

The State of Earth's Terrestrial Biosphere:

*How is it Responding to Rising Atmospheric
CO₂ and Warmer Temperatures?*



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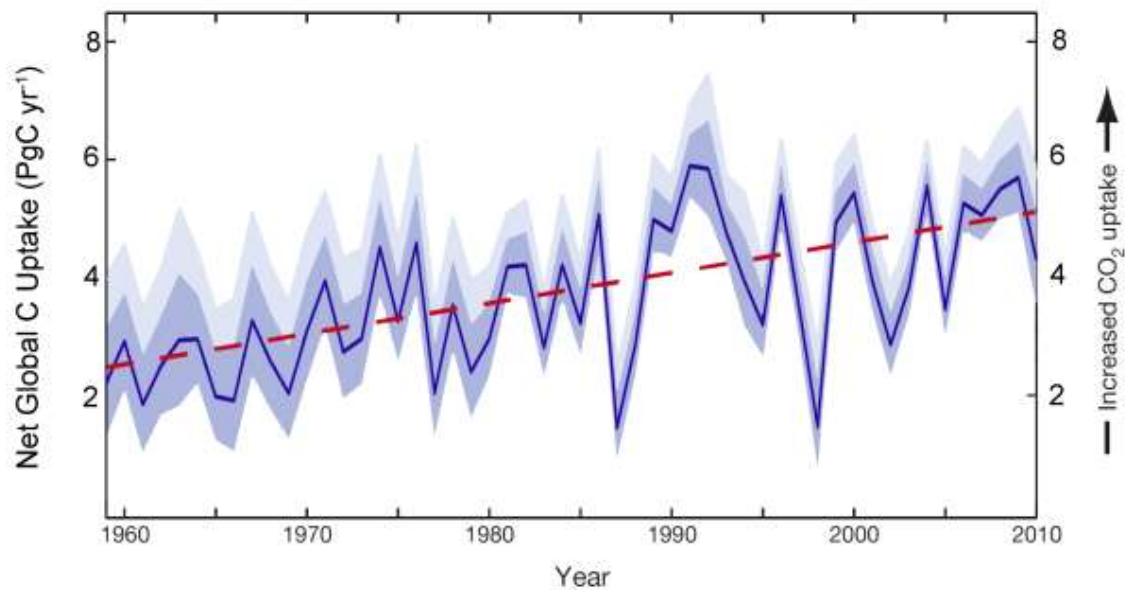
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EXECUTIVE SUMMARY

One of the potential consequences of the historical and ongoing rise in the air's CO₂ content is global warming, which phenomenon has further been postulated to produce all sorts of *other* undesirable consequences. The United Nations' Intergovernmental Panel on Climate Change, for example, contends that *current* levels of temperature and changing precipitation patterns (which they believe are mostly driven by the modern rise in atmospheric CO₂) are beginning to stress Earth's natural and agro-ecosystems *now* by reducing plant growth and development. And looking to the *future*, they claim that unless drastic steps are taken to reduce the ongoing rise in the air's CO₂ content (e.g., scaling back on the use of fossil fuels that, when consumed, produce CO₂), the situation will only get worse – that crops will fail, food shortages will become commonplace, and many species of plants (and the animals that depend on them for food) will be driven to *extinction*.

Such concerns, however, are not justified. In the ensuing report we present a meta-analysis of the peer-reviewed scientific literature, examining how the productivities of Earth's plants have responded to the 20th and now 21st century rise in global temperature and atmospheric CO₂, a rise that climate alarmists claim is unprecedented over *thousands* of years (temperature) to *millions* of years (CO₂ concentration). Based on that analysis, we find the following:

- The productivity of the planet's terrestrial biosphere, on the whole, has been *increasing* with time, revealing a great *greening of the Earth* that extends throughout the entire globe.
 - Satellite-based analyses of net terrestrial primary productivity (NPP) reveal an increase of around 6-13% since the 1980s.
- There is no empirical evidence to support the model-based claim that future carbon uptake by plants will diminish on a global scale due to rising temperatures. In fact, just the *opposite* situation has been observed in the real world.
 - Earth's land surfaces were a net *source* of CO₂-carbon to the atmosphere until about 1940. From 1940 onward, however, the terrestrial biosphere has become, in the mean, an *increasingly greater sink* for CO₂-carbon.
 - Over the past 50 years, for example, global carbon uptake has *doubled* from 2.4 ± 0.8 billion tons in 1960 to 5.0 ± 0.9 billion tons in 2010 (see figure below).
- The observed global greening has occurred in spite of all the many real and imagined assaults on Earth's vegetation that have occurred over the past several decades, including wildfires, disease, pest outbreaks, deforestation, and climatic changes in temperature and precipitation, *more* than compensating for any of the negative effects these phenomena may have had on the global biosphere.



Annual global net carbon (C) uptake by Earth's lands and oceans (solid blue line) from 1959-2010, adapted from Ballantyne et al. (2012). The linear trend (dashed red line) and 1σ (dark shaded bands) and 2σ (light shaded bands) uncertainties are also shown.

- There is compelling evidence that the atmosphere's rising CO_2 content – which alarmists consider to be the chief culprit behind all of their concerns about the future of the biosphere (via the indirect threats they claim it poses as a result of CO_2 -induced climate change) – is most likely the primary *cause* of the observed greening trends.
- In the future, Earth's plants should be able to successfully adjust their physiology to accommodate a warming of the *magnitude* and *rate-of-rise* that is typically predicted by climate models to accompany the projected future increase in the air's CO_2 content. Factoring in plant productivity gains that will occur as a result of the *aerial fertilization effect* of the ongoing rise in atmospheric CO_2 , plus its accompanying *transpiration-reducing effect* that boosts plant water use efficiency, the world's vegetation possesses an *ideal mix of abilities* to reap a *tremendous* benefit in the years and decades to come.

Given such findings, the recent “greening of the Earth” observed by a host of scientists will likely continue throughout the years and decades to come.



INTRODUCTION

For well over a century, scientists have been concerned about potential consequences of Earth's rising atmospheric carbon dioxide (CO₂) concentration on the biosphere. Driven by gaseous emissions from the burning of fossil fuels such as coal, gas and oil, the air's CO₂ content has risen steadily from a mean concentration of about 280 parts per million (ppm) in 1800 to a value of approximately 392 ppm today. And if current fuel consumption trends continue, it is projected that the planet's atmospheric CO₂ concentration may *double* sometime before the end of this century (IPCC, 2007). In light of such projections, it is only natural that scientists have long sought to understand how this important trace constituent of the atmosphere might affect the climate and biology of our planet; and tens of billions of research dollars have been spent investigating this issue over the past few decades. So what has been learned from this effort?

In short, two conflicting viewpoints have emerged. One is that which is proffered by the UN's Intergovernmental Panel on Climate Change (IPCC), which has subsequently been mirrored by the U.S. Environmental Protection Agency and many other organizations throughout the world, where it is claimed that the increasing carbon dioxide content of the atmosphere will lead to catastrophic global warming, which will *further* produce all sorts of undesirable consequences, including catastrophic sea level rise, dramatic increases in extreme weather phenomena such as droughts, floods and hurricanes, reduced agricultural output, and the destruction of many natural ecosystems. Those holding this viewpoint are often

referred to as *climate alarmists*, because they are alarmed by these potentially negative consequences.

Opposite this constituency are those, including the Nongovernmental International Panel on Climate Change (NIPCC), who – although conceding that humans are indeed causing the air's CO₂ concentration to rise – contend that many of the IPCC's conclusions far outstrip or even contradict the implications of a vast array of real-world data that should have informed the theoretical models upon which the alarmists' concerns are based. These *climate skeptics*, as they have come to be known, maintain that many more of the IPCC's claims have also been reached without considering the findings of important scientific studies that refute their alarmist assertions.

One such topic of disagreement concerns the future productivity of Earth's biosphere. Based on computer model projections, climate alarmists have long suggested that CO₂-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. Climate skeptics, on the other hand, foresee a much different future. Citing empirical observations of enhanced vegetative growth in numerous CO₂-enrichment experiments conducted on a host of different plants, coupled with productivity measurements made over the past several decades out in the real-world of nature, they assert it is *far* more likely that just the *opposite* will occur. To them, higher atmospheric CO₂ concentrations and warmer temperatures will significantly stimulate the planet's vegetation, creating a

bright and more prosperous future for Earth's biosphere.

Which of these two worldviews is the closest to reality? Perhaps the best way to answer this question is to compare the model-based *projections* of the climate alarmists with the real-world *observations* of the climate skeptics. Theoretical projections may or may not be correct, but real-world observations are *always* right; and as such, the only truly objective method of evaluating climate model projections and their biological implications is by comparing them with real-world data. In what follows, therefore, we conduct just such an appraisal, examining real-world observations of Earth's vegetative productivity over the most recent era of global warming and rising atmospheric CO₂ concentrations to see how they compare with model-based predictions of vegetative decline.

Both global temperature and atmospheric CO₂ concentration have experienced significant increases over the past century, rising to levels that climate alarmists claim are unprecedented over *thousands* of years (temperature) to *millions* of years (CO₂ concentration). Over just the past three decades, in fact, the Earth has experienced the warmest temperatures of the instrumental temperature record and a handful of intense and persistent El Niño events, while the air's CO₂ content has increased by 16% over the past three decades and by 30% over the past century.

Clearly, if there ever was a period of time over which to test the model-based projections of biospheric decline in response to rising atmospheric temperature and CO₂ concentration, *this is it!* And in the

following pages *we do just that*, conducting an expansive investigation into the pertinent peer-reviewed scientific literature and reporting what many hundreds of scientists have found to be the case.

Our examination begins with a discussion of what has been learned with respect to the terrestrial biosphere *as a whole*, after which we proceed with a regional analysis, exploring terrestrial productivity trends on continental and sub-continental scales. Finally, we conclude with a brief summarization of the vast array of findings and offer our best estimate of the state of Earth's terrestrial biosphere in response to temperatures and CO₂ concentrations projected by climate-alarmist models for the end of the current century.

GLOBAL TERRESTRIAL PRODUCTIVITY

We begin our review of global terrestrial productivity with the study of Reichenau and Esser (2003), who investigated the individual influences of ENSO, volcanic eruptions and the North Atlantic Oscillation (NAO) on the 1958-1994 time series of anomalous CO₂ fluxes with the help of the High Resolution Biosphere Model of Esser *et al.* (1994) and real-world CO₂ measurements. Although the two researchers could conclude nothing about the NAO, other than to say "the influence of the NAO remain[s] unclear," they were able to determine that periods of anomalous rising atmospheric CO₂ concentrations coincided with El Niño periods, while periods of anomalous declining atmospheric CO₂ concentrations coincided with periods of significant volcanism.

Enlarging on these observations, they say that “the globally averaged effect of [the El Niño] circulation pattern on the terrestrial biosphere is a net release of carbon,” in agreement with the results of earlier investigations of the subject (Bacastow, 1976; Bacastow *et al.*, 1980), which in turn “confirms earlier findings that the terrestrial biosphere is mainly responsible for atmospheric CO₂ variations on the ENSO timescale (Keeling *et al.*, 1995; Lee *et al.*, 1998; Feely *et al.*, 1999; Gerard *et al.*, 1999; Rayner and Law, 1999; Battle *et al.*, 2000; Bousquet *et al.*, 2000; Houghton, 2000; Knorr, 2000, Le Quere *et al.*, 2000; Langenfelds *et al.*, 2002).” At the other end of the spectrum, Reichenau and Esser report that “volcanic eruptions with considerable aerosol production may create disturbances of the (biospheric) carbon cycle by increasing the photosynthetic carbon uptake due to the enhanced diffuse fraction of the incoming [solar] radiation,” which accords with the findings of Roderick *et al.* (2001), Cohan *et al.* (2002), Law *et al.* (2002) and Gu *et al.* (2002, 2003).

The many published studies of anomalous CO₂ fluxes between Earth’s surface and its atmosphere clearly indicate that *warm* El Niño conditions tend to *reduce* biospheric productivity, while *cool* volcanic conditions tend to *enhance* biospheric productivity. At first glance, therefore, it would appear that the findings of this study support the climate-alarmist hypothesis, implying that “cool is good” and “warm is bad” for the planet’s plants. But there is much more to the story.

For one thing, the productivity-enhancing effect of volcanic eruptions arises not from their cooling influence, but from their increasing the amount of diffuse solar

radiation received at the Earth’s surface, which allows for an enhanced penetration of solar radiation deeper into plant canopies, which reduces within-canopy shade and boosts rates of canopy net photosynthesis. As for the productivity-reducing effect of El Niños, it could well be more a consequence of changes in global precipitation patterns than of the direct effect of an increase in temperature. It is known from the work of Indermuhle *et al.* (1999), for example, that the pattern of biospheric productivity over the last 7,000 years of the Holocene was essentially that of a slow monotonic decline from the peak growth conditions of the interglacial’s Climatic Optimum, which productivity decline, in their words, was “due to a change from the warmer and wetter mid-Holocene climate to colder and drier conditions.”

Additional evidence of the benefits of long-term warming on plants comes from the study of Lin *et al.* (2010), who conducted a meta-analysis of data they obtained from 127 individual studies and found that for the totality of terrestrial plants included in their analysis, “warming significantly increased biomass by 12.3%,” while noting there was a “significantly greater stimulation of woody (+26.7%) than herbaceous species (+5.2%).” They also found that the warming effects on plant biomass production “did not change with mean annual precipitation or experimental duration,” and that “other treatments, including CO₂ enrichment, nitrogen addition, drought and water addition, did not alter warming responses of plant biomass.” As a result, the Chinese researchers conclude, in their words, that “results in this and previous meta-analyses (Arft *et al.*, 1999; Rustad *et al.*, 2001;

Dormann and Woodin, 2001; Walker *et al.*, 2006) have revealed that warming generally increases terrestrial plant biomass, indicating enhanced terrestrial carbon uptake via plant growth and net primary productivity.”

Viewed from these perspectives, it would appear that long-term global warming tends to substantially *increase* biospheric productivity. Short-term deviations from this basic relationship that are evident in anomalous variations of CO₂ fluxes between the Earth’s surface and atmosphere are likely just that: *short-lived* and *anomalous*.

Also examining carbon fluxes was Langenfelds *et al.* (1999), who analyzed O₂/N₂ measurements of the contents of a suite of tanks filled with background air collected at Cape Grim, Tasmania between April 1978 and January 1997. The rates of carbon storage in the world’s oceans and the terrestrial biosphere they derived from these data indicated the terrestrial biosphere was essentially in balance with respect to surface fluxes of carbon throughout this 19-year interval. However, it is known from other studies that tropical deforestation produced a huge net loss of carbon during each of those years. As a result, Langenfelds *et al.* necessarily acknowledged the existence of a terrestrial carbon sink of like magnitude. This “compensating growth of the [terrestrial] biosphere,” as they describe it, was suggested by them to be due to “reforestation, higher rates of net production in response to climatic trends, fertilisation by elevated levels of atmospheric CO₂ or nitrogen deposition or a combination of these factors.” Thus, the biosphere appears to be re-sequestering all

of the carbon that man takes out of it yearly.

With respect to the “fertilization of elevated levels of atmospheric CO₂,” in a broad review of the scientific literature, Idso and Idso (2011) described a number of biological consequences of this ongoing phenomena. The best known of these important impacts is probably CO₂’s *aerial fertilization effect*, which works its wonders on plants that utilize all three of the major biochemical pathways of photosynthesis (C₃, C₄ and CAM). In the case of herbaceous plants, this phenomenon typically boosts their productivities by about a third in response to a 300 ppm increase in the air’s CO₂ content, while it enhances the growth of woody plants by 50% or more as demonstrated in literally thousands of laboratory and field experiments (Idso and Singer, 2009).

Next comes *plant water use efficiency*, which may be defined as the amount of organic matter produced per unit of water transpired to the atmosphere. This parameter is directly enhanced by the aerial fertilization effect of atmospheric CO₂ enrichment, as well as by its *anti-transpirant effect*, which is produced by CO₂-induced decreases in the number density and degree of openness of leaf stomatal apertures that occur at higher atmospheric CO₂ concentrations. Here, too, CO₂-induced percentage increases as large as, or even larger than, those exhibited by plant productivity are commonplace.

One of the important ramifications of this CO₂-induced increase in plant water use efficiency is the fact that it enables plants to grow and reproduce in areas that were previously too dry for them. With

consequent increases in ground cover in these regions, the adverse effects of wind- and water-induced soil erosion are also reduced. Hence, there is a tendency for desertification to be reversed and for vast tracts of previously unproductive land to become supportive of more abundant animal life, both above- and below-ground, in what could appropriately be called a “*greening of the Earth*.”

In addition to helping vegetation overcome the stress of limited water supplies, elevated levels of atmospheric CO₂ help plants to better cope with other environmental stresses, such as low soil fertility, low light intensity, high soil and water salinity, high air temperature, various oxidative stresses and the stress of herbivory. When confronted with the specter of global warming, for example, many experiments have revealed that concomitant enrichment of the air with CO₂ tends to increase the temperature at which plants function at their optimum, often making them even better suited to the warmer environment than they were to the cooler environment to which they were originally adapted. Under the most stressful of such conditions, in fact, extra CO₂ sometimes is the deciding factor in determining whether a plant lives or dies.

These benefits of atmospheric CO₂ enrichment apply to both agricultural and natural ecosystems; and as Wittwer (1995) has noted, “the rising level of atmospheric CO₂ could be the one global natural resource that is progressively increasing food production and total biological output in a world of otherwise diminishing natural resources of land, water, energy, minerals, and fertilizer.” This phenomenon is thus a means, he says, “of inadvertently increasing

the productivity of farming systems and other photosynthetically active ecosystems,” and that “the effects know no boundaries and both developing and developed countries are, and will be, sharing equally.”

In light of these several observations, plus the fact that the air’s CO₂ content has risen substantially over the past two centuries – especially since 1950 – one would expect to see some evidence of the “greening of the Earth” (Idso, 1986) that they imply. And, as indicated in the papers below, more and more researchers like Langenfelds *et al.* are acknowledging these stimulatory effects on Earth’s biosphere.

In another approach to the subject, Idso (1995) laid out the evidence for a worldwide increase in the growth rates of Earth’s forests that has been coeval with the progression of the Industrial Revolution and the rising CO₂ content of the atmosphere. The development of this concept *began* with the study of LaMarche *et al.* (1984), who analyzed annual growth rings of two species of pine tree growing near the timberline in California, Colorado, Nevada and New Mexico (USA), and who thereby discovered large increases in growth rate between 1859 and 1983, which rates exceeded what might have been expected from climatic trends but were consistent with the global trend of atmospheric CO₂. The developmental journey then *continued* with a study of ring-width measurements of Douglas fir trees in British Columbia, Canada, that also revealed a marked increase in growth in the trees’ latter decades (Parker *et al.*, 1987), leading the principal investigator of the project to state that “environmental influences other than increased CO₂ have not been found

that would explain this [phenomenon].” West (1988) reported much the same thing with respect to long-leaf pines in Georgia, i.e., that their annual growth increments had begun to rise at an unusual rate about 1920, increasing by approximately 30% by the mid-1980s; and he too stated that “the increased growth cannot be explained by trends in precipitation, temperature, or Palmer Drought Severity Index,” leaving the rising CO₂ content of the atmosphere as the likely cause of the increase in productivity.

Contemporaneously, stands of Scots pines in northern Finland were found to have experienced growth increases ranging from 15 to 43% between 1950 and 1983 (Hari *et al.*, 1984; Hari and Arovaara, 1988). As to the cause of this phenomenon, the researchers stated that “CO₂ seems to be the only environmental factor that has been changing systematically during this century in the remote area under study,” and it was thus to this factor that they looked for an explanation of their observations.

The next major development in the *continuing saga* was the finding of Graybill and Idso (1993) that very long ring-width chronologies (some stretching back nearly 1800 years) of high-altitude long-lived bristlecone, foxtail and limber pine trees in Arizona, California, Colorado and Nevada (USA) all developed an unprecedented upward growth trend somewhere in the 1850s that continued as far towards the present as the records extended. In this case, too, like the ones that preceded it, comparisons of the chronologies with temperature and precipitation records ruled out the possibility that either of these climatic variables played a significant role in enhancing the trees’ growth rates, strongly implicating the historical rise in the air’s CO₂

content as the factor responsible for their ever-increasing productivity over the prior century and a half.

Perhaps the most striking evidence of all for the significant 20th-century growth enhancement of Earth’s forests by the historical increase in the air’s CO₂ concentration was provided by the study of Phillips and Gentry (1994). Noting that turnover rates of mature tropical forests correlate well with measures of net productivity (Weaver and Murphy, 1990), the two scientists assessed the turnover rates of 40 tropical forests from around the world in order to test the hypothesis that global forest productivity was increasing *in situ*. In doing so, they found that the turnover rates of these highly productive forests had indeed been rising ever higher since at least 1960, with an apparent pan-tropical acceleration since 1980. In discussing what might be causing this phenomenon, they stated that “the accelerating increase in turnover coincides with an accelerating buildup of CO₂,” and as Pimm and Sugden (1994) stated in a companion article, it was “the consistency and simultaneity of the changes on several continents that lead Phillips and Gentry to their conclusion that enhanced productivity induced by increased CO₂ is the most plausible candidate for the cause of the increased turnover.”

Four years later, a group of eleven researchers headed by Phillips (Phillips *et al.*, 1998) reported another impressive finding. Working with data on tree basal area (a surrogate for tropical forest biomass) for the period 1958-1996, which they obtained from *several hundred* plots of mature tropical trees scattered about the world, they found that average forest

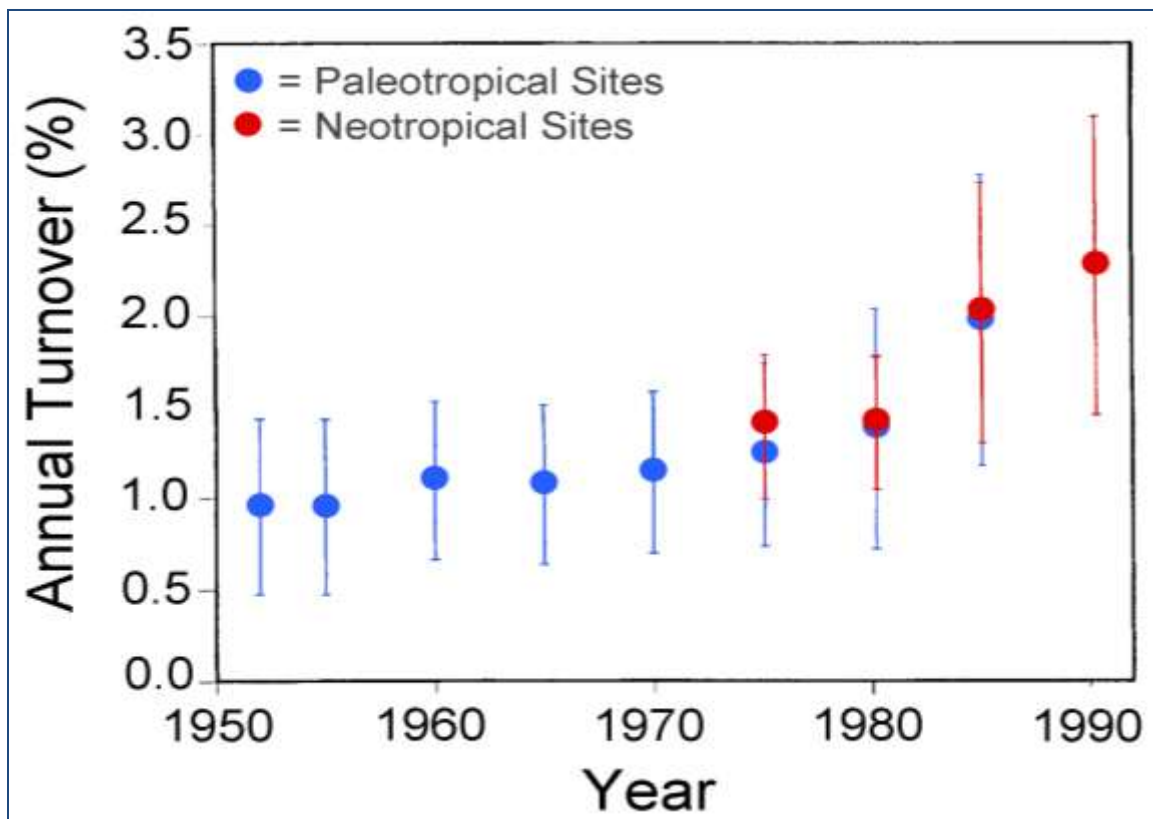


Figure 1. Average annual turnover rates (a surrogate for net productivity) for various tropical forests around the world since 1950. Adapted from Phillips and Gentry (1994).

biomass for the tropics as a whole had increased substantially (Figure 1). In fact, they calculated that the increase amounted to approximately 40% of the missing terrestrial carbon sink of the entire globe. Hence, they suggested that “intact forests may be helping to buffer the rate of increase in atmospheric CO₂, thereby reducing the impacts of global climate change,” as Idso (1991a,b) had earlier suggested, and they identified the aerial fertilization effect of the ongoing rise in the air’s CO₂ content as one of the factors responsible for this phenomenon. Other contemporary studies also supported their findings (Grace *et al.*, 1995; Malhi *et al.*, 1998), verifying the fact that neotropical forests were indeed accumulating ever more carbon; and Phillips *et al.* (2002) continued to state that this phenomenon

was occurring “possibly in response to the increasing atmospheric concentrations of carbon dioxide (Prentice *et al.*, 2001; Malhi and Grace, 2000).”

As time progressed, however, the conclusions of Phillips and company began to be repeatedly challenged (Sheil, 1995; Sheil and May, 1996; Condit, 1997; Clark, 2002; Clark *et al.*, 2003). In response to those challenges, Phillips, joined by 17 other researchers (Lewis *et al.*, 2004c), including one who had earlier criticized his and his colleagues’ conclusions, published a new analysis that vindicated Phillips *et al.*’s earlier thoughts on the subject.

One of the primary concerns of the critics of Phillips *et al.*’s work was that their meta-analyses included sites with a wide range of

tree census intervals (2-38 years), which they claimed could be confounding or “perhaps even driving conclusions from comparative studies,” as Lewis *et al.* (2004c) describe it. However, in Lewis *et al.*'s detailed study of this potential problem, which they concluded was indeed real, they found that re-analysis of Phillips *et al.*'s published results “shows that the pan-tropical increase in stem turnover rates over the late 20th century cannot be attributed to combining data with differing census intervals.” Or as they state more obtusely in another place, “the conclusion that turnover rates have increased in tropical forests over the late 20th century is robust to the charge that this is an artifact due to the combination of data that vary in census interval (cf. Sheil, 1995).”

Lewis *et al.* (2004c) additionally noted that “Sheil’s (1995) original critique of the evidence for increasing turnover over the late 20th century also suggests that the apparent increase could be explained by a single event, the 1982-83 El Niño Southern Oscillation (ENSO), as many of the recent data spanned this event.” However, as they continued, “recent analyses from Amazonia have shown that growth, recruitment and mortality rates have simultaneously increased within the same plots over the 1980s and 1990s, as has net above-ground biomass, both in areas largely unaffected, and in those strongly affected, by ENSO events (Baker *et al.*, 2004; Lewis *et al.*, 2004a; Phillips *et al.*, 2004).”

Continuing on in our analysis, in a review of these several global forest studies, as well as many others (which led to their citing 186 scientific journal articles), Boisvenue and Running (2006) examined reams of “documented evidence of the impacts of

climate change trends on forest productivity since the middle of the 20th century.” In doing so, they found that “globally, based on both satellite and ground-based data, climatic changes seemed to have a generally positive impact on forest productivity when water was not limiting,” which was most of the time, because they report that “less than 7% of forests are in strongly water-limited systems.” As such, there has been what Boisvenue and Running call a significant “greening of the biosphere” in recent years, the world’s forests in particular.

Three years later in another review of the scientific literature pertaining to this important issue of global biospheric productivity, Lewis *et al.* (2009a) evaluated tropical forest inventory data, plant physiology experiments, ecosystem flux observations, Earth observations, atmospheric measurements and dynamic global vegetation models. In doing so, the five researchers report that both theory and experiments suggest that over the past several decades “plant photosynthesis should have increased in response to increasing CO₂ concentrations, causing increased plant growth and forest biomass.” And in this regard they find that “long-term plot data collectively indicate an increase in carbon storage, as well as significant increases in tree growth, mortality, recruitment, and forest dynamism.” They also say that satellite measurements “indicate increases in productivity and forest dynamism,” and that five Dynamic Global Vegetation Models, incorporating plant physiology, competition, and dynamics, all predict increasing gross primary productivity, net primary productivity, and carbon storage when forced using late-twentieth century

climate and atmospheric CO₂ concentration data.” In addition, they state that “the predicted increases in carbon storage via the differing methods are all of similar magnitude (0.2% to 0.5% per year).”

Another intriguing indication that these CO₂- and temperature-induced biological benefits are indeed in process of occurring in the real world of nature comes from the decline in the air’s diurnal temperature range (DTR) that is evident in many parts of the world (Easterling *et al.*, 1997). By way of explanation, Collatz *et al.* (2000) employed a simple land surface subroutine in a general circulation model of the atmosphere that included parameterizations of canopy physiological responses to various environmental changes; and by running the model with and without the vegetation subroutine, they were able to determine the degree of influence that the planet’s plant life may have on near-surface air temperature in a world of rising temperature and atmospheric CO₂ concentration.

In this regard, it was determined that realistic changes in the amount and physiological activity of Earth’s plant life can produce changes in DTR of the order observed in the real world. In addition, the researchers explicitly state that their results “suggest that reported increases in vegetation cover in the Northern Hemisphere during the 1980s [Myneni *et al.*, 1997] could have contributed to the lowered DTR.” Thus, whereas it has long been believed that the declining diurnal temperature range near the surface of the Earth is a “fingerprint” of deleterious CO₂-induced global warming, it appears that the declining DTR may rather be an indication of beneficial CO₂-induced “global greening.”

In another paper, Alexandrov and Oikawa (2002) constructed a model of biospheric productivity based on empirical observations. Applied to the period 1980-90, it suggests that the total terrestrial carbon sink induced by the aerial fertilization effect of the contemporaneous increase in the air’s CO₂ content was approximately 1.3 Pg C yr⁻¹, which result compares well with estimates of up to 1.1 Pg C yr⁻¹ derived from independent empirical observations of same-period anthropogenic CO₂ emissions, changes in land use, CO₂ uptake by the world’s oceans, and increases in the air’s CO₂ concentration.

