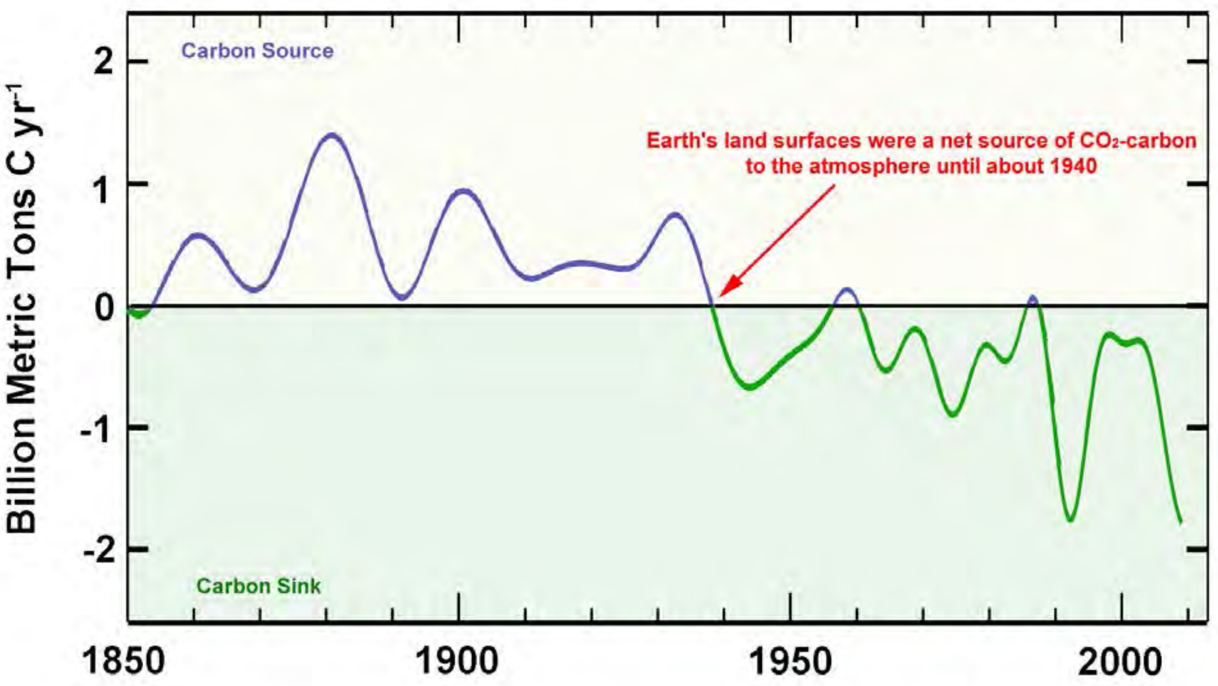


***Figure III.A.5.1**. Five-year smoothed rates of carbon transfer from land to air (positive values, blue color of line) or from air to land (negative values, green colored portion of the line) vs. time.*

This fact is further borne out in another study examining the sources and sinks of CO_2, and which includes data for both the land *and* ocean. As seen in Figure III.A.5.2, the global carbon uptake has actually *doubled* over the past half-century, from 2.4 to 5.0 billion tonnes per year.[196]

Additional evidence for this great *greening of the Earth*, as it is often called, is seen in satellite-derived data. But what is most surprising about these observations is the fact that they are even occurring at all—that is, *if* one accepts the claims of climate alarmists that are echoed in the Endangerment Finding.

Consider, for example, their concerns that since 1980 the Earth has weathered four of the warmest decades in the modern instrumental temperature record, as well as a handful of intense and persistent El Niño events, large-scale deforestation, "unprecedented" forest fires, and episodes of persistent, widespread and severe drought. At the same time, the air's CO_2 content has increased by more than 22% and the human population has grown by nearly 75%. To global warming alarmists, the Earth has recently been in the throes of a veritable climate Armageddon, if you will. So just how bad has the terrestrial biosphere suffered in response to these much-feared events?

---

[196] Ballantyne, A.P., Alden, C.B., Miller, J.B., Tans, P.P. and White, J.W. 2012. Increase in observed net carbon dioxide uptake by land and oceans during the past 50 years. *Nature* **488**: 70-72.

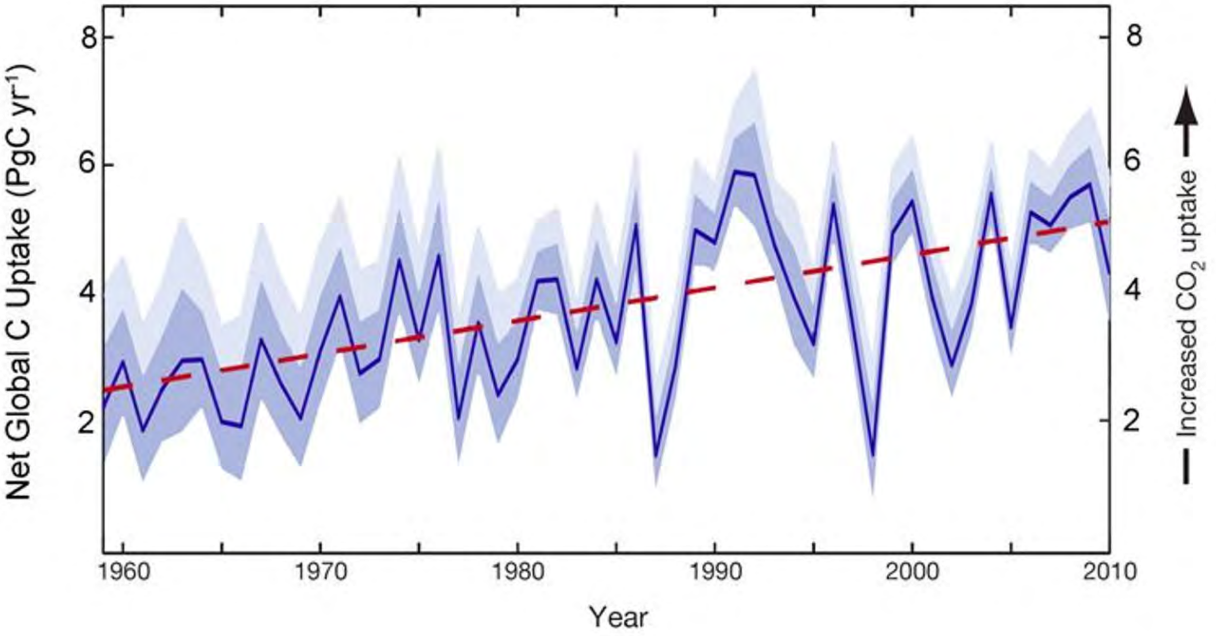


Figure III.A.5.2. *Annual global net carbon (C) uptake by Earth's lands and oceans (1959-2010).*

To answer frankly, it has suffered *not at all!* Increasing levels of atmospheric CO_2 have actually helped to *overpower* these and other growth-inhibiting influences in all but a few locales. Such was the conclusion of a team of researchers who analyzed long-term satellite-derived *leaf area index* records, together with the output of ten global ecosystem models for the period 1982-2009.[197] The results of their analysis revealed a persistent and widespread greening of the globe's vegetated area, evidenced by the green, blue and violet shading in Figure III.A.5.3. Further analyses revealed that CO_2 fertilization effects explained 70% of the observed greening trend, followed by nitrogen deposition (9%), climate change (8%) and land cover change (4%).

Similar results were reported in 2017 by another research team.[198] Working with over 2100 globally-distributed databases, they analyzed the spatiotemporal patterns of net primary production over the past half-century, which patterns are illustrated in Figure III.A.5.4. Their results indicated that, for the planet as a whole, net primary production increased significantly by 21.5 percent over the past five decades. Not surprisingly, the authors report that atmospheric CO_2 concentration was the dominant factor controlling the interannual variability and increase of global net primary production over the period of study.

---

[197] Zhu, Z., Piao, S., Myneni, R.B., Huang, M., Zeng, Z., Canadell, J.G., Ciais, P., Sitch, S., Friedlingstein, P., Arneth, A., Cao, C., Cheng, L., Kato, E., Koven, C., Li, Y., Lian, X., Liu, Y., Liu, R., Mao, J., Pan, Y., Peng, S., Penuelas, J., Poulter, B., Pugh, T.A.M., Stocker, B.D., Viovy, N., Wang, X., Wang, Y., Xiao, Z., Yang, H., Zaehle, S. and Zeng, N. 2016. Greening of the Earth and its drivers. *Nature Climate Change* DOI: 10.1038/NCLIMATE3004.

[198] Li, P., Peng, C., Wang, M., Li, W., Zhao, P., Wang, K., Yang, Y. and Zhu, Q. 2017. Quantification of the response of global terrestrial net primary production to multifactor global change. *Ecological Indicators* **76**: 245-255.

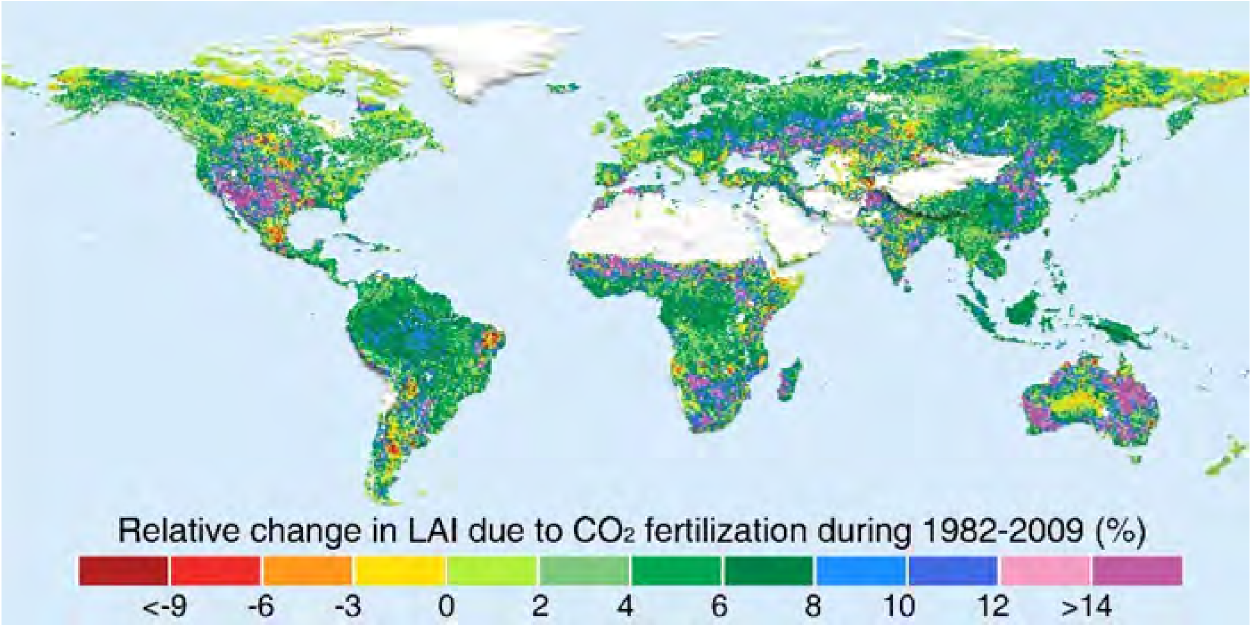
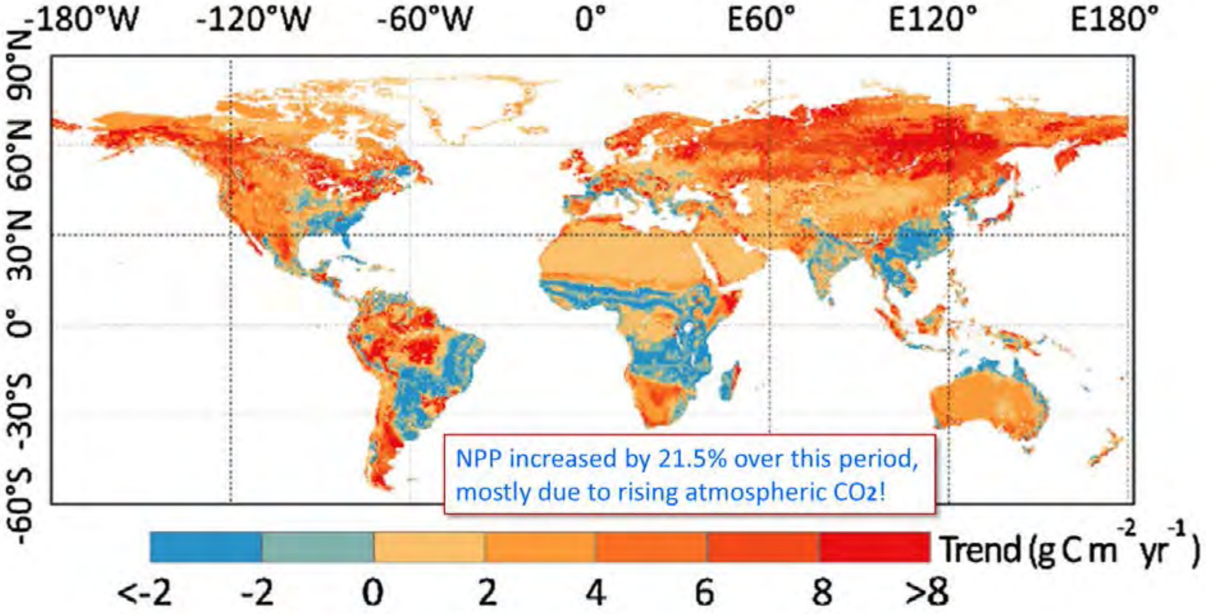


Figure III.A.5.3. *Spatial pattern of relative change of LAI due to CO_2 fertilization during 1982 to 2009. The relative change of LAI in each pixel is derived from the ratio of the increment of LAI driven by elevated atmospheric CO_2 to the 28-year average value of LAI simulated by model ensemble mean under scenario S1.*



NPP increased by 21.5% over this period, mostly due to rising atmospheric CO_2!

Figure III.A.5.4. *Spatial distribution of the trend in NPP during the period 1961-2010.*

Figure III.A.5.5 shows the results of a *third* independent group of scientists, who have further documented the growth-enhancing impacts of rising atmospheric CO_2 on the biosphere by investigating trends in gross primary production (GPP) over the period 1982-2011.[199] GPP is an ecological measure of ecosystem health. Higher GPP values correspond with more productive ecosystems in terms of their ability to produce biomass (plant growth) and support the higher trophic levels up the food chain.

Once again, as shown by the overwhelming presence of blue shading in this figure, despite the many real (and imagined) assaults on vegetation by humanity and nature alike, the terrestrial biosphere has met and *overcome* these challenges, in this instance increasing its GPP by 24.9 Pg C over this three-decade period. And once again, rising atmospheric CO_2 concentrations were found to be the principal cause of that increase, with the authors determining that a 10% increase in atmospheric CO_2 induces an approximate 8% increase in global gross primary production.