Similar findings were reported nearly a decade later by Gurney and Eckles (2011). Writing as background for their report, they state that “projections of atmospheric CO₂ concentrations and the resulting climate change rely to a significant degree on projections about future land and ocean uptake,” citing the work of Friedlingstein *et al.* (2006) and Sitch *et al.* (2008); and, therefore, they felt it important to attempt to learn how CO₂ uptake by Earth’s terrestrial surfaces has varied over the past three decades. In an effort to accomplish this objective, the two authors utilized the results of atmospheric CO₂ inversions – constrained by observed atmospheric CO₂ concentrations (Tans *et al.*, 1990) and simulated atmospheric transport – to estimate trends in air-to-land carbon fluxes, as per Enting (2002). This they did, as they describe it, “at spatial scales down to the continents using the results of the TransCom 3 international atmospheric CO₂ inversion inter-comparison (Gurney *et al.*, 2002, 2008),” which effort involved 13 participating modeling groups. Results of their analyses indicated that the global land carbon sink is *intensifying* (see Figure 2),

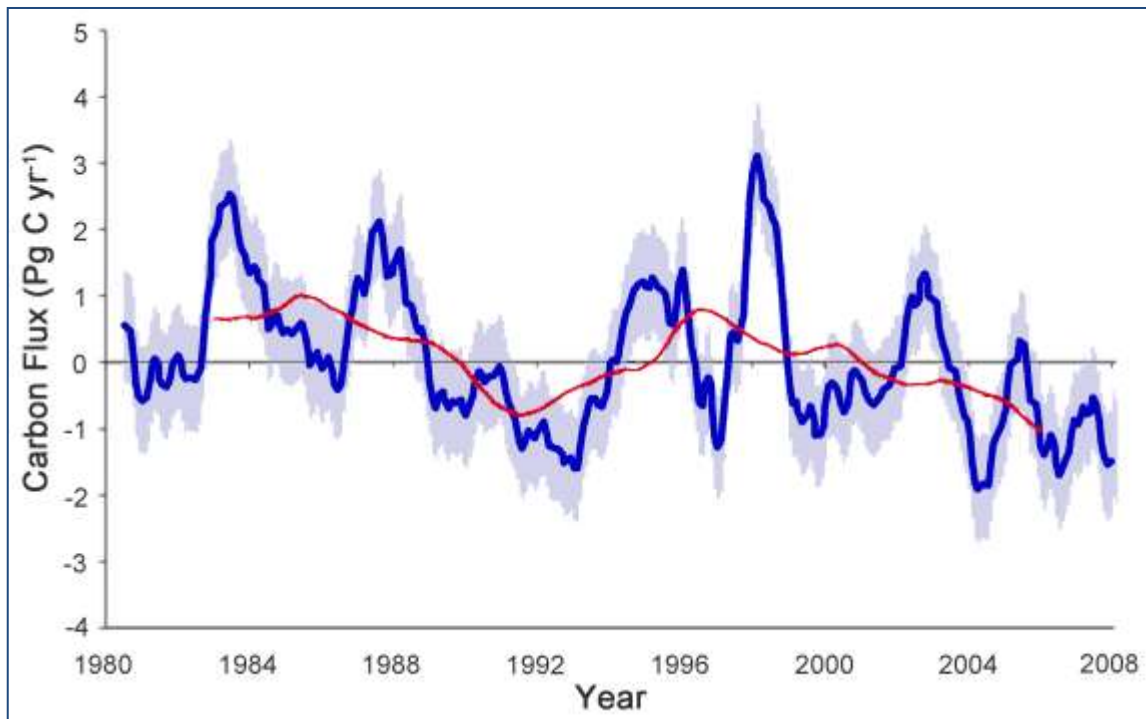


Figure 2. Global terrestrial biosphere net carbon exchange (positive from land to air, negative from air to land) over the period 1980-2008 (blue line), as calculated by Gurney and Eckles (2011). Also shown is the 5-yr running mean (red line) and total 1σ flux uncertainty (light blue shading).

and that it is doing so at a rate of 0.057 PgC/year/year, resulting in 1.65 PgC of additional uptake over the period examined (1980-2008), which finding, in their words, “is consistent with related findings in recent years,” citing in this regard the studies of Cao *et al.* (2002), Cao *et al.* (2005), Le Quere *et al.* (2009) and Piao *et al.* (2009).

Other studies have produced additional evidence for a worldwide increase in vegetative productivity all the way back to the inception of the Industrial Revolution. Joos and Bruno (1998), for example, used ice core data and direct observations of atmospheric CO₂ and ¹³C to reconstruct the histories of terrestrial and oceanic uptake of anthropogenic carbon over the past two centuries. In doing so, they discovered the biosphere typically acted as a source of CO₂ during the 19th century and the first decades of the 20th century, but that it

subsequently “turned into a sink.” In another paper, Lloyd (1999) calculated that from 1730 to the early 1980s the increase in temperate deciduous forest net primary productivity (NPP) due solely to the historical increase in the atmosphere’s CO₂ concentration was approximately 7%, and that the increase in NPP due to a modest proportional increase in nitrogen deposition over the same time period would have been about 25%. However, when CO₂ and nitrogen increased together in the model employed by Lloyd, the NPP stimulation was 40%, which is *more* than the sum of the individual contributions of the extra CO₂ and nitrogen.

In a subsequent study, Tans (2009) employed measurements of atmospheric and oceanic carbon contents, along with reasonably constrained estimates of global anthropogenic CO₂ emissions, to calculate

the residual fluxes of carbon (in the form of CO₂) from the terrestrial biosphere to the atmosphere (+) or from the atmosphere to the terrestrial biosphere (-), obtaining the results depicted in Figure 3.

Such findings, which do “not depend on models” but “only on the observed atmospheric increase and estimates of fossil fuel emissions,” led Tans to conclude that “suggestions that the carbon cycle is becoming less effective in removing CO₂

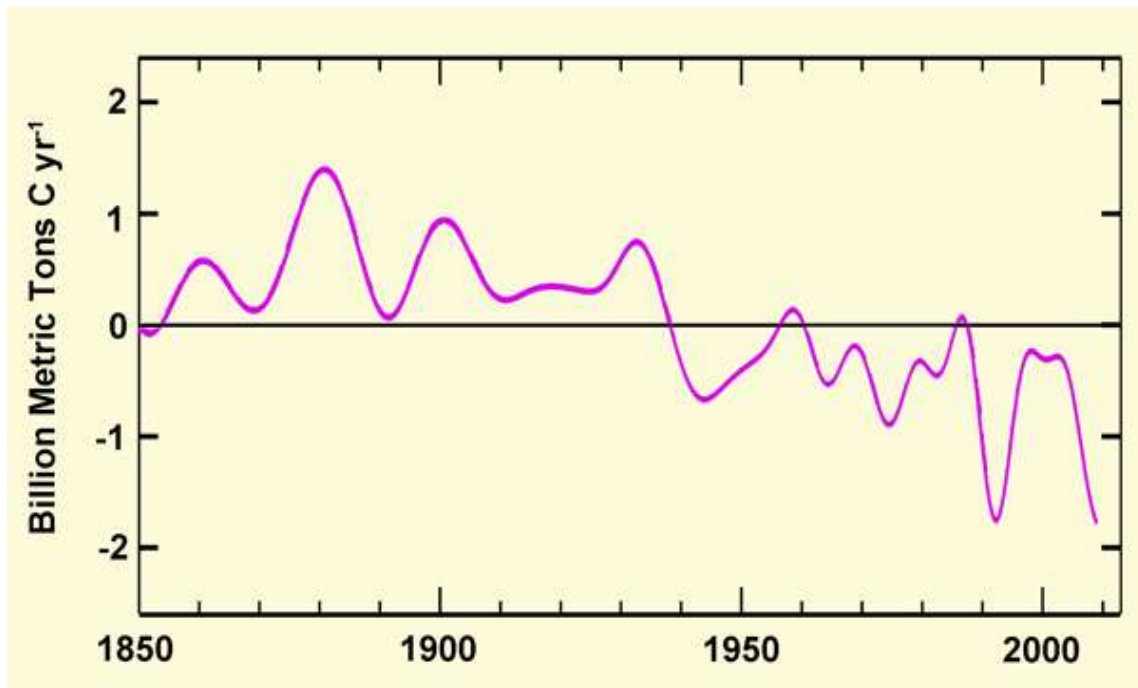


Figure 3. Five-year smoothed rates of carbon transfer from land to air (+) or from air to land (-) vs. time. Adapted from Tans (2009).

As can be seen from this figure, Earth’s land surfaces were a net *source* of CO₂-carbon to the atmosphere until about 1940, primarily due to the felling of forests and the plowing of grasslands to make way for expanded agricultural activities. From 1940 onward, however, the terrestrial biosphere has become, in the mean, an *increasingly greater sink* for CO₂-carbon; and it has done so even in the face of increasing temperatures, massive global deforestation, and rising atmospheric CO₂, more than compensating for any of the perceived negative effects these phenomena present to the global biosphere.

from the atmosphere (e.g., LeQuere *et al.*, 2007; Canadell *et al.*, 2007) can perhaps be true locally, but they do not apply globally, not over the 50-year atmospheric record, and not in recent years.” In fact, Tans goes on to say that “to the contrary” and “despite global fossil fuel emissions increasing from 6.57 GtC in 1999 to 8.23 in 2006, the five-year smoothed global atmospheric growth rate has not increased during that time, which requires more effective uptake [of CO₂] either by the ocean or by the terrestrial biosphere, or both, to satisfy atmospheric observations.” And the results portrayed in the figure above that was adapted from Tans’ paper

clearly indicate that this “more effective uptake” of CO₂-carbon has occurred primarily over land.

In discussing their findings, Nemani *et al.* mention a number of likely contributing factors to these significant NPP increases:

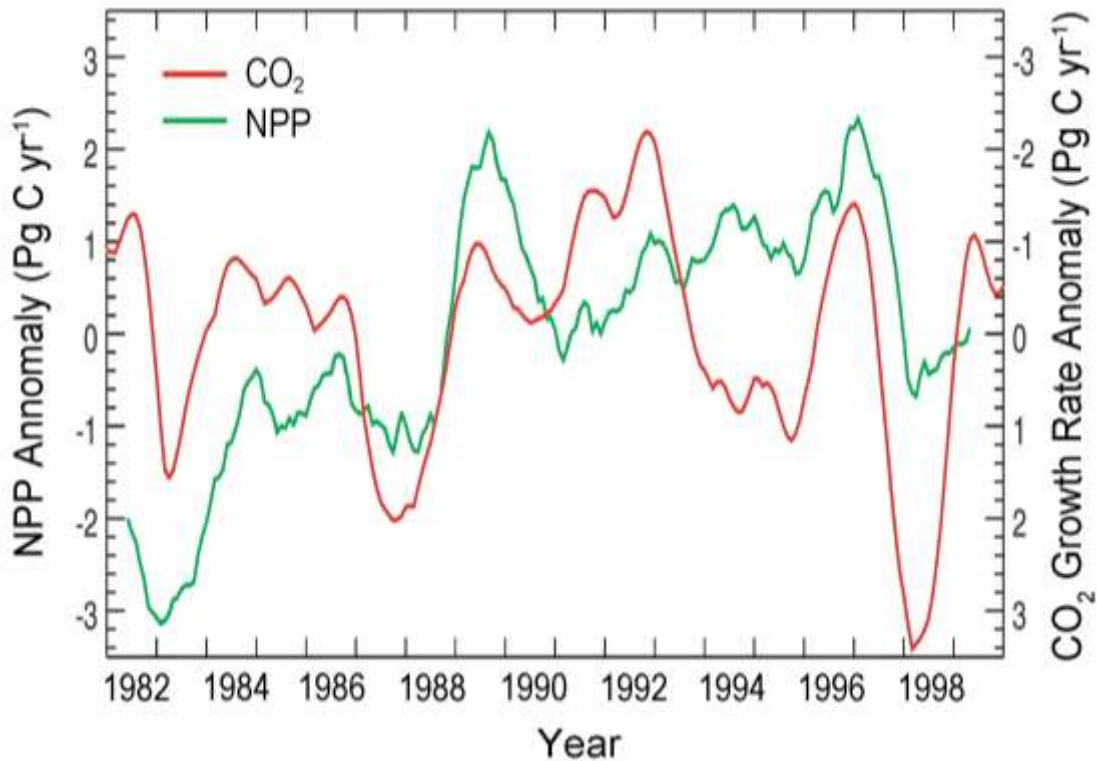


Figure 4. Interannual variations in global Net Primary Productivity (NPP) in relation to atmospheric CO₂ growth rate over the period 1982 to 1999. Adapted from Nemani *et al.* (2003).

Many researchers have also examined trends in biospheric productivity using satellite data. Nemani *et al.* (2003), for example, discovered a terrestrial biosphere that is growing ever more robust (see Figure 4). Globally, the group of eight scientists determined that terrestrial net primary production (NPP) increased by 6.17%, or 3.42 PgC, over the 18 years between 1982 and 1999. What is more, they observed net positive responses over all latitude bands studied: 4.2% (47.5-22.5°S), 7.4% (22.5°S-22.5°N), 3.7% (22.5-47.5°N), and 6.6% (47.5-90.0°N).

nitrogen deposition and forest regrowth in northern mid and high latitudes, wetter rainfall regimes in water-limited regions of Australia, Africa, and the Indian subcontinent, increased solar radiation reception over radiation-limited parts of Western Europe and the equatorial tropics, warming in many parts of the world, and the aerial fertilization effect of rising atmospheric CO₂ concentrations.

With respect to the latter factor, Nemani *et al.* remark that “an increase in NPP of only 0.2% per 1-ppm increase in CO₂ could explain all of the estimated global NPP increase of 6.17% over 18 years and is

within the range of experimental evidence [italics added].” However, they report that NPP increased by more than 1% per year in Amazonia alone, noting that “this result cannot be explained solely by CO₂ fertilization.”

Although Nemani *et al.*'s conclusion may be correct, as was pointed out earlier, the aerial fertilization effect of atmospheric CO₂ enrichment is most pronounced at higher temperatures, rising from next to nothing at a mean temperature of 10°C to a 0.33% NPP increase per 1-ppm increase in CO₂ at a mean temperature of 36°C for a mixture of plants comprised predominantly of herbaceous species (Idso and Idso, 1994). For woody plants, this number could likely be two (Idso, 1999) or even three (Saxe *et al.*, 1998; Idso and Kimball, 2001; Leavitt *et al.*, 2003) times larger, yielding a 0.7% to 1% NPP increase per 1-ppm increase in CO₂, which would indeed represent the lion's share of the growth stimulation observed by Nemani *et al.* in tropical Amazonia.

Be that as it may, the all-important take-home message of Nemani *et al.*'s study is that satellite-derived observations reveal the planet's terrestrial biosphere has significantly increased, as opposed to decreased, its productivity over the last two decades of the 20th century in the face of a host of environmental stresses.

In another study, Chen *et al.* (2004) utilized the monthly satellite-derived Normalized Difference Vegetation Index (NDVI) dataset of 1987-1997 that was obtained from the Advanced Very High Resolution Radiometer to calculate an 11-year history of global (75°N to 55°S) terrestrial NPP, deriving three different results based on the three different “NPP coefficient sets” of

Whittaker and Likens (1975), Atjay *et al.* (1979) and Olson *et al.* (1983). Based on the beginning and end points of the graphical presentations of Chen *et al.*'s results, it can be calculated that global terrestrial NPP increased by approximately 6.6% between 1987 and 1997 when the Atjay *et al.* coefficients were used, 9.9% when the Olson *et al.* coefficients were used, and 13.8% when the Whittaker and Likens coefficients were used, for a mean NPP increase of about 10% over the 11-year period.

Cao *et al.* (2004) derived net primary production (NPP) values at 8-km and 10-day resolutions for the period 1981-2000 using variables based almost entirely on satellite observations, as described in the Global Production Efficiency Model (GLO-PEM), which consists, in their words, “of linked components that describe the processes of canopy radiation absorption, utilization, autotrophic respiration, and the regulation of these processes by environmental factors (Prince and Goward, 1995; Goetz *et al.*, 2000).” In following this procedure, they learned that over the last two decades of the 20th century, *when the heat was on*, “there was an increasing trend toward enhanced terrestrial NPP,” which they say was “caused mainly by increases in atmospheric carbon dioxide and precipitation.”

A year later, Cao *et al.* (2005) used the CEVSA (Carbon Exchanges in the Vegetation-Soil-Atmosphere system) model (Cao and Woodward, 1998; Cao *et al.*, 2002), forced by observed variations in climate and atmospheric CO₂, to quantify changes in NPP, soil heterotrophic respiration (HR) and net ecosystem production (NEP) from 1981 to 1998. As an

independent check on the NPP estimate of CEVSA, they also estimated 10-day NPP from 1981-2000 with the GLO-PEM model that uses data almost entirely from remote sensing, including both the normalized difference vegetation index and meteorological variables (Prince and Goward, 1995; Cao *et al.*, 2004). This protocol revealed, in Cao *et al.*'s words, that "global terrestrial temperature increased by 0.21°C from the 1980s to the 1990s, and this alone increased HR more than NPP and hence reduced global annual NEP." However, they found that "combined changes in temperature and precipitation increased global NEP significantly," and that "increases in atmospheric CO₂ produced further increases in NPP and NEP." They also discovered that "the CO₂ fertilization effect [was] particularly strong in the tropics, compensating for the negative effect of warming on NPP." Enlarging on this point, they write that "the response of photosynthetic biochemical reactions to increases in atmospheric CO₂ is greater in warmer conditions, so the CO₂ fertilization effect will increase with warming in cool regions and be high in warm environments." The end result of the application of these models and measurements was their finding that global NEP increased "from 0.25 Pg C yr⁻¹ in the 1980s to 1.36 Pg C yr⁻¹ in the 1990s."

Commenting on their findings, Cao *et al.* note that "the NEP that was induced by CO₂ fertilization and climatic variation accounted for 30% of the total terrestrial carbon sink implied by the atmospheric carbon budget (Schimel *et al.*, 2001), and the fraction changed from 13% in the 1980s to 49% in the 1990s," which indicates the growing importance of the CO₂ fertilization effect. Also, they say that "the increase in

the terrestrial carbon sink from the 1980s to the 1990s was a continuation of the trend since the middle of the twentieth century, rather than merely a consequence of short-term climate variability," which suggests that as long as the air's CO₂ content continues its upward course, so too will its stimulation of the terrestrial biosphere likely continue its upward course.

Using a newly-developed satellite-based vegetation index (Version 3 Pathfinder NDVI) in conjunction with a gridded global climate dataset (global monthly mean temperature and precipitation at 0.5° resolution from New *et al.*, 2000), Xiao and Moody (2005) analyzed trends in global vegetative activity from 1982 to 1998. The greening trends they found exhibited substantial latitudinal and longitudinal variability, with the most intense greening of the globe located in high northern latitudes, portions of the tropics, southeastern North America and eastern China. Temperature was found to correlate strongly with greening trends in Europe, eastern Eurasia and tropical Africa. Precipitation, on the other hand, was *not* found to be a significant driver of increases in greenness, except for isolated and spatially fragmented regions. Some decreases in greenness were also observed, mainly in the Southern Hemisphere in southern Africa, southern South America and central Australia, which trends were associated with concomitant increases in temperature and decreases in precipitation. There were also large regions of the globe that showed no trend in greenness over the 17-year period, as well as large areas that underwent strong greening that showed no association with trends of either temperature or precipitation. These greening trends, as they concluded, must

have been the result of other factors, such as “CO₂ fertilization, reforestation, forest regrowth, woody plant proliferation and trends in agricultural practices.”

In still another analysis, Young and Harris (2005) investigated, for the majority of Earth’s land surface, a near 20-year time series (1982-1999) of NDVI data, based on measurements obtained from the Advanced Very High Resolution Radiometer (AVHRR) carried aboard U.S. National Oceanic and Atmospheric Administration satellites. In doing so, they employed two different datasets derived from the sensor: the Pathfinder AVHRR Land (PAL) data set and the Global Inventory Modeling and Mapping Studies (GIMMS) dataset. Based on their analysis of the PAL data, the two researchers determined that “globally more than 30% of land pixels increased in annual average NDVI greater than 4% and more than 16% persistently increased greater than 4%,” while “during the same period less than 2% of land pixels declined in NDVI and less than 1% persistently declined.” With respect to the GIMMS dataset, they report that “even more areas were found to be persistently increasing (greater than 20%) and persistently decreasing (more than 3%).” All in all, they report that “between 1982 and 1999 the general trend of vegetation change throughout the world has been one of increasing photosynthesis.”

As for what has been *responsible* for the worldwide increase in photosynthesis – which is the ultimate food source for nearly all of the biosphere – the researchers mention global warming, as well as “associated precipitation change and increases in atmospheric carbon dioxide,” citing Myneni *et al.* (1997) and Ichii *et al.* (2002). In addition, they say that “many of

the areas of decreasing NDVI are the result of human activity,” primarily deforestation (Skole and Tucker, 1993; Steininger *et al.*, 2001) and urbanization Seto *et al.* (2000).

One year later, Piao *et al.* (2006a) set the stage for their study by noting that “enhanced terrestrial vegetation growth in the middle and high latitudes of the Northern Hemisphere over the past two decades has been well documented (Zhou *et al.*, 2001; Nemani *et al.*, 2003),” but they report that “the mechanisms for this phenomenon are still under debate.” Using a leaf area index data set for the period 1981-2000, which was created from satellite-derived observations of the normalized difference vegetation index parameter for land areas above 25°N latitude, the authors therefore set out to investigate “spatial patterns of mechanisms controlling current enhanced vegetation growth in the Northern Hemisphere,” focusing on “how recent changes in precipitation, temperature [and] atmospheric CO₂ concentration have influenced vegetation growth.” And what did they find?

Over the final two decades of the 20th century, the researchers found the mean rate of increase in growing-season leaf area index to have been 0.0041/year, and that 13% of that increase was provided by increases in precipitation, 31% was provided by increases in temperature, and that fully 49% was provided by the increase in the atmosphere’s CO₂ concentration.

In another study focusing on *leaf area index* (LAI) data derived from satellite observations, Liu *et al.* (2010) looked for, and computed changes in, this important plant growth parameter for six different

latitude bands that included all of Earth's continents but Antarctica over the period July 1981 through December 2006. These bands were 50-90°N, 30-50°N, 10-30°N, 10°N-10°S, 10-30°S and 30-63°S. In doing so, Liu *et al.* determined that LAI "prominently increased" throughout Europe, Siberia, the Indian Peninsula, America and south Canada, the south region of the Sahara, the southwest corner of Australia, and the Kgalagadi Basin; while it declined in southeast Asia, southeastern China, central Africa, central and southern South America, and arctic areas in North America. Yet in spite of these latter *negative* results, they found that *all six* of the latitudinal bands they analyzed showed *positive trends*. Consequently, for the *globe as a whole* (i.e., the conglomerate of the six different latitude bands they analyzed), they determined that "LAI has increased at a rate of 0.0013 per year during July 1981-December 2006," while for the middle and high northern latitudes (north of 30°N), the linear LAI trend was 0.0032 per year.

In spite of all the positive evidences for increased global biospheric productivity listed above, some have challenged whether or not such trends are real or sustainable in a CO₂-induced globally-warmed world of the future.

Introducing their work, Gloor *et al.* (2010) indicate that the ratio of *CO₂ accumulating in the atmosphere* to the *CO₂ flux into the atmosphere due to human activities* – which is known as the *airborne fraction* (AF) – is central to predicting changes in Earth's surface temperature due to greenhouse gas-induced warming; and they note that this ratio has remained remarkably constant over the past five decades. However, they report that Canadell *et al.* (2007) and

Raupach *et al.* (2008) claim to have detected a long-term *increasing* trend in the airborne fraction that they interpret as being indicative of "a decreasing trend in the efficiency of the ocean and land carbon sinks."

In examining this issue further, Gloor *et al.* report that Knorr (2009) had already challenged Canadell *et al.* and Raupach *et al.* with respect to their detection of a positive AF trend, "arguing that given the noise in the data, the trend is not detectable." Thus, they go on to challenge the *second* claim of Canadell *et al.* and Raupach *et al.*, i.e., their contention that a positive AF trend is indicative of a decreasing planetary carbon sink efficiency by investigating "the question of what controls trends and decadal scale variations in CO₂ airborne fraction using simple linear models describing the evolution of an atmospheric perturbation in CO₂."

In doing so, the three researchers determined, first of all, that there is no one-to-one association between positive trends in CO₂ flux to the atmosphere (due to fossil fuel emissions and changes in land use) and negative trends in Earth's carbon sink efficiency. Secondly, they found that in order to detect trends in sink efficiencies from the time course of fossil fuel-derived CO₂ emissions and temporal changes in land use, "it is necessary to disentangle the spin-up time and fossil fuel growth rate variation signatures in the airborne fraction from signatures due to other causes." And when they make the pertinent calculations for fossil-fuel and land-use changes, they say they "do indeed find a positive trend in the residuals," but they argue that this trend "is not statistically significant after correcting for known events such as the temporal

distribution of the extrinsic forcings and likely omissions in the emissions (particularly from land-use change),” further noting that their analysis suggests that “trends in airborne fraction are not a very good diagnostic to detect changes in carbon sink efficiency because variations in the signal are complex and the signal-to-noise ratio is small.”

In describing another challenge to the recent greening of the Earth, Zhao and Running (2010) state that “previous studies have shown that climate constraints were

on to show, in fact, there is likely no cause for concern.

In viewing a graphical representation of this trend (Figure 5 below), it can be seen that apart from the starting point of the initial year (2000) of their study, there is only *one other year* (2004) in which the global NPP was *greater* than what it was at the end of the study (2009). And since global NPP was on the *rise* from 1982-1999, what the more recent data show would more accurately be described as a *leveling off* of that prior upward trend.

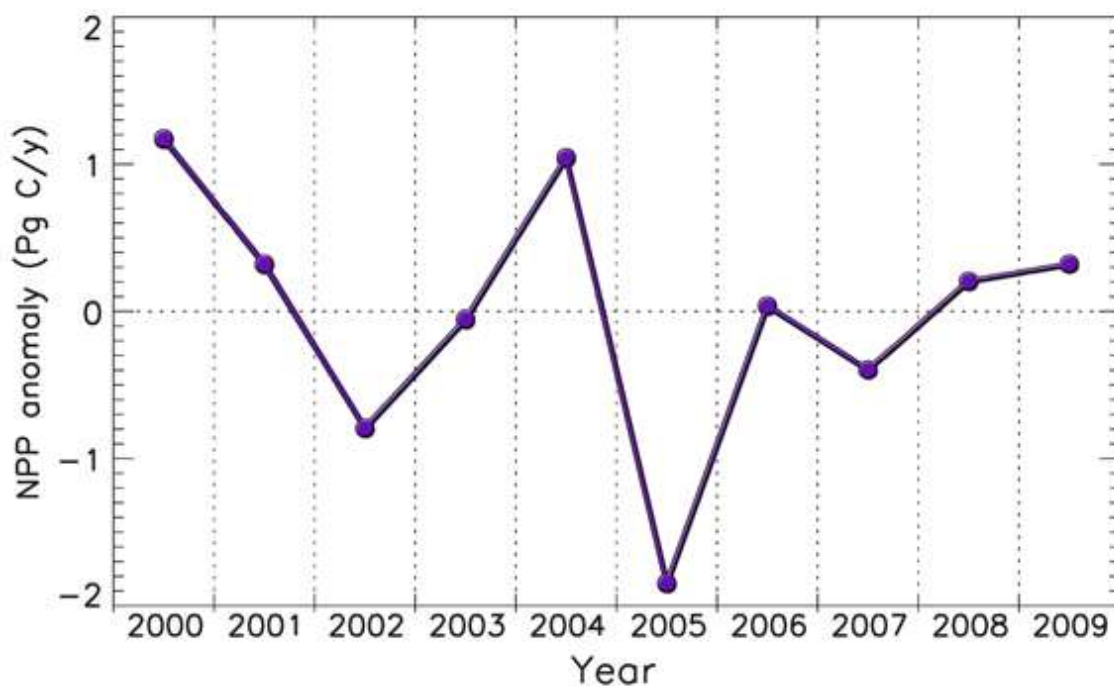


Figure 5. Interannual variations from the mean of global NPP over the past ten years. Adapted from Zhao and Running (2010).

relaxing with increasing temperature and solar radiation, allowing an upward trend in NPP [net primary production] from 1982-1999,” but that over the past decade (2000-2009), satellite data “suggest a reduction in the global NPP,” which finding caused some alarm among the climate-alarmist community. But, as Zhao and Running go

But what about the future? Zhao and Running correctly report that the leveling off of global NPP over the past decade was induced by *drought*; and more frequent and more intense droughts have long been predicted by climate alarmists to accompany global warming. In this regard, therefore, it is of more than passing interest

that the two researchers found that “NPP in the tropics explains 93% of variations in the global NPP,” and that “tropical rainforests explain 61% of global NPP variations.” These findings are especially important because of the work of Coelho and Goddard (2009), who studied *El Niño-induced tropical droughts* as portrayed in climate models.

In introducing their study, the latter two researchers write that “the majority of drought-related hazards and the attendant economic losses and mortality risks reside in the tropics,” citing Dilley *et al.* (2005); and they further note that “changes in climate variability, including more frequent and damaging extreme events such as drought, is one of many anticipated impacts of climate change.” More specifically (and germane to the subject at hand), they write that “El Niño brings widespread drought (i.e., precipitation deficit) to the tropics,” and that “stronger or more frequent El Niño events in the future” would “exacerbate drought risk in highly vulnerable tropical areas.”

As a result of these observations, the two researchers evaluated “the patterns, magnitude, and spatial extent of El Niño-induced tropical droughts during a control period in the twentieth century in climate simulations, which have realistic evolution of greenhouse gases,” after which they examined “the projected changes in the characteristics of El Niño and in the strength of the identified patterns of El Niño-induced tropical drought in the twenty-first century,” which then allowed them to examine patterns of mean precipitation changes in order to “assess whether those changes exacerbate or ameliorate the risk of El Niño-induced drought conditions in

the twenty-first century.” So what did they find?

In the first instance, Coelho and Goddard found that the models they studied “exhibit realistic patterns, magnitude, and spatial extent of El Niño-induced drought patterns in the twentieth century,” and they further observed that “the teleconnections are not projected to change in the twenty-first century,” although they add that “a possible slight reduction in the spatial extent of droughts is indicated over the tropics as a whole.” And they report that “all model groups investigated show similar changes in mean precipitation for the end of the twenty-first century, with increased precipitation projected between 10°S and 10°N.”

In conclusion, it would appear -- at least from a climate modeling perspective -- tropical drought can probably be expected to *decrease* throughout the remainder of the twenty-first century, which should enable the historical “greening of the Earth” to continue, although there may well be decadal periods of drought-induced “leveling off” of global NPP that give rise to periodic concerns.

In the most recent satellite-based study designed to determine the net long-term trend in vegetative vigor of the entire planet, De Jong *et al.* (2012) employed “detection of trend changes in normalized difference vegetation index (NDVI) satellite data between 1982 and 2008,” based on “time series of 648 fortnightly images [that] were analyzed using a trend breaks analysis procedure,” which feat was accomplished for fourteen different classes of land cover (biomes). According to the four researchers, *short-term greening and*

browning trends were observed over portions of the studied period for almost 15% of Earth's land surface; but they found that for the *entire* time period, "net greening was detected in all biomes," and that "the net global figure – considered over the full length of the time series – showed greening since the 1980s."

Finally, in one last remaining study, Ballantyne *et al.* (2012) used "global-scale atmospheric CO₂ measurements, CO₂ emission inventories and their full range of uncertainties to calculate changes in global CO₂ sources and sinks during the past fifty years." In describing their results the five U.S. scientists say their mass balance analysis shows that "net global carbon uptake has increased significantly by about 0.05 billion tonnes of carbon per year and that global carbon uptake doubled, from 2.4 ± 0.8 to 5.0 ± 0.9 billion tonnes per year, between 1960 and 2010" (see Figure 6).

Commenting on the significance of their findings, in the concluding paragraph of their *Nature* article, they state that "although present predictions indicate diminished C uptake by the land and oceans in the coming century, with potentially serious consequences for the global climate, as of 2010 there is no empirical evidence that C uptake has started to diminish on the global scale." In fact, as their results clearly indicate, just the *opposite* appears to be the case, with global carbon uptake actually *doubling* over the past half-century. As such, this most recent effort refutes the recent hypothesis by Canadell *et al.* (2007) and Raupach *et al.* (2008), who claimed to have detected a decreasing trend in the efficiency of the planet's carbon sinks, and vindicates the many studies listed above revealing an ever more greening of planet Earth.