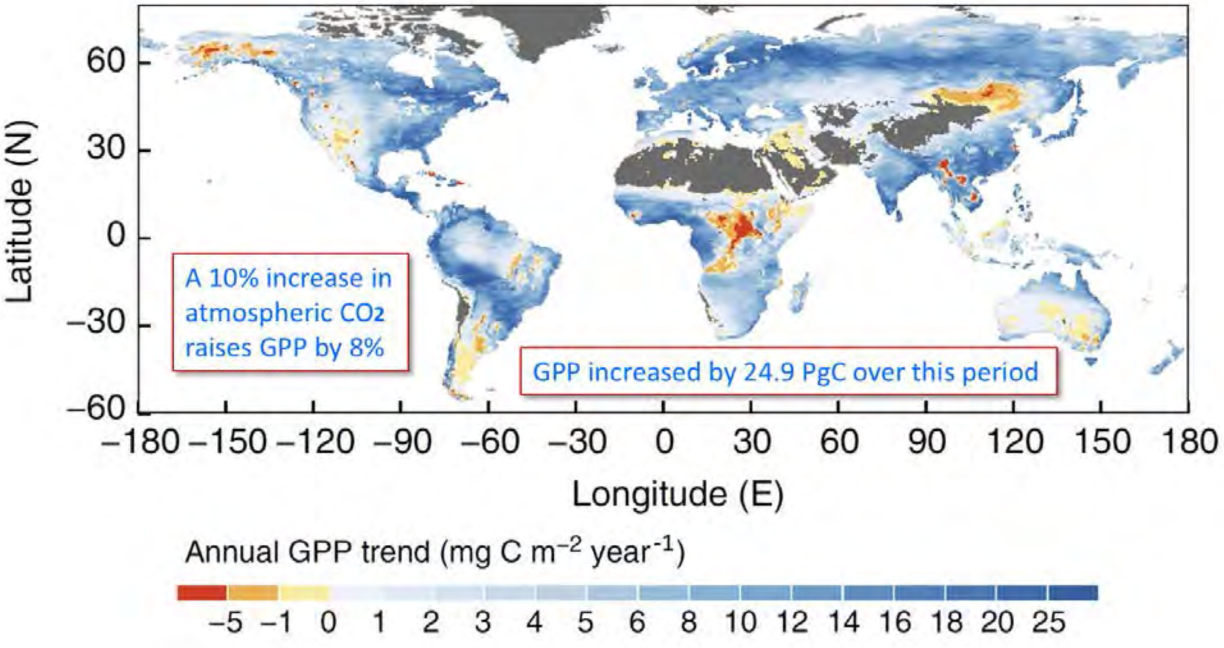


***Figure III.A.5.5**. Estimated spatial trends in annual gross primary production over 1982-2011.*

Moving closer to the present, Sun *et al*. (2018)[200] employed a series of global data sets in an effort to estimate global monthly gross primary productivity over the period 1982-2015. Their results are highlighted in Figure III.A.5.6. As indicated, the spatial distribution of the linear trends in gross primary productivity is *overwhelmingly positive*, demonstrating that a large and

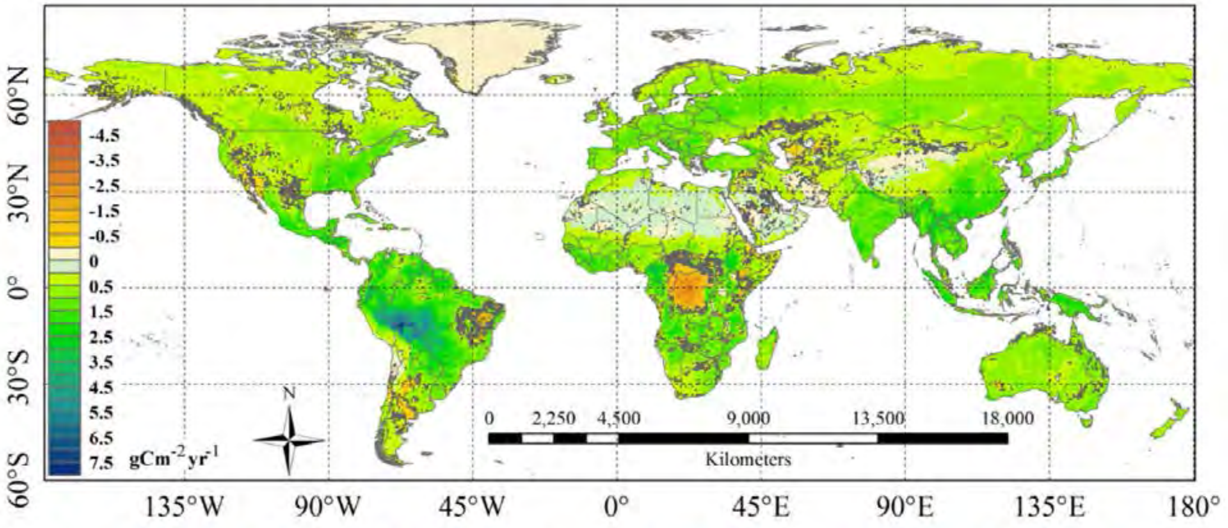
---

[199] Cheng, L., Zhang, L., Wang, Y.-P., Canadell, J.G., Chiew, F.H.S., Beringer, J., Li, L., Miralles, D.G., Piao, S. and Zhang, Y. 2017. Recent increases in terrestrial carbon uptake at little cost to the water cycle. *Nature Communications* **8**: 110, DOI:10.1038/s41467-017-00114-5.

[200] Sun, Z., Wang, X., Yamamoto, H., Tani, H., Zhong, G., Yin, S. and Guo, E. 2018. Spatial pattern of GPP variations in terrestrial ecosystems and its drivers: Climatic factors, CO_2 concentration and land-cover change, 1982-2015. *Ecological Informatics* **46**: 156-165.

significant vegetative enhancement has occurred in over 75% of the land area over the past 34 years.

With respect to the factors responsible for these trends, the researchers analyzed five potential influences, including land-cover change, rising atmospheric CO_2 concentrations, and changes in solar radiation, temperature and soil water status. Their results indicated that increases in atmospheric CO_2 accounted for the largest contribution to the globally-averaged gross primary productivity trends, accounting for 65.73%, which percentage is *more than five times the value* of the next most significant contributing factor of temperature.



75% of the land area experienced positive increases in GPP. CO2 accounted for 66% of the GPP trends.

Figure III.A.5.6*. The spatial distribution of linear trends in gross primary production for the period 1982-2015.*

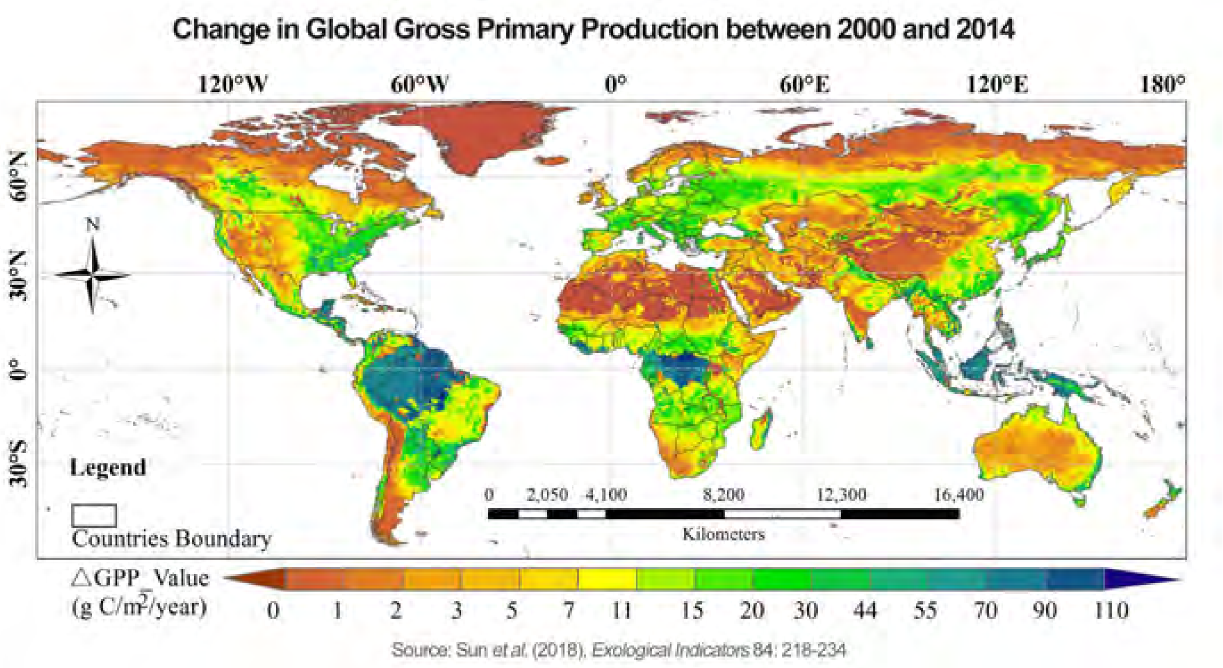
In a similar study, Sun *et al*. (2018)[201] also investigated the change in global gross primary productivity (GPP), focusing on the recent period between 2000 and 2014. Not surprisingly, as illustrated in Figure III.A.5.7, they also report that GPP values are increasing *everywhere* across the globe, with the exception of those regions which are hostile for life (the cold and light-limiting ice caps and water-limiting deserts).

This observation further confirms that rising levels of atmospheric CO_2 and recent changes in climate over the past two decades (temperature, precipitation, etc) have not negatively impacted the terrestrial biosphere, but rather *enhanced* it. What is more, the fact that the *highest* increases in GPP are found in locations of the *lowest* latitudes, suggests that a little global warming could do the terrestrial biosphere much good and would probably further enhance GPP if the planet continues to warm. Certainly they show an a minimum that GPP is not presently limited by

---

[201] Sun, Z., Wang, X., Yamamoto, H., Tani, H., Zhong, G. and Yin, S. 2018. An attempt to introduce atmospheric CO_2 concentration data to estimate the gross primary production by the terrestrial biosphere and analyze its effects. *Ecological Indicators* **84**: 218-234.

temperature at the lower latitudes because of the great enhancements to GPP that are observed there.


Change in Global Gross Primary Production between 2000 and 2014

Source: Sun *et al.* (2018), *Exological Indicators* 84: 218-234

Figure III.A.5.7. *The change in global gross primary production (GPP) for the terrestrial biosphere between the period 2000 and 2014.*

Also publishing there work in 2018 was the research team of Yu *et al*. (2018).[202] Working with MODIS satellite data, the team of seven researchers analyzed the spatial and temporal variation in terrestrial gross primary productivity (GPP) and net primary productivity (NPP) over the period 2004 to 2012. Figure III.A.5.8 depicts both the GPP and NPP values for the terrestrial biosphere in both 2004 and 2012. According to Yu *et al*., total GPP increased from 108.84 Pg C in 2004 to 119.73 Pg C in 2012, representing a linear increase of 1.25% per year, or 10% between 2004 and 2012. Similarly, global NPP increased from 61.15 Pg C in 2004 to 69.53 Pg C in 2012, rising 1.7% per year for a total increase of 13.7% across the eight year period. Furthermore, the authors report that, in general, GPP and NPP values in 2012 were higher than that observed in 2004 "at all land cover types."

The above enhancements in GPP and NPP also indicate the health of the terrestrial biosphere has been *improving* over time, in line with the other studies highlighted in this section. The significance of such observations cannot be overstated; despite the occurrence of many real (and imagined) assaults on Earth's vegetation over the past few years and decades, including wildfires, disease, pest outbreaks, deforestation, and supposedly unprecedented climatic changes in temperature and precipitation, global terrestrial GPP and NPP is ***not*** diminishing. Rather, its

---

[202] Yu, T., Sun, R., Xiao, Z., Zhang, Q., Liu, G., Cui, T. and Wang, J. 2018. Estimation of global vegetation productivity from Global Land Surface Satellite data. *Remote Sensing* **10**: 327, doi:10.3390/rs10020327.

increase or improvement is primarily caused by growth-related benefits associated with Earth's rising atmospheric CO_2 concentration.

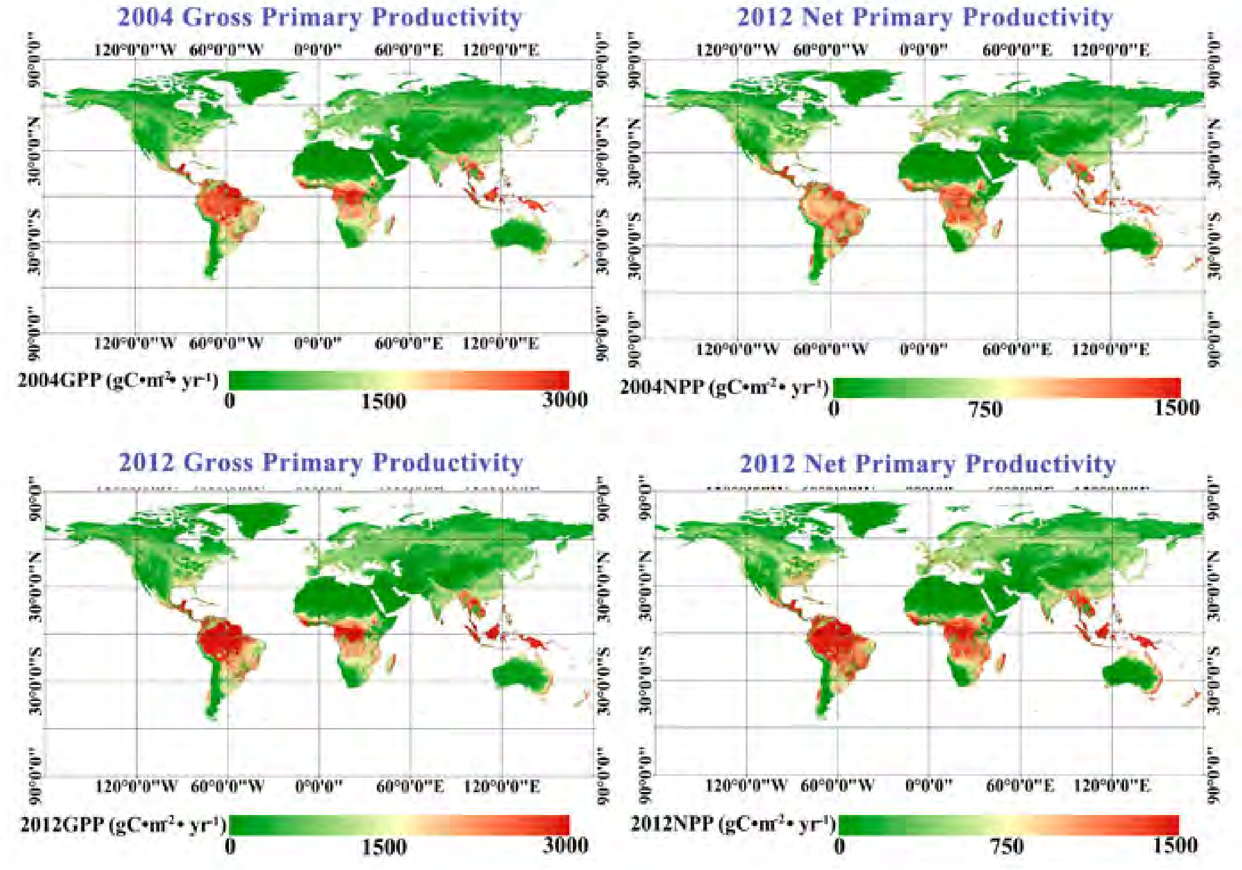


Figure III.A.5.8. *Global 1 km gross (left column) and net (right column) primary productivity in 2004 (top row) and 2012 (bottom row).*

In another study, published last year in the journal *Nature Climate Change*, Fernández-Martínez *et al*. (2019)[203] utilized multidecadal inversion models and an ensemble of dynamic global vegetation models (DVGMs) to estimate global net ecosystem production (NEP) over the period 1995 to 2014. The inversion models provided gridded estimates for the net fluxes of land-atmosphere CO_2 exchange, i.e. NEP, which were then examined in conjunction with atmospheric CO_2, climate, land-use, and atmospheric nitrogen and sulfur deposition data to determine the relative impacts of these several factors on global NEP trends.

Results of their study reveal that global NEP increased by 117 to 178 Tg C yr^{-1} depending on the inversion model used, which increase was strongly influenced by NEP gains in Siberia, Asia,

---

[203] Fernández-Martínez, M., Sardans, J., Chevallier, F., Ciais, P., Obersteiner, M., Vicca, S., Canadell, J.G., Bastos, A., Friedlingstein, P., Sitch, S., Piao, S.L., Janssens, I.A. and Peñuelas, J. 2019. Global trends in carbon sinks and their relationships with CO_2 and temperature. *Nature Climate Change* **9**: 73-79.

Oceania and South America (see Figure III.A.5.9). Latitudinally, the majority of the NEP increases occurred in the tropics, where despite containing only around 22% of the global land area (excluding Antarctica), this region accounted for around half of the total NEP increase.

With respect to the *cause* responsible for the rising NEP trend, the authors report that “increasing CO_2 was the main factor … with a consistent positive temporal contribution for almost all the latitudinal bands considered.” And in this regard they note that, “proportionally, increasing CO_2 accounted for more than 90% of the trends in NEP” (see Figure III.A.5.9, right side), whereas the proportional contribution from temperature amounted to less than 10%.

In further calculating the global sensitivity of NEP to increasing CO_2, the authors determined that a 1 ppm rise in atmospheric CO_2 was able to sequester between 6 and 8 Tg of carbon. Consequently, given these several findings, Fernández-Martínez *et al*. conclude that their study “highlights the dominant role of rising atmospheric CO_2 concentrations triggering an increase in land carbon sinks over the entire planet from 1995 to 2014.” And it adds further proof to the ever-growing narrative that the *whole* of the terrestrial biosphere is benefitting from the CO_2 fertilization effect.