In considering all of the above, it is clear

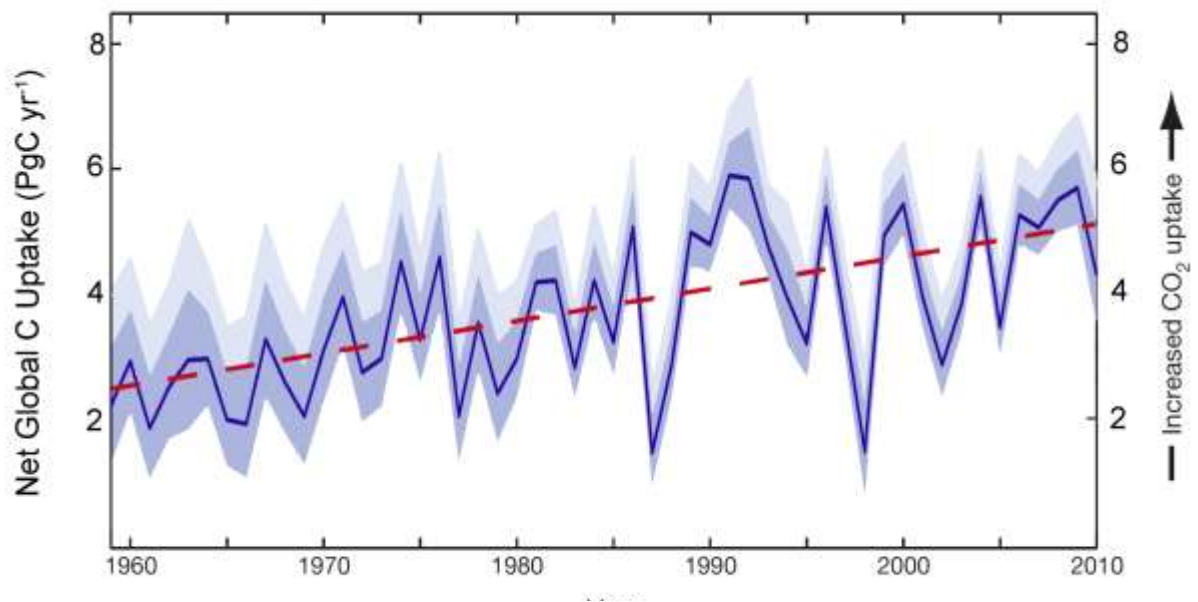


Figure 6. Annual global net carbon (C) uptake by Earth's lands and oceans (solid blue line) from 1959-2010, adapted from Ballantyne *et al.* (2012). The linear trend (dashed red line) and 1 σ (dark shaded bands) and 2 σ (light shaded bands) uncertainties are also shown.

that the terrestrial biomass of the globe has indeed been *rising*; and it appears to be doing so at a *remarkable rate*. It is also clear that recent increases in atmospheric CO₂ and temperature have *positively* impacted those trends, likely responsible for the lion's share of the observed increase. It should also be noted that this remarkable increase in biospheric productivity and observed *greening of the Earth* has occurred in spite of several *real* assaults on the globe's vegetation, e.g., deforestation and other land-use changes.

CONTINENTAL-SCALE ANALYSES OF TERRESTRIAL PRODUCTIVITY

We next proceed with an analysis of terrestrial productivity trends on continental and sub-continental scales, detailing what researchers have reported for Africa, Asia, Australia, Europe, North America and South America.

AFRICA

Introducing our examination of Africa, we note that nearly three decades ago Idso (1986) published a small item in *Nature* that advanced the idea that the aerial fertilization effect of the CO₂ that is liberated by the burning of coal, gas and oil was destined to dramatically enhance the productivity of Earth's vegetation. In fact, in a book he had published four years *earlier* (Idso, 1982), he had predicted that "CO₂ effects on both the managed and unmanaged biosphere will be overwhelmingly positive," if not "mind-boggling." And in a monograph based on a lecture he gave a few years later (Idso, 1995), he said that "we appear to be

experiencing the initial stages of what could truly be called a *rebirth of the biosphere*, the beginnings of a biological rejuvenation that is without precedent in all of human history." Nowhere does this projection appear to be more correct than in Africa, one of the hottest places on Earth.

According to a 2002 *New Scientist* article by Fred Pearce, entitled "Africa's deserts are in 'spectacular' retreat," vegetation is reclaiming great tracts of barren land across the entire southern edge of the Sahara. According to the author, "the southern Saharan desert is in retreat, making farming viable again in what were some of the most arid parts of Africa." In addition, he states that "Burkina Faso, one of the West African countries devastated by drought and advancing deserts 20 years ago, is growing so much greener that families who fled to wetter coastal regions are starting to go home."

And the good news was not confined to Burkina Faso. "Vegetation," according to Pearce, "is ousting sand across a swathe of land stretching from Mauritania on the shores of the Atlantic to Eritrea 6000 kilometers away on the Red Sea coast." What is more, besides being widespread in space, the greening was widespread in time, having been happening since at least the mid-1980s.

Quoting Chris Reij of the Free University of Amsterdam, Pearce wrote that "aerial photographs taken in June show 'quite spectacular regeneration of vegetation' in northern Burkina Faso." The data indicated the presence of more trees for firewood and more grassland for livestock. In addition, a survey that Reij was collating showed, according to Pearce, "a 70 percent

increase in yields of local cereals such as sorghum and millet in one province in recent years.” Also studying the area was Kjeld Rasmussen of the University of Copenhagen, who reported that since the 1980s there had been a “steady reduction in bare ground” with “vegetation cover, including bushes and trees, on the increase on the dunes.”

Pearce also reported on the work of a team of geographers from Britain, Sweden and Denmark that had spent much of the prior summer analyzing archived satellite images of the Sahel. Citing Andrew Warren of University College London as a source of information on this study, he said the results showed “that ‘vegetation seems to have increased significantly’ in the past 15 years, with major regrowth in southern Mauritania, northern Burkina Faso, north-western Niger, central Chad, much of Sudan and parts of Eritrea.”

But are such findings unique? Not in the least. In a study of a series of satellite images of the Central and Western Sahel that were taken from 1980 to 1995, Nicholson *et al.* (1998) could find no evidence of any overall expansion of deserts and no drop in the rainfall use efficiency of native vegetation. And it has further been observed in a satellite study of the *entire* Sahel from 1982 to 1990 (Prince *et al.*, 1998) that a steady *rise* in rainfall use efficiency has been detected, suggesting that plant productivity and coverage of the desert had actually *increased* during this period.

That the greening phenomenon has continued apace is further borne out by the study of Eklundh and Olsson (2003), who analyzed Normalized Difference Vegetation

Index (NDVI) data obtained from the U.S. National Oceanic and Atmospheric Administration’s satellite-borne Advanced Very High Resolution Radiometer whenever it passed over the African Sahel for the period 1982-2000. As they describe their findings, “strong positive change in NDVI occurred in about 22% of the area, and weak positive change in 60% of the area,” while “weak negative change occurred in 17% of the area, and strong negative change in 0.6% of the area.” In addition, they report that “integrated NDVI has increased by about 80% in the areas with strong positive change,” while in areas with weak negative change, “integrated NDVI has decreased on average by 13%.” The primary story told by these data, therefore, is one of strong positive trends in NDVI for large areas of the African Sahel over the last two decades of the 20th century; and Eklundh and Olsson conclude that the “increased vegetation, as suggested by the observed NDVI trend, could be part of the proposed tropical sink of carbon.”

In the years that have followed, many more scientists have confirmed the recent stunning increase in African vegetation. In 2005, Africa was featured in a special issue of the *Journal of Arid Environments* entitled “The ‘Greening’ of the Sahel.” Therein, Anyamba and Tucker (2005) described their development of an NDVI history of the region for the period 1981-2003. Comparing this history with the precipitation history of the Sahel developed by Nicholson (2005), they found that “the persistence and spatial coherence of drought conditions during the 1980s is well represented by the NDVI anomaly patterns and corresponds with the documented rainfall anomalies across the region during this time period.” In addition, they report

that “the prevalence of greener than normal conditions during the 1990s to 2003 follows a similar increase in rainfall over the region during the last decade.”

In another analysis of NDVI and rainfall data in the same issue of the *Journal of Arid Environments*, Olsson *et al.* (2005) also report finding “a consistent trend of increasing vegetation greenness in much of the region,” which they describe as “remarkable.” And they say that increasing rainfall over the last few years “is certainly one reason” for the greening phenomenon. However, they find that the increase in rainfall “does not fully explain” the increase in greenness.

For one thing, the three Swedish scientists note that “only eight out of 40 rainfall observations showed a statistically significant increase between 1982-1990 and 1991-1999.” In addition, they report that “further analysis of this relationship does not indicate an overall relationship between rainfall increase and vegetation trend.” So what else could be driving the increase in greenness?

Olsson *et al.* suggest that “another potential explanation could be improved land management, which has been shown to cause similar changes in vegetation response elsewhere (Runnstrom, 2003).” However, in more detailed analyses of Burkina Faso and Mali, where production of millet rose by 55% and 35%, respectively, since 1980, they could find “no clear relationship” between agricultural productivity and NDVI, which argues against the land management explanation.

A third speculation of Olsson *et al.* is that the greening of the Sahel could be caused

by increasing rural-to-urban migration. In this scenario, widespread increases in vegetation occur as a result of “reduced area under cultivation,” due to a shortage of rural laborers, and/or “increasing inputs on cropland,” such as seeds, machinery and fertilizers made possible by an increase in money sent home to rural households by family members working in cities. However, Olsson *et al.* note that “more empirical research is needed to verify this [hypothesis].” And in response to this call for additional research, many scientists answered in the months and years that followed.

In a model-based study, Ichii *et al.* (2005) “simulated and analyzed 1982-1999 Amazonian, African, and Asian carbon fluxes using the Biome-BGC prognostic carbon cycle model driven by National Centers for Environmental Prediction reanalysis daily climate data,” after which they “calculated trends in gross primary productivity (GPP) and net primary productivity (NPP).” In doing so, solar radiation variability was found to be the primary factor responsible for interannual *variations* in GPP, followed by temperature and precipitation variability. In terms of GPP *trends*, the authors report that “recent changes in atmospheric CO₂ and climate promoted terrestrial GPP increases with a significant linear trend in all three tropical regions.” In the African region, for which we are most interested in terms of the present discussion, the rate of GPP increase was about 0.3 PgC year⁻¹ per decade. As for the major cause of the increased growth, Ichii *et al.* favored carbon dioxide, reporting that “CO₂ fertilization effects strongly increased recent NPP trends in regional totals.”

In another study published that same year, Herrmann *et al.* (2005) investigated the “temporal and spatial patterns of vegetation greenness and rainfall variability in the African Sahel and their interrelationships based on analyses of Normalized Difference Vegetation Index (NDVI) time series for the period 1982-2003 and gridded satellite rainfall estimates.” Based on their analysis, the three researchers determined that “the overall trend in monthly maximum NDVI [was] positive over a large portion of the Sahel region, reaching up to 50% increase in the average NDVI in parts of Mali, Mauritania and Chad” (Figure 7). In addition, they found that “rainfall emerges as the dominant causative factor in the dynamics of vegetation greenness in the Sahel at an 8 km spatial resolution,” but that “the

vegetation greenness [was] beyond what would be expected from the recovery of rainfall conditions alone.”

In a discussion of their findings, Herrmann *et al.* state that their study “confirms previous regional-scale findings for the period 1982-1999 by Eklundh and Olsson (2003) and Olsson *et al.* (2005), who observed widespread positive trends of both time-integrated NDVI and NDVI amplitudes, and Anyamba and Tucker (2005), who [observed] increases in growing season NDVI across most parts of the region.” In concluding, they thus say that “a greening of the Sahel expressed in positive trends in NDVI indicates a net increase in biomass production during the period 1982-2003, which challenges the notion of irreversible desertification in the Sahel.”

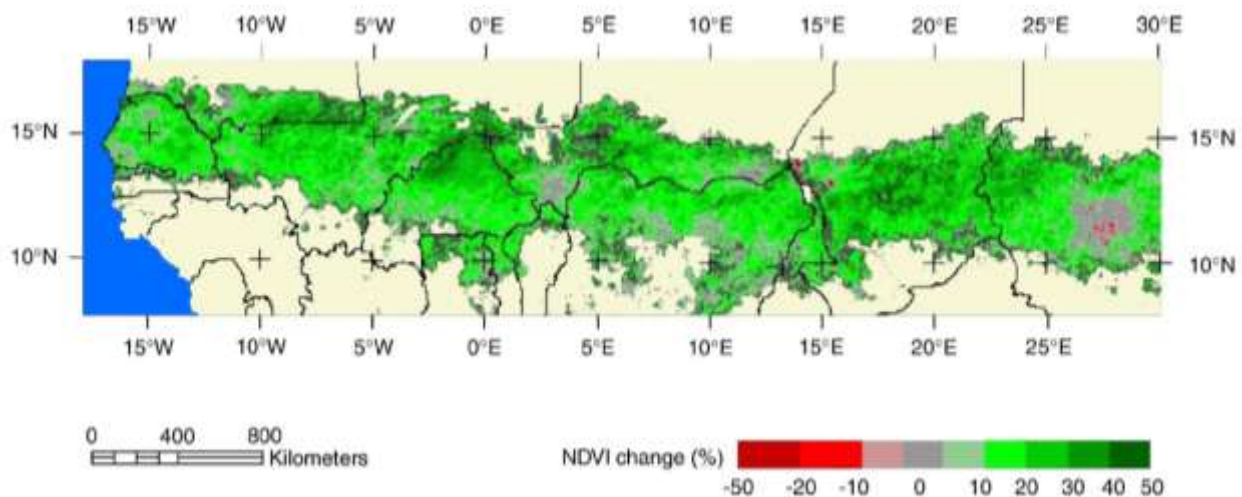


Figure 7. Percent change in vegetation greenness throughout the African Sahel over the period 1982–2003 based on monthly AVHRR NDVI time series data. Percentages indicate changes in average NDVI between 1982 and 2003. Adapted from Herrmann *et al.* (2005).

presence of spatially coherent and significant long-term trends in the residuals suggests that there might be another, weaker, causative factor,” which is also suggested by the fact that the “recovery of

Writing as background for their work on the subject, Midgley and Seydack (2006) note that “present and predicted future impacts of global environmental change on intact forests are both alarming and contentious,”

and that “some local models have predicted the *demise* [italics added] of South Africa’s only significant extent of indigenous forest, the Knysna forest, by 2050,” as reported by Midgley *et al.* (2001). In a study designed to see how bad things had become by the end of the 20th century, the pair of authors measured and analyzed the growth of all trees greater than 10 cm in diameter at breast height in 108 0.04-ha plots distributed throughout an unharvested nature reserve within the Knysna forest over the period 1991-2001.

Following a protocol that provided what they say is “probably an under-estimate,” the two researchers determined that “net basal area and aboveground biomass increased over the 10-year study period by 2% and there was a 1.2% increase in stem numbers, distributed almost equally amongst all size-classes.” Yet, because of the particular nature of the Knysna forest, Midgley and Seydack say that “over relatively short periods such as our decade, the aboveground biomass of this forest is more sensitive to negative/stressful conditions that would increase mortality, than to factors which may increase growth.” Nevertheless, and *in spite of this*, they found that “biomass increased.” And because “precipitation over the period 1991-2001 was some 5% less than the long-term average,” they concluded that the observed increase in growth rate “may have been the effect of the increase in global atmospheric carbon dioxide.”

In a contemporaneous study, Seaquist *et al.* (2006) provided important new details about the “greening up” of the African Sahel. Using a satellite data-driven light-use efficiency model to assess changes in absolute amounts of net primary

production (NPP), expressed as carbon content, and its inter-annual variability in the African Sahel for the period 1982-1999, Seaquist *et al.* report that an extensive, albeit discontinuous, east-west band of NPP increase ($>10 \text{ g C m}^{-2} \text{ year}^{-1}$) was identified. The band extended up to about 17°N , and included several hotspots ($>20 \text{ g C m}^{-2} \text{ year}^{-1}$) in central Senegal, south-western Mali, southern Chad, southern Sudan, as well as the Ivory Coast and southern Benin. For the Sahel in its entirety, the researchers determined that the mean rate of change per pixel was $8.4 \text{ g C m}^{-2} \text{ year}^{-1}$, which yields a total mean rate of change of $51.0 \text{ Mt C year}^{-1}$ and an absolute net gain in NPP over the entire 18-year period of 918.0 Mt C . In addition, they report that “this increase is associated with a decrease in the inter-annual variability of NPP for the 1990s compared to the 1980s,” such that “overall, the increase in NPP through time appears to be associated with an increase in the stability of this ecosystem,” with the changes in carbon capture and increase in stability being driven primarily by rainfall “followed by atmospheric CO_2 .”

Focusing more on carbon sequestration, Lewis *et al.* (2009a) documented changes in aboveground carbon storage in “79 permanent sample plots spanning 40 years (1968-2007), located in closed-canopy moist forest, spanning West, Central and Eastern Africa,” based on data obtained from more than 70,000 individual trees spread across ten countries. Their work revealed that “aboveground carbon storage in live trees increased by $0.63 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ between 1968 and 2007,” and that “extrapolation to unmeasured forest components (live roots, small trees, necromass) and scaling to the continent implies a total increase in carbon storage in

African tropical forest trees of 0.34 Pg C year⁻¹.”

In discussing their results, the 33 researchers who conducted the study say the observed changes in carbon storage “are similar to those reported for Amazonian forests per unit area, providing evidence that increasing carbon storage in old-growth forests is a pan-tropical phenomenon,” and they report that “combining all standardized inventory data from this study and from tropical America and Asia together yields a comparable figure of 0.49 Mg C ha⁻¹ year⁻¹,” which equates to “a carbon sink of 1.3 Pg C year⁻¹ across all tropical forests during recent decades,” which can account for roughly *half* of the so-called *missing carbon sink*, which has been long sought but never found (but is now, perhaps, half-found).

As for what the driving force is that seems to have breathed new life into old trees, Lewis *et al.* write in the concluding sentence of the abstract of their paper that “taxon-specific analyses of African inventory and other data suggest that widespread changes in resource availability, such as *increasing atmospheric carbon dioxide concentrations* [italics added], may be the cause of the increase in carbon stocks, as some theory (Lloyd and Farquhar, 1996) and models (Friedlingstein *et al.*, 2006; Stephens *et al.*, 2007; Ciais *et al.*, 2008) predict.”

Returning once again to a model-based study, Ciais *et al.* (2009) modeled the terrestrial carbon balance of Africa over the past century (1901-2002) using a spatially-resolved process-based vegetation model (ORCHIDEE), which is forced by changing climate, human-induced changes in land use, and a parameterization of natural fires.

This work revealed that the African net terrestrial carbon (C) balance increased from a net CO₂ source to the atmosphere of 0.14 Pg C per year in the 1980s to a net sink of 0.15 Pg C per year in the 1990s.” In addition, they say that the land use flux due to deforestation was “a source of 0.13 Pg C per year,” and that “this implies that climatic trends (mainly increasing precipitation) and CO₂ increase (the fertilization effect), are causing a sink of 0.28 Pg C per year which offsets the land-use source.”

In further discussing their findings, the five researchers indicate that “the trend of gross primary production is closely matching the trend in satellite observed NDVI,” or Normalized Difference Vegetation Index; and they write that their simulated trend in gross primary production “is also consistent with an increased vegetation activity over [the] Sahel reported by Eklundh and Olsson (2003) and Olsson *et al.* (2005),” while at the continental-scale the gross primary production trend can be largely (70%) explained by the CO₂ fertilization effect. Primarily in response to the ongoing rise in the air’s CO₂ content, therefore, it would appear from the results of this study that the African continent is significantly “greening up,” and that it has recently been doing so at a significantly enhanced rate.

One year later, Doherty *et al.* (2010) modeled future changes in land biogeochemistry and biogeography in the region bounded by 12.5°N, 12.5°S, 25°E and 42.5°E, representing most of East Africa (Kenya, Tanzania, Uganda, Rwanda, Burundi, Ethiopia, and Somalia), as well as portions of Central Africa (the Democratic Republic of Congo and Southern Sudan). This they did using eighteen future climate

projections derived from nine general circulation models that figured prominently in the IPCC's Fourth Assessment Report, employing the projections as input to the Lund-Potsdam-Jena dynamic global vegetation model that simulates changes in vegetation and ecosystem carbon cycling under future climate conditions, based on what they describe as "a coupled photosynthesis-hydrological scheme [that] computes gross primary productivity, plant respiration, and evapotranspiration on a daily time step based on the current climate, atmospheric CO₂ concentration, vegetation structure and phenological state, and soil water content."

As a result of this effort, Doherty *et al.* report that "all simulations showed future increases in tropical woody vegetation over the region at the expense of grasslands," noting that "regional increases in net primary productivity (18-36%) and total carbon storage (3-13%) by 2080-2099 compared with the present-day were common to all simulations," and that "seven out of nine simulations continued to show an annual net land carbon sink in the final decades of the 21st century because vegetation biomass continued to increase." In light of these findings, the researchers write that "overall, our model results suggest that East Africa, a populous and economically poor region, is likely to experience some ecosystem service benefits through increased precipitation, river runoff and fresh water availability," and they state that "resulting enhancements in net primary productivity may lead to improved crop yields in some areas." What is more, they specifically state that their results "stand in partial contradiction of other studies that suggest possible negative consequences for

agriculture, biodiversity and other ecosystem services caused by temperature increases."

With respect to the continent as a whole, Scheiter and Higgins (2009) write that "recent IPCC projections suggest that Africa will be subject to particularly severe changes in atmospheric conditions" in the years and decades ahead, and that these changes could have equally severe repercussions for its flora and fauna. However, they say that how the continent's "grassland-savanna-forest complex will respond to these changes has rarely been investigated," and that "most studies on global carbon cycles use vegetation models that do not adequately account for the complexity of the interactions that shape the distribution of tropical grasslands, savannas and forests."

In an attempt to overcome these shortcomings, the two scientists developed a new vegetation model -- the *adaptive dynamic global vegetation model* (aDGVM) -- that employs established sub-models for photosynthesis, respiration, canopy scaling, competition for water, competition for light, reproduction and mortality, and which additionally contains the novel elements of dynamic carbon allocation and phenology functions, as well as a fire model that estimates fire intensity as a function of fuel biomass, fuel moisture and wind speed, and which simulates topkill (stem mortality) as a function of individual tree size and fire intensity, all of which phenomena are related to the individual plant's physiological state and the environmental conditions surrounding it.

Forward simulations to the year 2100 with this impressive model suggest, in the words

of the two researchers, that “grasslands will spread into the Sahara and into the horn of Africa, such that the total area covered by deserts or bare soil decreases by 5.7%.” In addition, they say “it is predicted that 34.6% of today’s grasslands are transformed into savannas,” and that “45.3% of today’s savannas are transformed into deciduous woodlands.” As a result, they indicate that “the total biomass stored in each of the biomes increases, with high relative changes in grasslands and savannas (by 256% and 241%, respectively)” and with a 102% increase in tree biomass. Thus, the CO₂- and warming-induced *greening of the Earth* phenomenon, which has been manifest throughout the entire world over the past few decades, seems destined to continue throughout the entire 21st century in Africa.

Finally, Heubes *et al.* (2011) modeled the future spatial distribution of desert, grassland, savanna, deciduous and evergreen forest in West Africa using six bioclimatic models. None of these models, however, took any account of the photosynthetic-enhancing and transpiration-reducing effects of projected increases in atmospheric CO₂ concentration, being based *solely* on the *climatic* projections of 17 general circulation models of the atmosphere for emissions scenario A2a, as described in the Fourth Assessment Report of the IPCC (2007), which projections were downscaled to 0.1 degree of latitude and longitude as described by Ramirez and Jarvis (2008). So what did their work reveal?

The six scientists report finding “a climate-driven greening trend,” with “northward spread of grassland into the Sahara and the replacement of savannas by deciduous

forest,” which results they say “are concordant with results from Cramer *et al.* (2001), Scholze *et al.* (2006) and Scheiter and Higgins (2009),” although they add that the latter investigators “attributed the greening to increased CO₂ levels.” Further to this point, they state that the models they used “indicate that climatic change alone can yield this pattern,” where “the expected ‘greening’ of the Sahara is primarily driven by increasing precipitation,” as they note has also been suggested by Hickler *et al.* (2005).

Using satellite images that reflect the region’s current vegetation state, Heubes *et al.* additionally modeled “real” as opposed to “potential” vegetation, which enabled them to “clearly show,” as they describe it, “effects of human activity negatively affecting tree cover, as also demonstrated by other case studies, e.g. in Senegal (Vincke *et al.*, 2010) and Mali (Ruelland *et al.*, 2010). More specifically, they report that in West Africa, “agricultural expansion, sometimes facilitated by other human activities such as wood extraction, has been identified as major drivers of forest loss and degradation,” citing Norris *et al.* (2010).

In further describing their findings, “considering climate change alone,” in the words of Heubes *et al.*, “the model results of potential vegetation (biomes) show a ‘greening’ trend by 2050.” However, they say that “the modeled effects of human impact suggest future forest degradation.” Thus, it can readily be appreciated that the *additional* impetus for greening that is provided by the ongoing rise in the air’s CO₂ content may well spell the difference between *better* days or *sadder* days for the biomes of West Africa and the welfare of the region’s growing human population in

the years and decades ahead. For it is clear from the research presented above, that the ongoing rise in the air's CO₂ concentration and its *anti-transpiration effect* (which improves plant water-use efficiency) are enhancing the vegetative productivity of Africa.

ASIA

Many scientists have examined terrestrial productivity trends in Asia, with a vast majority of those studies focusing on locations in China. As such, we have arranged our section on Asia into two sub-headings: *China* and *All Other Asian Countries*. In addition, given the sheer number of studies conducted in China, we have further divided our treatment of China into five sub-regions: *Country-wide*, *Deserts*, *Forests*, *Grasslands*, and the *Tibetan Plateau*.

CHINA

Country-wide

In examining how vegetative productivity has fared throughout all of China over the past few decades, we begin with the modeling work of Liu *et al.* (2004), who derived detailed estimates of the economic impact of predicted climate change on agriculture in China. This was accomplished using county-level agricultural, climate, social, economic and edaphic data for 1275 agriculture-dominated counties for the period 1985-1991, together with the outputs of three general circulation models of the atmosphere that were based on five different scenarios of anthropogenic CO₂-induced climate change that yielded a mean countrywide temperature increase of 3.0°C and a mean precipitation increase of 3.9%

for the 50-year period ending in AD 2050. In doing so, they determined that "*all of China* [italics added] would *benefit* [italics added] from climate change in most scenarios." In addition, they state that "the effects of CO₂ fertilization should [also] be included, for some studies indicate that this may produce a significant increase in yield," an increase, it should be noted, that is extremely well established.

The great significance of these findings is readily grasped when it is realized, in Liu *et al.*'s words, that "China's agriculture has to feed more than one-fifth of the world's population, and, historically, China has been famine prone." As one example of this fact, they report that "as recently as the late 1950s and early 1960s a great famine claimed about thirty million lives (Ashton *et al.*, 1984; Cambridge History of China, 1987)." Acting together, therefore, it is clear that the increases in China's agricultural production estimated to result from the direct effects of increased anthropogenic CO₂ emissions *plus* the increases due to the changes in temperature and precipitation typically predicted to result from these emissions as well, could easily prove the deciding factor in determining whether China's population *will* or *will not* be able to adequately feed itself at the midpoint of the current century.

Fang *et al.* (2003) also looked at the whole of China, finding that its terrestrial NPP increased by 18.7% between 1982 and 1999. Referring to this result as "an unexpected aspect of biosphere dynamics," they say that this increase "is much greater than would be expected to result from the fertilization effect of elevated CO₂, and also greater than expected from climate, based on broad geographic patterns." But it may

not be, considering that from 1982 to 1999, the atmosphere's CO₂ concentration rose by approximately 27.4 ppm, which increase could be expected to have increased the NPP of the conglomerate of forest types found in China by about 7.3% (see <http://www.co2science.org/articles/V5/N38/EDIT.php> for an explanation of this calculation). But this increase is only a *part* of the total NPP increase one could expect, for Fang *et al.* note that “much of the trend in NPP appeared to reflect a change towards an earlier growing season,” which was driven by the 1.1°C increase in temperature they found to have occurred in their region of study between 1982 and 1999.

Following this lead, it should be noted from the study of White *et al.* (1999), which utilized 88 years of data (1900-1987) that were obtained from 12 different locations within the eastern U.S. deciduous forest that stretches from Charleston, SC (32.8°N latitude) to Burlington, VT (44.5°N latitude), that a 1°C increase in mean annual air temperature increases the length of the forest's growing season by approximately five days. In addition, White *et al.* determined that a one-day extension in growing season length increased the mean forest NPP of the 12 sites they studied by an average of 1.6%. Hence, there could easily be an *additional* NPP increase due to the warming-induced growing season expansion experienced in China from 1982 to 1999 of 1.6%/day x 5 days = 8.0%, which brings the total CO₂-induced plus warming-induced increase in NPP to 15.3%.

Last of all, as noted previously in our report, there is a well-documented positive synergism between increasing air temperature and CO₂ concentration (Idso

and Idso, 1994), such that the 1°C increase in temperature experienced in China between 1982 and 1999 could *easily* boost the initial CO₂-induced 7.3% NPP enhancement to the 10.7% enhancement that when combined with the 8.0% enhancement caused by the warming-induced increase in growing season length would produce the 18.7% increase in NPP detected in the satellite data. And in view of these observations, the findings of Fang *et al.* are seen to be right in line with what would be expected to result from the increases in air temperature and atmospheric CO₂ concentration that occurred between 1982 and 1999 in China: a dramatically stimulated terrestrial biosphere that is growing ever more productive with each passing year.

In a similar study, Piao *et al.* (2005a) say their results suggest that “terrestrial NPP in China increased at a rate of 0.015 Pg C yr⁻¹ over the period 1982-1999, corresponding to a total increase of 18.5%, or 1.03% annually.” They also found that “during the past 2 decades the amplitude of the seasonal curve of NPP has increased and the annual peak NPP has advanced,” which they say “may indirectly explain the enhanced amplitude and advanced timing of the seasonal cycle of atmospheric CO₂ concentration (Keeling *et al.*, 1996),” the former of which phenomena they further suggest “was probably due to the rise in atmospheric CO₂ concentration, elevated temperature, and increased atmospheric N and P deposition,” while the latter phenomenon they attribute to “advanced spring onset and extended autumn growth owing to climate warming.”

Citing a total of 20 scientific papers at various places in the following quote from

their research report, Piao *et al.* conclude that “results from observed atmospheric CO₂ and O₂ concentrations, inventory data, remote sensing data, and carbon process models have all suggested that terrestrial vegetation NPP of the Northern Hemisphere has increased over the past 2 decades and, as a result, the northern terrestrial ecosystems have become important sinks for atmospheric CO₂.”

Covering the same time period of examination (1982-1999), Zhu *et al.* (2007) analyzed 18 years of climatic data and satellite observations of Normalized Difference Vegetation Index (NDVI) throughout all of China, calculating terrestrial vegetative net primary productivity (NPP) using the revised light-use efficiency model of Zhu *et al.* (2006) and Zhu *et al.* (2007).