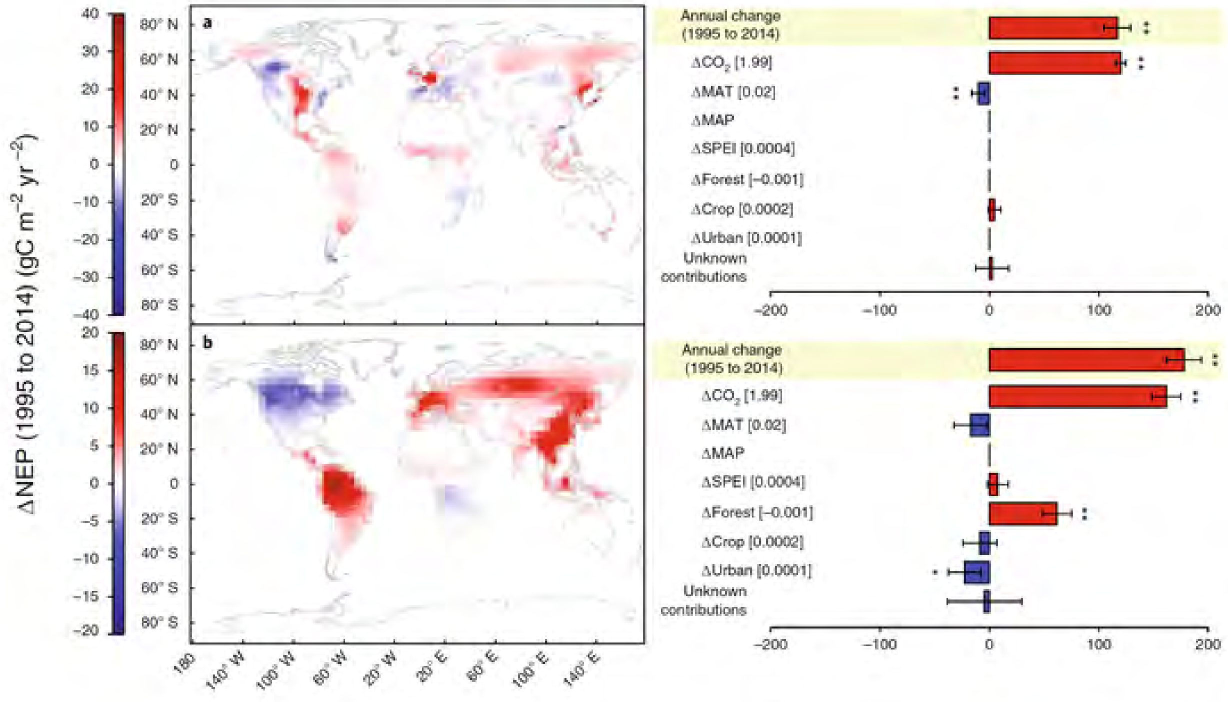


Figure III.A.5.9. *Global trends in NEP and their contributing factors as determined by the MACC-II (Panel a) and Jena CarboScope (Panel b) inversions models. Global temporal contributions of* CO_2*, climate and land-use change to the trends in NEP (annual change) are shown on the right side of each panel. The difference between the modelled temporal contributions and the trends (shaded) was treated as an unknown contribution to the temporal variation in NEP. Statistically significant (*$P < 0.01$*) temporal variations of the predictors are shown in square brackets (*CO_2*, ppm* yr^{-1}*; temperature, °C* yr^{-1}*; precipitation, mm* yr^{-2}*; SPEI,* *s.d.; forests, crops and urban areas, percentage of land-use cover per pixel) . Error bars indicate 95% confidence intervals. Significance levels: *P < 0.01, **P < 0.001.*

And finally, the latest study to confirm a CO_2-induced greening of the Earth as much comes from the research team of O'Sullivan *et al*. (2019).[204] As their contribution to this topic, the six scientists used the Community Land Model version 4.5, which "simulates biophysical, hydrological, and biogeochemical exchange processes between the land and the ocean," to estimate changes in NPP over the period 1901-2016. Furthermore, their computer analyses provided a quantifying measure of the impact of various drivers on the NPP chances, which drivers included the individual and combined effects of CO_2 enrichment, nitrogen deposition and climate. Pertinent findings are presented in Figure III.A.5.10 and Figure III.A.5.11 below.

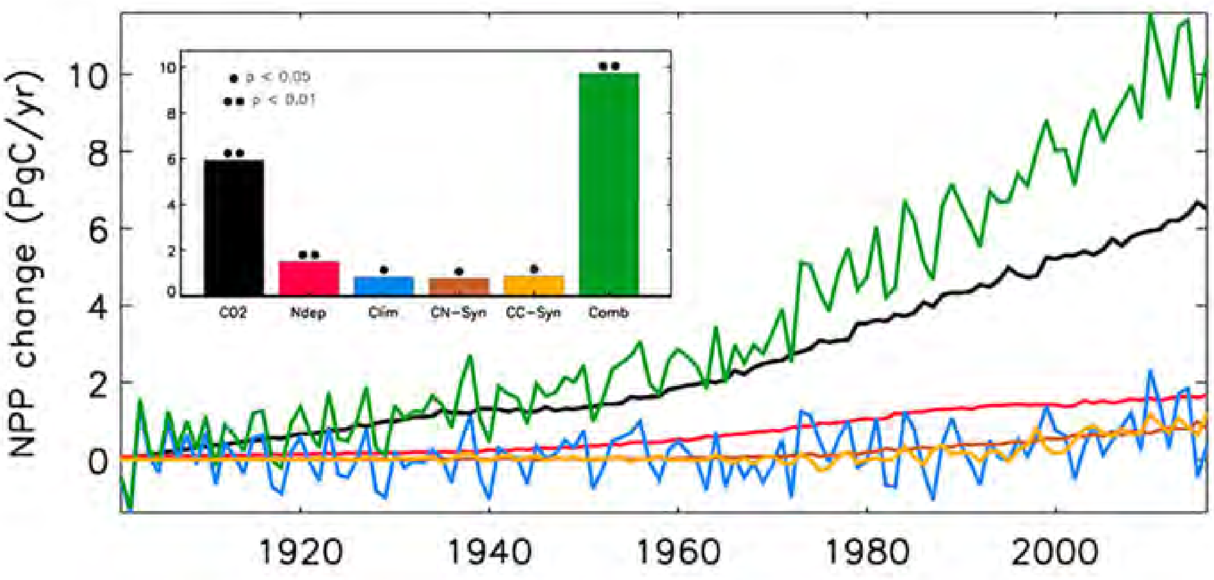


***Figure III.A.5.10**. Model-derived annual mean change in global net primary production (NPP) over the period 1901-2016 due to CO_2 fertilization (CO_2), nitrogen deposition (Ndep), climate change (Clim), carbon-nitrogen synergy (CN-Syn), carbon-climate synergy (CC-Syn), and the combined effects (Comb). Inset shows the change in NPP from 1901-1910 to 2007-2016. Statistically significant (• $p < 0.05$, •• $p < 0.01$; Mann-Whitney U test) changes are highlighted.*

As shown in Figure III.A.5.10, simulated NPP "increased substantially over the 20th century to the present day from 56.2 (mean of 1901-1910) to 66.0 Pg C/year (mean of 2007-2016) with positive contributions from all drivers considered, including rising CO_2 concentrations (i.e., CO_2 fertilization), nitrogen deposition, climate, and carbon-nitrogen as well as carbon-climate synergies." Accordingly, the relative contribution of these drivers to the overall NPP increase amounted to 60% for CO_2 fertilization, 15% for nitrogen deposition, 8% for climate, 8% from a combined CO_2/nitrogen deposition effect, and 9% for a combined CO_2/climate effect. Thus the

---

[204] O'Sullivan, M.O., Spracklen, D.V., Batterman, S.A., Arnold, S.R., Gloor, M. and Buermann, W. 2019. Have synergies between nitrogen deposition and atmospheric CO_2 driven the recent enhancement of the terrestrial carbon sink? *Global Biogeochemical Cycles* **33**: https://doi.org/10.1029/2018GB005922.

steady rise in atmospheric CO_2 was directly or indirectly responsible for 77% of the simulated NPP increase since 1901.

A spatial display of the changes in NPP due to atmospheric CO_2 enrichment over the period of study is presented in Figure III.A.5.11. And, O'Sullivan *et al*. further note that, on the whole, the majority of the Earth's vegetated land surface "increased net carbon uptake over the historical period, with the tropics, East Asia, North America, and northern Eurasia dominating" (authors' Figure 4f, but not shown here).

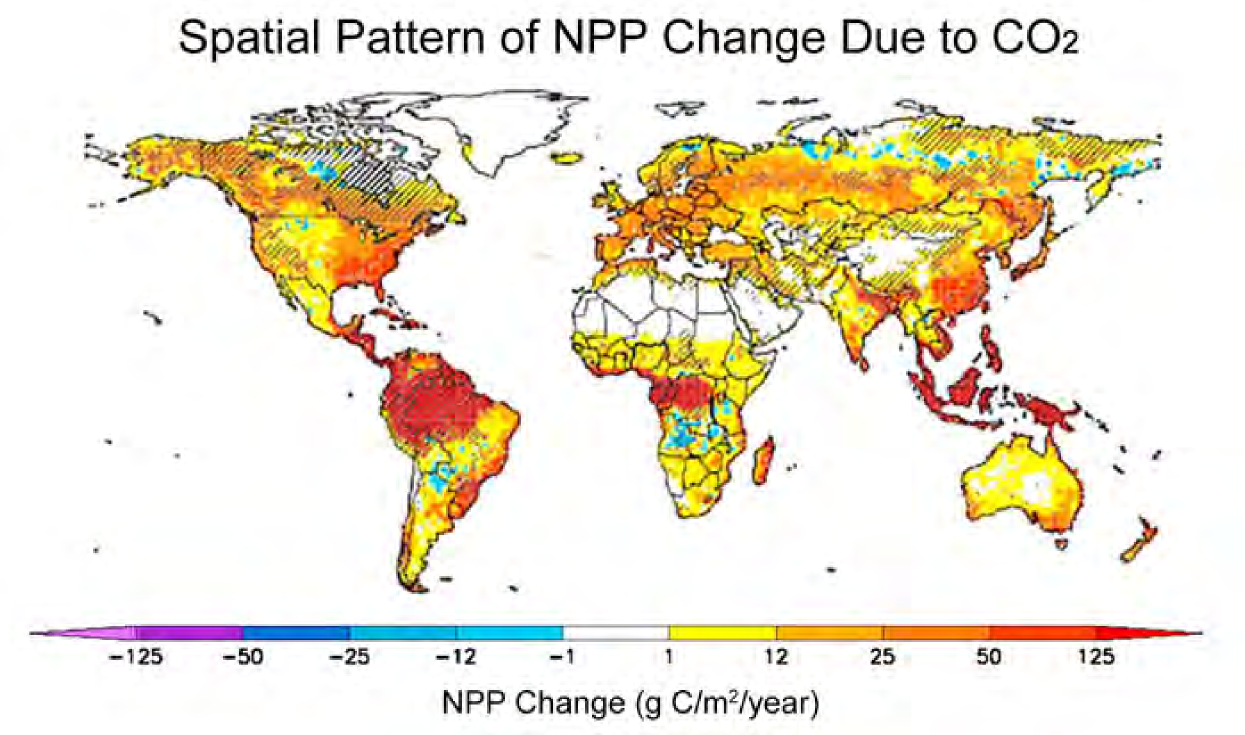


Figure III.A.5.11. *Spatial patterns of net primary production (NPP) change (g C/m*^{2}*/year) as a result of) CO_2 fertilization. NPP changes were calculated as the difference between 2007-2016 (final decade) and 1901-1910 (first decade) mean values. Significant ($p < 0.05$; Mann-Whitney U test) changes highlighted with hatching.*

In considering all of the above studies highlighted in this section, it is clear that fears of a soon-to-be-collapsing terrestrial biosphere as promoted in the EPA's Endangerment Finding are vastly overstated. Rather than declining in vigor, the world's land vegetation has increased its robustness over the past twelve decades. And the *reason* for that enhancement, ironically, is the very action EPA claims should be decimating it: humanity's increasing use of fossil fuels.

The combustion of fossil fuels is the principal driver of the contemporary increase witnessed in both atmospheric CO_2 *and* nitrogen deposition, which are the two most important factors driving the positive trends in NPP. All of humanity and nature should therefore be thankful for the use of fossil fuels instead of demonizing it as the EPA and so many other climate alarmists do. They couldn't be more misguided.

Information on additional peer-reviewed scientific studies on this topic can be accessed by clicking on the links below, or from under the heading of Biospheric Productivity here: http://www.co2science.org/subject/b/subject_b.php.

Biospheric Productivity

- Africa
- Asia
  - China
    - Country-Wide
    - Deserts
    - Forests
    - Grasslands
    - Tibetan Plateau
  - Other Countries
- Europe
- Global
  - The Distant and Historic Past
  - The Recent Past
  - The Future
- Hemispheric
- Miscellaneous
- North America
  - Central USA
  - Eastern USA
  - Entire Continent
  - High Latitude Regions
  - Western USA
- Oceans
- South America

6. Nutrition

Studies of the effects of atmospheric CO_2 enrichment on the *quality* of the different plant parts that comprise human diets have typically lagged far behind studies designed to assess the effects of elevated CO_2 on the *quantity* of plant biomass produced. Some noteworthy exceptions, however, were the early studies of Barbale (1970)[205] and Madsen (1971, 1975),[206,207] who discovered that increasing the air's CO_2 content produced a modest increase in the vitamin C

---

[205] Barbale, D. 1970. The influence of the carbon dioxide on the yield and quality of cucumber and tomato in the covered areas. *Augsne un Raza (Riga)* **16**: 66-73.

[206] Madsen, E. 1971. The influence of CO_2-concentration on the content of ascorbic acid in tomato leaves. *Ugeskr. Agron*. **116**: 592-594.

[207] Madsen, E. 1975. Effect of CO_2 environment on growth, development, fruit production and fruit quality of tomato from a physiological viewpoint. In: P. Chouard and N. de Bilderling (Eds.), *Phytotronics in Agricultural and Horticultural Research*. Bordas, Paris, pp. 318-330.

concentration of tomatoes, while Kimball and Mitchell (1981)[208] 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)[209] 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, Idso *et al*. (2002)[210] evaluated the effects of an extra 300 ppm of CO_2 on the vitamin C concentrations of fully-ripened sour orange citrus tree fruit. Their work revealed that the vitamin C concentration of the juice of the oranges grown in the CO_2-enriched air was enhanced by approximately 5% above that of the juice of the ambient-treatment oranges, which modest increase, in the words of the eight researchers "bodes well for this key agricultural product that plays a vital role in maintaining good health in human populations around the globe."

Further support for the significance of the above statement was provided by Idso and Idso (2001),[211] 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,[212,213] and that subclinical scurvy symptoms are increasing among adults.[214]" In addition, they reported that "Hampl *et al*. (1999)[215] 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)[216] have determined that 12 to 16% of U.S. college students have marginal plasma concentrations of vitamin C." Therefore, as they continued, "since vitamin C intake correlates strongly with the consumption of citrus juice,[217] and since the only high-vitamin-C juice consumed in any quantity by children is orange juice,[218] the modest role played by the ongoing rise in the air's CO_2 content in increasing the vitamin C

---

[208] Kimball, B.A. and Mitchell, S.T. 1981. Effects of CO_2 enrichment, ventilation, and nutrient concentration on the flavor and vitamin C content of tomato fruit. *HortScience* **16**: 665-666.

[209] Tajiri, T. 1985. Improvement of bean sprouts production by intermittent treatment with carbon dioxide. *Nippon Shokuhin Kogyo Gakkaishi* **32(3)**: 159-169.

[210] Idso, S.B., Kimball, B.A., Shaw, P.E., Widmer, W., Vanderslice, J.T., Higgs, D.J., Montanari, A. and Clark, W.D. 2002. The effect of elevated atmospheric CO_2 on the vitamin C concentration of (sour) orange juice. *Agriculture, Ecosystems and Environment* **90**: 1-7.

[211] Idso, S.B. and Idso, K.E. 2001. Effects of atmospheric CO_2 enrichment on plant constituents related to animal and human health. *Environmental and Experimental Botany* **45**: 179-199.

[212] Ramar, S., Sivaramakrishman, V. and Manoharan, K. 1993. Scurvy - a forgotten disease. *Archives of Physical Medicine and Rehabilitation* **74**: 92-95.

[213] Gomez-Carrasco, J.A., Cid, J.L.-H., de Frutos, C.B., Ripalda-Crespo, M.J. and de Frias, J.E.G. 1994. Scurvy in adolescence. *Journal of Pediatric Gastroenterology and Nutrition* **19**: 118-120.

[214] Dickinson, V.A., Block, G. and Russek-Cohen, E. 1994. Supplement use, other dietary and demographic variables, and serum vitamin C in NHANES II. *Journal of the American College of Nutrition* **13**: 22-32.

[215] Hampl, J.S., Taylor, C.A. and Johnston, C.S. 1999. Intakes of vitamin C, vegetables and fruits: which schoolchildren are at risk? *Journal of the American College of Nutrition* **18**: 582-590.

[216] Johnston, C.S., Solomon, R.E. and Corte, C. 1998. Vitamin C status of a campus population: College students get a C minus. *Journal of American College Health* **46**: 209-213.

[217] Dennison, B.A., Rockwell, H.L. and Baker, S.L. 1998. Fruit and vegetable intake in young children. *Journal of the American College of Nutrition* **17**: 371-378.

[218] Hampl, J.S., Taylor, C.A. and Johnston, C.S. 1999. Intakes of vitamin C, vegetables and fruits: which schoolchildren are at risk? *Journal of the American College of Nutrition* **18**: 582-590.

concentration of orange juice could ultimately prove to be of considerable significance for public health in the United States and elsewhere."

In the two decades since, a much larger body of literature has accumulated examining the beneficial impacts of elevated CO_2 on the nutritional properties of plants. The two subsections below highlight only a small number of such studies, focusing on common food plants and medicinal plants. Links to additional studies are provided at the end of each subsection.

(i) Common Food Plants

Writing to introduce their work, Muthusamy *et al*. (2019)[219] say that although the impacts of elevated CO_2 on "the nutritional quality of crops is being explored continuously, the information on L-ascorbic acid biosynthesis in leafy vegetables like Chinese cabbage (*Brassica campestris* L. spp. *pekinensis Rupr*), bok choy (*Brassica rapa* spp. *chinensis*) and root vegetables like red young radish (*Raphanus raphanistrum* ssp. *sativus* L.) and radish (*Raphanus raphanistrum* ssp. *sativus* L.) is limited." Thus it became their objective to investigate the effect of elevated CO_2 on various growth and health-related characteristics (antioxidative properties) of these four vegetables known for their high nutritional value, including ascorbic acid, soluble fibers and nutraceuticals with anti-cancer properties.

The work was conducted in the laboratory, where under controlled conditions they grew seedlings of the four plants under four different CO_2 concentrations (350, 700, 1000, and 4000 ppm) over a period of 7 days. Thereafter, they performed a series of analyses to determine the CO_2 effect on the antioxidative properties of these four cruciferous vegetables.