In describing their results, Zhu *et al.* say they indicate that “climatic changes in China have eased some critical climatic constraints on plant growth.” They note, for example, that “water availability most strongly limits vegetation growth over 28% of the whole country surface, whereas temperature limits growth over 43% and radiation over 29%,” but they report that “from 1982 to 1999, modeled NPP increased by 1.42% per year in water-limited regions of Northwest China, 1.46% per year in temperature-limited regions of Northeast China and Tibet Plateau, and 0.99% per year in radiation-limited regions of South China and East China.” Summed over the entire 18-year period, *total* Chinese terrestrial vegetation NPP increased by 24.2%. Last of all, they report that “interannual variations of NPP in Chinese terrestrial vegetation are positively correlated with global increases in

atmospheric CO₂ growth rate, indicating that NPP in Chinese terrestrial vegetation will increase with the global increases in atmospheric CO₂ growth rate.”

Writing as background for their work, Peng *et al.* (2011) report that “using satellite-derived normalized difference vegetation index (NDVI) datasets, previous studies have found that vegetation growth significantly increased in most areas of China during the period 1982-99 and that the increased vegetation growth was significantly correlated with increased temperature (e.g., Zhou *et al.*, 2001; Piao *et al.*, 2003).” In addition, they report that “the increased temperature boosted vegetation growth through an increase in growing season length and enhanced photosynthesis (e.g., Zhou *et al.*, 2001; Slayback *et al.*, 2003; Piao *et al.*, 2006b).”

Against this backdrop, Peng *et al.* used NOAA/AVHRR NDVI composites at a spatial resolution of 0.083° and 15-day intervals that were produced by the Global Inventory Modeling and Mapping Studies (GIMMS) program, as described by Tucker *et al.* (2005), to explore vegetation activity over the whole of China for the period 1982-2010, noting that “the GIMMS NDVI datasets have been corrected to minimize the effects of volcanic eruptions, solar angle and sensor errors and shifts,” as described by Zhou *et al.* (2001) and Slayback *et al.* (2003), and citing the fact that these datasets have also proved to be “one of the best products to depict the temporal change of vegetation growth,” as demonstrated by Beck *et al.* (2011). At the national scale, the results of their analysis revealed that for the average growing season (April-October), a linear regression model predicts a significant increasing NDVI

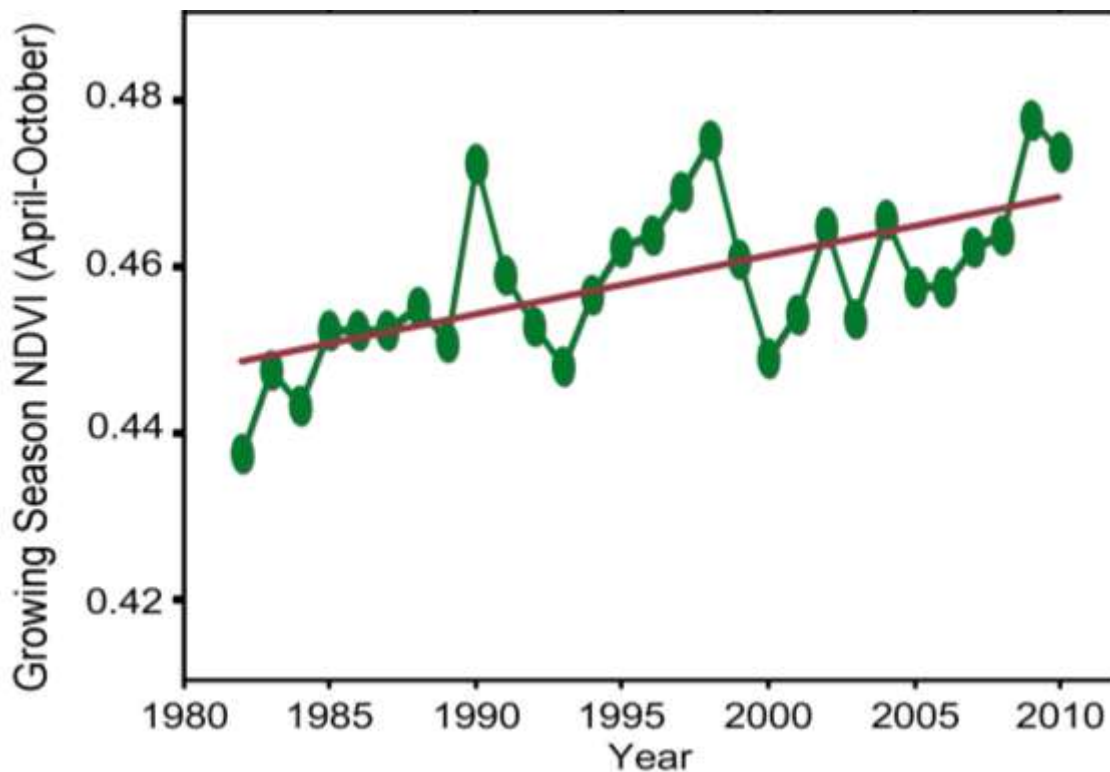


Figure 8. Inter-annual variations in growing season (April-October) NDVI for China over the period 1982-2010. The linear trend in the data, as mentioned in the text, is also shown. Adapted from Peng *et al.* (2011).

trend of 0.0007/year from 1982 to 2010, with an R^2 value of 0.40 and $P < 0.001$ (see Figure 8). And they say that they also found increasing trends for all three *sub-sets* of the growing season: April-May, June-August and September-October.

Expanding the temporal domain of analysis back in time was Mao *et al.* (2009), who used a modified version of the Sheffield Dynamic Global Vegetation Model described by Woodward and Lomas (2004) to study changes in the structure, composition and carbon storage of vegetation and soils throughout all of China in response to changes in climate and atmospheric CO_2 concentration that occurred between 1901 and 2000. According to the researchers who

conducted this study, their modeling exercise suggested that “during the past 100 years a combination of increasing CO_2 with historical temperature and precipitation variability in continental China have caused the total vegetation carbon storage to increase by 2.04 Pg C, with 2.07 Pg C gained in the vegetation biomass but 0.03 Pg C lost from the organic soil carbon matter.” They also found that “the increasing CO_2 concentration in the 20th century is primarily responsible for the increase of the total potential vegetation carbon.” However, because the biological effects of temperature and precipitation were *negative*, the historical increase in the air’s CO_2 content was actually *totally* responsible for the net storage of carbon in China’s terrestrial vegetation and soil over

the 20th century, since without the aerial fertilization effect of CO₂, there would have been a net *loss* of carbon that exceeded in absolute value the net gain that ultimately prevailed.

Lastly, with one eye on the past and the other looking toward the future, Mu *et al.* (2008) used “a well-documented daily ecosystem process model Biome-BGC (Running and Hunt, 1993; White *et al.*, 2000; Thornton *et al.*, 2002) to differentiate the effects of changing climate and increasing CO₂ on the carbon cycle for terrestrial China for two time periods, 1961-2000 (present conditions), and future (2071-2110) conditions with projected climate change under doubled CO₂.” In doing so the five researchers found that “during 1961-2000 at the national scale, changes in climate reduced carbon storage in China’s ecosystems, but increasing CO₂ compensated for these adverse effects of climate change, resulting in an overall increase in the carbon storage of China’s ecosystems,” while “under the future scenario (2071-2110), with a doubling [of] CO₂, China will experience higher precipitation and temperature,” but once again “the concomitant doubling of CO₂ will continue to counteract the negative effects of climate change on carbon uptake in the future, leading to an increase in carbon storage relative to current levels.”

Given each of the findings presented above, it would appear that rather than *devastating* the landscape, the historical increases in atmosphere’s CO₂ concentration and temperature have actually *fostered* a significant *greening of China*, observed throughout the length and breadth of the country.

Deserts

In reviewing how deserts have fared throughout China in response to rising air temperatures and atmospheric CO₂ concentrations, we begin with the work of Brogaard *et al.* (2005). In their analysis they examined the dry northern and northwestern regions of the country – including the Inner Mongolia Autonomous Region (IMAR) – which had been thought to have experienced declining vegetative productivity over the past few decades due to “increasing livestock numbers, expansion of cultivated land on erosive soils and the gathering of fuel wood and herb digging,” which practices were believed to have been driven by rising living standards that in combination with a growing population were assumed to have increased the pressure on these marginal lands. In the case of increasing grazing, for example, Brogaard *et al.* note that the total number of livestock in the IMAR increased from approximately 46 million head in 1980 to about 71 million in 1997.

To better assess the seriousness of this supposedly “ongoing land degradation process,” as they describe it, the researchers adapted a satellite-driven parametric model, originally developed for Sahelian conditions, to the central Asian steppe region of the IMAR by including “additional stress factors and growth efficiency computations.” The applied model, in their words, “uses satellite sensor-acquired reflectance in combination with climate data to generate monthly estimates of gross primary production.” And to their great surprise, this work revealed that “despite a rapid increase in grazing animals on the steppes of the IMAR for the 1982-1999 period,” their model

estimates did “*not* indicate declining biological production [italics added].”

Clearly, some strong positive influence compensated for the increased human and animal pressures on the lands of the IMAR over the period of Brogaard *et al.*'s study. In this regard, they mention the possibility of increasing productivity on the agricultural lands of the IMAR, but they note that crops are grown on “only a small proportion of the total land area.” Other potential contributing factors they mention are “an increase in precipitation, as well as afforestation projects.” Two things that are *not* mentioned are the aerial fertilization effect and the transpiration-reducing effect of the increase in the air's CO₂ concentration that was experienced over the study period. Applied together, the sum of these several positive influences (and possibly others that remain unknown) was demonstrably sufficient to keep plant productivity from declining in the face of greatly increasing animal and human pressures on the lands of the IMAR from 1982 to 1999.

Working in the semi-arid Loess Plateau of northwestern Shanxi, China, Yang *et al.* (2011) studied characteristics of *Caragana microphylla* plantations that had been established there five, ten, twenty, thirty and forty years previously, in efforts to combat desertification, which in the 1960s had claimed 48.5% of the region's surface area. These perennial leguminous and sand-binding shrubs were chosen for the task because they have well-developed stems with many clustered branches and large root systems capable of adapting to poor nutrient conditions; and they were thus positioned in groups to act as sand barriers and windbreaks. So what did Yang

et al. learn by scrutinizing the different-aged plants' environments?

The establishment and development of the *C. microphylla* shrubs, in the words of the five Chinese scientists, “improved soil texture, enhanced soil organic matter (SOM), total nitrogen (TN), and cation exchange capacity (CEC).” In addition, they report that “SOM, TN, and CEC were significantly higher at the center than at the outside of the shrub canopies and were higher at the 0-5 cm depth than at the 5-10 cm depth.” Moreover, they state that “the differences in SOM, TN, and CEC from the center to the outside of shrub canopies were greater under 30- and 40-year-old shrubs than under 10- and 5-year-old shrubs.” And they even discovered that the spatiotemporal heterogeneity of the soil properties “facilitated the development of herbaceous species diversity and the restoration of the [region's] natural ecosystem,” which had previously been lost to desertification.

In a somewhat different study, Peng *et al.* (2010) used snow-depth measurements collected at 279 meteorological stations scattered across China, plus co-located satellite-derived Normalized Difference Vegetation Index (NDVI) data, to investigate spatio-temporal changes in snow depth over the period 1980-2006 and the effects of those changes on vegetative growth the following spring and summer. In doing so, the five researchers learned that “over the past three decades, winter snow depth overall increased in northern China, particularly in the most arid and semiarid regions of western China where desert and grassland are mainly distributed,” and they say that in those specific areas there were positive correlations between mean winter

snow depth and spring NDVI data. More germane to this review, however, they note that Piao *et al.* (2005b) determined that the net primary productivity of the same desert and grasslands during 1982-1999 “increased by 1.6% per year and 1.1% per year, respectively,” and that “desertification has been reversed in some areas of western China since the 1980s,” citing the work of Runnstrom (2000), Wu (2001), Zhang *et al.* (2003) and Piao *et al.* (2005b).

In discussing the implications of their findings, Peng *et al.* write that the “increase in vegetation coverage in arid and semiarid regions of China, possibly driven by winter

(Qian *et al.*, 2002; Zhao *et al.*, 2004).” Thus, as the world has warmed over the past three decades, there has been another concomitant climatic change across China above 40°N latitude (an increase in winter snow depth) that has prompted a biological change (increased vegetative growth in desert areas and grasslands) that has prompted yet another climatic change (a reduction in sand-dust storms), all of which changes would be recognized by most people as *positive developments*.

In another study, Piao *et al.* (2005b) used a time series of NDVI data from 1982 to 1999, together with precipitation and

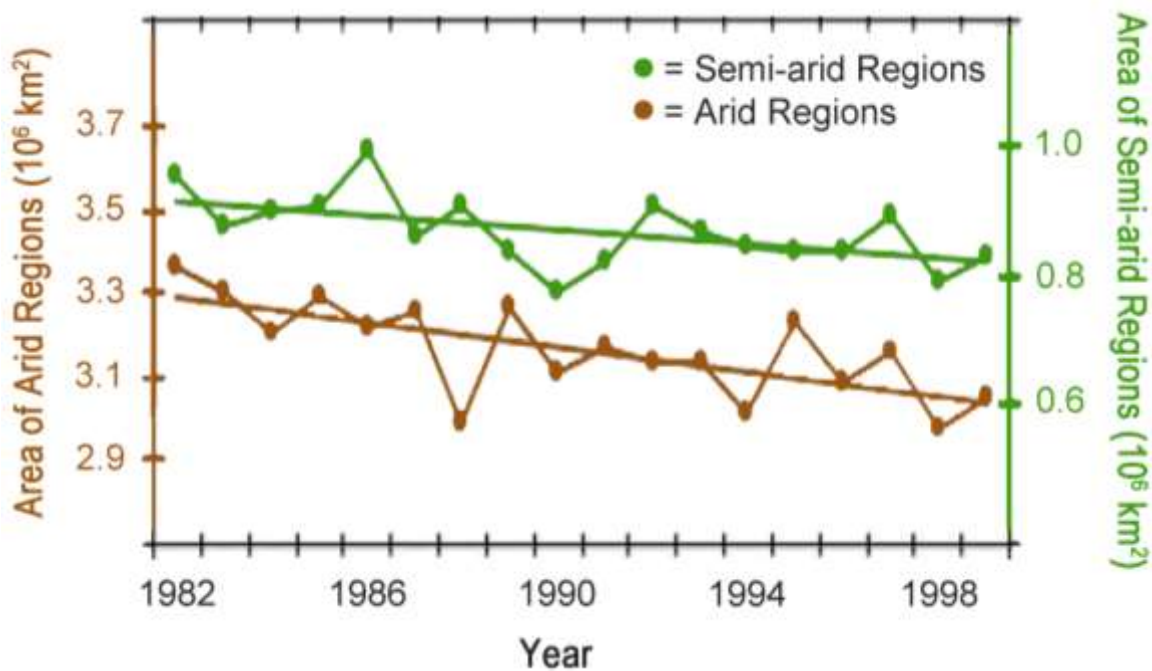


Figure 9. Interannual variation in area of arid (brown line) and semiarid region (green line) in China over the period 1982 to 1999. Adapted from Piao *et al.* (2005b).

snow, will likely restore soil and enhance its anti-wind-erosion ability, reducing the possibility of released dust and mitigating sand-dust storms,” while noting that the frequency of sand-dust storms has indeed “declined in China since the early 1980s

temperature data, to investigate variations of desert area in China by “identifying the climatic boundaries of arid area and semiarid area, and changes in NDVI in these areas.” In doing so, they discovered that “average rainy season NDVI in arid and

semiarid regions both increased significantly during the period 1982-1999.” Specifically, they found that the NDVI increased for 72.3% of total arid regions and for 88.2% of total semiarid regions, such that the area of arid regions decreased by 6.9% and the area of semiarid regions decreased by 7.9% (see Figure 9). They also report that by analyzing Thematic Mapper satellite images, “Zhang *et al.* (2003) documented that the process of desertification in the Yulin area, Shannxi Province showed a decreased trend between 1987 and 1999,” and that “according to the national monitoring data on desertification in western China (Shi, 2003), the annual desertification rate decreased from 1.2% in the 1950s to -0.2% at present.”

Further noting that “variations in the vegetation coverage of these regions partly affect the frequency of sand-dust storm occurrence (Zou and Zhai, 2004),” Piao *et al.* concluded that “increased vegetation coverage in these areas will likely fix soil, enhance its anti-wind-erosion ability, reduce the possibility of released dust, and consequently cause a mitigation of sand-dust storms.” Interestingly, in this regard, they report that “recent studies have suggested that the frequencies of strong and extremely strong sand-dust storms in northern China have significantly declined from the early 1980s to the end of the 1990s (Qian *et al.*, 2002; Zhao *et al.*, 2004).” It would thus appear that the dreaded climatic change claimed to have been experienced by the globe over the latter part of the 20th century was either (1) not so dreaded after all or (2) *totally dwarfed* by opposing phenomena that significantly *benefited* China, as its lands grew ever greener during this period and its increased

vegetative cover helped to stabilize its soils and throw feared desertification into reverse.

Writing as background for their work, Zhao *et al.* (2011) note that “many studies based on analyses of satellite images have detected a greening trend at global (Myneni *et al.*, 1997; Nemani *et al.*, 2003; Potter *et al.*, 2007; Zhou *et al.*, 2001) and regional scales (Donohue *et al.*, 2009; Fang *et al.*, 2004; Herrmann *et al.*, 2005).” However, they say that “the response of vegetation to climatic changes widely differed by biome (Fang *et al.*, 2005; Piao *et al.*, 2006c) and bioregion (Verbyla, 2008).” Against this backdrop and focusing on the grassland-oasis-desert complex of northwest China, the four Chinese researchers “investigated spatio-temporal changes in vegetation growth and their responses to a changing climate by biome and bioregion, using satellite-sensed Normalized Difference Vegetation Index (NDVI) data from 1982 to 2003, along with corresponding climate data.”

As a result of their efforts, the researchers found that over the 22 years of their study, when annual mean temperature increased by 0.06°C/year, “about 30% of the total vegetated area showed an annual increase of 0.7% in growing season NDVI,” which trend “occurred in all biomes and all bioregions except Sawuer, a sub-region of the study area with no significant climate change.” And breaking this result into three sub-periods, they report that the NDVI increase was *remarkable* during 1982-1988, then tended to be *slight*, and finally actually *declined a bit* from 1998 to 2003, which pattern largely resembles the concomitant pattern of *global* air temperature change, which could have been responsible for the

shifts in regional precipitation that appeared to be driving the observed shifts in NDVI. And in further support of this connection, Zhao *et al.* note that “previous analyses of satellite-measured vegetation growth suggested a greening trend of vegetation in the central United States (Wang *et al.*, 2001, 2003) and the Sahel (Anyamba and Tucker, 2005; Herrmann *et al.*, 2005) due to the effects of increasing precipitation at seasonal or annual scales.”

Given the findings presented above, in response to what had been called the most dramatic global warming and CO₂ rise of the past two millennia, the vegetation in China’s deserts has fared remarkably well.

Forests

How have forests fared across China in response to the increasing air temperatures and atmospheric CO₂ concentrations of the past few decades? Writing as background for their study, Ren *et al.* (2011) state that “in recent decades, there has been increased concern that elevated tropospheric ozone (O₃) and climate change have [negatively] influenced the ability of China’s ecosystems to provide people with essential goods and services.” Consequently, in an effort designed to explore this concern, they investigated “the potential effects of elevated O₃ along with climate change/variability on NPP [net primary production] and NCE [net carbon exchange] in China’s forest ecosystems for the period 1961-2005 using a process-based dynamic land ecosystem model (DLEM, Tian *et al.*, 2005, 2010a,b),” while additionally considering “other environmental factors such as *land-cover/land-use change* (LCLUC), increasing [atmospheric] CO₂ and nitrogen deposition.”

In describing their findings, Ren *et al.* report that O₃ pollution had *consistent negative effects* on forest production, reducing total NPP by 0.2 to 1.6% from the 1960s to 2000-2005, such that *without* O₃ pollution, carbon uptake rates would have *increased* by 3.5% in the 1960s and 12.6% in the 6 years 2000-2005. Climate change, on the other hand, had both negative *and* positive effects on NPP and NCE; and it was thus the major factor controlling the inter-annual *variability* of these two productivity parameters.

LCLUC also had negative impacts on NPP and NCE; but Ren *et al.* found that “nitrogen deposition alone could compensate for the combined negative effects of O₃ and LCLUC in China.” They also report that an increase in NPP occurred in the CO₂-N *combination* simulation, which they say “was consistent with previous studies (e.g., Ollinger *et al.*, 2002; Felzer *et al.*, 2004; Hanson *et al.*, 2005).” And they found that CO₂ and nitrogen deposition *working together* “could offset the combined negative effects of O₃ pollution, climate change and LCLUC on annual NCE.” Therefore, it would appear that the combination of *atmospheric CO₂ enrichment* and *nitrogen deposition* provide powerful antidotes for the negative effects of ozone pollution, land-cover/land-use change and various deleterious climatic phenomena with regard to their impacts on NPP and NCE in China *and*, by inference, other parts of the world as well.

In another study, Su *et al.* (2004) used an ecosystem process model to explore the sensitivity of the net primary productivity (NPP) of an oak forest near Beijing (China) to the global climate changes projected to result from a doubling of the atmosphere’s CO₂ concentration from 355 to 710 ppm.

The results of this work suggested that the aerial fertilization effect of the specified increase in the air's CO₂ content would raise the forest's NPP by 14.0%, that a concomitant temperature increase of 2°C would boost the NPP increase to 15.7%, and that adding a 20% increase in precipitation would push the NPP increase all the way to 25.7%. Last of all, they calculated that a 20% increase in precipitation and a 4°C increase in temperature would also boost the forest's NPP by 25.7%.

In another model study, Su *et al.* (2007) used a process-based model (BIOME-BGC) "to investigate the response of *Picea schrenkiana* forest to future climate changes and atmospheric carbon dioxide concentration increases in the Tianshan Mountains of northwestern China," which they "validated by comparing simulated net primary productivity (NPP) under current climatic conditions with independent field-measured data." The specific climate change scenario employed in this endeavor was a double-CO₂-induced temperature increase of 2.6°C and a precipitation increase of 25%. So what did they find?

When the predicted precipitation increase was considered by itself, the NPP of the *P. schrenkiana* forest increased by 14.5%; while the predicted temperature increase by itself increased forest NPP by 6.4%, and the CO₂ increase by itself boosted NPP by only 2.7%. When the predicted increases in precipitation and temperature occurred *together*, forest NPP increased by a larger 18.6%, which is just slightly less than the sum of the two individual effects; but when the CO₂ concentration increase was added to the mix and all three factors increased together, the Chinese researchers report that forest NPP "increased *dramatically*

[italics added], with an average increase of about 30.4%."

Su *et al.* conclude that comparison of the results derived from the various scenarios of their study indicates that "the effects of precipitation and temperature change were simply additive, but that the synergy between the effects of climate change and doubled CO₂ was important," as it made the whole response much larger than the sum of its separate responses, due to the fact that "feedback loops associated with the water and nitrogen cycles [which may be influenced significantly by atmospheric CO₂ enrichment] ultimately influence the carbon assimilation response."

Grasslands

Noting that the climate of China's temperate grasslands "experienced dramatic change in the past several decades," Piao *et al.* (2006) thought it important to investigate the impact of that climate change on the productivity of the country's grasslands. This they did by analyzing Normalized Difference Vegetation Index (NDVI) data obtained from the U.S. National Oceanic and Atmospheric Administration's very high resolution radiometer at a spatial resolution of 8 x 8 km and at 15-day intervals from January 1982 to December 1999, comparing those results with temperature, precipitation and Thornthwaite (1948) moisture index data generated from 680 well-distributed climate stations across China.

Piao *et al.*'s results indicated little to no increase in precipitation and moisture index, respectively, over the period of their study. In the case of temperature, however, there was a least-squares linear

warming of 0.89°C between 1982 and 1999 with $R = 0.59$ and $P = 0.009$, which they described as “dramatic.” Even more dramatic, however, was their finding that “mean growing season NDVI increased significantly ($R = 0.73$, $P = 0.001$) from 0.25 in 1982 to 0.28 in 1999,” or by approximately 12%.

At first glance it would appear that the dramatic increase in temperature is what drove the dramatic increase in grassland productivity. However, more detailed

So what might have compensated for the temporally-decreasing strength of the growth enhancement provided by the warming of the region? As possible contenders, Piao *et al.* mention the “atmospheric CO₂ fertilization effect, increased nutrient deposition, and human activity such as grazing management [and] land abandonment due to migration into urban areas.”

One year later, using national grassland resource inventory data, a normalized

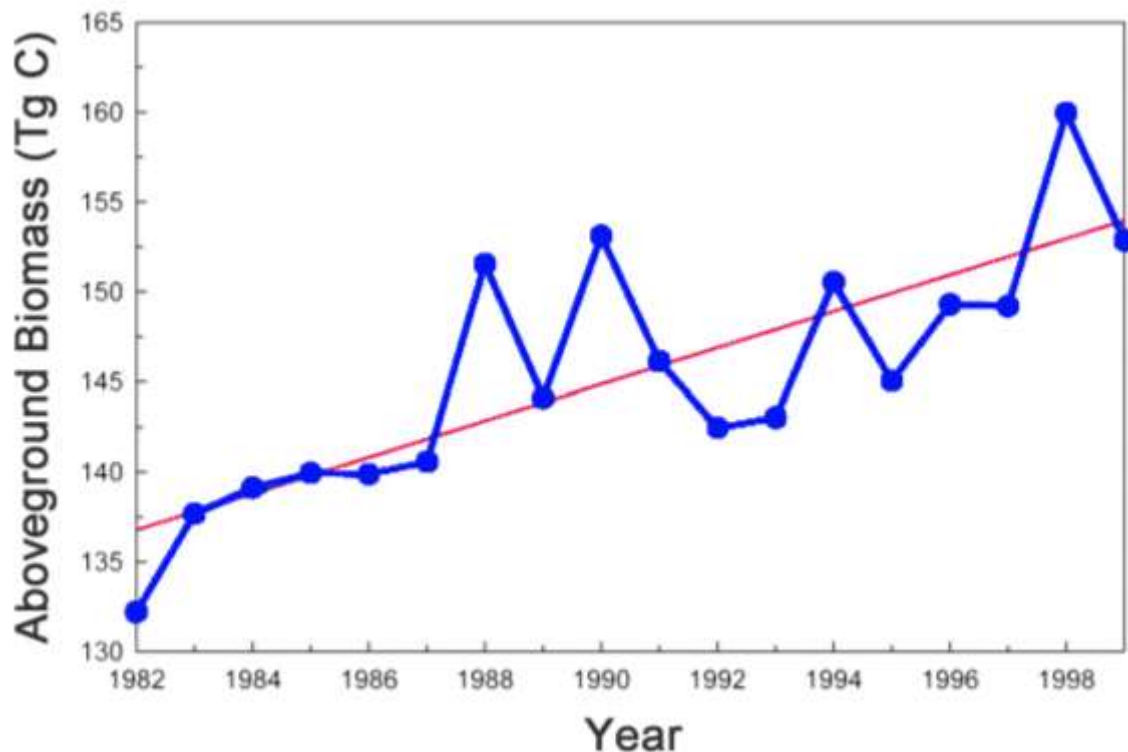


Figure 10. Interannual variations in aboveground biomass for China's grassland over the period of 1982–1999. Adapted from Piao *et al.* (2007).

analyses revealed, in the researchers' words, that “the positive effect of temperature on the growth of grassland *decreased* [italics added] as temperature *rose* [italics added].”

difference vegetation index (NDVI) time series data set, and a satellite-based statistical model, Piao *et al.* (2007) identified changes in the size and distribution of the aboveground biomass carbon (C) stocks of China's grasslands between 1982 and 1999. Specifically, the

authors found that over the 18-year period of their study, “aboveground biomass C stocks ... significantly increased from 136.3 Tg C in the early 1980s to 154.0 Tg C in the late 1990s,” for a total increase of 13% (Figure 10). As for what factors might have been responsible for the C-stock increase, they note that “growing season average temperature for the study area increased by 0.052°C per year and growing season precipitation also tended to increase,” which led them to conclude that “increased temperature may be associated with increasing C stocks and interannual changes in precipitation may be a factor in the fluctuations of C stocks.” In addition, they suggest the “atmospheric CO₂ fertilization effect and human activity such as land management may also partly account for the observed increase in biomass C stocks of China’s grassland.”

Lastly, in a somewhat different study, Peng *et al.* (2010) used snow-depth measurements collected at 279 meteorological stations scattered across China, plus collocated satellite-derived Normalized Difference Vegetation Index (NDVI) data, to investigate spatio-temporal changes in snow depth over the period 1980-2006 and the effects of those changes on vegetative growth the following spring and summer. In doing so, the five researchers learned that “over the past three decades, winter snow depth overall increased in northern China, particularly in the most arid and semiarid regions of western China where desert and grassland are mainly distributed,” and they say that in those specific areas there were positive correlations between mean winter snow depth and spring NDVI data. More germane to this review, however, they note that Piao *et al.* (2005) determined that the

net primary productivity of the same desert and grasslands during 1982-1999 “increased by 1.6% per year and 1.1% per year, respectively,” and that “desertification has been reversed in some areas of western China since the 1980s,” citing the work of Runnstrom (2000), Wu (2001), Zhang *et al.* (2003) and Piao *et al.* (2005a).

In discussing the implications of their findings, Peng *et al.* write that the “increase in vegetation coverage in arid and semiarid regions of China, possibly driven by winter snow, will likely restore soil and enhance its antiwind-erosion ability, reducing the possibility of released dust and mitigating sand-dust storms,” while noting that the frequency of sand-dust storms has indeed “declined in China since the early 1980s (Qian *et al.*, 2002; Zhao *et al.*, 2004).” Thus, as the world has warmed over the past three decades, there has been another concomitant climatic change across China above 40°N latitude (an increase in winter snow depth) that has prompted a biological change (increased vegetative growth in desert areas and grasslands) that has prompted yet another climatic change (a reduction in sand-dust storms), all of which changes amount to *positive developments*.

Tibetan Plateau

Taking a long temporal view on how vegetative productivity has fared in this region of China, Herzs Schuh *et al.* (2011) “critically review possible driving forces for early- to mid-Holocene vegetation shifts on the upper Tibetan Plateau (including precipitation, growing season length, radiation, human impact) with particular emphasis on changing CO₂ concentrations to better predict future environmental change and impacts on the Tibetan Plateau

in a rapidly changing world.” In so doing, the four researchers report that “numerous pollen records from across the upper Tibetan Plateau indicate that *Kobresia*-dominated high-alpine meadow invaded alpine steppes during the mid- to late-Holocene.” But they say that their investigation, which employed a pollen-moisture transfer function, suggested that “this marked vegetation change cannot be satisfactorily explained by climate change.” In addition, they indicate that “a literature review did not reveal convincing evidence for any widespread human impact on mid-Holocene vegetation.” Thus, they propose that the reconstructed vegetation changes were likely the result of “a response to Holocene CO₂ concentration changes,” with values rising from approximately 260 ppm in the early Holocene to near-present-day values on the order of 375 ppm.

This conclusion is based on four lines of evidence: the fact that “high-elevation vegetation is particularly sensitive to CO₂ changes due to lowered CO₂ partial pressure,” the fact that “water conservation of steppe vegetation in response to experimental CO₂ enrichment was of the same order of magnitude as inferred from mid- to late-Holocene Tibetan pollen records,” the fact that “modern remote sensing-aided vegetation monitoring of the Central Tibetan Plateau yielded an increase in biomass, most probably as a response to modern CO₂ increase,” even in spite of “increasing land-use by herding,” as well as the fact that “experimental CO₂ fertilization of dry grassland and desert vegetation performed in several regions world-wide has stimulated plant growth directly through enhanced photosynthesis and indirectly through enhanced water-use efficiency (Morgan *et al.*, 2004).”

Focusing in on the past century, Zhuang *et al.* (2010) used a process-based biogeochemistry model – the Terrestrial Ecosystem Model or TEM, which also employed a soil thermal model – to examine permafrost dynamics and their effects on the carbon dynamics of the Tibetan Plateau. This was done by “parameterizing and verifying” the TEM using existing real-world data for soil temperature, permafrost distribution and carbon and nitrogen distributions throughout the region, and then extrapolating the model and its parameters to the whole of the plateau.

In describing their findings, the six scientists report that “during the 20th century, the Tibetan Plateau changed from a small carbon source or neutral in the early part of the century to a sink later” (Figure 11), noting that “net primary production and soil respiration increased by 0.52 and 0.22 Tg C/year, respectively, resulting in a regional carbon sink increase of 0.3 Tg C/year,” so that “by the end of the century, the regional carbon sink reached 36 Tg C/year and carbon storage in vegetation and soils is 32 and 16 Pg C, respectively.”

Zhuang *et al.* say the “increasing soil temperature and deepening active layer depth enhanced soil respiration, increasing the net nitrogen mineralization rate,” and that “together with the [positive] effects of warming air temperature and rising CO₂ concentrations on photosynthesis, the stronger plant nitrogen uptake due to the enhanced available nitrogen stimulate[d] plant carbon uptake, thereby strengthening the regional carbon sink as the rate of increase in net primary production was faster than that of soil respiration.” Thus, they say their study implies that “future

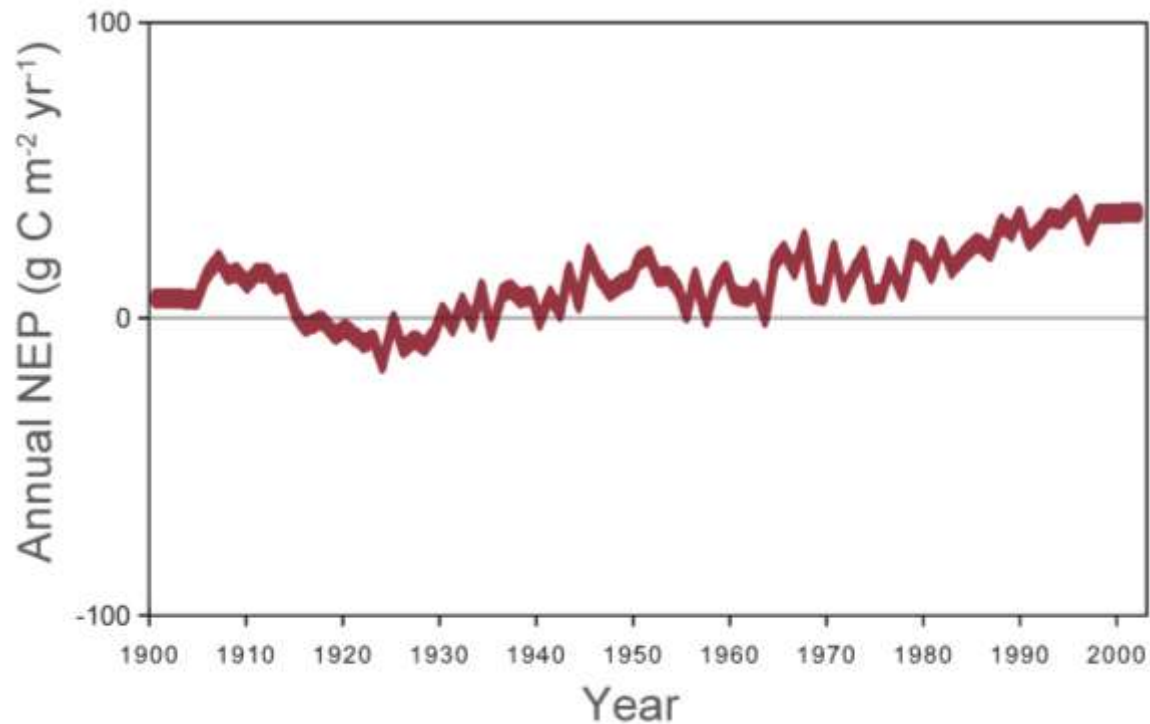


Figure 11. Five year running average of Net Ecosystem Production (NEP) on the Tibetan Plateau over the period 1901-2002. Negative values reveal the region to be a carbon source, positive values indicate it is a carbon sink. Adapted from Zhuang *et al.* (2010).

warming will increase thawing of the permafrost, increase soil temperature and dry up soil moisture,” and that “these physical dynamics may enhance [the] future strength of the regional carbon sink, since the rate of increase of net primary production is higher than that of soil respiration on the Tibetan Plateau.”

Further evidence that the productivity of the Tibetan Plateau’s vegetation has recently increased is found in satellite-based measurements taken over the past three decades. Piao *et al.* (2006d), for example, investigated net primary production (NPP) derived from a carbon model (Carnegie-Ames-Stanford approach, CASA) and its interannual change in the Qinghai-Xizang (Tibetan) Plateau using 1982-1999 NDVI data and paired ground-based information on vegetation, climate,

soil, and solar radiation. This work revealed that over the entire study period, NPP rose at a mean annual rate of 0.7%. However, Piao *et al.* report that “the NPP trends in the plateau over the two decades were divided into two distinguished periods: without any clear trend from 1982 to 1990 and significant increase from 1991 to 1999.”

The three researchers say their findings suggest that “vegetation growth on the plateau in the 1990s has been much enhanced compared to that in [the] 1980s, consistent with the trend in the northern latitudes indicated by Schimel *et al.* (2001).” In addition, they say that “previous observational and NPP modeling studies have documented substantial evidence that terrestrial photosynthetic activity has increased over the past two to three decades in the middle and high latitudes in

the Northern Hemisphere,” and that “satellite-based NDVI data sets for the period of 1982-1999 also indicate consistent trends of NDVI increase,” citing multiple references in support of each of these statements. Piao *et al.*'s findings, therefore, add to the growing body of evidence that reveals that a significant *Greening of the Earth* is occurring in response to (1) the ongoing recovery of the planet from the growth-inhibiting chill of the Little Ice Age, which was likely *the coldest period of the current interglacial*, plus (2) the aerial fertilization effect of the historical and still-ongoing rise in the atmosphere's CO₂ concentration, as well as (3) the growth-promoting effect of anthropogenic nitrogen deposition.

In one final study, interannual variations of Tibetan Plateau vegetative productivity were investigated by Zhou *et al.* (2007) using a 21-year (1982-2002) normalized difference vegetation index (NDVI) dataset to quantify the consequences of changes in temperature and precipitation for the regional ecosystem. Based on their analysis, the authors reported that “the maximum, minimum and mean temperature fluctuations all present an increasing trend over the 21 years,” and that “the NDVI is comparatively large during the warm years, such as 1988, 1994, 1998 and 1999,” and that “relatively small NDVI values are well coupled with the cold extreme and mean temperature in 1982, 1983 and 1997.” This type of relationship, as they continue, “suggests a positive correlation between vegetation activity and surface air temperature on the plateau,” and in this regard they report that “the correlation coefficient between the NDVI and the maximum, minimum and mean temperature reaches 0.674 (significant at

the 99% level), 0.53 (significant at the 95% level) and 0.55 (significant at the 99% level), respectively.” In contrast, they find that “the precipitation fluctuation does not show a detectable trend, and therefore its correlation with DNVl is not obvious.”

Zhou *et al.* conclude their study by remarking that “vegetation variability on the Tibetan Plateau might be mostly driven by thermal impacts (i.e., surface air temperature), whereas precipitation impact is less clear.” Overall, they say “vegetation activity demonstrates a gradual enhancement in an oscillatory manner during 1982-2002,” suggesting a significant positive impact to what climate alarmists call “unprecedented” global warming over what Zhou *et al.* describe as “one of the most prominent features on Earth.”

ALL OTHER ASIAN COUNTRIES

Moving outward from China, we next review how vegetative productivity has fared throughout other countries in Asia over the past few decades.

We begin with the work of Grunzweig *et al.* (2003), who tell the tale of the Yatir forest (a 2800-hectare stand of Aleppo and other pine trees) that had been planted some 35 years earlier at the edge of the Negev Desert in Israel. An intriguing aspect of this particular forest, which they characterize as growing in poor soil of only 0.2 to 1.0 meter's depth above chalk and limestone, is that although it is located in an arid part of Asia that receives less annual precipitation than all of the other scores of FluxNet stations in the global network of micrometeorological tower sites that use eddy covariance methods to measure exchanges of CO₂, water vapor and energy

between terrestrial ecosystems and the atmosphere (Baldocchi *et al.*, 2001), the forest's annual net ecosystem CO₂ exchange was just as high as that of many high-latitude boreal forests and actually higher than that of most temperate forests. But how could this possibly be?

Grunzweig *et al.* note that the increase in atmospheric CO₂ concentration that has occurred since pre-industrial times should have improved water use efficiency (WUE) in most plants by increasing the ratio of CO₂ fixed to water lost via evapotranspiration. That this hypothesis is indeed correct has been demonstrated by Leavitt *et al.* (2003) within the context of the long-term atmospheric CO₂ enrichment experiment of Idso and Kimball (2001) on sour orange

trees. It has also been confirmed in nature by Feng (1999), who obtained identical (to the study of Leavitt *et al.*) CO₂-induced WUE responses for 23 groups of naturally-occurring trees scattered across western North America over the period 1800-1985, which response, Feng concludes, "would have caused natural trees in arid environments to grow more rapidly, acting as a carbon sink for anthropogenic CO₂," which is exactly what Grunzweig *et al.* found to be happening in the Yatir forest on the edge of the Negev Desert. In addition, the latter researchers report that "reducing water loss in arid regions improves soil moisture conditions, decreases water stress and extends water availability," which "can indirectly increase carbon sequestration by influencing plant distribution, survival and

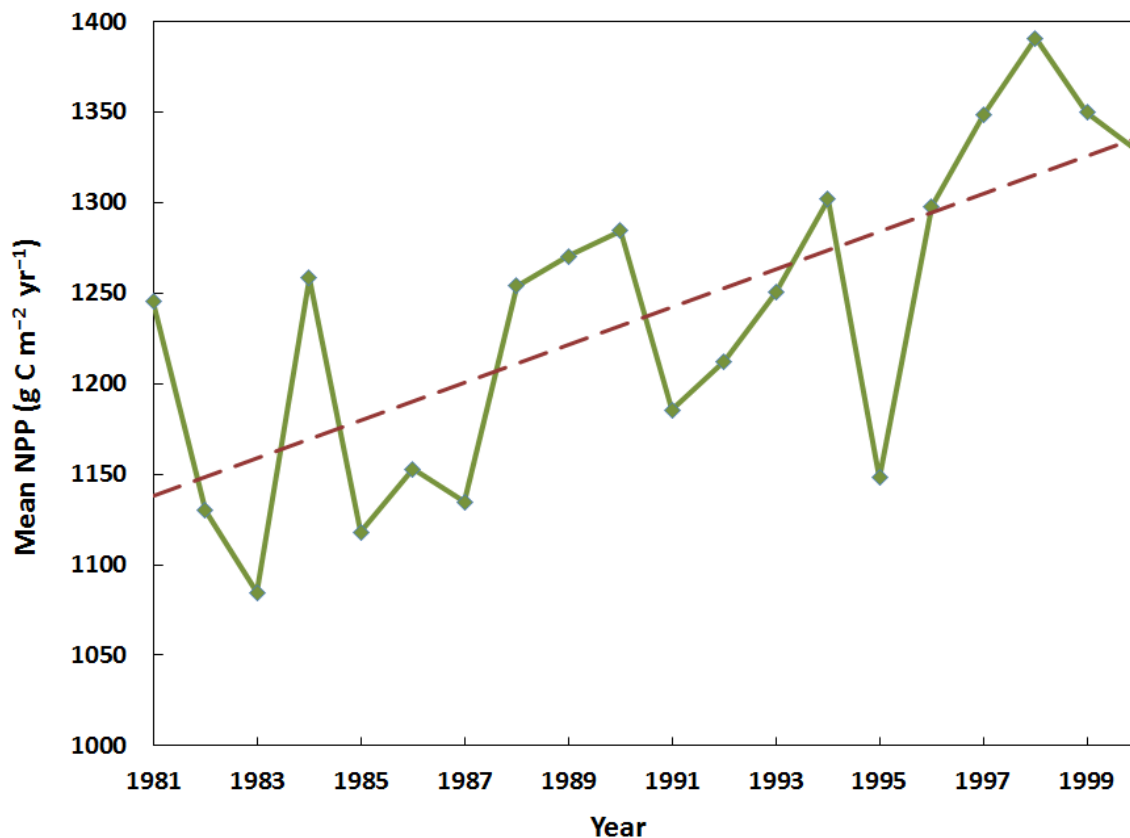


Figure 12. Average annual NPP estimated for India over the period 1981-2000 using NOAA-AVHRR data, as per Singh *et al.* (2011).

expansion into water-limited environments.”

Further eastward, Singh *et al.* (2011) used U.S. National Oceanic and Atmospheric Administration (NOAA) satellite-derived Advanced Very High Resolution Radiometer (AVHRR) data, together with the Global Production Efficiency Model (GloPEM) developed by Prince and Goward (1995), to calculate annual NPP over all of India for the period 1981-2000 (Figure 12). According to the five researchers, regression analysis of the 20-year NPP database showed a significant increase in the temporal trend of NPP over India ($r=0.7$, $p<0.001$), with the mean rate of increase being $10.43 \text{ gC/m}^2/\text{year}$, which yields a mean rate-of-increase in carbon fixation of 34.3 TgC/year for the entire country, including its arid and semi-arid regions, its forests, and its dry-land and irrigated agricultural regions.

Moving north into Russia, in an area that extends from $72^{\circ}02'N$ to $72^{\circ}40'N$ and from $101^{\circ}15'E$ to $102^{\circ}06'E$ – a total of approximately 36,000 ha that includes the Ary-Mas forest (the northernmost forest on the planet) plus larch forests on southeastern slopes descending to the Khatanga River – Kharuk *et al.* (2006) analyzed remote-sensing images made by Landsat satellites in 1973 and 2000. In doing so, they found that “the most significant changes were observed in the class of normal larch stands (canopy density > 0.3): their area increased by 66%,” while “the areas of open and sparse forests ($0.1 < \text{canopy density} < 0.3$, and canopy density < 0.1) increased by 16 and 8%, respectively, whereas the background area became 19% smaller.” In addition, they report that the rates of expansion of larch onto tundra “for

sparse, open, and normal stands were estimated at 3, 9, and 11 m per year, respectively.” However, they remark that “since sparse stands are at the forefront of advancement to the tundra, the rate for this class (approximately 3 m per year) should be regarded as the rate of larch expansion in general,” and that “the above rates reflect not only the expansion of trees into the tundra, but also an increase in the density of sparse and open stands.”

With respect to the cause of the changes identified, Kharuk *et al.* feel that they were “induced by climatic trends,” and that the continuation of this process “will result in the expansion of larch to the Arctic coast,” which they describe as a “phenomenon that took place in the Holocene.” Thus, it would appear that the Ary Mas forest is merely *reclaiming* that which had previously been *lost* by the progressive cooling of the planet after the Holocene Climatic Optimum, which cooling culminated in the *record interglacial cold* of the Little Ice Age from which the Earth and its biosphere are now making an impressive comeback.

In another forest-related study from Russia, Lapenis *et al.* (2005) analyzed trends in forest biomass in all 28 ecoregions of the Russian territory, based on data collected from 1953 to 2002 within 3196 sample plots comprised of about 50,000 entries, which database, in their words, “contains all available archived and published data.” This work revealed that over the period 1961-1998, as they describe it, “aboveground wood, roots, and green parts increased by 4%, 21%, and 33%, respectively,” such that “the total carbon density of the living biomass stock of the Russian forests increased by ~9%.” They also report there was a concomitant

increase of ~11% in the *area* of Russian forests. In addition, the team of US, Austrian and Russian scientists reported that “within the range of 50-65° of latitude [the range of 90% of Russian forests], the relationship between biomass density and the area-averaged NDVI is very close to a linear function, with a slope of ~1,” citing the work of Myneni *et al.* (2001). Therefore, as they continue, “changes in the carbon density of live biomass in Russian forests occur at about the same rate as the increase in the satellite-based estimate in the seasonally accumulated NDVI,” which observation strengthens the findings of *all* satellite-based NDVI studies.

Acknowledging that remote sensing data suggest that tundra vegetation in North America may be responding to recent warming via enhanced photosynthetic activity (Goetz *et al.*, 2005; Verbyla, 2008), Forbes *et al.* (2010a) write that “at a circumpolar scale, the highest photosynthetic activity and strongest growth trends are reported in locations characterized by erect shrub tundra (Reynolds *et al.*, 2006),” noting that “live leaf phytomass from deciduous shrubs, shown to have increased in northern Alaska during the second half of the last century (Sturm *et al.*, 2001; Tape *et al.*, 2006), is believed to be a key driver of the observed trends (Jia *et al.*, 2003; Goetz *et al.*, 2005; Verbyla, 2008).” Against this backdrop and working with *Salix lanata* L. (*sensu lato*) -- an abundant deciduous dioecious willow with nearly circumpolar geographic distribution from the northern boreal forest of Russia to the northern limits of the Low Arctic -- Forbes *et al.* analyzed annual ring growth for 168 stem slices of 2- to 3-cm thickness that they collected from 40 discrete individuals spread across 15 sample

sites within an area of approximately 3 x 2.3 km, which was located at about 68°40'N, 58°30'E.

The three researchers say their work revealed “a clear relationship with photosynthetic activity for upland vegetation at a regional scale for the period 1981-2005, confirming a parallel ‘greening’ trend reported for similarly warming North American portions of the tundra biome,” and they state that “the standardized growth curve suggests a significant increase in shrub willow growth over the last six decades.” Additionally, while noting that “the quality of the chronology as a climate proxy is exceptional,” Forbes *et al.* state that their findings “are in line with field and remote sensing studies that have assigned a strong shrub component to the reported greening signal since the early 1980s,” adding that the growth trend agrees with the qualitative observations of nomadic reindeer herders, which suggest there have been “recent increases in willow size in the region.” In fact, they say that their analysis “provides the best proxy assessment to date that deciduous shrub phytomass has increased significantly in response to an ongoing summer warming trend.”

Still in Russia, but focusing in on the arid lands of Central Asia, Lioubimtseva *et al.* (2005) describe a number of findings pertinent to the subject at hand that are generally not available to the international scientific community, due to their publication in the Russian language. According to the four-member team of Russian and American scientists, “there has been a general warming trend in Central Asian republics on the order of 1-2°C since the beginning of the 20th century,” but they add that it is expressed most strongly in

winter and that “the amplitude of this trend seems to be comparable with Holocene climate variability,” suggesting that it is nothing unusual nor does it require an anthropogenic explanation. Citing the IPCC (2001), on the other hand, they report that precipitation has remained basically unchanged throughout the 20th century, stating that “there were no discernible trends in annual precipitation during 1900-95 for the region as a whole, nor in most parts of this region.”

In the face of unchanging precipitation and significant warming, it might be expected that the aridity of Central Asia would have increased significantly in recent years, especially throughout the 1990s, when climate alarmists claim the world saw its most oppressive heat of both the 20th century and the past two millennia. However, Lioubimtseva *et al.* report that “analyses of the NOAA AVHRR temporal series since the 1980s showed a decrease in aridity from 1991-2000 compared to 1982-1990 in the northern part of the region and a southward shift of the northern boundary of the desert zone in Central Asia,” citing the work of Zolotokrylin (2002). So what’s the explanation for this unexpected development? Lioubimtseva *et al.* suggest it could well have been the historical rise in the air’s CO₂ content.

The scientists begin their elucidation of this hypothesis by noting that “an increased atmospheric CO₂ concentration has direct and relatively immediate effects on two important physiological processes in plants: it increases the photosynthetic rate, but decreases stomatal opening and therefore the rate at which plants lose water,” so that “the combination of these two factors, increased photosynthesis and decreased

water loss, implies a significant increase of water [use] efficiency (the ratio of carbon gain per unit water loss) and ... a reduction in the sensitivity to drought stress in desert vegetation as a result of elevated atmospheric CO₂,” citing the work of Smith *et al.* (2000) in support of this concept. As a result, they note that these effects could “increase productivity and biomass of natural desert vegetation,” which would, of course, make the land appear (and effectively be) less arid.

Buttressing this reasoning with experimental evidence obtained from the region itself, Lioubimtseva *et al.* report that “CO₂-enrichment experiments (both chamber and free-air) conducted in the Kara Kum (Voznesensky, 1997) and Kyzyl Kum (Voznesensky, 1997; Zelensky, 1977) deserts showed a 2-4 times increase in the photosynthetic rate under the saturating CO₂ concentrations,” and that “three Kara Kum species (*Eminium lehmanii*, *Rhemum turkestanuikum* and *Ephedra stobilacea*) responded with a six-fold increase in photosynthetic rate (Nechaeva, 1984).” In addition, they report that “the CO₂ fertilization effects included not only higher vegetation but also microphytic communities including mosses, lichens, fungi, algae, and cyanobacteria,” which communities, in their words, “form biogenic crusts on the soil surface varying from a few millimeters to several centimeters in thickness and play a significant role in the desert ecosystems controlling such processes as water retention and carbon and nitrogen fixation in soils.”

In examining a larger area of Asia, Zhou *et al.* (2001) analyzed satellite-derived Normalized Difference Vegetation Index (NDVI) data from July 1981 to December

1999, between 40 and 70° N latitude. In doing so they found a persistent increase in growing season vegetative productivity in excess of 12% over this broad contiguous swath of Asia stretching from Europe through Siberia to the Aldan plateau, where almost 58% of the land is forested. And in a companion study, Bogaert *et al.* (2002) determined that this productivity increase occurred at a time when this vast Asian region showed an overall warming trend “with negligible occurrence of cooling.”

In another study encompassing all of Asia, Ichii *et al.* (2005) simulated and analyzed carbon fluxes over the period 1982-1999 “using the Biome-BGC prognostic carbon cycle model driven by National Centers for Environmental Prediction reanalysis daily climate data,” after which they “calculated trends in gross primary productivity (GPP)

and net primary productivity (NPP).” In doing so, solar radiation variability was found to be the primary factor responsible for interannual *variations* in GPP, followed by temperature and precipitation variability. In terms of GPP *trends*, the authors report that “recent changes in atmospheric CO₂ and climate promoted terrestrial GPP increases with a significant linear trend in all three tropical regions.” More specifically, they report the rate of GPP increase for Asia to have been about 0.3 PgC year⁻¹ per decade. As for the major cause of the increased growth, Ichii *et al.* favored carbon dioxide, reporting that “CO₂ fertilization effects strongly increased recent NPP trends in regional totals.”

In one final study designed to examine a large portion of the Northern Hemisphere (East Asia, including China, Japan, Korea and

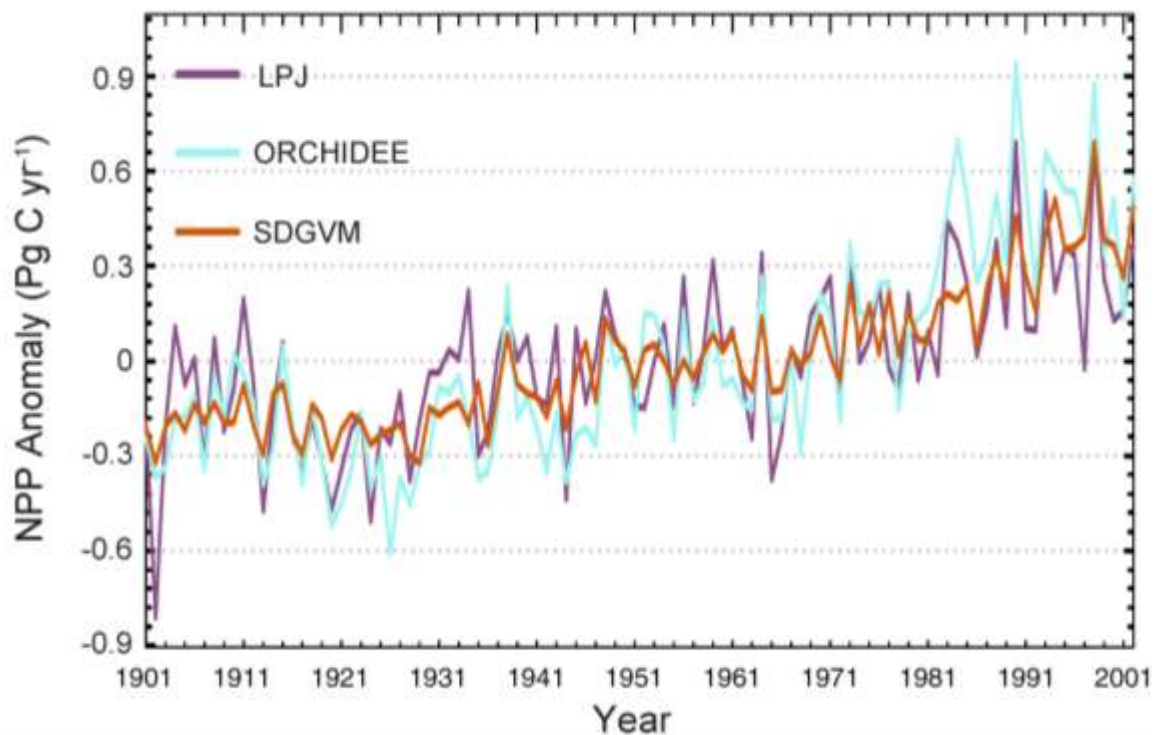


Figure 13. Terrestrial Net Primary Productivity anomalies for East Asia over the period 1901-2002 as determined from the three process-based ecosystem models described in the text (LPJ, ORCHIDEE, and SDGVM). Adapted from Piao *et al.* (2011).

Mongolia), the eleven researchers of Piao *et al.* (2011) used three process-based ecosystem models -- the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM) described by Sitch *et al.* (2003), the ORganizing Carbon and Hydrology In Dynamic Ecosystems (ORCHIDEE) model described by Krinner *et al.* (2005), and the Sheffield model (SDGVM) described by Woodward and Lomas (2004) -- to investigate East Asia's *net primary productivity* (NPP) response to the climatic change and rising atmospheric CO₂ concentration of the past century, which they did by running each of the three models from 1901 to 2002, using observed values of monthly climatology and annual global atmospheric CO₂ concentrations (Figure 13).

Results indicated that between 1901 and 2002, modeled NPP "significantly increased by 5.5-8.5 Tg C per year (15-20% growth)", and the authors say that this increase in NPP "caused an increased cumulated terrestrial carbon storage of about 5-11 Pg C," about 50-70% of which "is located in vegetation biomass." And they add that "40-60% of the accumulated carbon uptake of the 20th century is credited to the period of 1980-2002," which latter interval, according to climate alarmists, was the warmest two-decade-interval of that century-long period. Thus, as demonstrated in this study, it is readily evident that as the air's CO₂ concentration and temperature rose to their highest values of the past century, they only served to *enhance* the terrestrial vegetative productivity of East Asia. And in light of the many other observations described above, plant productivity across the rest of Asia appears to be following suit as rising atmospheric CO₂ concentrations and

temperatures have actually been a great *blessing* for this portion of Earth's biosphere, especially for its water-stressed deserts and arid regions that appear to be *thriving*.

AUSTRALIA

Moving on to Australia, we continue our review of what researchers have discovered with respect to terrestrial productivity in this part of the world.

Noting that "a number of processes are thought to be threatening the ecological integrity of monsoon rainforests in Northern Australia," Banfai and Bowman (2006) decided to test this *retracting rainforest claim* with a comprehensive repeat aerial photography study of the Northern Territory's Kakadu National Park, where monsoon rainforest exists as an archipelago of hundreds of small patches scattered within a larger eucalypt savanna matrix. More specifically, two Australian researchers from Charles Darwin University's School for Environmental Research set out to assess changes to the boundaries of 50 monsoon rainforest patches using temporal sequences of digitized aerial photography taken in 1964, 1984, 1991 and 2004, with the intent to understand the relative importance of factors driving any change.

Results indicated that "rainforest patches increased in size between 1964 and 2004 by an average of 28.8%" (see Figure 14), and after lengthy analyses of several phenomena that might possibly have been responsible for the range increases, the two researchers concluded that "the expansion is likely to have been primarily driven by increases in variables such as rainfall and

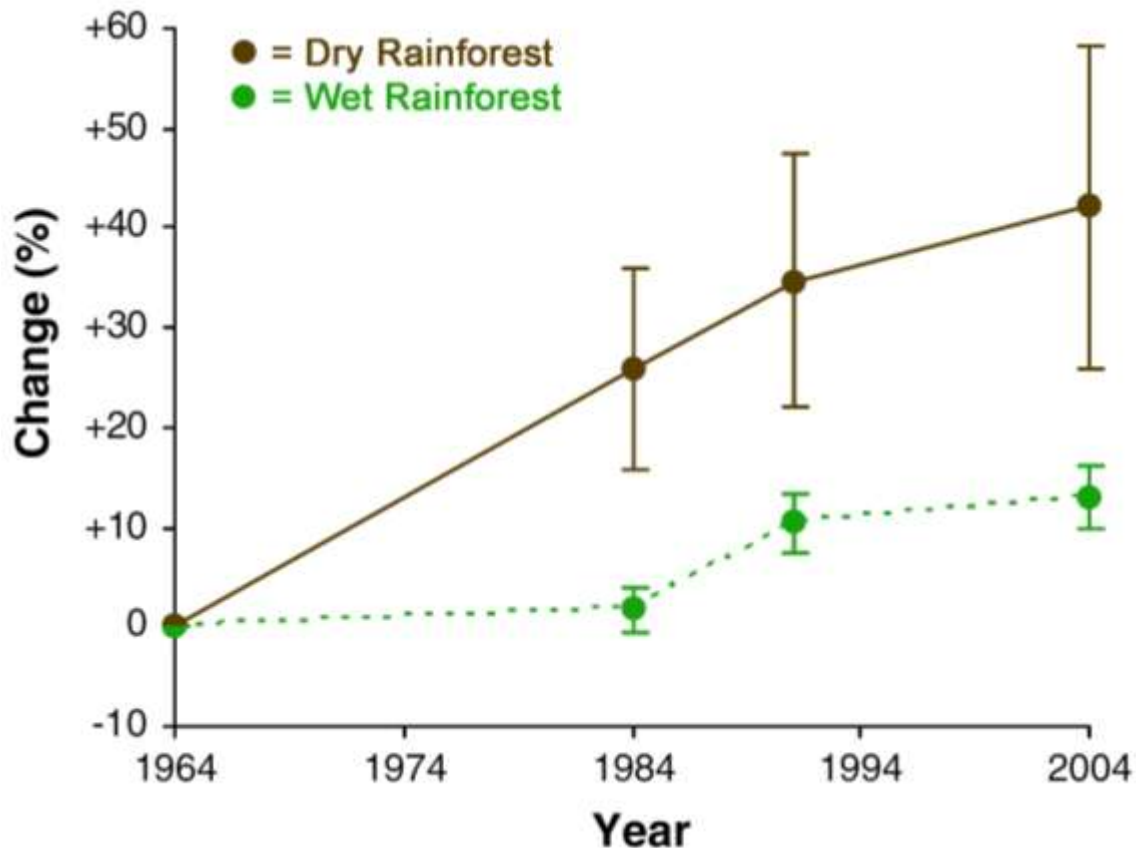


Figure 14. Average percentage change in rainforest area in Kakadu National Park, Northern Territory of Australia, relative to 1964 for dry rainforest (brown line) and wet rainforest (green dashed line). Standard errors are indicated. Adapted from Banfai and Bowman (2006).

atmospheric CO₂.” In this regard, for example, they note that “the average [area] change for dry rainforests from 1964 to 2004 was an increase of 42.1%, whereas for wet rainforests [the increase] was one-third of this at 13.1%.” In addition, in the case of dry rainforests, they report there was “an almost linear increase in rainforest area over the study period,” in harmony with the concomitant upward trends of both atmospheric CO₂ and rainfall.