In discussing their findings, Muthusamy *et al*. report that elevated CO_2 induced a 0.53 to 1.62-fold increase in ascorbic acid (Vitamin C) content in the vegetable seedlings (see Figure III.A.6.i.1), which increase they say either directly or indirectly improved the radical scavenging activities of Super Oxide Dismutase in a concentration dependent manner. What is more, elevated CO_2 also activated Ascorbate peroxidase-6 to control the accumulation of the reactive oxygen species H_2O_2.

The above findings are significant in that ascorbic acid "acts as an antioxidant to protect photosystem from free radicals, thereby increasing photosynthesis rate under enriched CO_2 conditions which favors high biomass production." Such improvement in antioxidant activities under elevated CO_2 thus, not only helped these plants to grow better, but improved their nutritional value, which is great news for those who grow and consume these vegetables.

Strawberry (*Fragaria ananassa*) is in high demand globally, gaining further prominence in recent years due its nutritional properties, including minerals, vitamin C, folates, antioxidants and polyphenols. How these and other key nutritional substances and properties of this fruit

---

[219] Muthusamy, M., Hwang, J.E., Kim, J.A., Jeong, M.J., Park, H.C. and Lee, S.I. 2019. Elevated carbon dioxide significantly improves ascorbic acid content, antioxidative properties and restricted biomass production in cruciferous vegetable seedlings. *Plant Biotechnology Reports* **13**: 293-304.

might be changed or altered in response to future climate change was the question examined by Balassoriya *et al*. (2019).[220]

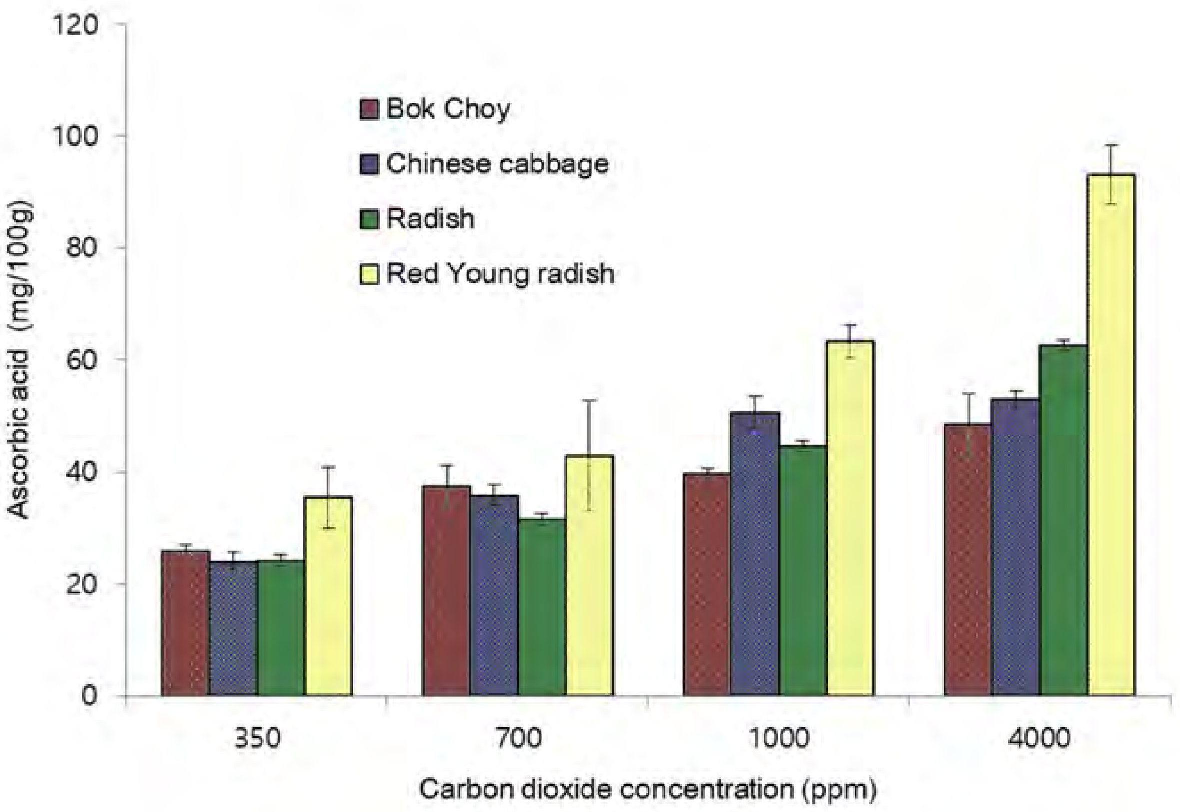


Figure III.A.6.i.1. *Vitamin C (Ascorbic acid, AsA) content in Chinese cabbage, bok choy, red young radish and radish seedlings exposed to different CO_2 concentrations (350, 700, 1000 and 4000 ppm).*

Working in controlled-environment chambers as the Parkville Campus of the University of Melbourne, Australia, the four scientists who conducted this study grew two strawberry cultivars (Albion and San Andreas) under two temperatures (25°C or 30°C) and three CO_2 concentrations (400, 650 or 950 ppm). At harvest, they analyzed multiple nutritional properties of the fresh strawberry fruit to ascertain how they changed in response to increasing temperature and/or atmospheric CO_2.

The results are summarized in Figure III.A.6.i.2 below. As noted by the authors, when compared to plants growing under ambient conditions, "elevated CO_2 and higher temperature caused significant increases in total polyphenol, flavonoid, anthocyanin and antioxidants in both strawberry cultivars."

---

[220] Balasooriya, H.N., Dassanayake, K.B., Seneweera, S. and Ajlouni, S. 2019. Impact of elevated carbon dioxide and temperature on strawberry polyphenols. *Journal of the Science of Food and Agriculture* **99**: 4659-4669.

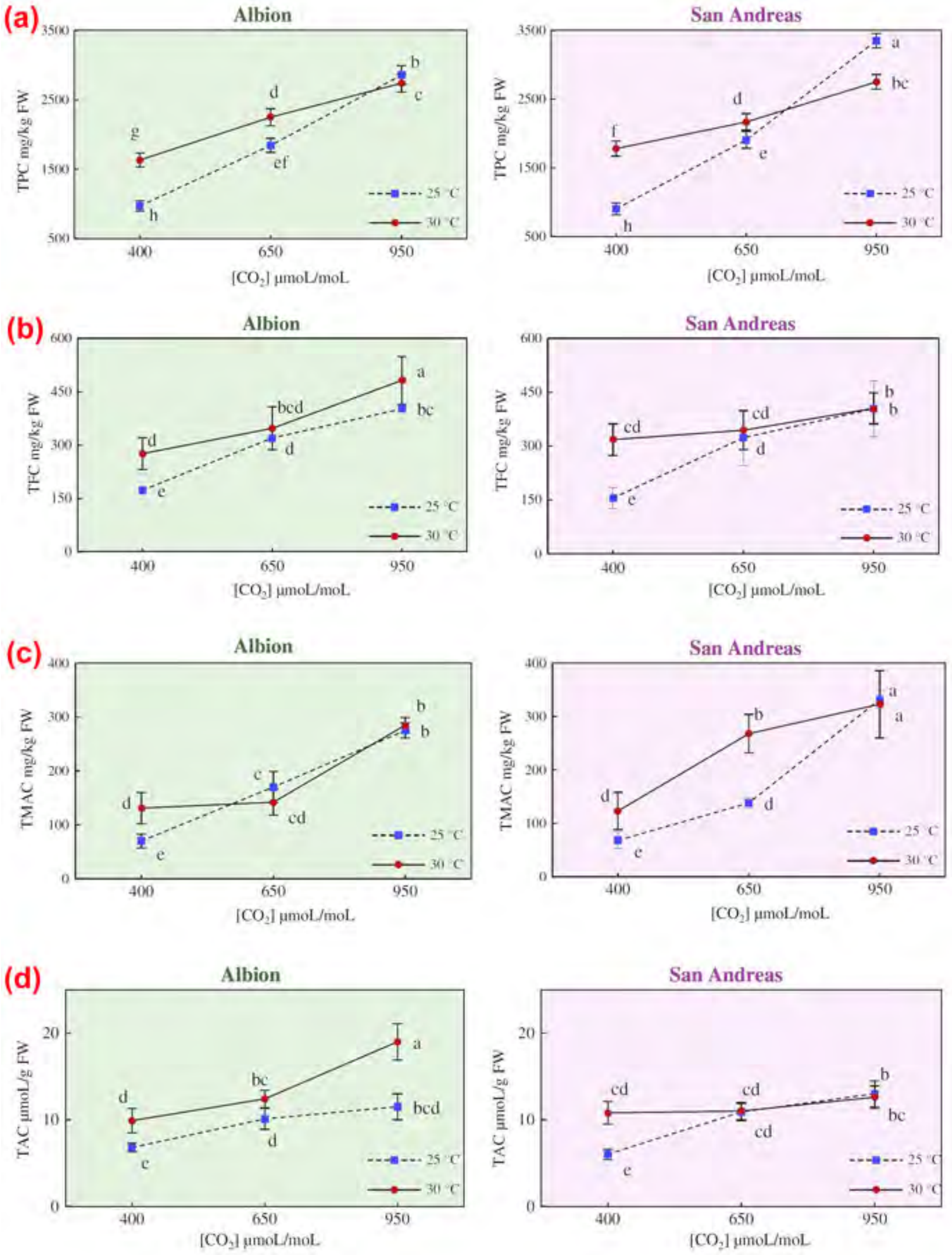


***Figure III.A.6.i.2**. Total polyphenolic content (TPC, Panel a), total flavonoid contents (TFC, Panel b), total monomeric anthocyanin contents (TMAC, Panel c) and total antioxidant contents (TAC, Panel d) of two different strawberry cultivars (‘Albion’ and ‘San Andreas’) at different combinations of temperature and CO_2. Error bars indicate the standard deviation of data (n = 12). Different letters are significantly ($P \geq 0.05$) different.*

Commenting on these important findings, Balasooriya *et al*. note that, “as polyphenols, flavonoids, anthocyanins, and antioxidants are considered to be important fruit bioactive compounds, increasing the content of such fruit nutrients with elevated CO_2, higher temperature and their interactions would improve strawberries’ functional properties.” “Consequently,” they continue, “strawberries grown under higher temperatures (30°C) and elevated CO_2 (650 and 950 ppm) could support better human health.”

Writing as background for their intriguing study, Saleh *et al*. (2018)[221] note that “parsley and dill are valuable sources of minerals, vitamins, unsaturated fatty acids, phenolic acids, flavonoids and other bioactive compounds that support their nutritional and medicinal benefits,” citing the works of Slupski *et al*. (2005),[222] Parry *et al*. (2006),[223] Lisiewska *et al*. (2006)[224] and Karkleliene *et al*. (2014).[225] Furthermore, they write that these two herbs are “recognized for their antioxidant, antibacterial, antifungal, anti-inflammatory, antidiabetic and anticancer activities, citing the additional works of Wong and Kitts (2006),[226] Farshori *et al*. (2013)[227] and Chahal *et al*. (2017).[228] Yet despite the well-documented nutritional and health-promoting benefits of these two plants, little is known about the potential effects of rising atmospheric CO_2 concentrations on these important plant properties/qualities.

Hoping to remedy this lack of knowledge, the team of four researchers set out to investigate the impact of elevated CO_2 on the nutritional and health-promoting qualities of parsley (*Petroselinum crispum*) and dill (*Anethum graveolens*). In so doing, Saleh *et al*. grew plant seedlings in pots in controlled environment chambers under either ambient (378 ppm) or elevated (627 ppm) CO_2 levels over a period of four weeks. And at the end of this interval, they conducted a series of analyses to measure the impact of atmospheric CO_2 concentration on the concentrations of 81 metabolites and minerals.

In discussing their findings, Saleh *et al*. report that elevated CO_2 significantly improved parsley and dill biomass production by a measure of approximately 1.5-fold relative to ambient-grown plants. More importantly, however, the authors found that elevated CO_2 “triggered improvements in the levels of soluble sugars, starch, organic acids, some essential amino acids, most of [the] unsaturated fatty acids, total phenolics, total flavonoids and vitamins A and E.” Moreover, they note that “parallel improvements in the total antioxidant capacity, antiprotozoal, antibacterial and anticancer activities were recorded for parsley and dill in response to elevated CO_2.” Additionally, elevated CO_2 did not affect the levels of four plant macronutrients (K, Ca, Mg, and

---

[221] Saleh, A.M., Selim, S., Jaouni, S.A. and AbdElgawad, H. 2018. CO_2 enrichment can enhance the nutritional and health benefits of parsley (*Petroselinum crispum* L.) and dill (*Anethum graveolens* L.). *Food Chemistry* **269**: 519-526.

[222] Slupski, J., Lisiewska, Z. and Kmiecik, W. 2005. Contents of macro and microelements in fresh and frozen dill (*Anethum graveolens* L.). *Food Chemistry* **91**: 737-743.

[223] Parry, J., Hao, Z., Luther, M., Su, L., Zhou, K. and Yu, L. 2006. Characterization of coldpressed onion, parsley, cardamom, mullein, roasted pumpkin, and milk thistle seed oils. *Journal of the American Oil Chemists’ Society* **83**: 847-854.

[224] Lisiewska, Z., Kmiecik, W. and Korus, A. 2006. Content of vitamin C, carotenoids, chlorophylls and polyphenols in green parts of dill (*Anethum graveolens* L.) depending on plant height. *Journal of Food Composition and Analysis* **19**: 134-140.

[225] Karkleliene, R., Dambrauskiene, E., Juškeviciene, D., Radzevicius, A., Rubinskiene, M. and Viškelis, P. 2014. Productivity and nutritional value of dill and parsley. *Horticultural Science* **41**: 131-137.

[226] Wong, P.Y.Y. and Kitts, D.D. 2006. Studies on the dual antioxidant and antibacterial properties of parsley (*Petroselinum crispum*) and cilantro (*Coriandrum sativum*) extracts. *Food Chemistry* **97**: 505-515.

[227] Farshori, N.N., Al-Sheddi, E.S., Al-Oqail, M.M. and Siddiqui, M.A. 2013. Anticancer activity of *Petroselinum sativum* seed extracts on MCF-7 human breast cancer. *Asian Pacific Journal of Cancer Prevention* **14**: 5719-5723.

[228] Chahal, K.K., Kumar, A., Bhardwaj, U. and Kaur, R. 2017. Chemistry and biological activities of *Anethum graveolens* L. (dill) essential oil: a review. *Journal of Pharmacognosy and Phytochemistry* **6**: 295-306.

P) or micronutrients (Zn, Cu, Fe, and MN), with the exception of Ca and Zn, the concentrations of which were significantly enhanced in dill and parsley, respectively. Consequently, in light of all of the above findings, it should come as no surprise that Saleh *et al*. conclude that "manipulation of elevated CO_2 as a strategy to improve the growth and nutritional and health benefits of herbal plants is worthwhile."

Moving on, Onion (*Allium cepa*) is a key global food crop with over 80 million tons produced annually. It is also increasingly recognized for its medicinal properties, which may hold certain benefits for human health (Cheng *et al*., 2013).[229] Consequently, there is much interest in improving the growth and yield of this important crop; and scientists have begun to examine ways to do just that.

One of the latest groups to conduct such a study was that of Bettoni *et al*. (2017),[230] who investigated the responses of yellow onion (cv. Alfa São Francisco-Cycle VIII) to three growth-influencing variables, including (1) an agronomic effect (with or without application of humic acids), (2) an environmental factor (normal or elevated atmospheric CO_2 levels; 360 or 700 ppm, respectively), and (3) a biotic influence (with or without inoculation of mycorrhizal fungi). The onions were all grown from seed and placed in greenhouses under various combinations of the three growth-related factors. And what did their experiment reveal?

Mycorrhizal inoculation was shown to have a mixed influence on onion growth, whereas the application of humic acid always enhanced it. However, elevated CO_2 appeared to exert the most significant influence of the three variables examined, increasing photosynthetic activity and both the fresh and dry weights of the onion bulbs, as well as the bulb concentrations of starch (from 10 to 146%), total soluble sugars (from 48 to 67%), total soluble proteins (from 86 to 293%) and soluble phenolics (from 7 to 30%). These increases in sugars and proteins, according to Bettoni *et al*., "enhanced the energetic value of [the] onions," while "the increase in phenolics improved their antioxidant properties."

In commenting on these several findings, the authors say their results confirm the facts that onion bulb quality and yield can be significantly enhanced by agronomic, environmental and biotic factors, principally by raising the CO_2 content of the air, as they observed here. But the end of the good news does not stop there, as the researchers note that elevated CO_2 also increased the ratio between soluble solids and total titratable acidity, which increase, they say, "may enhance the perception of sweetness and make onions more pleasant for consumption." Thus, by simply adding more CO_2, a simple onion was transformed into a larger, more nutritious and more tasteful vegetable!

---

[229] Cheng, A., Chen, X., Jin, Q., Wang, W., Shi, J. and Liu, Y. 2013. Comparison of phenolic content and antioxidant capacity of red and yellow onions. *Czech Journal of Food Sciences* **31**: 501-508.

[230] Bettoni, M.M., Mogor, A.F., Pauletti, V. and Goicoechea, N. 2017. The interaction between mycorrhizal inoculation, humic acids supply and elevated atmospheric CO_2 increases energetic and antioxidant properties and sweetness of yellow onion. *Horticulture, Environment, and Biotechnology* **58**: 432-440.

In yet another study, recognizing that "more CO_2 is beneficial to plant growth because plants feed on CO_2," Fu *et al*. (2015)[231] say they "tested the effect of CO_2 levels from 400 to 5,000 ppm on the yield and antioxidant capacity of Chinese cabbage, *Brassica chinensis*, and lettuce, *Lactuca sativa*." In doing so, they grew the plants hydroponically in half-strength Hoagland's solution under high-pressure sodium lamps in growth chambers maintained at CO_2 concentrations of 400 ppm (ambient) and 1,000, 2,000, 3,000 and 5,000 ppm (enriched) for 40 days, after which the plants' shoot and root fresh weights were determined, along with their total antioxidant concentrations.

This work revealed, as the eight Chinese scientists report, that "the best harvest biomass occurred at 2,000 [ppm] of CO for Chinese cabbage and 2000–3000 [ppm] CO for lettuce," where the fresh weights of shoot and root biomass in Chinese cabbage were each increased by approximately 60 percent, whereas lettuce plants experienced a larger 73 and 91 percent increase in shoot and root fresh weight, respectively. In addition, Fu *et al*. found that "the antioxidant components in both vegetables containing polyphenols, flavonoids and vitamin C were higher at CO_2 ranging from 1,000 to 3,000 ppm than those at the ground level of CO_2 [400 ppm] with the largest contents at 2,000 and/or 3,000 ppm CO_2" (see Figure III.A.6.i.3), which concentrations are fully 2.5 to 7.5 times greater than the atmospheric CO_2 concentration of today. The much smaller rise of atmospheric CO_2 that is predicted for the end of this century (approximately 700 ppm) will thus provide only a *portion* of the benefits that this magnificent molecule *could* bestow on these two plants were the concentration to rise even higher.

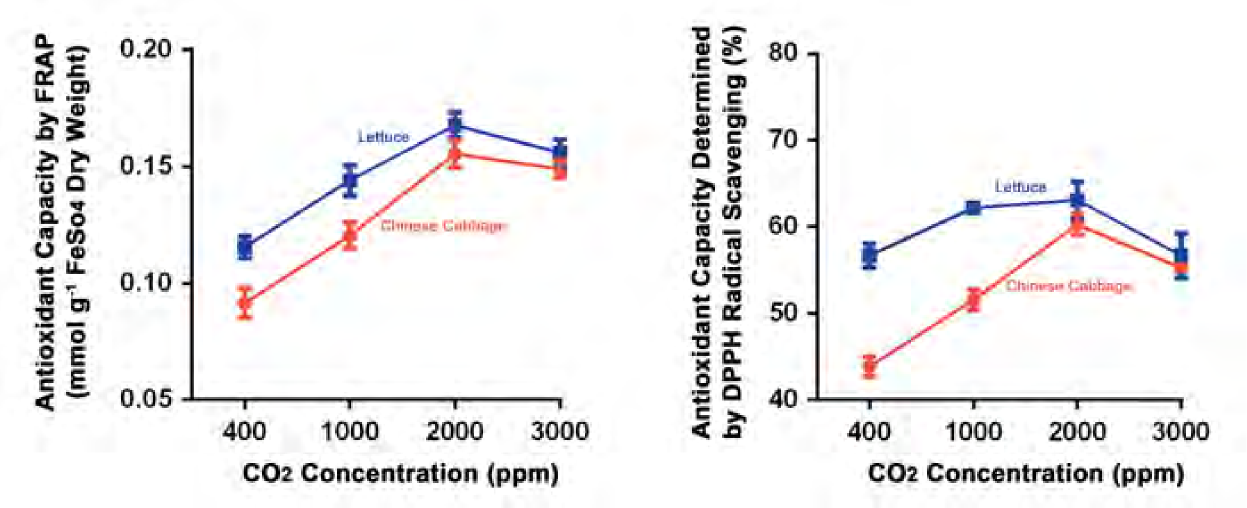


Figure III.A.6.i.3. *An evaluation of the total antioxidant capacity of Chinese cabbage and lettuce in response to the increase in CO_2 concentration by using the FRAP assays (left panel) well as measuring the clearance rate of DPPH free radicals (right panel). FRAP is the abbreviation of ferric ion reducing antioxidant potential, DPPH is the abbreviation of diphenyl-picryl-hydrazylhydrate.*

---

[231] Fu, Y., Shao, L., Liu, H., Li, H., Zhao, Z., Ye, P., Chen, P. and Liu, H. 2015. Unexpected decrease in yield and antioxidants in vegetable at very high CO_2 levels. *Environmental Chemistry Letters* **13**: 473-479.

Working with four soybean cultivars (Zhongke-maodou 1, Zhongke-maodou 2, Zhongke-maodou 3 and Hei-maodou), Li *et al*. (2018)[232] assessed the effects of elevated CO_2 on the nutritional quality of soybean seeds at the fresh edible (R6) and mature (R8) stages of growth. In particular, they examined changes in crude protein, oil, isoflavones, free amino acids, fatty acids and mineral elements. Plants were grown in pots in open-top chambers at the Northeast Institute of Geography and Agroecology at the Chinese Academy of Sciences, Harbin, China, at either 390 or 550 ppm atmospheric CO_2 concentrations during the growing season under well-watered and fertilized conditions.

Results from the study revealed that soybean "is likely to benefit from the accumulation of seed fat and isoflavone" under elevated CO_2. With respect to the accumulation of seed fat, Li *et al*. write that elevated CO_2 "consistently increased oleic acid (18:1) concentrations by decreased linoleic acid (18:2) concentrations at R6 and R8," which finding "indicates that elevated CO_2 improves soybean oil quality, with potential benefits for human health," while also noting that high levels of oleic acid "enhance the oxidative stability of soybean oil, giving it a longer shelf life." With respect to the accumulation of isoflavone, the scientists state that "the increase in isoflavone concentration of soybean observed in response to elevated CO_2 suggests improved nutritional value of soybean under the scenario of rising CO_2 levels," explaining that "foods with high levels of isoflavone have been recommended by the U.S. Food and Drug Administration" due to the "health-promoting effects of isoflavones on human vasomotor symptoms, the cardiovascular system, the breast, uterus, bone, and cognition," citing the works of Morrison *et al*. (2008)[233] and Clarkson *et al*. (2011).[234]

Finally, in review on the topic, Dong *et al*. (2018)[235] examined 57 published works, which included CO_2 enrichment studies on root vegetables (carrot, radish, sugar beet and turnip), stem vegetables (broccoli, celery celtuce, Chinese kale, ginger, onion, potato and scallion), leafy vegetables (cabbage, Chinese cabbage, chives, fenugreek, Hongfengcat, lettuce, oily sowthistle, palak and spinach) and fruit vegetables (cucumber, hot pepper, strawberry, sweet pepper and tomato). The specific focus of their analysis was to examine measurements of nutritional quality on the vegetables, including measurements of soluble sugars, organic acids, protein, nitrates, antioxidants and minerals.

The results of the analysis revealed a CO_2-induced stimulation of soluble sugar accumulation in the edible parts of vegetables. Quantitatively, Dong *et al*. report that elevated CO_2 "increased the concentrations of fructose, glucose, total soluble sugar, total antioxidant capacity, total phenols,

---

[232] Li, Y., Yu, Z., Jin, J., Zhang, Q., Wang, G., Liu, C., Wu, J., Wang, C. and Liu, X. 2018. Impact of elevated CO_2 on seed quality of soybean at the fresh edible and mature stages. *Frontiers in Plant Science* **9**: Article 1413, doi: 10.3389/fpls.2018.01413.

[233] Morrison, M.J., Cober, E.K., Saleem, M.F., McLaughlin, N.B., Fregeau-Reid, J., Ma, B.L., Yan, W., and Woodrow, L. 2008. Changes in isoflavone concentration with 58 years of genetic improvement of short-season soybean cultivars in Canada. *Crop Science* **48**: 2201-2208.

[234] Clarkson, T.B., Utian, W.H., Barnes, S., Gold, E.B., Basaria, S.S., Aso, T., *et al*. 2011. The role of soy isoflavones in menopausal health: report of The North American Menopause Society/Wulf H. Utian Translational Science Symposium in Chicago, IL (October 2010). Menopause: *The Journal of the North American Menopause Society* **18**: 732-753.

[235] Dong, J., Gruda, N., Lam, S.K., Li, X. and Duan, Z. 2018. Effects of elevated CO_2 on nutritional quality of vegetables: A review. *Frontiers in Plant Science* **9**: Article 924, doi: 10.3389/fpls.2018.00924.

total flavonoids, ascorbic acid, and calcium in the edible part of vegetables by 14.2%, 13.2%, 17.5%, 59.0%, 8.9% 45.5%, 9.5%, and 8.2%, respectively, but [that it] decreased the concentrations of protein, nitrate, magnesium, iron, and zinc by 9.5%, 18.0%, 9.2%, 16.0%, and 9.4%. The concentrations of titratable acidity, total chlorophyll, carotenoids, lycopene, anthocyanins, phosphorus, potassium, sulfur, copper, and manganese were not affected" (see Figure III.A.6.i.4).

In commenting on their findings, Dong *et al*. say that "overall, elevated CO_2 promotes the accumulation of antioxidants in vegetables, thus improving vegetable quality," while adding that the CO_2-induced stimulation of total antioxidant capacity, total phenols, total flavonoids, ascorbic acid, and chlorophyll b indicate "an improvement of beneficial compounds in vegetables." And for those concerned about the decreases in protein, nitrate, magnesium, iron, and zinc that were also observed in the meta-analysis, these slight declines can be reduced, if not reversed, through the application of several management approaches that were investigated and discussed by the authors, including "(1) selecting vegetable species or cultivars that possess greater ability in carbon fixation and synthesis of required quality-related compounds; (2) optimizing other environmental factors (e.g., moderate CO_2 concentrations, moderate light intensity, increased N availability, or increased fertilization of Fe or Zn) to promote carbon fixation and nutrient uptake interactively when growing plants under elevated CO_2; (3) harvesting vegetable products earlier in cases of over maturity and reduced benefit of elevated CO_2 to vegetative growth; and (4) combining elevated CO_2 with mild environmental stress (e.g., ultraviolet-B radiation or salinity) in instances when this enhances vegetable quality and might counteract the dilution effect or direct metabolic pathways toward the synthesis of health-beneficial compounds."

All in all, it would therefore appear that CO_2-induced plant nutritional enhancements far outweigh any CO_2-induced plant nutritional declines. Thus, it can reasonably be concluded that rising atmospheric CO_2 concentrations will yield future health benefits to both human and animal plant consumers.

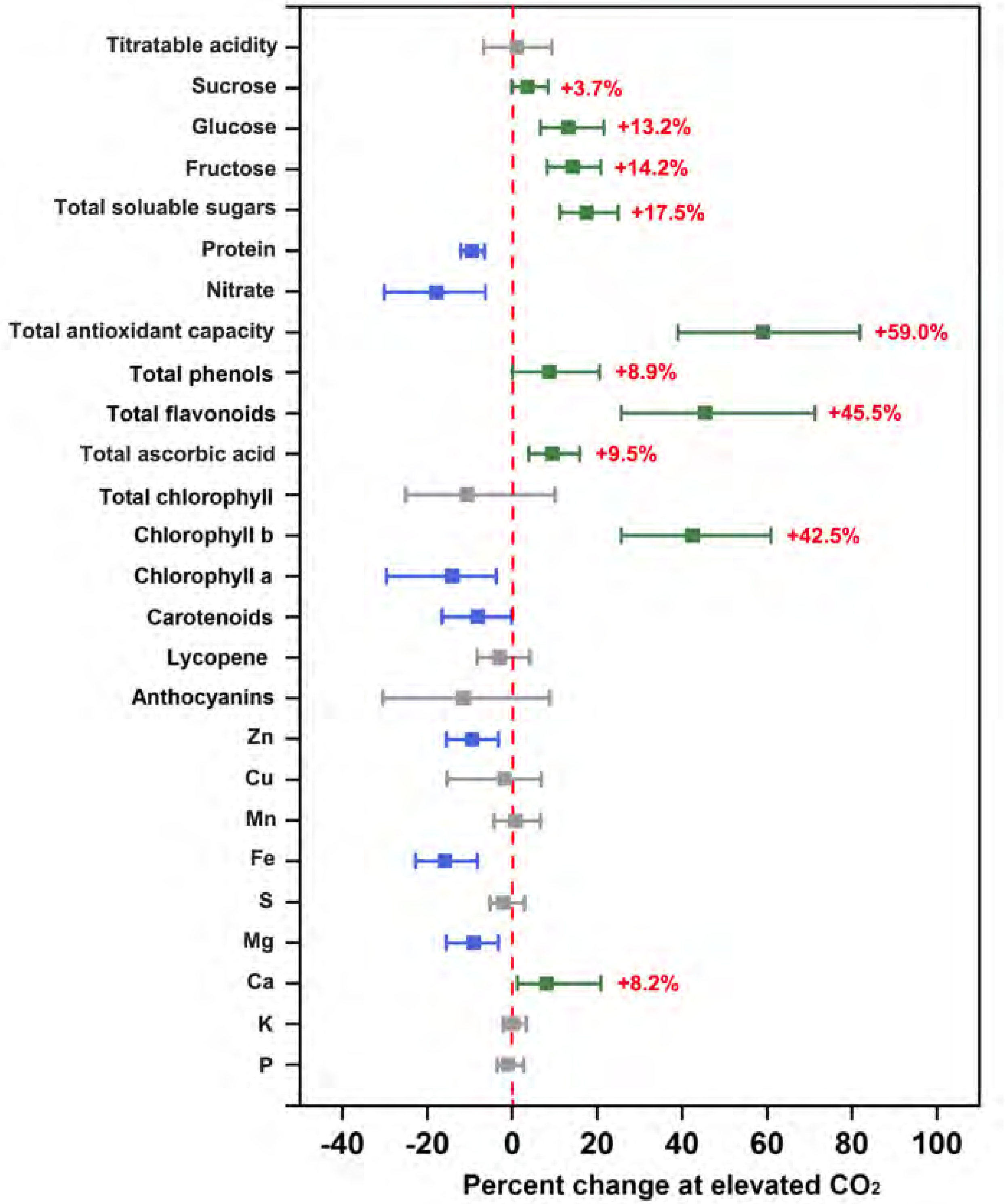


Figure III.A.6.i.4. *Effects of elevated* CO_2 *on the concentrations of various plant compounds and minerals in vegetables. Data are means of percent change (relative to ambient* CO_2*) with 95% confidence intervals. Green squares and error bars represent positive changes, blue negative changes, and grey indicate no significant change.*

Information on additional peer-reviewed scientific studies on the nutritional quality of plants can be accessed by clicking on the links below, or from under the heading of Antioxidants (http://www.co2science.org/subject/a/antioxidants.php), Health Effects (http://www.co2science.org/subject/h/subject_h.php), or Nutrition (http://www.co2science.org/subject/n/nutrition.php).

Antioxidants

Health Effects
- CO2
  - Health-Harming Substances
  - Health-Promoting Substances
    - Common Food Plants
    - Wines
  - Other

Nutrition

(ii) Medicinal Plant Properties

In prefacing their work, Kaundal *et al*. (2018)[236] note that Indian valerian (*Valeriana jatamansi*) is an important medicinal and aromatic herb that grows in steep, rocky and moist areas with sandy loam soil from Afghanistan to southwest China, and into India, Nepal, Bhutan and Burma. The herb is known for its essential oil extracted from its rhizomes and roots, which oils are in high demand in "flavor, pharmaceutical and perfumery industries [where] about 30 products [using the oil] are commercially available." In particular, the roots of the plant are "used for treating ulcers, convulsions, jaundice, cardiac debility, dry cough, asthma, seminal weakness, skin diseases, leprosy, general debility and for sleep enhancement." Unfortunately, the authors report that due to the high demand of Indian valerian's essential oil, this plant "is on the verge of becoming extinct" because of "over-exploitation of underground parts for its medicinal value."

Because rising levels of atmospheric CO_2 typically promote plant photosynthesis and the production of secondary compounds, it stands to reason that the essential oil content of Indian valerian would also be augmented under elevated CO_2, which increase could bode well for the survival of this important medicinal species. And so it was the objective of the three Indian researchers to examine the impact of elevated CO_2 on the essential oil content of *V. jatamansi*. The experiment was conducted in Palampur, India, at the research farm of the CSIR-Institute of Himalayan Bioresource Technology over the period November 2013 to March 2015. Plant seedlings (cv. Himbala) were sown in pots and subjected to ambient (390 ppm) or elevated (550 ppm) CO_2 conditions in a free-air CO_2-enrichment (FACE) environment. At the end of the

---

[236] Kaundal, M., Bhatt, V. and Kumar, R. 2018. Elevated CO_2 and temperature effect on essential oil content and composition of *Valeriana jatamansi* Jones. with organic manure application in a western Himalayan region. *Journal of Essential Oil Bearing Plants* **21**: 1041-1050.

experiment, root samples were extracted so that the impact of elevated CO_2 on the essential oil content could be determined.