In further support of the validity of their findings, and “contrary to the view that monsoon rainforests are contracting,” the two researchers indicate that other repeat aerial photography studies conducted in Northern Australia have *also* revealed

rainforest “expansion at the expense of more open vegetation.” These studies include those of monsoon rainforests in Litchfield National Park near Darwin (Bowman *et al.*, 2001) - where forest patches nearly *doubled* in size between 1941 and 1994 - and in the Gulf of Carpentaria (Bowman *et al.*, 2006). In addition, they write that “these changes parallel the observed expansion of tropical rainforest on the east coast of Australia (Harrington and Sanderson, 1994; Russell-Smith *et al.*, 2004).”

Introducing their study of the subject, Macinnis-Ng *et al.* (2011) say that “woody thickening” is typically defined as “the increase in woody standing biomass in a

landscape already containing woody biomass.” Both it and woody plant invasion, as they continue, “are global phenomena that are commonly observed in arid and semi-arid regions, including Australia (Bowman *et al.*, 2001; Burrows *et al.*, 2002; Asner *et al.*, 2003; Fensham *et al.*, 2005; Scott *et al.*, 2006; Witt *et al.*, 2009),” the “tropical rainforests of Central and South America (Phillips *et al.*, 1998), and temperate forests globally (Birdsey *et al.*, 1993).” And although they note that “the cause of woody thickening remains debated,” they say “there is an increasing awareness of potential roles for climate and changes in atmospheric CO₂ concentration in causing woody thickening (and woody invasion),” citing the studies of Fensham *et al.* (2005), Berry and Roderick (2006), Davis *et al.* (2007) and Sankaran *et al.* (2008).

Against this backdrop, the four researchers proceed to examine the responses of *gross primary production* (GPP) and water use of a typical Australian woodland using the *soil-plant atmosphere* (SPA) model of Williams *et al.* (1996), which they successfully applied to the functioning of a temperate open woodland in Australia (Zeppel *et al.*, 2008) that provided a methodology for testing the conceptual model of Eamus and Palmer (2007), which posits that the increasing atmospheric CO₂ concentration and the declining evaporative demand “may explain the global phenomenon of woody thickening.”

Based on their analysis, Macinnis-Ng *et al.* were able to demonstrate that as the air’s CO₂ content rises, plant stomatal conductance decreases, such that water use per tree decreases and, therefore, soil water content increases, leading to increases in leaf area index that allow more

light to be intercepted, enabling existing trees to grow bigger (even in the case of photosynthetic acclimation), which set of phenomena comprises the complex process of woody thickening. Noting that their results “provide a valid mechanism for the conclusion of Berry and Roderick (2002) that evergreen vegetation has increased across Australia over the past 200 years as a result of CO₂ enrichment,” they conclude that “woody thickening in Australia and probably globally can be explained by the changes in landscape GPP and soil moisture balance arising principally from the increased atmospheric CO₂ concentration.”

EUROPE

Turing to Europe, using an empirically-based mechanistic model of Mediterranean shrub vegetation, Osborne *et al.* (2000) set out to address two important questions: (1) Has recent climate change, especially increased drought, negatively impacted Mediterranean shrublands? and (2) Has the historical increase in the air’s CO₂ concentration modified this impact? The data-based model they employed suggests that the warming and reduced precipitation experienced in the Mediterranean area over the past century should have had negative impacts on net primary production and leaf area index. When the measured increase in atmospheric CO₂ concentration experienced over the period was factored into the calculation, however, these negative influences were overpowered, with the net effect that both measures of vegetative prowess *increased*: net primary productivity by 25% and leaf area index by 7%. These results, in their words, “indicate that the recent rise in atmospheric CO₂ may already have had significant impacts on productivity, structure and water relations

of sclerophyllous shrub vegetation, which tended to offset the detrimental effects of climate change in the region.”

With respect to model-predicted changes in Earth’s precipitation regime, a doubling of the air’s CO₂ content is projected to lead to a modest intensification of the planet’s hydrologic cycle. In the case of the Mediterranean region over the last century, however, there has been a recent tendency toward *drier* conditions. Hence, the specific case investigated by Osborne *et al.* represents a *much-worse-case* scenario than what is predicted by current climate models for the Earth as a whole. Nevertheless, the area’s vegetation has done even better than it did before the climatic change, thanks to the overpowering beneficial biological effects of the concurrent rise in the air’s CO₂ content.

In another model-based study, Cheddadi *et al.* (2001) employed a standard biogeochemical model (BIOME3) – which uses monthly temperature and precipitation data, certain soil characteristics, cloudiness and atmospheric CO₂ concentration as inputs – to simulate the responses of various biomes in the region surrounding the Mediterranean Sea to changes in both climate (temperature and precipitation) and the air’s CO₂ content. Their first step in this endeavor was to validate the model for two test periods: the present and 6000 years before present (BP). Recent instrumental records provided actual atmospheric CO₂, temperature and precipitation data for the present period; while pollen data were used to reconstruct monthly temperature and precipitation values for 6000 years BP, and ice core records were used to determine the atmospheric CO₂ concentration of that

earlier epoch. These efforts suggested that winter temperatures 6000 years ago were about 2°C cooler than they are now, that annual rainfall was approximately 200 mm less than today, and that the air’s CO₂ concentration averaged 280 ppm, which is considerably less than the value of 345 ppm the researchers used to represent the present, i.e., the mid-point of the period used for calculating 30-year climate normals at the time they wrote their paper. Applying the model to these two sets of conditions, they demonstrated that “BIOME3 can be used to simulate ... the vegetation distribution under ... different climate and CO₂ conditions than today.”

Cheddadi *et al.*’s next step was to use their validated model to explore the vegetative consequences of an increase in anthropogenic CO₂ emissions that pushes the air’s CO₂ concentration to a value of 500 ppm and its mean annual temperature to a value 2°C higher than today’s mean value. The basic response of the vegetation to this change in environmental conditions was “a substantial southward shift of Mediterranean vegetation and a spread of evergreen and conifer forests in the northern Mediterranean.”

More specifically, in the words of the researchers, “when precipitation is maintained at its present-day level, an evergreen forest spreads in the eastern Mediterranean and a conifer forest in Turkey.” Current xerophytic woodlands in this scenario become “restricted to southern Spain and southern Italy and they no longer occur in southern France.” In northwest Africa, on the other hand, “Mediterranean xerophytic vegetation occupies a more extensive territory than today and the arid steppe/desert boundary

shifts southward,” as each vegetation zone becomes significantly more verdant than it is currently.

What is the basis for these positive developments? Cheddadi *et al.* say “the replacement of xerophytic woodlands by evergreen and conifer forests could be explained by the enhancement of photosynthesis due to the increase of CO₂.” Likewise, they note that “under a high CO₂ stomata will be much less open which will lead to a reduced evapotranspiration and lower water loss, both for C₃ and C₄ plants,” adding that “such mechanisms may help plants to resist long-lasting drought periods that characterize the Mediterranean climate.”

Contrary to what is often predicted for much of the world’s moisture-challenged lands, therefore, the authors were able to report that “an increase of CO₂, jointly with an increase of *ca.* 2°C in annual temperature would not lead to desertification on any part of the Mediterranean unless annual precipitation decreased drastically,” where they define a *drastic* decrease as a decline of 30% or more. Equally important in this context is the fact that Hennessy *et al.* (1997) have indicated that a doubling of the air’s CO₂ content would in all likelihood lead to a 5 to 10% *increase* in annual precipitation at Mediterranean latitudes, which is also what is predicted for most of the rest of the world. Hence, the results of the present study – where precipitation was held constant – may validly be considered to be a *worst-case* scenario, with the *true* vegetative response being even *better* than the good-news results reported by Cheddadi *et al.*, even when utilizing what

we believe to be erroneously-inflated global warming predictions.

Introducing their work, Bellassen *et al.* (2011) write that “several parties to the United Nations Framework Convention on Climate Change (UNFCCC) are calling for ‘forward-looking baselines’,” so that country-specific scenarios based on forest age structure could be used “to credit only the part of the forest sink going beyond business-as-usual practices.” And they thus proceed to derive such a baseline for all of Europe.

Using ORCHIDEE-FM – a process-based vegetation model that differs from earlier versions of ORCHIDEE by “its explicit representation of stand growth and idealized forest management” – Bellassen *et al.* applied the model on a grid across Europe to “simulate changes in the net ecosystem productivity (NEP) of forests with and without changes in climate, CO₂ and age structure.” In doing so, the six scientists report that the model they used “simulates carbon stocks and volume increments that are comparable ... with inventory-derived estimates at country level for 20 European countries,” providing “an upwards trend of forest NEP of 1 ± 0.5 g C/m²/year between 1950 and 2000 across the EU 25,” ending with “a mean European forest NEP of 175 ± 52 g C/m²/year in the 1990s” (see Figure 15). And they say that “61% of the change in NEP [over the last half of the 20th century] was attributed to changes in CO₂, 26% to changes in climate, and 13% to changes in forest age structure.”

As intriguing as these model-based studies are, however, it is important to examine this issue through the lens of real-world

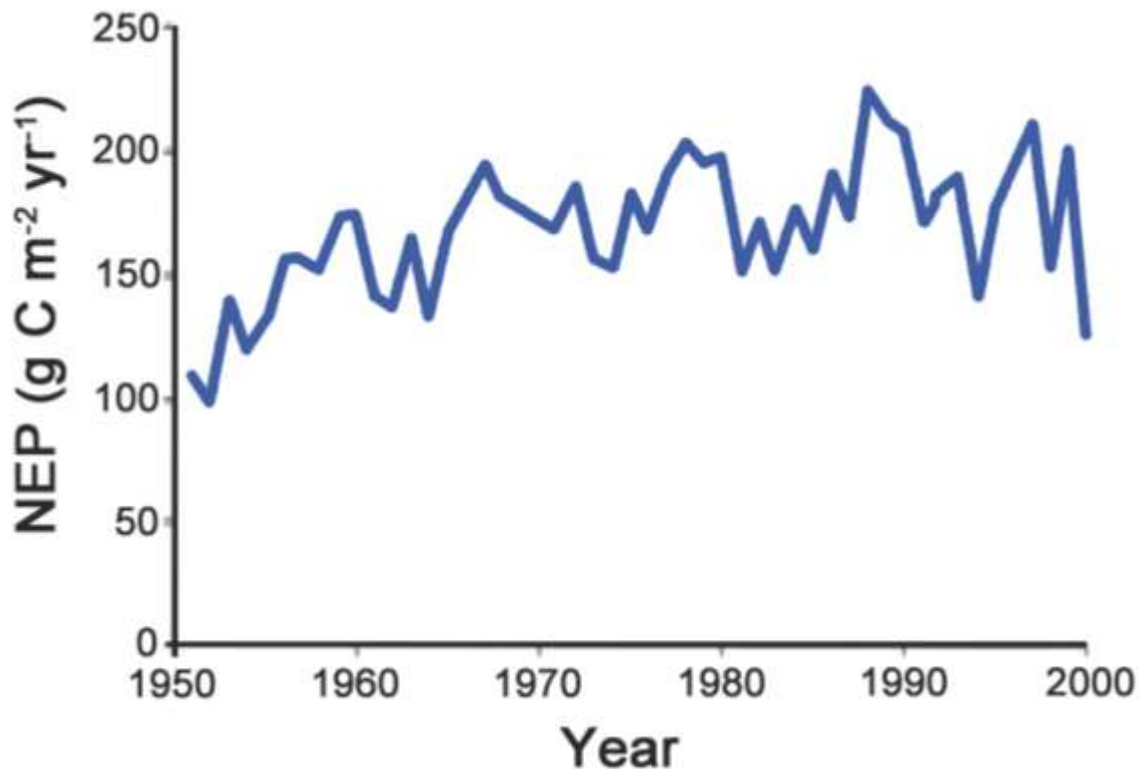


Figure 15. Simulated reconstruction of Net Ecosystem Productivity (NEP) in European forests from 1951-2000. Adapted from Bellassen *et al.* (2011).

data to see how plant productivity has responded to modern warming, which the IPCC claims is unprecedented over the past one to two thousand years. And, fortunately, a number of scientists have done just that.

Allen *et al.* (1999), for example, analyzed sediment cores from a lake in southern Italy and from the Mediterranean Sea, developing high-resolution climate and vegetation data sets for this region over the last 102,000 years. These materials indicated that rapid changes in vegetation were well correlated with rapid changes in climate, such that complete shifts in natural ecosystems would sometimes occur over periods of less than 200 years. Over the warmest portion of the record (the

Holocene), the total organic carbon content of the vegetation reached its highest level, more than doubling values experienced over the rest of the record, while other proxy indicators revealed that during the more productive woody-plant period of the Holocene, the increased vegetative cover also led to less soil erosion. The results of this study thus demonstrate that the biosphere can successfully respond to rapid changes in climate. As the 15 researchers involved in the work put it, “the biosphere was a full participant in these rapid fluctuations, contrary to widely held views that vegetation is unable to change with such rapidity.” Furthermore, their work revealed that *warmer* was always *better* in terms of plant growth; and, therefore, it is likely that future warming in this region

may return it to a higher level of biological productivity than what it currently exhibits.

Examining a much shorter time period was Bert *et al.* (1997), who calculated a 120-year (1860-1980) history of *intrinsic water-use efficiency* (defined as the ratio of CO₂ assimilation rate to stomatal conductance for water vapor) for silver fir (*Abies alba* Mill.) trees, based on $\delta^{13}\text{C}$ data obtained from cores extracted from individual trees of this species that grew within 208 pure stands in the Jura Mountains near the border that separates France and Switzerland. Results indicated that from 1860 to 1930 there was little net change in silver fir water-use efficiency; but over the next half-century (1930 to 1980), when the atmosphere's CO₂ concentration rose at a rate that was more than three times greater than its rate-of-rise over the earlier period,

this important tree physiological property rose by approximately 30% (see Figure 16). With regard to their findings, the three researchers state that their results – which were “obtained at the level of mature trees” – are “consistent with the physiological effects of increasing CO₂ concentrations as observed in controlled experiments on young seedlings,” and that they are additionally “consistent with the strong increases in radial growth observed for *Abies alba* in western Europe over the past decades.”

Working in the Vienna basin of Austria in the European Eastern Alps, Leal *et al.* (2008) discovered what they describe as “a very clear change in the sensitivity of the growth rate of [black pine (*Pinus nigra*)] tree stems to water availability in the late 20th century,” noting that “trees previously

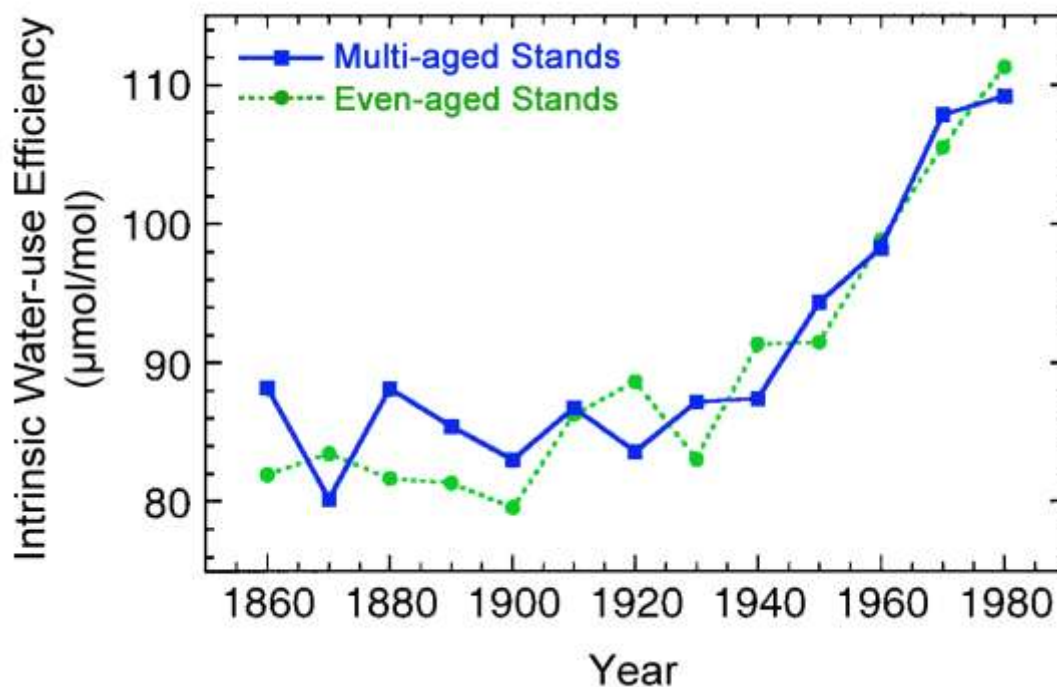


Figure 16. Intrinsic water-use efficiency (the ratio of CO₂ assimilation rate to stomatal conductance for water vapor) calculated from tree rings sampled in multi-aged and even-aged forest stands from the Jura Mountains in Eastern France for the period 1860-1980. Adapted from Bert *et al.* (1997).

sensitive to spring-summer drought show a lack of response to this climatic parameter in recent decades.” That is to say, as they explain it, that “tree-ring indices were larger in the second half of the 20th century than predicted given prevailing spring-summer drought conditions and the previous sensitivity of growth to these conditions.” In addition, they found “a decrease in correspondence between the occurrence of extreme events in precipitation and rate of change of growth,” such that “in the second half of the century this correspondence was not significant,” and that “recent extreme droughts did not result in the formation of very narrow rings, which means the droughts were not as limiting to tree growth as they had been in the past.”

The five researchers concluded their paper by suggesting that the greater atmospheric

CO₂ concentrations of the latter decades of the 20th century “induced improved water-use efficiency enabling *P. nigra* growing in the Vienna basin to avoid the impact of recurrent dry conditions,” which phenomenon has also been observed in many other parts of the world in a number of different tree species, which is but another indication of the propensity of the ongoing rise in the air’s CO₂ content to promote a greening of the Earth.

Martinez-Vilalta *et al.* (2008) used tree-ring data from the Catalan Ecological and Forest Inventory “to study the temporal variability of Scots pine stem radial growth (period 1901-1997) across a relatively large region (Catalonia, NE Spain) situated close to the southern limit of the distribution of the species.” This inventory “included a total of 10,664 plots randomly distributed

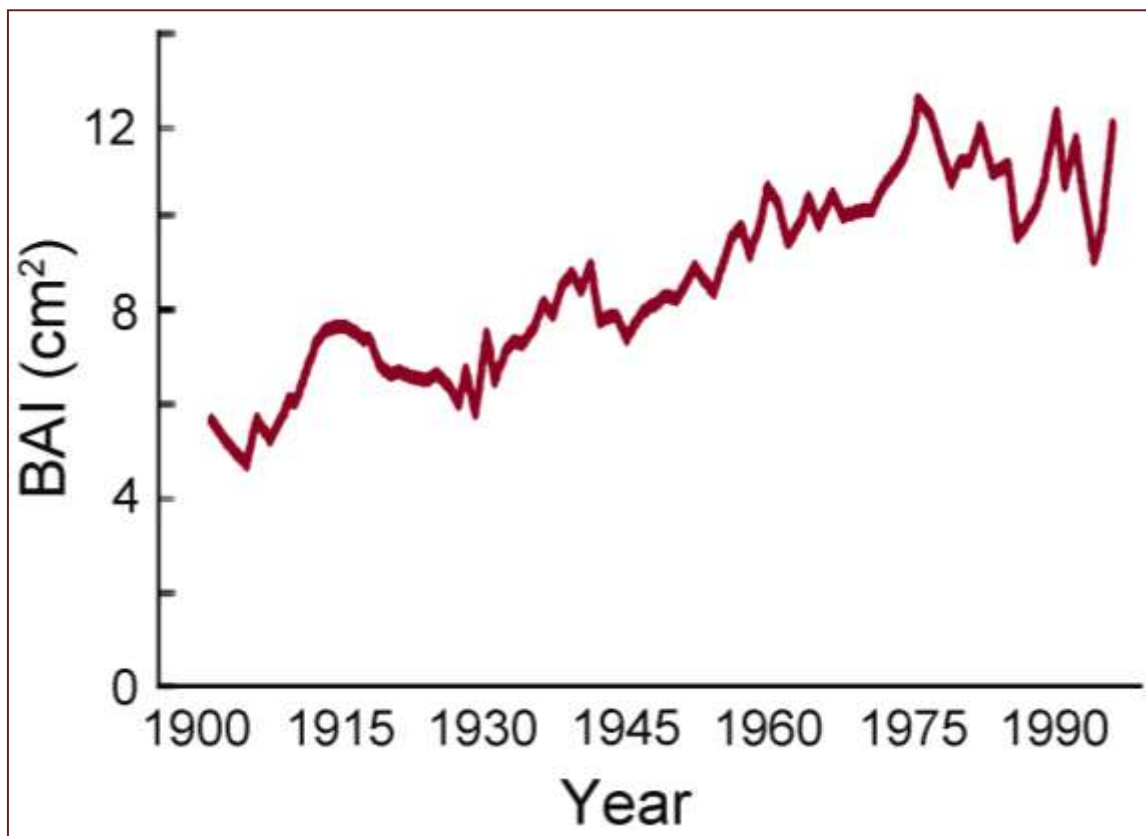


Figure 17. Basal area increment (BAI) for Scots pine trees growing in NE Spain over the period 1901-1997. Adapted from Martinez-Vilalta *et al.* (2008).

throughout the forested area of Catalonia.” Scots pine was present in 30.2% of the plots, and it was the dominant tree species in 18.4% of them.

In describing their findings, the researchers say they found “an overall increase of 84% in Scots pine BAI [basal area increment] during the 20th century (see Figure 17), consistent with most previous studies for temperate forests” and in harmony with the *greening of the Earth* phenomenon that has accompanied the historical increase in the air’s CO₂ content. And in this regard, they make a point of stating that “this trend was associated with increased atmospheric CO₂ concentration,” which they interpreted to be “a fertilization effect.” What is more, the five scientists also note that over the same time period there was “a marked increase in temperature across the study region (0.19°C per decade on average),” and they report that “this warming had a negative impact on radial growth, particularly at the drier sites.” However, they found that “its magnitude was not enough to counteract the fertilization effect.”

Noting that “protected areas provide excellent opportunities for [determining] baseline descriptions and trends that ... can be used to evaluate the impact of global environmental change on terrestrial ecosystem functioning,” Alcaraz-Segura *et al.* (2008) employed satellite-derived *normalized difference vegetation index* (NDVI) data – which provide a measure of net primary production that is described by them as “the most integrative indicator of ecosystem functioning” – to “evaluate the impact of global environmental change on terrestrial ecosystem functioning of [Spain’s] national parks,” which provides a

sound basis for determining what could have been expected to have occurred throughout the rest of the country and much of Europe (Julien *et al.*, 2006) *independent of confounding effects not related to global environmental change*. So what did they find?

The four researchers, hailing from Argentina, Spain and the United States, report that “most parks showed areas with positive NDVI trends that tended to have higher proportions of Mediterranean coniferous and mixed forests, oro-Mediterranean scrublands, heathlands, maquis and garrigues,” while “negative trends were scarce.” Alcaraz-Segura *et al.* conclude the report of their findings by stating that “protected areas are changing in the short term and, at least in terms of vegetation greenness, they are changing in a directional way,” such that “a large part of the Spanish National Parks is intercepting more photosynthetically active radiation than in the past.”

Working at a site just three kilometers from the Abisko Scientific Research Station (68°21’N, 18°49’E) in the Northern Swedish Scandes, Hallinger *et al.* (2010) studied male plants of the medium-sized *Juniperus nana* shrub, collecting the main stems of five to eight shrubs every hundred meters of elevation until the shrub zone ended. Ring-width measurements on these stems were then performed, as they describe it, “to measure radial and vertical growth, to track growth changes over time, to age the shrub individuals and to correlate annual shrub growth with climate,” the characteristics of which latter factor were derived from records of the nearby Abisko Station. And what did their measurements reveal?

According to the three researchers, their analysis “documented a distinct increase in radial and vertical growth rates of *J. nana* shrubs during recent decades in the subalpine zone of North Sweden” (see Figure 18), and they say that “the age structure of shrubs along the elevational gradient provides evidence that an upslope advance of the altitudinal shrubline is underway.” In addition, they state that they “observed significant, strong and stable correlations between annual ring width and summer temperatures (June, July, August),” and that “the acceleration of radial and vertical growth since 1970 also coincides with the recent three decades of rising arctic air temperatures and the

warming trend of 0.2°C per decade for the average temperature since 1956 at Abisko.” These findings, in their words, add to the “mounting evidence that shrubs are expanding into alpine and arctic areas because of climate warming,” and they note that “this expansion occurs in both evergreen and deciduous shrub types,” citing the additional findings of Forbes *et al.* (2009).

Also working in the Swedish Scandes, Kullman (2010a) presented what he called “an integrative review of results from long-term monitoring of subalpine/alpine vegetation,” from which he derived “tentative projections of landscape

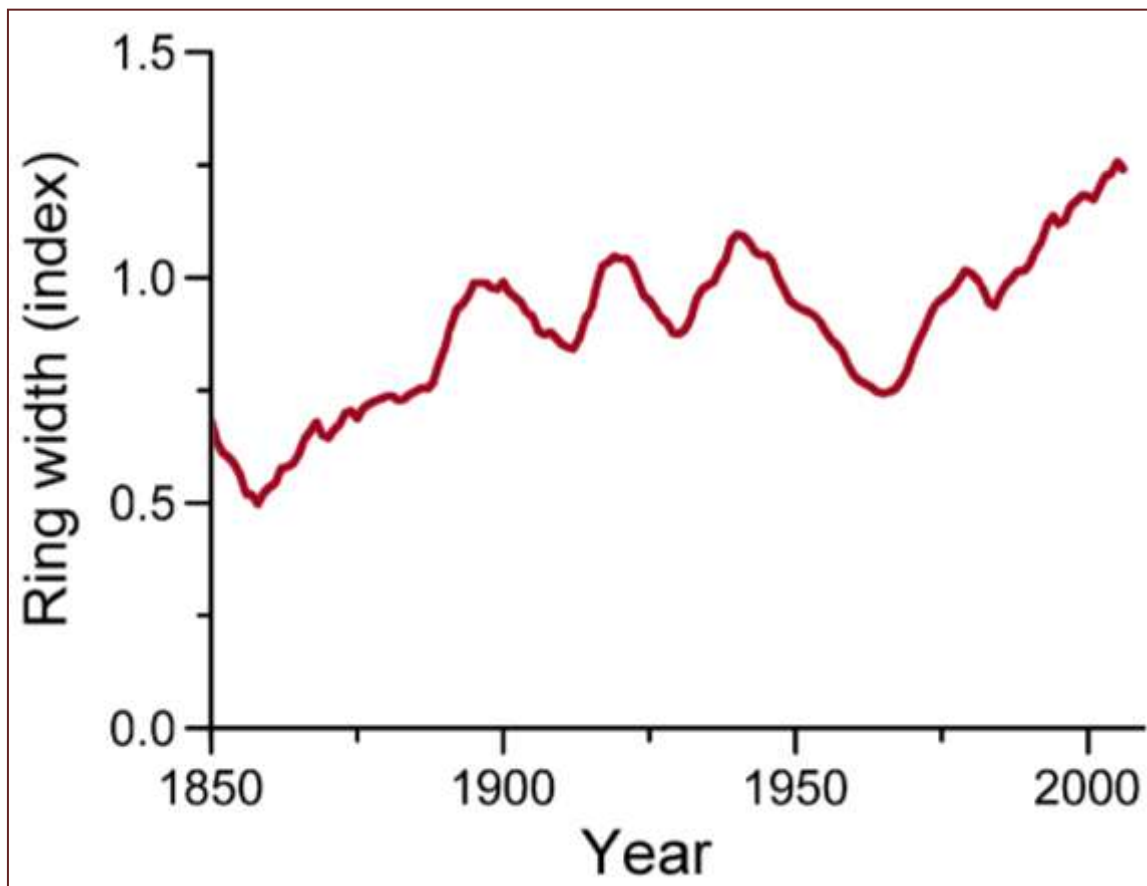


Figure 18. Indexed radial growth of juniper trees in the Northern Swedish Scandes over the period 1850-2006, smoothed with a 10-year filter. Adapted from Hallinger *et al.* (2010).

transformations in a potentially warmer future,” which were based on “actual observations and paleoecological data (Kullman and Kjallgren, 2006; Kullman 2006).” In doing so, the professor of physical geography at Sweden’s Umea University indicates that post-Little Ice Age warming has, at long last, broken the back of “a multi-millennial trend of plant cover retrogression” and “floristic and faunal impoverishment, all imposed by progressive and deterministic neoglacial climate cooling,” as he reports that the “upper range margin rise of trees and low-altitude (boreal) plant species, expansion of alpine grasslands and dwarf-shrub heaths are the modal biotic adjustments during the past few decades, after a century of substantial climate warming.” Currently, therefore, the situation is one where “alpine plant life is proliferating, biodiversity is on the rise and the mountain world appears more productive and inviting than ever.” And he makes it very clear that “in contrast to model predictions, no single alpine plant species has become extinct, neither in Scandinavia nor in any other part of the world in response to climate warming over the past century,” citing, in addition to his own studies, the work of Pauli *et al.* (2001, 2007), Theurillat and Guisan (2001), and Birks (2008).

So just how great is the recent proliferation of plant life of which Kullman writes? In a contemporaneous study published in the *Nordic Journal of Botany*, he provides an answer (Kullman, 2010c), reporting what he learned from species inventories he conducted on the uppermost 20 meters of four high-mountain summits in the Swedish Scandes (Kullman 2007a,b), the results of which he compared with the findings of “historical species inventories from the

early 1950s, executed by a highly competent and experienced botanist (Kilander, 1955),” which endeavor, in his words, “can be seen as an evaluation of a full-scale ‘natural experiment’ (cf. Grabherr *et al.*, 2001).”

Specifically, Kullman (2010c) writes that the species pools at the tops of the studied mountains have (1) “increased by 60-170% since the 1950s,” that (2) “some of the invading species are new to the alpine tundra, with more silvicolous and thermophilic properties than the extant alpine flora,” and -- last of all, that (3) “not a single species of the original flora has disappeared from any of the summits.” Concluding, Kullman thus writes that “the alpine flora appears to be more adaptive and responsive to climate change than generally believed,” and that “overall, a richer, greener and more productive alpine world has emerged in the wake of the recent climate warming episode (Kullman, 2010a, 2010b).”

Still in Sweden, but working on an east-facing slope of the Slattatjakka/Njulla mountains (68°21’N, 18°49’W) in the Abisko Valley about 200 km north of the Arctic Circle, Rundqvist *et al.* (2011) write that they documented “rapid and substantial increases in the abundance of prominent tree and shrub species near [the] tree-line and forest-line in sub-Arctic Sweden,” and that they “recorded an invasion by a thermophilic tree species not present in the plots 34 years ago.”