The results of the study are shown in Figure III.A.6.ii.1, which reveals that elevated CO_2 stimulated the essential oil content of Indian valerian by 17.7%, indicating in the words of the authors that "elevated CO_2 in the future could have [a] positive effect." And that is great news for this endangered plant and for those who benefit from using its essential oil.

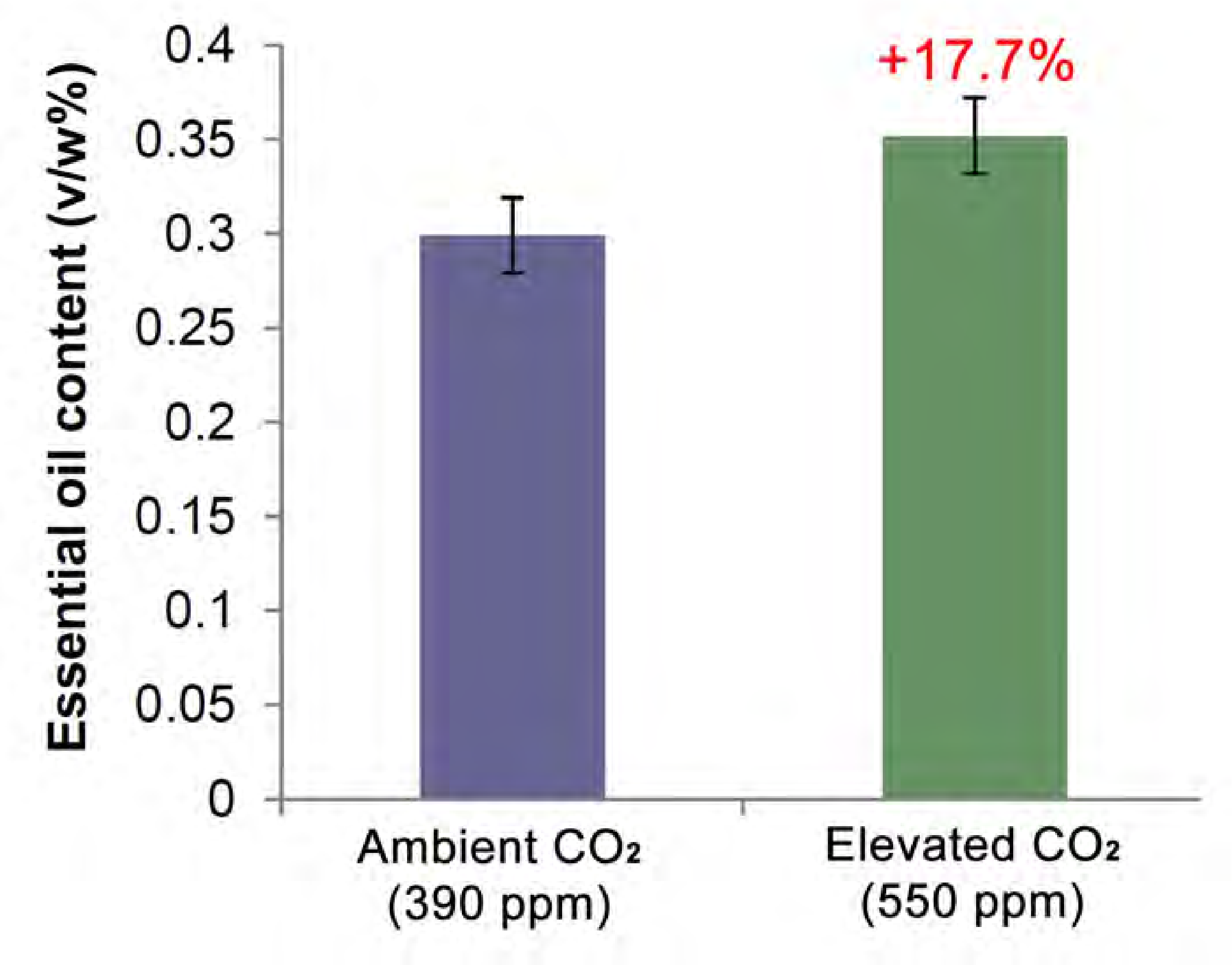


***Figure III.A.6.ii.1**. Effect of elevated CO_2 on the essential oil content of V. jatamansi.*

In another study, Al Jaouni *et al*. (2018)[237] investigated how elevated CO_2 could improve the growth and medicinal value of two commonly used herbs (basil and peppermint). To accomplish this objective, the researchers grew basil (*Ocimum basilicum*) and peppermint (*Mentha piperita*) plants from seed in controlled environment chambers under well-watered and well-fertilized conditions over a period of four weeks under either ambient (360 ppm) or elevated (620 ppm)

---

[237] Al Jaouni, S., Saleh, A.M., Wadaan, M.A.M., Hozzein, W.N., Selim, S. and AbdElgawad, H. 2018. Elevated CO2 induces a global metabolic change in basil (*Ocimum basilicum* L.) and peppermint (*Mentha piperita* L.) and improves their biological activity. *Journal of Plant Physiology* **224-225**: 121-131.

levels of atmospheric CO_2. Then, at the end of their month-long experiment, they collected and analyzed information on several growth-related and medicinal properties of the plants, noting, with regard to the latter, that both of these herbs are "well recognized for their antioxidant, anti-microbial, anti-inflammatory, anti-allergenic and anticancer properties.[238,239,240]"

In describing their findings, Al Jaouni *et al*. report that "elevated CO_2 significantly increased herbal biomass [by over 40%], improved the rates of photosynthesis and dark respiration, and altered the tissue chemistry." Metabolite profiling of both herbs further revealed that "the levels of non-structural carbohydrates, fumarate, glutamine, glutathione, ascorbate, phylloquinone (vitamin K1), anthocyanins and a majority of flavonoids and minerals were significantly improved by elevated CO_2." Lastly, the researchers found that elevated CO_2 "caused enhancement in antioxidant, antiprotozoal, anti-bacterial and anticancer (against urinary bladder carcinoma; T24P) activities in both plants."

The results of this study are quite encouraging, demonstrating the ability of rising atmospheric CO_2 to not only increase the growth and biomass of these two herbs, but to also improve their medicinal value.

Moving along, the tea plant (*Camellia sinensi*s) is a small evergreen shrub cultivated for the production of tea. Green tea is one form of drink that is derived from two leaves and a bud of *C. sinensis*. It is consumed around the world for its pleasant taste and health benefits, which are predominately derived from two groups of chemicals: polyphenols (in particular, catechins) and amino acids (chiefly theanine). Known health benefits of green tea include chemicals that help prevent cancer and other cardiovascular and neurodegenerative diseases, reduce high blood pressure, improve relaxation and inhibit the side effects of caffeine.

Despite the aforementioned benefits of *C. sinensis*, authors Li *et al*. (2017)[241] report that the effect of elevated CO_2 on the growth of tea plants and their production of primary and secondary metabolites linked to tea quality has not yet been examined, an omission they set out to rectify. More specifically, the team of nine Chinese scientists grew tea plants in controlled environment chambers for a period of 24 days under ambient (380 ppm) or elevated (800 ppm) concentrations of atmospheric CO_2, during which time they measured a number of primary metabolic processes related to photosynthesis and growth. In addition, they analyzed the concentrations of various polyphenols and amino acids to determine the impact of CO_2 enrichment on tea quality.

And what did their analyses reveal?

---

[238] Lv, J., Huang, H., Yu, L., Whent, M., Niu, Y., Shi, H., Wang, T.T.Y., Luthria, D., Charles, D. and Yu, L.L. 2012. Phenolic composition and nutraceutical properties of organic and conventional cinnamon and peppermint. *Food Chemistry* **132**: 1442-1450.

[239] Riachi, L.G. and De Maria, C.A.B. 2015. Peppermint antioxidants revisited. *Food Chemistry* **176**: 72-81.

[240] Szymanowska, U., Zlotek, U., Karas, M. and Baraniak, B. 2015. Anti-inflammatory and antioxidative activity of anthocyanins from purple basil leaves induced by selected abiotic elicitors. *Food Chemistry* **172**: 71-77.

[241] Li, X., Zhang, L., Ahammed, G.J., Li, Z.-X., Wei, J.-P., Shen, C., Yan, P., Zhang, L.-P. and Han, W.-Y. 2017. Stimulation in primary and secondary metabolism by elevated carbon dioxide alters green tea quality in *Camellia sinensis* L. *Scientific Reports* **7**: 7937, DOI:10.1038/s41598-017-08465-1.

Li *et al*. report that elevated CO_2 stimulated net photosynthesis by 142, 122, 137 and 88 percent on days 6, 12, 18 and 24 of the study, respectively. Growth and biomass accumulation also benefited from higher levels of CO_2. At the end of the experiment, for example, plant height and leaf, stem, shoot and root dry weights in the CO_2-enriched chambers were 14, 46, 25, 34 and 68 percent higher, respectively, than their ambient counterparts. In addition, elevated CO_2 increased the concentration of sugar, sucrose and starch in tea plant leaves.

With respect to tea *quality* attributes, the scientists determined that elevated CO_2 increased tea polyphenol, catechins, and amino acid concentrations by 28, 21 and 13 percent, respectively, while it decreased caffeine concentration by 24 percent (see Figure III.A.6.ii.2). Such observations, in the words of the authors, are to be considered "a sign of good quality."

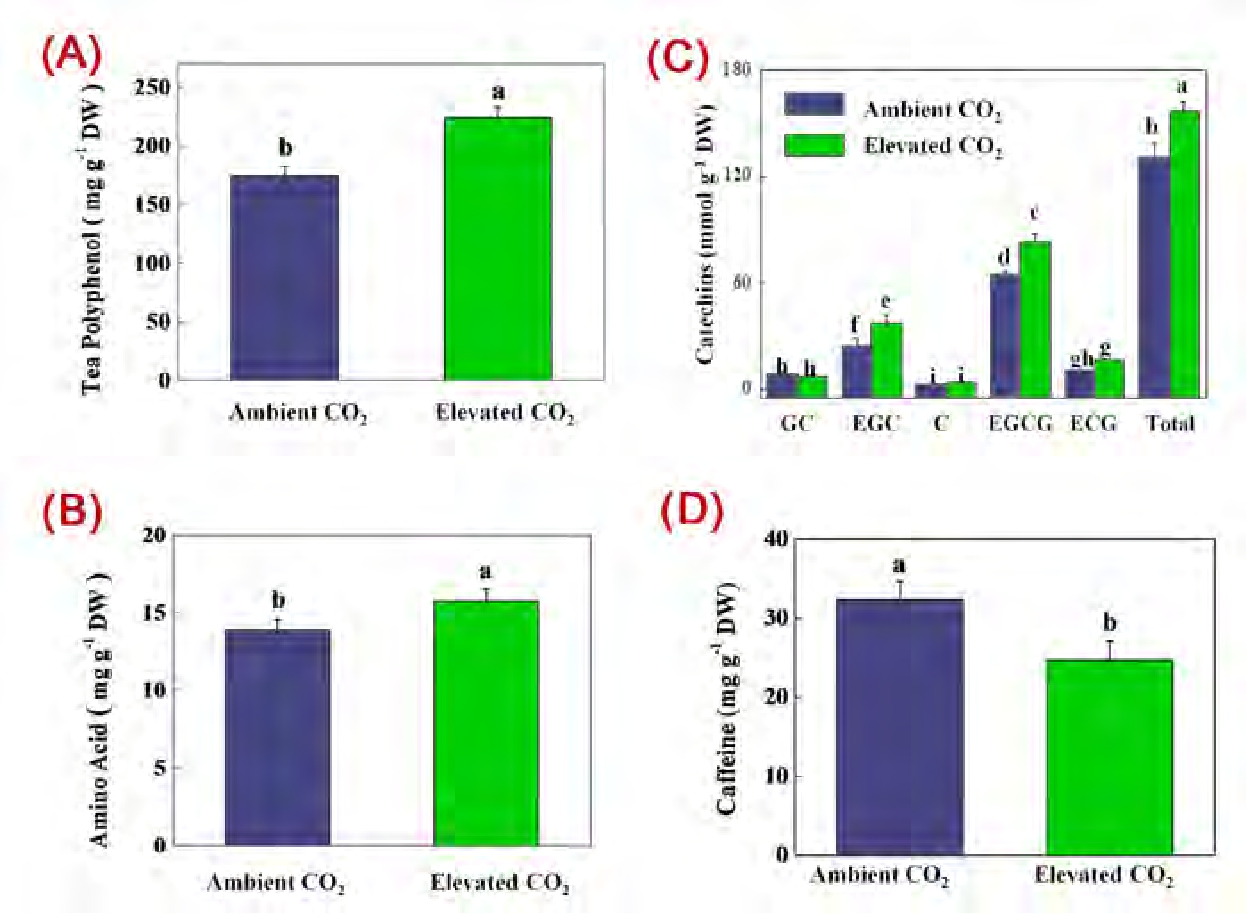


Figure III.A.6.ii.2. *Changes in polyphenol (Panel A), amino acid (Panel B), catechin (Panel C) and caffeine (Panel D) concentrations in leaves of tea seedlings grown at ambient (380 ppm) or elevated CO_2 concentrations (800 ppm). Leaf samples were harvested after exposure of tea plants to different concentrations of atmospheric CO_2 for 24 days. Data are the means of four replicates (± SD). Means denoted by different letters indicate significant differences between the treatments ($P < 0.05$).*

In further commenting on their several findings, Li *et al*. say their results indicate that rising CO_2 "not only improves primary metabolism, but also promotes secondary metabolism towards production of a quality green tea." In the future, therefore, increasing levels of atmospheric CO_2 will (1) stimulate the growth and development of *C. sinensis*, (2) enhance the production of health-benefiting substances in its leaves and (3) restrict a well-known health-harming one (caffeine).

According to Saldanha *et al*. (2014),[242] "*Pfaffia glomerata* (*fafia, ginseng brasileiro*), a medicinal plant that naturally grows in Brazil (Pott and Pott, 1994),[243] has great economic importance due to the production of secondary metabolites such as ß-ecdysone (20E),[244]" as a result of its "anabolic, analgesic, anti-inflammatory, anti-mutigenic, aphrodisiac, sedative and muscle tonic properties," which are described by Neto *et al*. (2005),[245] Fernandes *et al*. (2005),[246] Festucci-Buselli *et al*. (2008)[247] and Mendes (2011).[248] As a result of these facts, Saldanha *et al*. report that "many patents related to pharmacological and nutritional properties of genus *Pfaffia* have been published," citing Shibuya *et al*. (2001),[249] Bernard and Gautier (2005),[250] Olalde (2008),[251] Rangel (2008),[252] Loizou (2009)[253] and Higuchi (2011).[254] Not surprisingly, therefore, Saldanha *et al*. further note that "because of its economic relevance, the propagation of *P. glomerata* plays an essential role in producing raw material for the pharmaceutical industry," citing Saldanha *et al*. (2013).[255] Against this backdrop, using two types of explant supports—either agar or Florialite (a mixture of vermiculite and cellulose)—the nine Brazilian scientists

---

[242] Saldanha, C.W., Otoni, C.G., Rocha, D.I., Cavatte, P.C., Detmann, K. da S.C.,, Tanaka, F.A.O., Dias, L.L.C., DaMatta, F.M. and Otoni, W.C. 2014. CO2-enriched atmosphere and supporting material impact the growth, morphophysiology and ultrastructure of in vitro Brazilian-ginseng [*Pfaffia glomerata* (Spreng.) Pedersen] plantlets. *Plant Cell, Tissue and Organ Culture* **118**: 87-99.

[243] Pott, A. and Pott, V.S. 1994. Plantas do pantanal. Embrapa-SPI, Corumba, p. 320.

[244] Festucci-Buselli, R.A., Contim, L.A.S., Barbosa, L.C.A., Stuart, J.J. and Otoni, W.C. 2008. Biosynthesis and potential functions of the ecdysteroid 20-hydroxyecdysone - a review. *Botany* **86**: 978-987.

[245] Neto, A.G., Costa, J.M.L.C., Belati, C.C., Vinholis, A.H.C., Possebom, L.S., Silva Filho, A.A., Cunha, W.R., Carvalho, J.C.T., Bastos, J.K. and Silva, M.L.A. 2005. Analgesic and anti-inflammatory activity of a crude root extract of *Pfaffia glomerata* (Spreng) Pedersen. *Journal of Ethnopharmacology* **96**: 87-91.

[246] Fernandes, J.F.O., Brito, L.C.,Frydman, J.N.G., Santos-Filho,S.D. and Bernado-Filho, M. 2005. An aqueous extract of *Pfaffia* sp. does not alter the labeling of blood constituents with technetium-99 and the morphology of the red blood cells. *Revista Brasileira de Farmacognosia* **15**: 126-132.

[247] Festucci-Buselli, R.A., Contim, L.A.S., Barbosa, L.C.A., Stuart, J.J. and Otoni, W.C. 2008. Biosynthesis and potential functions of the ecdysteroid 20-hydroxyecdysone - a review. *Botany* **86**: 978-987.

[248] Mendes, F.R. 2011. Tonic, fortifier and aphrodisiac: adaptogens in the Brazilian folk medicine. *Revista Brasileira de Farmacognosia* **21**: 754-763.

[249] Shibuya, T., Ario, T. and Fukuda, S. 2001. Composition. *United States Patent*. US 6224872.

[250] Bernard, B. and Gautier, B. 2005. Use of ecdysteroids for preparing dermatological or cosmetological anti-hair loss compositions. *United States Patent*, US 0137175 AI.