In discussing their findings, the seven Swedish scientists describe how they mesh well with those of many other researchers, noting that “there is an indication that the shrub layer near the tree-line has expanded, since the 1930s, in the Abisko

area (Enquist *et al.*, 1933; Sandberg, 1963),” while “data from Canada, Fennoscandia, Alaska and Russia reveal that there is a Pan-Arctic expansion of shrubs and trees in progress (e.g. Kullman, 2002; Tommervik *et al.*, 2004; ACIA, 2005; Tape *et al.*, 2006; Karlsson *et al.*, 2007; Olofsson *et al.*, 2009; Hallinger *et al.*, 2010; Hedenas *et al.*, 2011).” And they state that the change in shrubs and small trees they observed is “consistent with anticipated changes due to climate change and reduced herbivory,” which change in climate, in their words, “could be interpreted as an ongoing natural re-establishment of plants at higher altitudes due to a natural increase in the temperature since the ‘Little Ice Age’ (Kammer *et al.*, 2007).”

Writing as background for their study, Hedenas *et al.* (2011) state that “during the last 15 years, there has been an increasing focus on how climate change has and will affect the distribution and extent of ecosystems around the globe including alpine and Arctic areas (e.g., Callaghan *et al.*, 2005),” and in this regard they report that “field studies and remote sensing have revealed a recent increase in altitude of the tree line (e.g., Kullman, 2002),” as well as “an extension and increased cover of mountain birch forest (Tommervik *et al.*, 2009; Rundqvist *et al.*, 2011).” More specifically, they say that Tommervik *et al.* have determined that “tree biomass has doubled over a 43-year period, within an area of Finnmarksvidda, and Rundqvist *et al.* have observed an increased density and cover of mountain birch in the treeline over the last three decades, within an area near Abisko village.”

In a continuation of these types of studies, Hedenas *et al.* say that in 2010 they re-

surveyed shrub, tree and vegetation data at 549 plots grouped into 61 clusters that were originally surveyed in 1997 in two areas close to the Abisko village, which is located approximately 200 km north of the Arctic Circle at 68°20'N, 18°50'E. Their results indicated that “tree basal area and biomass increased by 19% between 1997 and 2010 with the main increase occurring in established birch forest” (see Figure 19), and they say that this result “concur with the results of other studies which suggest that there has been a general increase in cover and biomass of trees and shrubs in sub-Arctic and Arctic areas,” additionally citing in this regard, the studies of Sturm *et al.* (2001), Tape *et al.* (2006), Danby and Hik (2007), Forbes *et al.* (2010a), Hallinger *et al.* (2010) and Van Bogaert *et al.* (2011). What is more, the 19% net increase in biomass occurred in spite of the increased browsing pressure provided by an increasing reindeer population over the period of their study, as well as periodic outbursts of geometrid moths – which severely defoliated the birch trees in their study area in 2004 (Babst *et al.*, 2010). As for the cause of this welcome phenomenon, they say “it has been suggested that increased nutrient availability associated with higher soil temperatures, and a longer growing season could underpin increased tree and shrub abundance and biomass in the Arctic (e.g., Chapin, 1983; Weih and Karlsson, 1997; Hartley *et al.*, 1999),” as a result of “a delayed re-expansion of shrubs and trees following the ‘Little Ice Age’,” as suggested by Grubb (2008).

Noting that forests are exposed to a changing environment and that “responses to recent climate change start to become visible if observation periods become long enough,” Pilegaard *et al.* (2011) present the

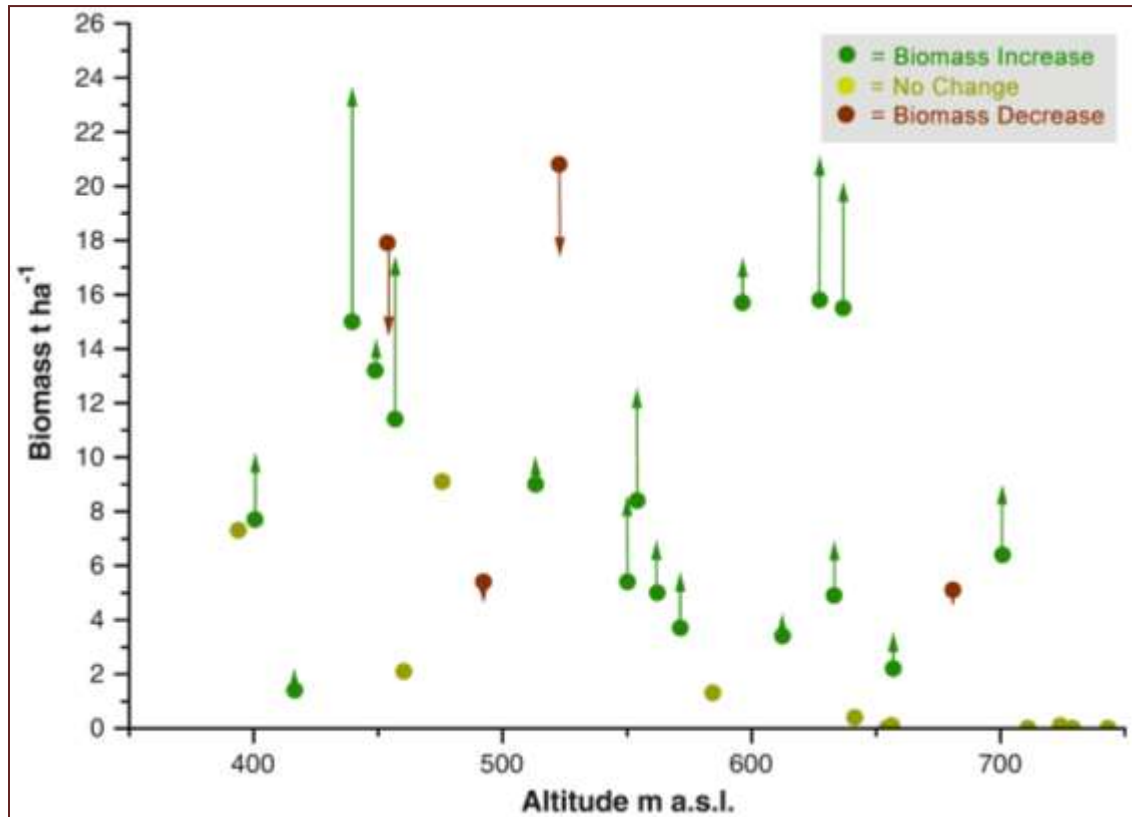


Figure 19. Change in mean tree biomass by altitude over the period 1997-2010 from various locations throughout the Swedish sub-Arctic. Colors reveal the direction of the change (green = biomass increase, yellow = no change, and red = biomass decrease), while arrows indicate the magnitude of the change over the 13-year period. Adapted from Hedenas et al. (2010).

results of continuous CO₂ flux measurements that they made above a mature Danish beech stand in the “Lille Bogeskov” forest located near Soro on the island of Zealand (55°29’13”N, 11°38’45”E) over the period 1996-2009, describing the long-term changes they observed and relating them to possible causes.

According to the researchers, they observed “significant linear trends of increasing gross ecosystem exchange (GEE: 29 g C/m²/year) and increasing net ecosystem exchange (NEE: 23 g C/m²/year), while the positive trend for ecosystem respiration (RE: 5 g C/m²/year) was not significant.” They also state that “the length of the carbon uptake period increased by 1.9 day/year, whereas

there was a non-significant increase of 0.3 day/year in the leafed period,” which means, in their words, that “the leaves stay active longer.” Nevertheless, they indicate that “the increase in the carbon uptake period explained only part of the increasing NEE (9 gC/m²/year).” And noting that “the maximum rate of photosynthetic assimilation increased by 15% during the 14-year period,” they speculate that the increase in canopy carbon uptake capacity “could be due to a combination of [the] increase in atmospheric CO₂, higher summer precipitation, and increased availability of nitrogen.”

Working in the Komi Republic in the northeast European sector of Russia,

Lopatin *et al.* (2006) (1) collected discs and cores from 151 Siberian spruce trees and 110 Scots pines from which they developed ring-width chronologies that revealed yearly changes in forest productivity, (2) developed satellite-based time series of NDVI for the months of June, July, August over the period 1982-2001, (3) correlated their site-specific ring-width-derived productivity histories with same-site NDVI time series, (4) used the resulting relationship to establish six *regional* forest productivity histories for the period 1982-2001, and (5) compared the six regional productivity trends over this period with corresponding-region temperature and precipitation trends. For all six vegetation zones of the Komi Republic, this work indicated that the 1982-2001 trends of integrated NDVI values from June to August were *positive*, and that the “increase in productivity reflected in [the] NDVI data [was] maximal on the sites with increased temperature and decreased precipitation.”

In discussing their findings, the three scientists state that “several studies (Riebsame *et al.*, 1994; Myneni *et al.*, 1998; Vicente-Serrano *et al.*, 2004) have shown a recent increase in vegetation cover in different world ecosystems.” What is special about their study, as they describe it, is that “in Europe, most forests are managed, except for those in northwestern Russia [the location of their work], where old-growth natural forests are dominant (Aksenov *et al.*, 2002).” Consequently, and because of their positive findings, they say we can now conclude that “productivity during recent decades also increased in relatively untouched forests,” where non-management-related “climate change with lengthening growing season, increasing CO₂ and nitrogen deposition” are the primary

determinants of changes in forest productivity.

In one final study that integrates all of Europe, Julien *et al.* (2006) “used land surface temperature (LST) algorithms and NDVI [Normalized Difference Vegetation Index] values to estimate changes in vegetation in the European continent between 1982 and 1999 from the Pathfinder AVHRR [Advanced Very High Resolution Radiometer] Land (PAL) dataset.” This program revealed that arid and semi-arid areas (Northern Africa, Southern Spain and the Middle East) have seen their mean LST increase and NDVI decrease, while temperate areas (Western and Central Europe) have suffered a slight decrease in LST but a more substantial increase in NDVI, especially in Germany, the Czech Republic, Poland and Belarus. In addition, parts of continental and Northern Europe have experienced either slight increases or decreases in NDVI while LST values have decreased. Considering the results in their totality, the Dutch and Spanish researchers concluded that, over the last two decades of the 20th century, “Europe as a whole has a tendency to greening,” and much of it is “seeing an increase in its wood land proportion.”

NORTH AMERICA

Like Asia, a significant amount of terrestrial productivity research has been conducted for locations in North America. As such, we subdivide this continent into several sub-regions as well, including the *Entire Continent*, *High Latitude Regions*, *Eastern USA*, *Central USA* and *Western USA*.

ENTIRE CONTINENT

In a paper entitled “Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981-1999,” which describes a study that covered essentially the entire North American continent, Zhou *et al.* (2001) determined that the satellite-derived *normalized difference vegetation index* (NDVI) rose by 8.44% over this period. Noting that the NDVI parameter “can be used to proxy the vegetation’s responses to climate changes because it is well correlated with the fraction of photosynthetically active radiation absorbed by plant canopies and thus leaf area, leaf biomass, and potential photosynthesis,” Zhou *et al.* went on to suggest that the increases in plant growth and vitality implied by their NDVI data were primarily driven by concurrent increases in near-surface air temperature. Since this warming was rather muted in North America, however, and in the United States in particular, where temperatures may have actually *declined* throughout the eastern part of the country over the period of the study, Ahlbeck (2002) suggested that the observed upward trend in NDVI was primarily driven by the concurrent rise in the air’s CO₂ content. Nevertheless, it is likely that both parameters probably played a role in the observed productivity increase, although the CO₂ increase was more likely the predominant one given the lack of temperature increase over the period of time under study.

About the same time, Hicke *et al.* (2002) conducted an independent study, computing net primary productivity (NPP) over North America for the years 1982-1998 using the Carnegie-Ames-Stanford Approach (CASA) carbon cycle model, which

was driven by a satellite NDVI record at 8-km spatial resolution. This effort revealed that NPP increases of 30% or more occurred across the continent from 1982 to 1998. During this period, the air’s CO₂ concentration rose by 25.74 ppm, as calculated from the Mauna Loa data of Keeling and Whorf (1998), which amount is 8.58% of the 300 ppm increase that is often used as a reference for expressing plant growth responses to atmospheric CO₂ enrichment. Consequently, for herbaceous plants that display NPP increases of 30-40% in response to a 300-ppm increase in atmospheric CO₂ concentration, the CO₂-induced NPP increase experienced between 1982 and 1998 would be expected to have been 2.6-3.4%. Similarly, for woody plants that display NPP increases of 60-80% in response to a 300-ppm increase in atmospheric CO₂ (Saxe *et al.*, 1998; Idso and Kimball, 2001), the expected increase in productivity between 1982 and 1998 would have been 5.1-6.9%. Since both of these NPP increases are considerably less than the 30% or more observed by Hicke *et al.*, additional factors must have helped to stimulate NPP over this period, some of which may have been concomitant increases in precipitation and air temperature, the tendency for warming to lengthen growing seasons and enhance the aerial fertilization effect of rising CO₂ concentrations, increasingly intensive crop and forest management, increasing use of genetically improved plants, the regrowth of forests on abandoned cropland, and improvements in agricultural practices such as irrigation and fertilization. Whatever the mix might have been, one thing is clear: its ultimate effect was *overwhelmingly positive*.

Two years later in another satellite-based study, Lim *et al.* (2004) correlated the monthly rate of relative change in NDVI, which they derived from advanced very high resolution radiometer data, with the rate of change in atmospheric CO₂ concentration during the natural vegetation growing season within three different eco-region zones of North America (Arctic and Sub-Arctic Zone, Humid Temperate Zone, and Dry and Desert Zone, which they further subdivided into 17 regions) over the period 1982-1992, after which they explored the temporal progression of annual minimum NDVI over the period 1982-2001 throughout the eastern humid temperate zone of North America. The result of these operations was that in all of the regions but one, according to the researchers, “ δCO_2 was positively correlated with the rate of change in vegetation greenness in the following month, and most correlations were high,” which they say is “consistent with a CO₂ fertilization effect” of the type observed in “experimental manipulations of atmospheric CO₂ that report a stimulation of photosynthesis and above-ground productivity at high CO₂.” In addition, they determined that the yearly “minimum vegetation greenness increased over the period 1982-2001 for all the regions of the eastern humid temperate zone in North America.”

As for the cause of this phenomenon, Lim *et al.* say that rising CO₂ could “increase minimum greenness by stimulating photosynthesis at the beginning of the growing season,” citing the work of Idso *et al.* (2000), who discovered that although new spring branch growth of sour orange trees began on exactly the same day of the year in both ambient (400 ppm) and CO₂-

enriched (700 ppm) open-top chambers, the *rate* of new-branch growth was initially *vastly* greater in the CO₂-enriched trees. Three weeks after branch growth began in the spring, for example, new branches on the CO₂-enriched trees were typically more than *four times* more massive than their counterparts on the ambient-treatment trees; while on a per-tree basis, over *six times* more new-branch biomass was produced on the CO₂-enriched trees, before declining to an approximate 80% stimulation typical of the bulk of the growing season.

Consequently, by looking for a manifestation of the CO₂ fertilization effect at the time of year it is apt to be most strongly expressed, Lim *et al.* may well have found it. Between 1982 and 2001, for example, the air’s CO₂ concentration rose by approximately 30 ppm. From Idso *et al.*’s findings of (1) more than a 300% initial increase in the biomass of new sour orange tree branches for a 300-ppm increase in the air’s CO₂ concentration and (2) more than a 500% initial increase in *per-tree* new-branch biomass, it can be calculated that yearly minimum greenness should have increased by something between *something just over 30%* and *something just over 50%*, if other woody plants respond to atmospheric CO₂ enrichment as sour orange trees do; and when the mean 19-year increase in NDVI for the seven regions for which Lim *et al.* present data is calculated, the result is an increase of *something just over 40%*, indicative of the fact that Lim *et al.*’s data are not only *qualitatively* consistent with their hypothesis, they are right on the mark *quantitatively* as well.

Lastly, in a somewhat similar study, but one that focused more intensely on *climate*

change, Xiao and Moody (2004) examined the responses of the normalized difference vegetation index integrated over the growing season (gNDVI) to annual and seasonal precipitation, maximum temperature (Tmax) and minimum temperature (Tmin) over an 11-year period (1990-2000) for six biomes in the conterminous United States (Evergreen Needleleaf Forest, Deciduous Broadleaf Forest, Mixed Forest, Open Shrubland, Woody Savanna and Grassland), focusing on within- and across-biome variance in long-term average gNDVI and emphasizing the degree to which this variance is explained by spatial gradients in long-term average seasonal climate. The results of these protocols indicated that the greatest positive climate-change impacts on biome productivity were caused by increases in spring, winter and fall precipitation, as well as increases in fall and spring temperature, especially Tmin, which has historically increased at roughly twice the rate of Tmax in the United States. Hence, “if historical climatic trends and the biotic responses suggested in this analysis continue to hold true,” in the words of Xiao and Moody, “we can anticipate further increases in productivity for both forested and non-forested ecoregions in the conterminous US, with associated implications for carbon budgets and woody proliferation,” which once again spells good news for the biosphere.

In light of each of the findings presented above, and in spite of all the real and perceived assaults on Earth’s vegetation (rising temperatures, drought, development and deforestation), plant productivity and growth in the mean has increased across all of North America over the past three decades, demonstrating the great capacity

of the biosphere to respond – and in a positive manner – to the many and varied challenges it faces.

HIGH LATITUDE REGIONS

For many years, the story out of the Arctic was that rising temperatures would change the land from a carbon sink to a carbon source, further exacerbating the cause of ecosystem change, i.e., regional warming, by adding to the atmosphere’s burden of greenhouse gases and hastening that portion of the biosphere’s inevitable degradation (Oechel *et al.*, 1993, 1995). In the early to mid-1970s, for example, when the first carbon balance studies of Alaskan Arctic ecosystems were conducted, both wet-sedge communities and moist-tussock tundra were observed to be net sinks of carbon. By the mid-1980s and early 1990s, however, following significant increases in air temperature and surface water deficit, both ecosystems had become net *sources* of carbon. Then, between 1992 and 1996, in response to *further* warming and drying that resulted, in the words of Oechel *et al.* (2000a), in “the highest average summer temperature and surface water deficit observed for the entire 39-year period,” both ecosystems’ net summer releases of CO₂ to the atmosphere *declined*, and they eventually became CO₂ *sinks*.

How did it happen? In the words of the scientists who conducted the work, their observations simply indicated “a previously undemonstrated capacity for ecosystems to metabolically adjust to long-term (decadal or longer) changes in climate.”

But how did *that* happen? Was there help along the way from the concomitant rise in the air’s CO₂ content and its *aerial*

fertilization and *anti-transpirant* effects? Although these well-documented consequences of atmospheric CO₂ enrichment are known to enable plants to better respond to the environmental challenges of both warming and drying, these effects were downplayed. Instead, the researchers noted some other possibilities that are also plausible.

First, there is the likelihood that during the initial stages of warming and soil drying, younger and more labile carbon would be rapidly decomposed, shifting the net summer carbon balance of the ecosystems from one of carbon sequestration to one of carbon evolution. After this initial perturbation, however, Oechel *et al.* suggest that “enhanced rates of net nitrogen-mineralization should eventually stimulate rates of gross primary production and atmospheric CO₂ sequestration.”

Another possibility is a gradual shift in plant species towards more productive types that would further reduce the large initial carbon losses over time. Writing on this subject, the researchers say “there is evidence that the relative abundance of deciduous shrubs has increased in response to climate change over the past 1-2 decades in Alaskan moist-tussock tundra ecosystems,” which is also something that is expected to occur as a consequence of the ongoing rise in the air’s CO₂ content. Capers and Stone (2011), for example, have reported that in response to rising air temperatures, “trees have established where they did not previously occur, both in alpine areas (Wardle and Coleman, 1992; Peterson, 1994; Kullman, 2001, 2002), and in arctic tundra (Lescop-Sinclair and Payette, 1995; Danby and Hik, 2007),” while “increasing shrub abundance also has been

reported in alpine (Klanderud and Birks, 2003) and arctic locations (Sturm *et al.*, 2001; Tape *et al.*, 2006; Wilson and Nilsson, 2009).” Be that as it may, and whatever the cause (or causes), it is clear that the productivity of vegetation in the northern reaches of the Northern Hemisphere has been increasing with time, as further illustrated in the following studies.

Noting that “canopy-forming shrubs are reported to be increasing at sites around the circumpolar Arctic,” Myers-Smith *et al.* (2011) (1) examined historic photographs, (2) repeated vegetation surveys, and (3) conducted monitoring of long-term plots on Canada’s Herschel Island (69.57°N, 138.91°W), in order to see what had occurred over the past century on this 100-km² parcel of land just off the western Arctic coast of Canada’s Yukon Territory. And based on all three of their lines of research, they say they “found evidence of increases of each of the dominant canopy-forming willow species (*Salix richardsonii*, *Salix glauca* and *Salix pulchra*), during the twentieth century,” along with evidence that “the majority of willow patches for each of these species became established between 1910 and 1960,” but “with stem ages and maximum growth rates indicating that some patches could have established as late as the 1980s.”

In discussing their findings, the seven scientists report that they represent but one example of the 20th-century *greening* of the Circumpolar Arctic, noting that “recent evidence indicates an expansion of canopy-forming shrubs at sites on the North Slope of Alaska (Sturm *et al.*, 2001; Tape *et al.*, 2006), on the coast of the Northwest Territories (Lantz *et al.*, 2009), in Northern Quebec (B. Tremblay *et al.*, personal

communication), and in northern Russia (Forbes *et al.*, 2010a).” In addition, they indicate that “in Arctic Alaska, canopy cover of alder shrubs has increased by 14-20% on average within the last 40 years, with increases of up to 80% in some areas (Tape *et al.*, 2006).” And they say that “studies of population structures of shrub and tree species indicate advancing of shrubs up slopes in alpine tundra ecosystems in subarctic Sweden (Hallinger *et al.*, 2010),” as well as in sites in Norway (Hofgaard *et al.*, 2009), while further noting that “local indigenous Nenets people in the western Russian Arctic report increasing willow shrubs (Forbes *et al.*, 2010b)” and that “similar observations of vegetation change by Inuit have been reported in Arctic Canada (Thorpe *et al.*, 2002).”

It is also of interest to note that the team of Canadian researchers states that “pollen records indicate that willows were widespread in Arctic ecosystems during warmer periods after the last glacial maximum (Brubaker *et al.*, 1983; Bigelow *et al.* (2003).” And these several observations would seem to suggest that the entire Circumpolar Arctic is in the process of returning to what could be called *the good old days*, when that part of the planet was a whole lot greener - and a whole lot livelier - than it has been for a long, long time.

Also documenting increased plant growth in the high latitudes of North America was Goetz *et al.* (2005), who transformed satellite-derived NDVI data obtained across boreal North America (Canada and Alaska) for the period 1982-2003 into photosynthetically-active radiation absorbed by green vegetation and treated the result as a proxy for relative June-August gross photosynthesis (Pg), stratifying

the results by vegetation type and comparing them with spatially-matched concomitant trends in surface air temperature data. Over the course of the study, this work revealed that area-wide tundra experienced a significant increase in Pg in response to a similar increase in air temperature; and Goetz *et al.* say that “this observation is supported by a wide and increasing range of local field measurements characterizing elevated net CO₂ uptake (Oechel *et al.*, 2000b), greater depths of seasonal thaw (Goulden *et al.*, 1998), changes in the composition and density of herbaceous vegetation (Chapin *et al.*, 2000; Epstein *et al.*, 2004), and increased woody encroachment in the tundra areas of North America (Sturm *et al.*, 2001).” In the case of interior forest, on the other hand, there was no significant increase in air temperature and essentially no change in Pg, with the last data point of the series being essentially indistinguishable from the first. This latter seemingly aberrant observation is in harmony with the fact that at low temperatures the growth-promoting effects of increasing atmospheric CO₂ levels are often very small or even non-existent (Idso and Idso, 1994), which is what appears to have been the case with North American boreal forests over the same time period. As a result, Canada’s and Alaska’s tundra ecosystems exhibited increasing productivity over the past couple of decades, while their boreal forests did not.

Writing as background for their study, Ropars and Boudreau (2012) state that “Myneni *et al.* (1997, 1998) were the first to report evidence of the pan-Arctic increase in vegetation cover,” noting that “by analyzing worldwide NDVI [Normalized Difference Vegetation Index] trends between 1981 and 1991, they showed that

the greatest increase in photosynthetic activity occurred in regions above 50°N,” and that “since then, this phenomenon has been observed for different regions,” including Alaska (Silapaswan *et al.*, 2001; Jia *et al.*, 2003; Verbyla, 2008), Russia (Forbes *et al.*, 2010a), Western Canada (Olthof and Pouliot, 2010), over a longer time span (Jia *et al.*, 2003; Goetz *et al.*, 2005; Verbyla, 2008; Forbes *et al.*, 2010a; Olthof and Pouliot, 2010) and at a better resolution (Jia *et al.*, 2003; Olthof and Pouliot, 2010). Against this backdrop and focusing on an area near the Boniface River research station 35 km east of Hudson Bay and 10 km south of the treeline in subarctic Quebec (Canada), Ropars and Boudreau (2012) evaluated changes in shrub cover

over a full half-century, via their comparison of two aerial photographs taken in July 1957 and a satellite image of the same area obtained in July 2008.

The efforts of the two researchers revealed that “both hilltops and terraces recorded an increase in shrub cover” (Figure 20), and they say that “the increase was significantly greater on terraces than on hilltops (21.6% versus 11.6%),” while further noting that “this finding corroborates other studies using a similar method conducted in different regions of the Arctic,” including Alaska (Sturm *et al.*, 2001; Tape *et al.*, 2006), northern Quebec (Tremblay, 2010), Russia (Forbes *et al.*, 2010) and studies which revealed a major increase of the

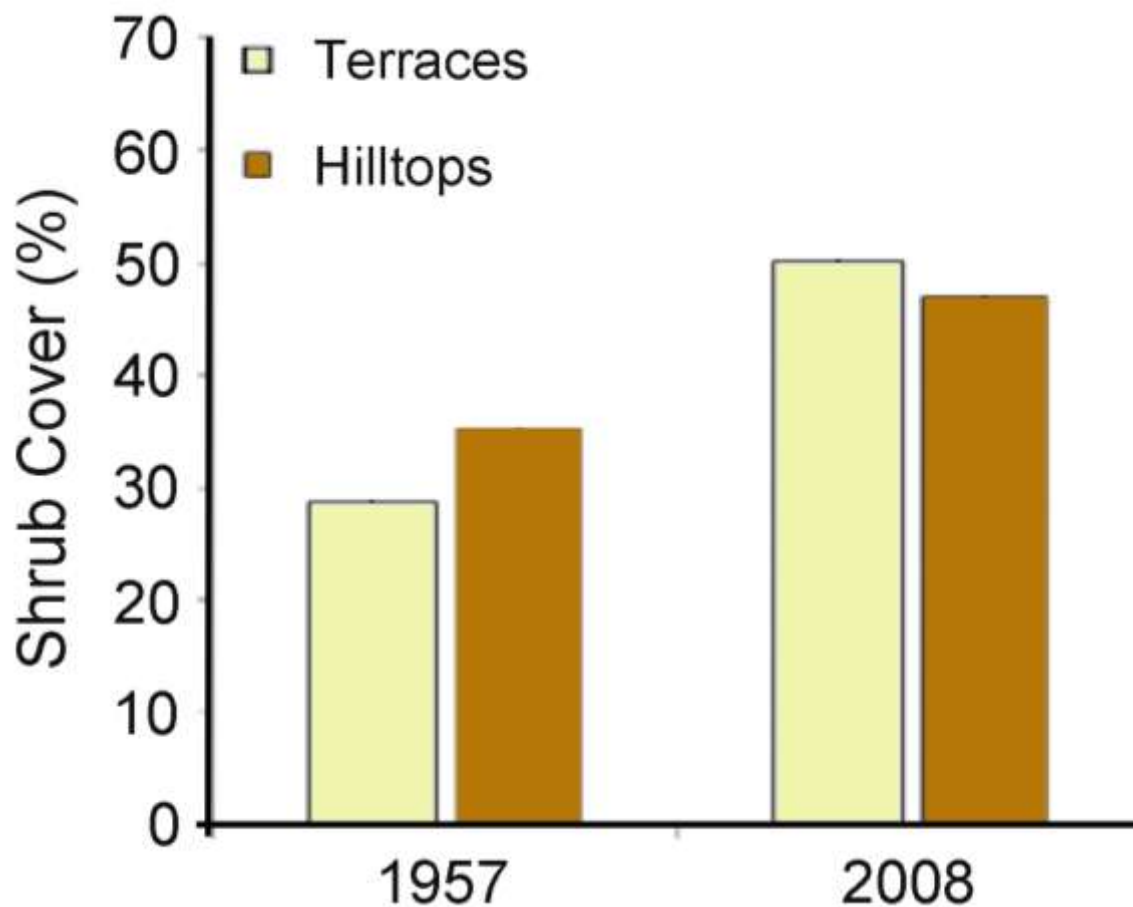


Figure 20. Percent shrub cover on terraces and hilltops in subarctic Quebec, Canada in 1957 and 2008. Adapted from Ropars and Boudreau (2012).

NDVI over the last few decades (Jia *et al.*, 2003; Verbyla, 2008). Ropars and Boudreau conclude their report by stating that “according to ground truthing, the shrub cover densification is associated mainly with an increase of *Betula glandulosa* Michx” - more commonly known as dwarf birch - and by noting that “the numerous seedlings observed during the ground truthing suggest that shrub densification should continue in the future.”

In the introduction to their report on the response of High Arctic tundra vegetation to the warming experienced in that part of the world over the past quarter-century, Hudson and Henry (2009) note that the Arctic has warmed by about 1.6°C over the past four decades, citing the analysis of McBean *et al.* (2005); and they state that this temperature increase has “led the Arctic Climate Impact Assessment (ACIA) and Intergovernmental Panel on Climate Change (IPCC) to predict that tundra ecosystems will be particularly threatened by climate change [i.e., warming] over the next century.” But are such predictions correct?

In an effort to provide some real-world perspective on the issue, Hudson and Henry measured biomass and composition changes in a heath community dominated by several vascular plants and bryophytes at an 8-km² coastal lowland adjacent to Alexandra Fiord on the east-central coast of Ellesmere Island, Nunavut, Canada. This they did over a period of 13 years (1995-2007), using a point-intercept method in permanent plots, and over a period of 27 years (1981-2008) using a biomass harvest comparison. And what did they find?

“Results from both methods,” in the words of the Canadian scientists, “indicate that the community became *more productive over time*,” that “bryophyte and evergreen shrub abundances *increased*,” while “deciduous shrub, forb, graminoid, and lichen cover *did not change*,” so that “species diversity also *remained unchanged* [italics added],” all of which changes - and *non*-changes -- stand in stark contrast to the “particularly threatening” view of the ACIA and IPCC.

In further support of their “contrary” findings, Hudson and Henry additionally report that “satellite-based remote sensing models, such as green trends derived from the normalized difference vegetation index (NDVI; e.g., Myneni *et al.*, 1997; Zhou *et al.*, 2001; Stow *et al.*, 2004; Verbyla, 2008), and global vegetation and ecosystem process simulations of the terrestrial carbon cycle (e.g., Kimball *et al.*, 2006; Zhang *et al.*, 2008), indicate increasing trends in vegetation photosynthetic activity and net primary production in the Arctic over the past several decades.” And with respect to what drove this welcome transformation of the tundra, Hudson and Henry say “it is likely that warming directly increased plant growth and reproduction and indirectly increased resource supply,” while noting that “increased temperatures also lengthened the growing season, increased soil temperature, deepened the active [soil] layer, and consequently may have influenced nutrient uptake in the plant community.”