[251] Olalde, J.A. 2008. Multiple sclerosis synergistic phyto-nutraceutical composition. *United States Patent*. US 0081046 AI.

[252] Rangel, J.A.O. 2008. Menopause disorder synergistic phyto-nutraceutical composition. *United States Patent*, US 7381432.

[253] Loizou, N.C. 2009. Health supplement. *United States Patent*, US 0110674 AI.

[254] Higuchi, M.L. 2011. Compositions for inhibiting atherosclerosis. *United States Patent*, US 7914781 B2.

[255] Saldanha, C.W., Otoni, C.G.,Notini,M.M., Kuki, K.N., Cruz, A.C.F., Rubio Neto, A., Dias, L.L.C. and Otoni, W.C. 2013. A CO_2-enriched atmosphere improves in vitro growth of Brazilian ginseng [*Pfaffia glomerata* (Spreng.) Pedersen]. *In Vitro Cellular and Developmental Biology - Plant* **49**: 433-444.

grew plantlets of *P. glomerata* in vitro within small acrylic chambers maintained at either 360 or 1,000 ppm CO_2 for a period of 35 days, after which they assessed the plants' aerial and root dry mass, as well as the accumulation of 20E in their leaves and stems.

In discussing their findings, Saldanah *et al*. report that the extra 640 ppm of CO_2 increased the aerial dry mass of the plantlets by 246% in the agar treatment and by 219% in the Florialite treatment, while it increased the root dry mass by 100% and 443% in the agar and Florialite treatments, respectively. In addition, they say that "the plants with a higher biomass also produced higher amounts of 20E." And in light of these findings Saldanah *et al*. state in the concluding sentence of their paper that their study highlights the fact that "a photoautotrophic system under CO_2 enrichment may be attractive for the achievement of autotrophy by CO_2, thus potentially being useful for the large-scale commercial production of *Pfaffia* seedlings or even for producing *Pfaffia* biomass containing high levels of ß-ecdysone." And that would help the pharmaceutical industry to produce a lot more of the medicinal products derived from this plant.

Writing as background for their work, Stutte *et al*. (2008)[256] say that "Scutellaria is a genus of herbaceous perennials of the Lamiaceae that includes several species with purported medicinal properties," citing Sato *et al*. (2000),[257] Joshee *et al*. (2002),[258] Awad *et al*. (2003)[259] and Bonham *et al*. (2005).[260] More particularly, they note that leaf extracts of *Scutellaria barbata* "have been used in traditional Chinese medicine to treat liver and digestive disorders and cancers," citing Molony and Molony (1998);[261] and they report that "research has shown extracts of *S. barbata* to be limiting to the growth of cell lines associated with lung, liver, prostate and brain tumors," citing Yin *et al*. (2004).[262] Likewise, they add that extracts of *Scutellaria lateriflora* and the isolated flavonoids from its extracts have also been shown to have anti-oxidant, anti-cancer and anti-viral properties.[263]"

In one final study of note in this section, Stutte *et al*. conducted a set of experiments "to determine the effects of CO_2 enrichment on the growth of *S. lateriflora* and *S. barbata* and on

---

[256] Stutte, G.W., Eraso, I. and Rimando, A.M. 2008. Carbon dioxide enrichment enhances growth and flavonoid content of two *Scutellaria* species. *Journal of the American Society of Horticultural Science* **133**: 631-638.

[257] Sato, Y., Suzaki, S., Nishikawa, T., Kihara, M., Shibata, H. and Higuti, T. 2000. Phytochemical flavones isolated from *Scutellaria barbata* and antibacterial activity against methicillin-resistant *Staphylococcus aureus*. *Journal of Entnopharmocology* **72**: 483-488.

[258] Joshee, N., Patrick, T.S., Mentreddy, R.S. and Yadav, A.K. 2002. Skullcap: Potential medicinal crop. In: Janick, J. and Whipkey, A. (Eds.). *Trends in New Crops and New Uses*. ASHS Press, Alexandria, Virginia, USA, p. 58-586.

[259] Awad, R., Arnason, J.T., Trudeau, V., Bergeron, C., Budziinski, J.W., Foster, B.C. and Merali, Z. 2003. Phytochemical and biological analysis of skullcap (*Scutellaria lateriflora* L.): A medicinal plant with anxiolytic properties. *Phytomedicine* **10**: 640-649.

[260] Bonham, M., Posakony, J., Coleman, L., Montgomery, B., Simon, J. and Nelson, P.S. 2005. Characterization of chemical constituents in *Scutellaria baicalensis* with antiondrogenic and growth-inhibitory activities towards prostate carcinoma. *Clinical Cancer Research* **11**: 3905-3914.

[261] Molony, D. and Molony, M.M.P. 1998. *The American Association of Oriental Medicines Complete Guide to Chinese Herbal Medicine*. Berkley Publishing Group, New York, New York, USA.

[262] Yin, X., Zhou, J., Jie, C., Xing, D. and Zhang, Y. 2004. Anticancer activity and mechanism of *Scutellaria barbata* extract on human lung cancer cell line A549. *Life Sciences* **75**: 2233-2244.

[263] Awad, R., Arnason, J.T., Trudeau, V., Bergeron, C., Budziinski, J.W., Foster, B.C. and Merali, Z. 2003. Phytochemical and biological analysis of skullcap (*Scutellaria lateriflora* L.): A medicinal plant with anxiolytic properties. *Phytomedicine* **10**: 640-649.

production of six bioactive flavonoids, apigenin, baicalin, baicalein, chrysin, scutellarein and wogonin that have been reported to have anti-cancer and anti-viral properties (reviewed in Cole *et al*., 2007;[264] Joshee *et al*., 2002)[265].” Results indicated that “both species showed an increased growth rate and total biomass in response to CO_2 enrichment from 400 to 1200 ppm CO_2, and time to flowering was accelerated by 7 to 10 days.” More specifically, they state that in the case of *S. barbata*, total flavonoid content increased 50% with enrichment of CO_2 to 1200 ppm and 81% with enrichment to 3000 ppm. And in the case of *S. lateriflora*, they say that “the total content of the measured bioactive flavonoids increased 2.4 times with enrichment to 1200 ppm CO_2, and 5.9 times with enrichment to 3000 ppm CO_2.”

In the concluding sentence of their paper’s abstract, Stutte *et al*. say “these results indicate that the yield and pharmaceutical quality of *Scutellaria* species can be enhanced with controlled environment production and CO_2 enrichment.” And they (the results) also indicate that the same can *qualitatively* be said for *Scutellaria* and other such plants *growing wild in the open air*, as its CO_2 concentration continues to gradually rise as a result of society’s continued burning of coal, gas and oil.

Information on additional peer-reviewed scientific studies on the medicinal properties of plants under elevated CO_2 can be accessed by clicking on this link: http://www.co2science.org/subject/h/co2healthmedicinal.php.

B. Human Benefits

It is undeniable that fossil energy initiated (and continues to sustain) the Industrial Revolution and the many human and environmental benefits that have emerged therefrom. Without adequate supplies of low-cost centralized energy, few, if any, of the major technological and innovative advancements of the past two centuries that have enhanced and prolonged human life could have occurred. Additionally, without the increased CO_2 emissions from fossil fuel use over the past two centuries, Earth’s terrestrial biosphere would be nowhere near as vigorous or productive as it is today. Rather, it would be devoid of the growth-enhancing, water-saving and stress-alleviating benefits it has reaped in managed and unmanaged ecosystems from rising levels of atmospheric CO_2 since the Industrial Revolution began.

The prior subsection examined such benefits are they pertain to the environment. The current section examines three such benefits as they pertain to humanity.

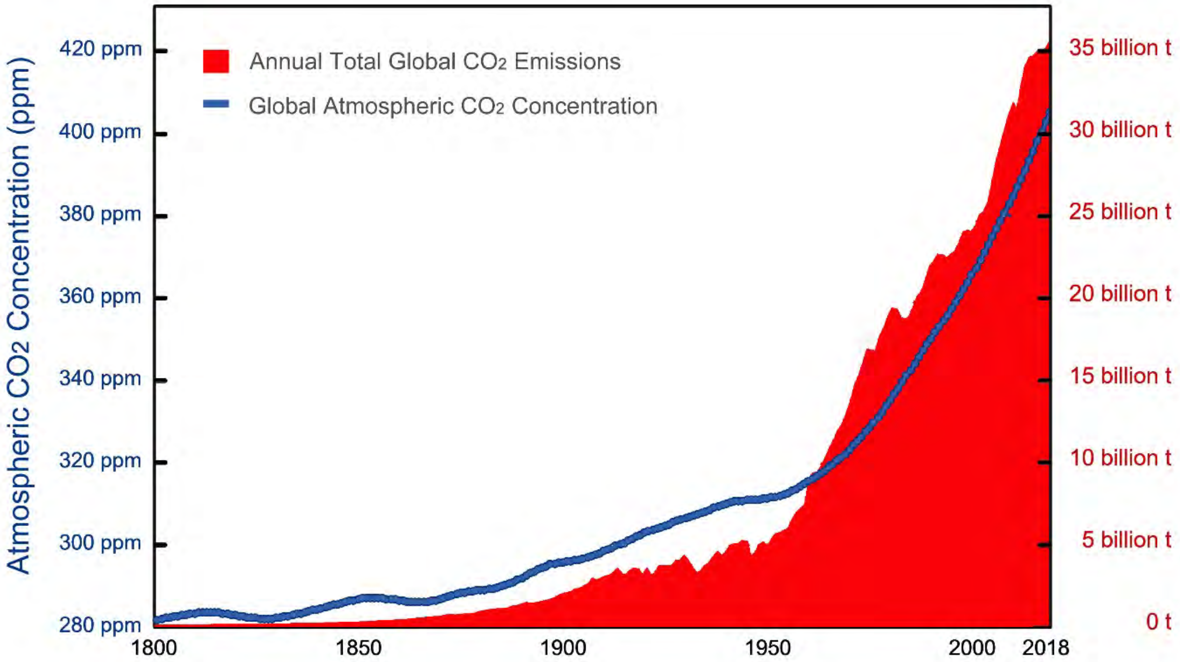
1. GDP

Perhaps the simplest yet most profound example of the many benefits that CO_2 emissions and fossil energy use afford humanity is witnessed in their relationship depicted in the following three figures.

---

[264] Cole, I.B., Saxena, P.K. and Murch,S.J. 2007. Medicinal biotechnology in the genus *scutellaria*. *In Vitro Cellular and Developmental Biology - Plant* **43**: 318-327.

[265] Joshee, N., Patrick, T.S., Mentreddy, R.S. and Yadav, A.K. 2002. Skullcap: Potential medicinal crop. In: Janick, J. and Whipkey, A. (Eds.). *Trends in New Crops and New Uses*. ASHS Press, Alexandria, Virginia, USA, p. 58-586.



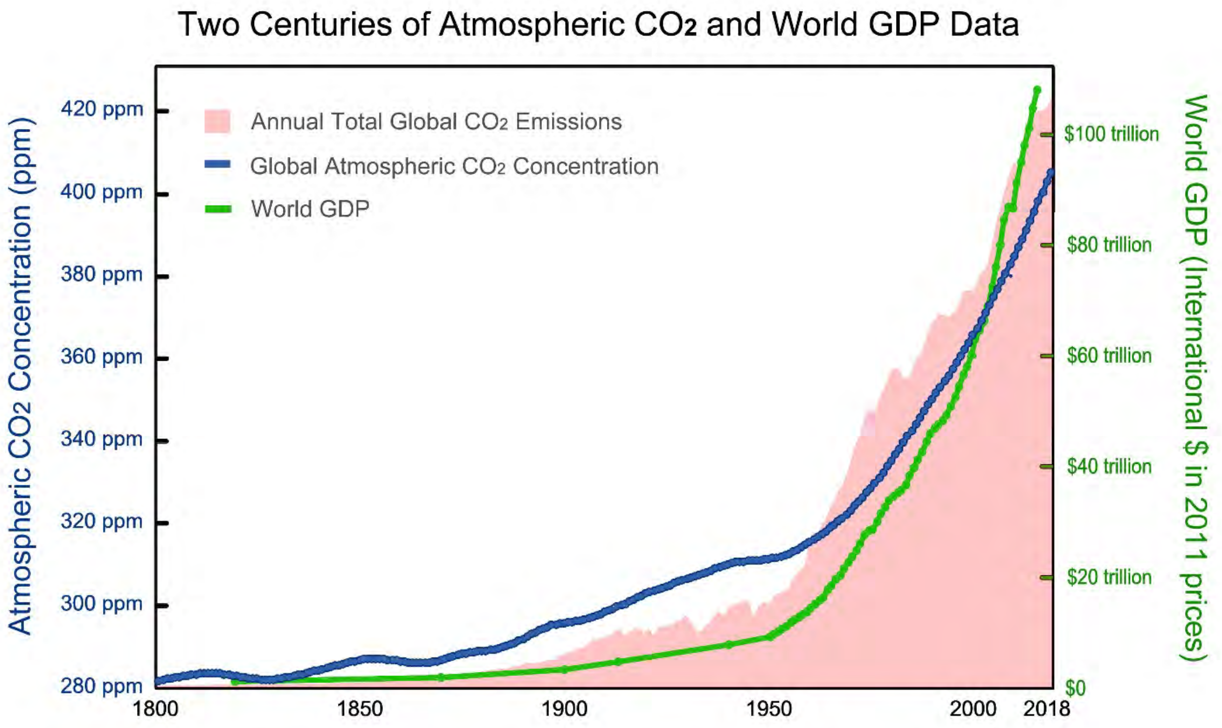
Sources: OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY OurWorldInData.org/economic-growth • CC BY OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY

Figure III.B.1.1*. Annual total global CO_2 emissions (shaded red area) and global atmospheric CO_2 concentration (blue line) from 1800 to 2018.*

Starting with Figure III.B.1.1, it is seen that, in the year 1800, global CO_2 emissions from fossil fuel use (the red shaded area of the figure) were essentially non-existent and they did not rise much over the course of the next century. However, by 1900, industrialization was well underway and CO_2 emissions began to rise in dramatic fashion with that industrialization, experiencing tremendous growth after the 1950s as countries all around the world expanded their use of fossil-derived energy in efforts to modernize and grow their economies.

Accompanying this increase in global CO_2 emissions over the past two centuries has been an equally impressive rise in the air's CO_2 content, which has increased from approximately 280 ppm in 1800 to a value of around 415 ppm today, illustrated by the blue line in Figure III.B.1.1.

In Figure III.B.1.2, a third time series of global gross domestic product, or GDP, is placed on top of the two CO_2 datasets in Figure III.B.1.1. Global GDP is a broad measure of the overall economic performance of the world economy. It represents the monetary value of all goods and services produced by the nations of the Earth in any given year. And, as illustrated by this composite image, it is seen that global GDP (the green line) is directly related to, and a beneficiary of, CO_2 emissions and the air's CO_2 content.



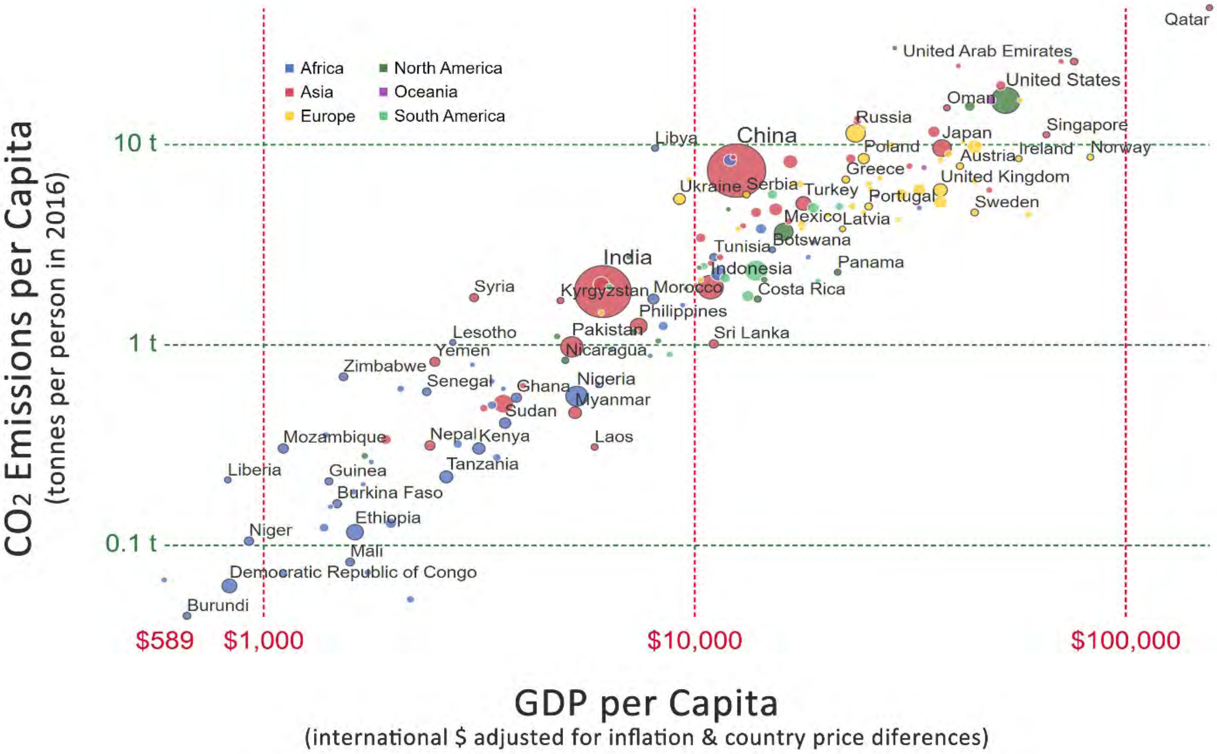
Sources: OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY OurWorldInData.org/economic-growth • CC BY OurWorldInData.org/co2-and-other-greenhouse-gas-emissions • CC BY

Figure III.B.1.2. *World GDP (green line) plotted with annual total global CO_2 emissions (shaded pink area) and global atmospheric CO_2 concentration (blue line) from 1800 to 2018.*

The positive relationship between CO_2 emissions and economic growth is also noted in this next figure on a county-wide or national level (Figure III.B.1.3). Here, per capita CO_2 emissions are plotted together with per capita GDP. Not surprisingly, countries with lower per capita CO_2 emissions have lower values of per capita GDP, whereas countries with higher per capita CO_2 emissions have higher per capita GDP.

Thus, nations that have embraced and increased their production of fossil energy have been amply rewarded with greater economic development and growth. Such economic prosperity, driven by fossil fuel utilization, has been proven over and over again throughout the past century as country after country has moved position along this graph from locations near the bottom left toward the upper right, as illustrated in this short animation for the United States.

In light of the relationships shown in the preceding figures, it is clear that the unprecedented global economic growth of the past two centuries that has lifted humanity to enjoy the innovations and comforts of the Modern Age occurred *because* of society's use of fossil fuels. Without adequate supplies of low-cost centralized energy, few, if any, of the major technological and innovative advancements of the past two centuries that have driven the Industrial Revolution and sustained and enhanced human life could have occurred.



Source: Global Carbon Project, Maddison (2017) OurWorldInData.org/co2-and-other-greenhouse-gas-emissions/ • CC BY

Figure III.B.1.3. *The relationship between country-wide per capita CO_2 emissions and per capita GDP. The population of a given country is depicted by the size of its circle.*

When considering and accounting for such benefits, plus the fact that *none* of the apocalyptic predictions of CO_2-induced climate catastrophe are coming true, it becomes scientifically and morally indefensible to demonize fossil energy and claim CO_2 emissions are a current threat to human health and welfare as the EPA's Endangerment Finding has done. Consequently, efforts to restrict CO_2 emissions or limit fossil energy should be avoided, as such actions will most certainly bring about adverse economic outcomes and lead to a host of other unintended consequences that will harm humanity.

To attack CO_2 is to attack human prosperity. *More*, not less, fossil energy is needed to enhance the future human environment.

2. Literacy

A second metric documenting the positive relationship between fossil fuel use and human prosperity is found in trends of global literacy.

Figure III.B.2.1 plots two centuries of annual fossil fuel consumption and global literacy data, which show illiteracy declining as a function of fossil fuel consumption. As indicated there, for most of the first hundred years of the record the vast majority of the population older than 15 was unable to read and write; in 1820 only one out of every ten persons older than 15 years was literate. By 1930 the literate portion of this population jumped to one-third. Fast forward to the present and 4.6 billion out of the 5.4 billion persons on earth today over the age of 15 can read and write. This incredible achievement stands in stark contrast with that from two centuries ago when there were less than 100 million who shared these literary skills. Thankfully, as nations have utilized fossil energy to industrialize, their populations have spent less time performing labors required of sustenance living and more time in the classroom becoming literate and gaining an education.

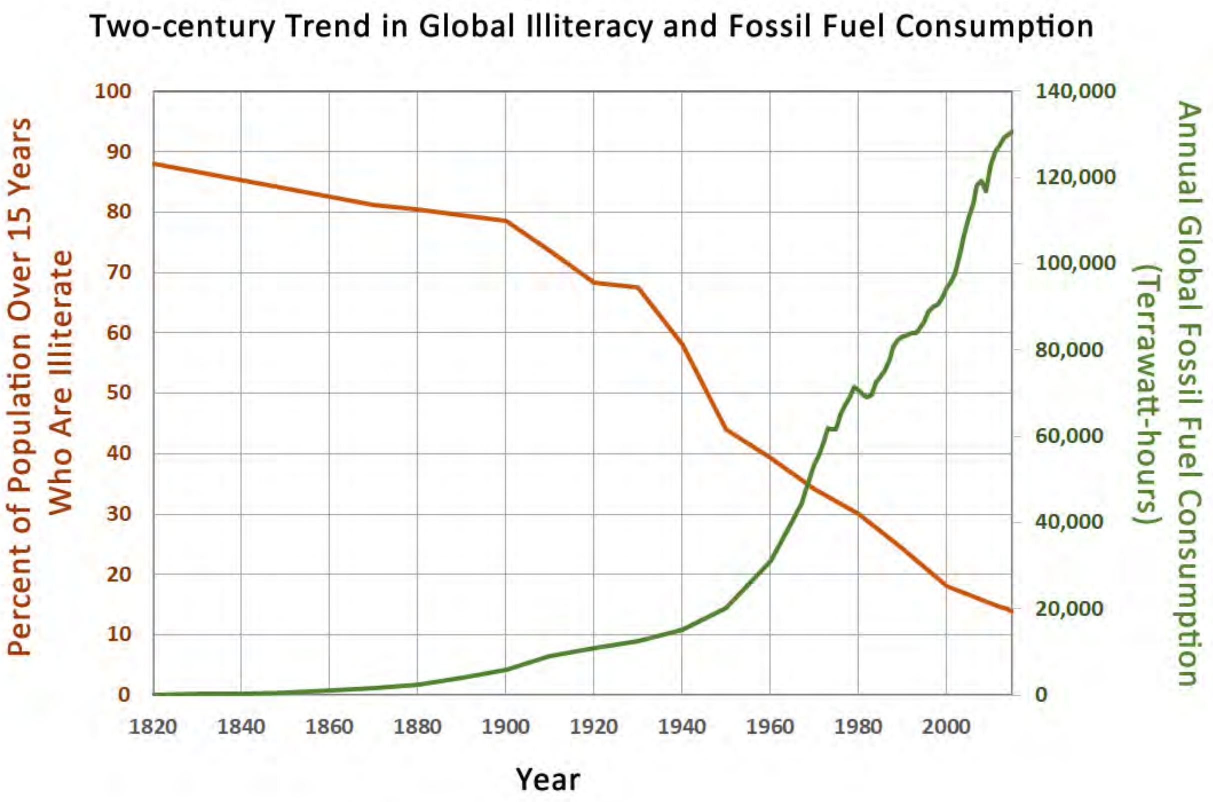


Figure III.B.2.1. *Annual total global CO_2 emissions (shaded red area) and global atmospheric CO_2 concentration (blue line) from 1800 to 2018.*

3. Life expectancy

Another key societal benefit of fossil fuel use and the CO_2 emissions that are a byproduct of its combustion is witnessed in their relationship with trends in life expectancy. Figure III.B.3.1 plots a two hundred year history of these three variables, revealing a high degree of correlation among the three records.

As revealed there, two hundred years ago the average life expectancy of a child born was a mere 29 years. Health care was relatively non-existent and 43% of the world's newborns died before reaching their 5th birthday. Thereafter, things began to change, though slowly at first. Society began to use fossil fuels on a much larger scale and industrialize. Rising energy production brought economic prosperity and literacy, which helped reduce poverty. Housing and sanitation improved. People ate more and they ate healthier, nutritious foods. A more educated population coupled with fast-developing societies provided fertile ground for key scientific breakthroughs in modern medicine that both saved and prolonged human lives.

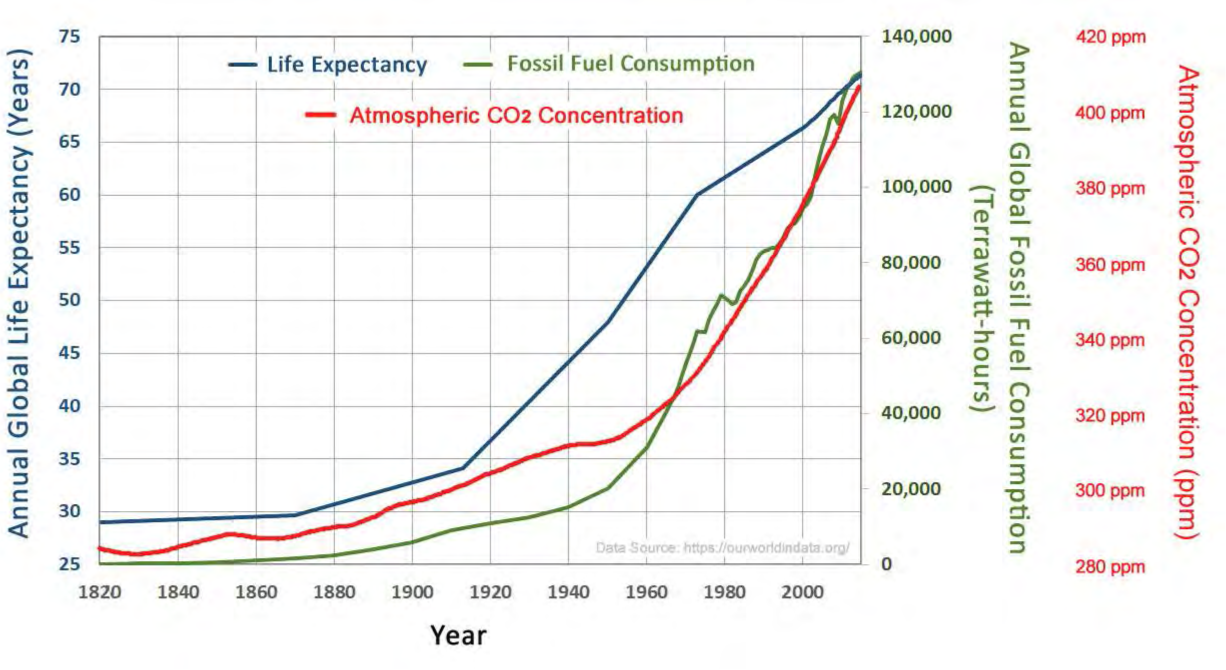
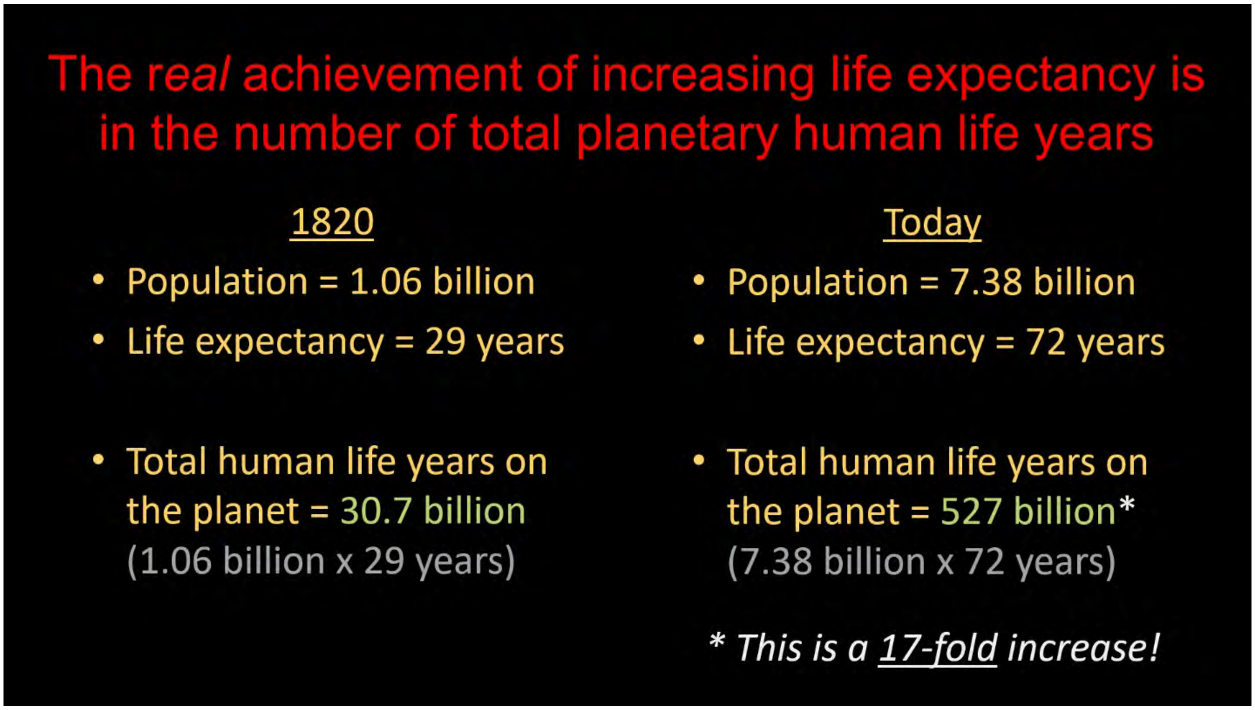


***Figure III.B.3.1**. Two-century trend in global life expectancy (blue line), fossil fuel consumption (green line) and atmospheric CO_2 concentration (red line).*

Across the whole of the 19th century life expectancy changed but little. Then, as fossil energy consumption really took off in the 20th century, so did human longevity, with global life expectancy *doubling* in value over the next ten decades, such that a person born today is expected to live to an average age of 72 years.

The real significance of this monumental accomplishment in human achievement, however, is *not* in the doubling of life expectancy in and of itself, but in *the number of persons who are experiencing it*.

Consider, for example, that in 1820 the world population was only 1.06 billion, whereas today it is 7.38 billion. By multiplying the population in each of these years by the corresponding average lifespan at that time, we find that the number of total human life years supported by the planet in 1820 amounted to 30.7 billion, whereas today it is a much greater 527 billion (see Figure III.B.3.2)!



The *real* achievement of increasing life expectancy is in the number of total planetary human life years

1820

- Population = 1.06 billion
- Life expectancy = 29 years

- Total human life years on the planet = 30.7 billion (1.06 billion x 29 years)

Today

- Population = 7.38 billion
- Life expectancy = 72 years

- Total human life years on the planet = 527 billion* (7.38 billion x 72 years)

** This is a 17-fold increase!*

Figure III.B.3.2*. Calculation of the difference in total planetary human life years in 1820 and 2020.*

Thus, thanks in large measure to benefits from enhanced fossil energy use, our planet now supports an increase in total human life years that is *17-fold higher* than it was just two centuries ago. Such improvements are astounding, demonstrating there are more people on Earth today who are living *longer* and *better* lives because of rising CO_2 and fossil fuel use. Those benefits will only continue in the years and decades ahead as long as energy remains accessible, affordable and plentiful.

IV. CONCLUSION

The underlying position in EPA's 2009 Endangerment Finding is that atmospheric CO_2 is a powerful greenhouse gas capable of causing dangerous global warming that will threaten life on the planet. In critically examining that position, this Petition for Repeal of the Endangerment Finding has presented convincing evidence based on real-world observations that it is not.

Atmospheric CO_2 is not the all-important greenhouse gas EPA claims it to be. Sufficient proof is documented in the historic temperature and CO_2 records. Sufficient proof is also found in the missing model-derived fingerprint of CO_2-induced warming in the tropical upper troposphere that observations fail to validate. And sufficient proof is noted in a vast array of real-world data that fail to match model projections for a host of subordinate temperature-related climate catastrophes.

Furthermore, it is clear based on a multitude of observations that, far from being a dangerous pollutant, rising atmospheric CO_2 is actually *benefitting* humanity and the natural world. It is undeniable that fossil energy initiated (and continues to sustain) the Industrial Revolution and the many human and environmental benefits that have emerged therefrom. Without adequate supplies of low-cost centralized energy, few, if any, of the major technological and innovative advancements of the past two centuries that have enhanced and prolonged human life could have occurred. Additionally, without the increased CO_2 emissions from fossil fuel use over the past two centuries, Earth's terrestrial biosphere would be nowhere near as vigorous or productive as it is today. Rather, it would be devoid of the growth-enhancing, water-saving and stress-alleviating benefits it has reaped in managed and unmanaged ecosystems from rising levels of atmospheric CO_2 since the Industrial Revolution began.

When considering and accounting for such *positive* improvements, it becomes scientifically and morally indefensible to demonize fossil fuel use and declare CO_2 emissions a current (or long-term) threat to human health and welfare. *More,* not less, fossil fuel use is needed to enhance human progress and sustain the natural world. Consequently, in light of all the above evidence, EPA must repeal and overturn its 2009 Endangerment Finding for greenhouse gases under Section 202(a) of the Clean Air Act.

Respectfully submitted,

Craig D. Idso, Ph.D.
Chairman[266]
Center for the Study of Carbon Dioxide and Global Change
5219 S. Reseda Street
Gilbert, AZ 85298
center@co2science.org
(480) 664-4923

Frederick Palmer, J.D.
Senior Fellow—CO_2 Policy[267]
Center for the Study of Carbon Dioxide and Global Change

Frank Clemente, Ph.D.
Senior Fellow—Energy Analytics[268]
Center for the Study of Carbon Dioxide and Global Change

---

[266] See http://www.co2science.org/about/chairman.php.
[267] See http://www.co2science.org/about/seniorfellow.php.
[268] See http://www.co2science.org/about/seniorfellow2.php.