But what if this area under study would have warmed even more? That was the focus of another paper by Hudson and Henry (2010) published the following year. In that study, the two authors used open-

top chambers to passively warm an evergreen-shrub heath by 1.0-1.3°C over a period of *fifteen years* (during which time there was also a significant *background* warming) at the same location at Alexandra Fiord, Nunavut, Canada (79°N), which effort they describe as “the longest-running passive warming experiment in the Canadian Arctic.” The results indicated, in the words of the two researchers, that “experimental warming did not strongly affect vascular plant cover, canopy height or species diversity, but it did increase bryophyte cover by 6.3% and decrease lichen cover by 3.5%,” although they note that “temporal changes in plant cover were more frequent and of greater magnitude than changes due to experimental warming,” as pointed out in their study published the year prior and highlighted above.

In another analysis, this time from Greenland, Madsen *et al.* (2011) compared the aboveground biomass of the graminoid marsh vegetation observed on Jameson Land, low Arctic, East Greenland in surveys conducted in 1982-1984, with similar surveys that were conducted in 2008, to see what had happened over the intervening period of significant global - and local - warming.

According to the five researchers, the data they obtained in 2008 yielded a standing crop biomass of 98.2 g/m², which was 2.34 *times greater* than what had been measured in the same location in 1984. In further support of the validity of their observations, they note that “on Bylot Island, northeast Canada, graminoid aboveground production in wetlands has increased by 84% between 1990 and 2007, most likely as a consequence of climate

warming,” citing Cadieux *et al.* (2008), while adding that “on Svalbard, it is known that early snow melt has a dramatic positive effect on the density of nesting geese and their fecundity,” citing Madsen *et al.* (2007) and noting that “the climate in East Greenland has been warming during the last 30 years.” Thus, it would appear that many of Earth’s higher-latitude terrestrial ecosystems might well be able to sustain *considerably* greater primary productivity, as well as *much* larger numbers of higher-trophic-level consumers, in a CO₂-enriched and warmer world.

Introducing their study of the subject, Villarreal *et al.* (2012) write that “climate warming is pronounced at high northern latitudes (ACIA, 2005; Serreze, 2010),” and that “time series analysis of satellite remote sensing between 1982 and 2008 suggests that there has been a greening of arctic landscapes,” citing Bhatt *et al.* (2010). More particularly, they note that “remotely detected changes in the normalized difference vegetation index (NDVI) of the arctic coastal plain near Barrow, Alaska, appear to be among the most dramatic recorded for much of the Arctic,” once again citing Bhatt *et al.* (2010). However, they say “there is a general scarcity of ground-based studies that examine vegetation change in the Arctic over decade time scales,” and it was this research niche that their study was designed to fill. More specifically, Villarreal *et al.* resampled (for species cover and presence, in 1999, 2008 and 2010) 330 marked plots at 33 sites that had been established in an area near Barrow at the northernmost point of the Alaskan Coastal Plain (71°18’N, 156°40’W) in 1972 as part of that year’s International Biological Program.

Results indicated that over the 38-year study period, ecosystem diversity “increased for most plant communities, and wetter communities changed more than dry and moist plant communities.” These findings are said by them to support other observational studies, such as that of Wilson and Nilsson (2009). And of the 19 species that comprised more than 80% of the overall relative cover, they say that five had higher relative cover in 2010 than 1972. In addition, they indicate that their results for changes in shrub cover “are somewhat consistent with other long-term observations and experimental studies that report increased shrub abundance (Myers-Smith *et al.*, 2011; Tape *et al.*, 2006; Walker *et al.*, 2006; Sturm *et al.*, 2001),” as well as warming-induced “treeline advancement (Lloyd, 2005; Danby and Hik, 2007).”

Also working in Alaska, Tape *et al.* (2006) analyzed *repeat photography* data from a photo study of the Colville River conducted between 1945 and 1953, as well as 202 new photos of the same sites that were obtained between 1999 and 2002, to determine the nature of shrub expansion in that region over the past half-century. This approach revealed, in their words, that “large shrubs have increased in size and abundance over the past 50 years, colonizing areas where previously there were no large shrubs.” In addition, they say their review of plot and remote sensing studies confirms that “shrubs in Alaska have expanded their range and grown in size” and that “a population of smaller, intertussock shrubs not generally sampled by the repeat photography, is also expanding and growing.” Taken together, they conclude that “these three lines of evidence allow us to infer a general increase in tundra shrubs across northern Alaska.”

As for the cause of the shrub expansion and when it began, Tape *et al.* are inclined to attribute it to large-scale pan-Arctic warming; and from analyses of logistic growth curves, they estimate that the expansion began about 1900, “well before the current warming in Alaska (which started about 1970).” Hence, they conclude that “the expansion predates the most recent warming trend and is perhaps associated with the general warming since the Little Ice Age.” These inferences appear reasonable, although the 80-ppm increase in the atmosphere’s CO₂ concentration since 1900 likely played a significant role in the shrub expansion as well.

In introducing their study, Elmendorf *et al.* (2012) state that “remote-sensing data indicate that contemporary climate warming has already resulted in increased productivity over much of the Arctic,” noting that “normalized difference vegetation index (NDVI) values have increased over the tundra biome in recent years, indicating a greening of the tundra ecosystem coincident with climate warming trends,” citing the studies of Pouliot *et al.* (2009) and Bhatt *et al.* (2010). However, they say that “plot-based evidence for vegetation transformation is not widespread,” a deficiency which they proceed to correct by analyzing “change in tundra vegetation surveyed between 1980 and 2010 in 158 plant communities spread across 46 locations throughout the Arctic,” the majority of which locations were from the continent of North America. And what did they find?

In the words of the 47 researchers hailing from 12 different countries who conducted the work, “we found biome-wide trends of increased height of the plant canopy and

maximum observed plant height for most vascular growth forms; increased abundance of litter; increased abundance of evergreen, low-growing and tall shrubs; and decreased abundance of bare ground.” These data confirm the findings of prior satellite assessments of the vegetative transformation of Earth’s northernmost collection of landscapes over the past three decades, thanks not only to global warming, but also to the aerial-fertilization and water-use-efficiency-enhancing effects of atmospheric CO₂ enrichment.

Further documentary evidence of enhanced plant productivity in the northern region of North America -- and the role of rising atmospheric CO₂ in that enhancement -- comes from the study of Wang *et al.* (2006), who examined ring-width development in cohorts of young and old white spruce trees in a mixed grass-prairie ecosystem in southwestern Manitoba, Canada, where a 1997 wildfire killed most of the older trees growing in high-density *spruce islands*, but where younger trees slightly removed from the islands escaped the ravages of the flames. There, “within each of a total of 24 burned islands,” in the words of the three researchers, “the largest dominant tree (dead) was cut down and a disc was then sampled from the stump height,” while “adjacent to each sampled island, a smaller, younger tree (live) was also cut down, and a disc was sampled from the stump height.”

After removing size-, age- and climate-related trends in radial growth from the ring-width histories of the trees, Wang *et al.* plotted the residuals as functions of time for the 30-year periods for which both the old and young trees would have been approximately the same age: 1900-1929 for the old trees and 1970-1999 for the young

trees. During the first of these periods, the atmosphere’s CO₂ concentration averaged 299 ppm; during the second it averaged 346 ppm. Also, the mean rate-of-rise of the atmosphere’s CO₂ concentration was 0.37 ppm/year for first period and 1.43 ppm/year for the second.

The results of this exercise revealed that the slope of the linear regression describing the rate-of-growth of the ring-width residuals for the later period (when the air’s CO₂ concentration was 15% greater and its rate-of-rise 285% greater) was more than *twice* that of the linear regression describing the rate-of-growth of the ring-width residuals during the earlier period. As the researchers describe it, these results show that “at the same developmental stage, a greater growth response occurred in the late period when atmospheric CO₂ concentration and the rate of atmospheric CO₂ increase were both relatively high,” and they say that “these results are consistent with expectations for CO₂-fertilization effects.” In fact, they say “the response of the studied young trees can be taken as strong circumstantial evidence for the atmospheric CO₂-fertilization effect.”

Another thing Wang *et al.* learned was that “postdrought growth response was much stronger for young trees (1970-1999) compared with old trees at the same development stage (1900-1929),” and they add that “higher atmospheric CO₂ concentration in the period from 1970-1999 may have helped white spruce recover from severe drought.” In a similar vein, they also determined that young trees showed a weaker relationship to precipitation than did old trees, noting that “more CO₂ would lead to greater water-use efficiency, which

may be dampening the precipitation signal in young trees.”

Taken together, the results presented here for the high latitude region of North America paint a picture of the planet’s terrestrial vegetation that is *opposite* of that promulgated by the world’s climate alarmists. Instead of heading down the road of environmental degradation toward extinction, land-based plants of the Arctic and near-Arctic regions of North America are *thriving*, thanks in large part to the ongoing rise in the atmosphere’s CO₂ concentration *and* global warming.

EASTERN USA

We begin our investigation of plant growth responses to rising atmospheric CO₂ and temperature in the Eastern United States with the model-based study of Pan *et al.* (2009), who examined “how changes in atmospheric composition (CO₂, O₃ and N deposition), climate and land-use affected carbon dynamics and sequestration in Mid-Atlantic temperate forests during the 20th century.” This they did by modifying and applying “a well-established process-based ecosystem model with a strong foundation of ecosystem knowledge from experimental studies,” which they validated “using the U.S. Forest Inventory and Analysis (FIA) data.” And what did they find?

For previously harvested and currently *regrowing* forests, the calibrated model produced the following percentage changes in *net ecosystem productivity* (NEP) due to observed changes in N deposition (+32%), CO₂ (+90%), O₃ (-40%), CO₂ + O₃ (+60%), CO₂ + N deposition (+184%), and CO₂ + N deposition + O₃ (+138%), while corresponding changes in NEP for

undisturbed forests were +18%, +180%, -75%, +78%, +290%, +208%. In addition, the results of Pan *et al.* revealed that “the ‘fertilization’ effect of N deposition mainly stimulates carbon allocation to short-lived tissues such as foliage and fine roots,” but that “the ‘fertilization’ effect by elevated CO₂ likely enhances more sustainable carbon storage such as woody biomass (including coarse roots).”

In discussing the future implications of their findings, the four USDA Forest Service scientists say they indicate that “the change in atmospheric composition, particularly elevated CO₂, will gradually account for more of the carbon sink of temperate forests in the Mid-Atlantic region,” and they opine that “such a significant ‘fertilization effect’ on the forest carbon sequestration could eventually result in a ‘greener world’ after a long period of chronic change in atmospheric composition and cumulative impact.”

Crossing the threshold into the realm of real-world data, Westfall and Amateis (2003) used mean height measurements made at three-year intervals over a period of 15 years from dominant stands of loblolly pine plantations growing at 94 locations spread across the southeastern United States to calculate a *site index* related to the mean growth rate for each of the five three-year periods. It was their expectation that the index would increase monotonically if growth rates were being enhanced above normal by some monotonically-increasing factor that promotes growth. The results indicated, in the words of the researchers, that the “mean site index over the 94 plots consistently increased at each re-measurement period,” which would suggest, as they further state, that “loblolly

pine plantations are realizing greater than expected growth rates.” And it should be added that the growth rate increases grow larger and larger with each succeeding three-year period.

As to what could be causing the monotonically increasing growth rates of loblolly pine trees over the entire southeastern United States, Westfall and Amateis named increases in temperature and precipitation in addition to rising atmospheric CO₂ concentrations. However, they report that a review of annual precipitation amounts and mean ground surface temperatures showed no trends in these factors over the period of their study. They also suggested that if increased nitrogen deposition were the cause, “such a factor would have to be acting on a regional scale to produce growth increases over the range of study plots.” Hence, they tended to favor the ever-increasing aerial

fertilization effect of atmospheric CO₂ enrichment as being responsible for the accelerating pine tree growth rates.

Writing as background for their research, McMahon *et al.* (2010) state “there are indications that forest biomass accumulation may be accelerating where nutrients and water are not limiting,” citing the work of Myneni *et al.* (1997), Lewis *et al.* (2004), Lewis *et al.* (2009b), Boisvenue and Running (2006), Delpierre *et al.* (2009), Salzer *et al.* (2009) and Chave *et al.* (2008); and, therefore, they felt it important to further investigate the subject because of the great significance such growth portends for the planet’s carbon balance and the future course of potential CO₂-induced global warming.

Using unique datasets of tree biomass collected over the prior 22 years from 55 temperate forest plots with known land-use

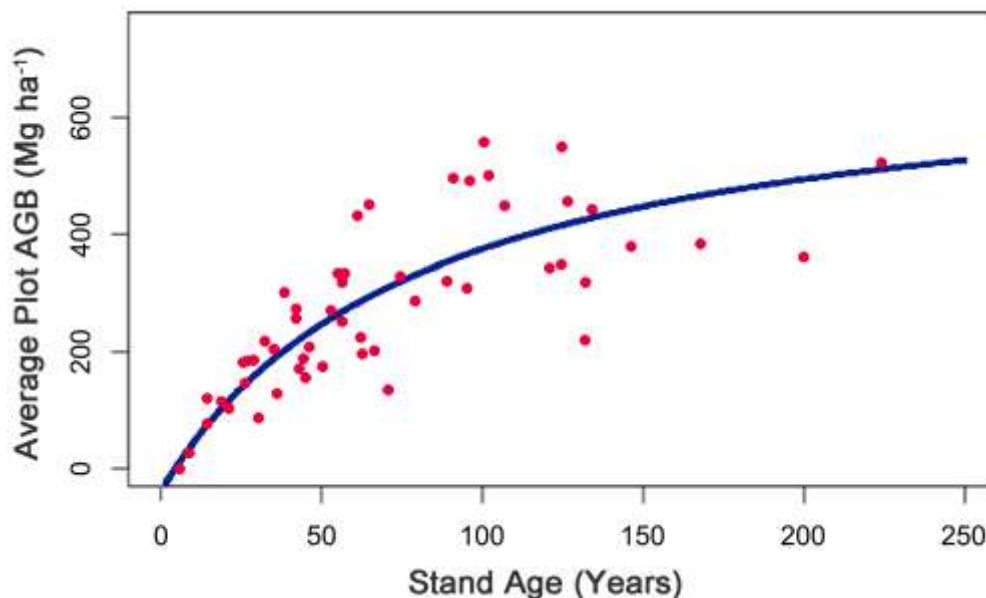


Figure 21. Graphic showing the relationship between above-ground biomass (AGB) and stand age of multiple-censused forest plots in a temperate deciduous forest in and near the Smithsonian Environmental Research Center in Edgewater, MD. From this plot it is seen that younger trees are growing faster than older ones. Adapted from McMahon *et al.* (2010).

histories and stand ages ranging from 5 to 250 years (which were derived from knowledge of when the stands had begun to regrow following major disturbances such as significant logging, various natural disasters that had decimated large patches of trees, or the clearing of trees to make room for agriculture that was ultimately abandoned), McMahon *et al.* “estimated biomass change, while controlling for stand regeneration” (see Figure 21). This they did within various parts of a temperate deciduous forest in the vicinity of the Smithsonian Environmental Research Center, Edgewater, Maryland (USA) by comparing recent (the prior 22 years or less) rates of biomass accumulation of the various stands with rates predicted for those age intervals by the overall growth function derived from the combined data of all of the stands. Then, last of all, they compared their findings with “over 100 years of local weather measurements and 17 years of on-site atmospheric CO₂ measurements.”

The results of this analysis revealed that “recent biomass accumulation greatly exceeded the expected growth caused by natural recovery,” noting that in stands younger than 50 years the observed rate increase was generally at least one-third of total growth, and that in older stands it typically was “the majority of growth,” even though past experience and the ensemble relationship of growth vs. age derived from the totality of their data suggest that “old forests should grow very little as they approach equilibrium.”

As for what could have caused the tremendous recent increases in forest plot growth rates detected by the Smithsonian scientists, they say that “increases in

temperature, growing season [which is largely driven by temperature], and atmospheric CO₂ have documented influences on tree physiology, metabolism, and growth,” and they state that these *global-change factors* -- the magnitudes of which rose significantly over the course of their study -- may well have been “critical to changing the rate of stand growth observed across stands.”

Further north, Capers and Stone (2011) “studied a community in western Maine, comparing the frequency and abundance of alpine plants in 2009 with frequency and abundance recorded in 1976,” while noting that “the 2009 survey was designed to provide a fair comparison with that of 1976,” which was conducted and described by Stone (1980). In doing so, the two researchers found that the 2009 survey “provided evidence of the increasing importance of woody plants - both trees and shrubs - in the alpine community” (Figure 22), commenting that “the most widespread tree species increased dramatically.” In addition, they say they “recorded an increase in total species richness of the community with the addition of four lower montane species that had not been recorded previously.” And in another important positive finding, they say they “found no evidence that species with high-arctic distributions had declined more than other species.”

In discussing their findings, Capers and Stone state that the changes they recorded “are consistent with those reported in tundra communities around the world.” And although there is some concern that the observed increase in species richness could ultimately turn out to be temporary if alpine species were to disappear because of

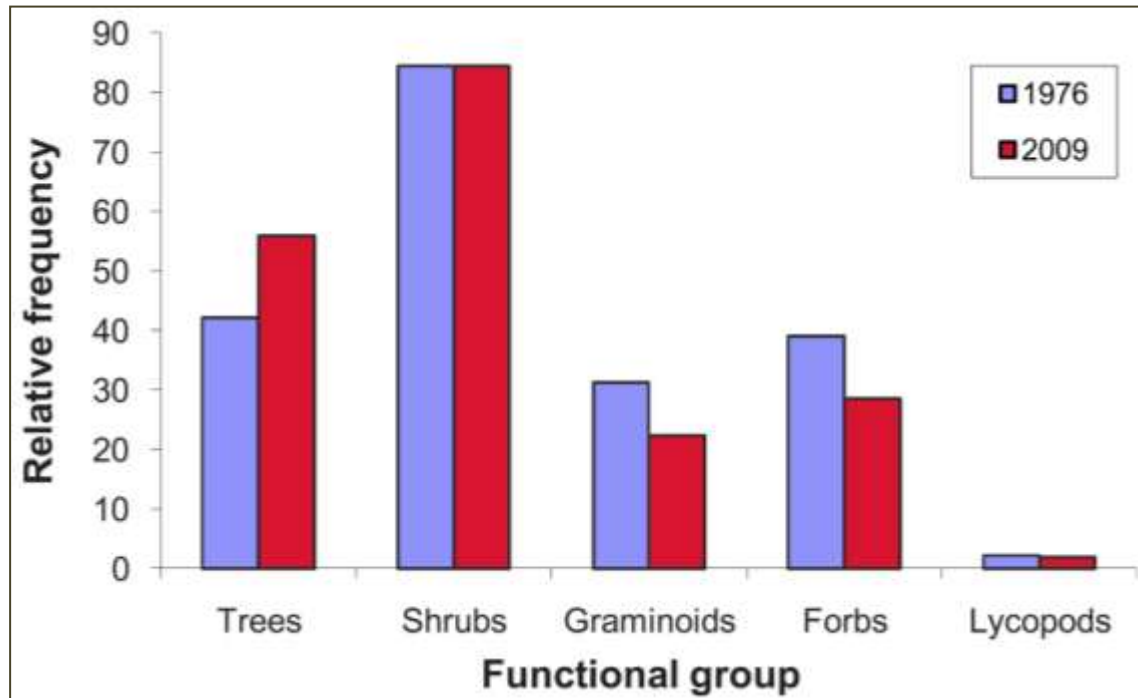


Figure 22. The relative frequency five functional plant groups from surveys taken in 1976 and 2009 in a Northeast United States alpine plant community. The relative frequency of trees increased by a significant 14%, whereas the changes in forbs and graminoids were only marginally significant. Adapted from Capers and Stone (2011).

competition from the new species appearing on the scene, they state that “species losses resulting from competition have not typically been found with rising richness in high alpine areas, possibly because newly arriving species occupy different microhabitats,” citing the work of Walther *et al.* (2005).

Lastly, in a somewhat different study, working within and around Baltimore, Maryland, USA, Ziska *et al.* (2004) characterized the gradual changes that occur in a number of environmental variables as one moves from a *rural* location (a farm approximately 50 km from the city center) to a *suburban* location (a park approximately 10 km from the city center) to an *urban* location (the Baltimore Science Center approximately 0.5 km from the city center). At each of these locations, four 2 x

2 m plots were excavated to a depth of about 1.1 m, after which they were filled with identical soils, the top layers of which contained seeds of naturally-occurring plants of the general area. These seeds sprouted in the spring of the year, and the plants they produced were allowed to grow until they senesced in the fall, after which all of them were cut at ground level, removed, dried and weighed.

Along the rural to suburban to urban transect, the only consistent differences in the environmental variables Ziska *et al.* measured were a rural to urban increase of 21% in average daytime atmospheric CO₂ concentration and increases of 1.6 and 3.3°C in maximum (daytime) and minimum (nighttime) daily temperatures, respectively, which changes, in their words, “were consistent with most short-term (~50

year) global change scenarios regarding CO₂ concentration and air temperature.” In addition, they determined that “productivity, determined as final above-ground biomass, and maximum plant height were positively affected by daytime and soil temperatures as well as enhanced CO₂, increasing 60 and 115% for the suburban and urban sites, respectively, relative to the rural site.”

In light of these observations, the three researchers say their results suggest that “urban environments may act as a reasonable surrogate for investigating future climatic change in vegetative communities,” and those results indicate that rising air temperatures and CO₂ concentrations tend to produce dramatic increases in the productivity of the natural ecosystems typical of the greater Baltimore area and, by inference, probably those of many other areas as well.

In considering each of the studies discussed above, it would appear that late 20th-century increases in air temperature and atmospheric CO₂ concentration did not negatively affect plant communities in the eastern United States. In direct contrast, in fact, local and regional productivity there was significantly *enhanced*; and there is little reason not to believe such enhancements will continue throughout the foreseeable future.

CENTRAL USA

Turning to the central United States, working with two species of oak (*Quercus velutina* Lam. and *Quercus coccinea* Muench.) and one of pine (*Pinus echinata* Mill.) in the Ozark Mountains of Missouri, USA, Voelker *et al.* (2006) report that since

1850 the stem growth of the three species has risen “coincidentally with increases in atmospheric CO₂,” such that the overall trend in ring-width in recent years is “nearly two times that” experienced prior to 1850 (Figure 23). In addition, they note that the “long-term increases in radial growth appear unrelated to historical disturbance levels for the region, to long-term changes in relevant climatic variables, or to productivity of sites sampled.” And based on these findings, the four Department of Forestry researchers from the University of Missouri suggest that as the atmosphere’s CO₂ concentration continues to rise, aided by continued nitrogen deposition, it will likely “stimulate further increases in the rates of stand development and carbon storage.”

Introducing their study of the subject, Cole *et al.* (2010) write that quaking aspen (*Populus tremuloides* Michx.) is a dominant forest type in north-temperate, montane, and boreal regions of North America,” stating that it is, in fact, “the most widely distributed tree species on the continent,” while noting that aspen -- and related poplars -- are “quintessential foundation species (Ellison *et al.*, 2005), shaping the structure and function of the communities and ecosystems in which they occur (Whitham *et al.*, 2006; Schweitzer *et al.*, 2008; Madritch *et al.*, 2009).” This being the case, they felt it important to attempt to determine how this *keystone species* may have responded to the increase in atmospheric CO₂ concentration that has occurred over the past several decades, especially within the context of the climatic changes that occurred concurrently.

To accomplish this goal, the four researchers collected branches from 919

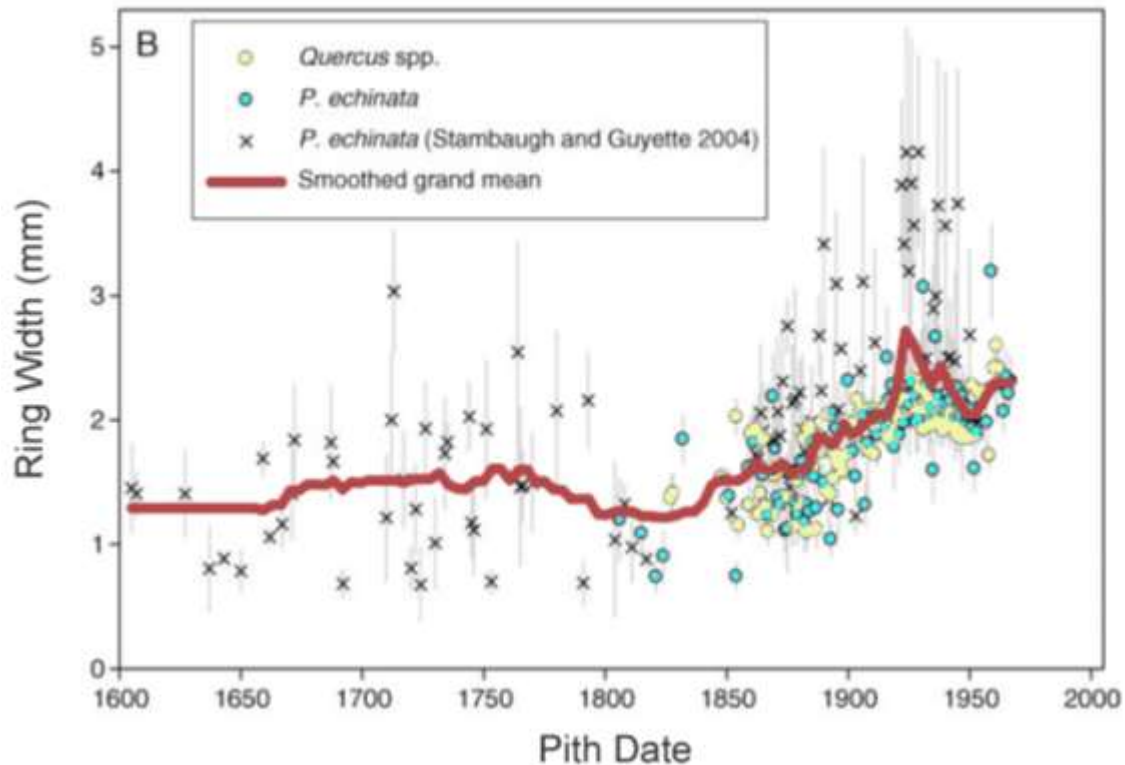


Figure 23. Mean ring width responses by pith date calculated across 11 equally spaced cambial ages from 1 to 50, for randomly sampled oak and pine trees in the Ozark Mountains of Missouri, USA. The means for *P. echinata* (Stambaugh and Guyette 2004) were calculated from three cambial ages but were shifted to the pith date for accurate intercomparisons among data sets (see Voelker et al., 2006). The smoothed grand mean was calculated across each of the closest 14 ring widths. Adapted from Voelker et al. (2006).

trees after their leaves had dropped in the fall, obtaining samples that represented 189 genets or clones (five trees per clone) at eleven sites distributed throughout three regions of Wisconsin (USA). The sampled trees ranged from 5 to 76 years of age and came from second-growth unmanaged forests south of the areas defoliated by forest tent caterpillars in 1980-1982, 1989-1990 and 2001-2002. In addition, they recorded trunk diameter at breast height for each sampled tree, which parameter, in their words, “is very highly correlated with total biomass in aspen,” citing the work of Bond-Lamberty *et al.* (2002).

So what did the Minnesota and Wisconsin scientists learn? First of all, they determined that “age-specific ring width increased over time,” and that “the greatest increase occurred for relatively young trees, so that young trees grew faster in recent years than did young trees several decades ago.” During the past half-century, for example, they found that the growth of trees 11-20 years old rose by 60% (Figure 24). In addition, they observed that “rising CO₂ causes ring width to increase at all moisture levels, apparently resulting from improved water use efficiency,” so that “the overall increase results from historical increases in both CO₂ and water availability.” And when they separated out

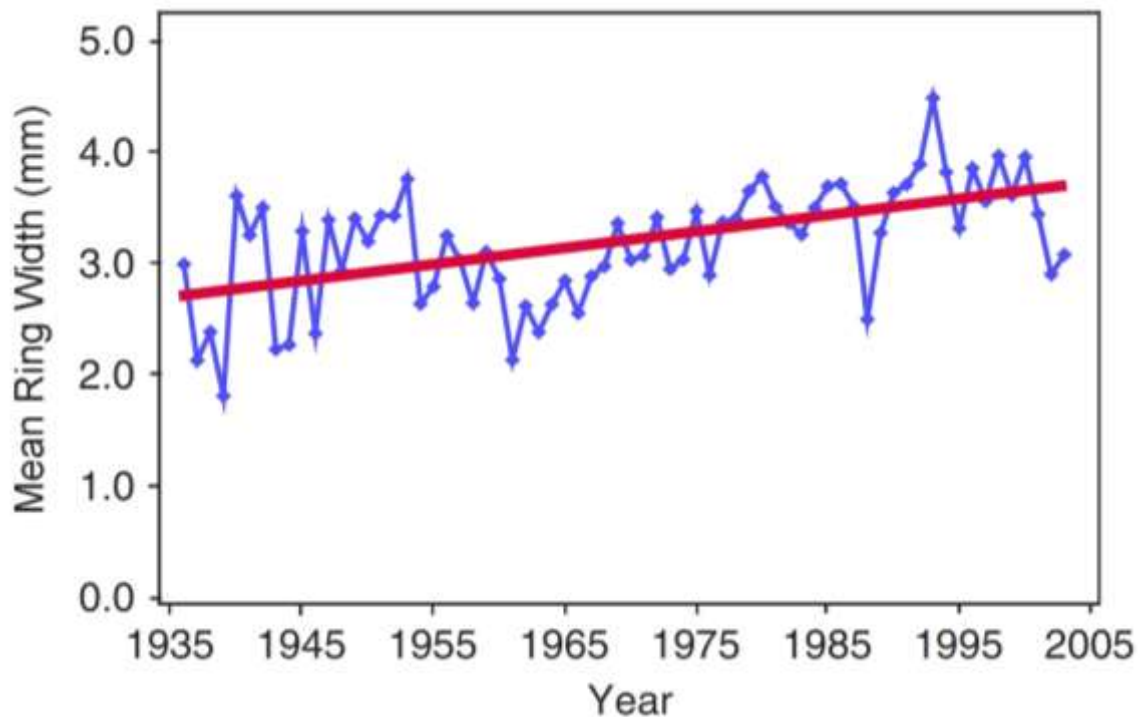


Figure 24. Mean ring width of quaking aspen trees sampled in Wisconsin, USA. Adapted from Cole *et al.* (2010).

the impacts of the two factors, they found that “the effect of rising CO₂ had been to increase ring width by about 53%,” as a result of “a 19.2% increase in ambient CO₂ levels during the growing season, from 315.8 ppm in 1958 (when CO₂ records began) to 376.4 ppm in 2003.”

This is a truly remarkable finding; and Cole *et al.* comment that “the magnitude of the growth increase uncovered by this analysis raises the question of how much other major forest species have responded to the joint effects of long-term changes in CO₂ and precipitation.

The U.S. Northern Great Plains is another area where woody plants have responded positively to the 20th-century increase in atmospheric CO₂ by expanding their ranges, and that expansion has led to greater

benefits beneath the soil as well. According to Springsteen *et al.* (2012), “changes in soil attributes under woody vegetation have been documented in the arid grasslands of the southern Great Plains, including increases in soil carbon and nitrogen,” citing the work of Reynolds *et al.* (1999), Hibbard *et al.* (2001, 2003), McCulley *et al.* (2004), Schade and Hobbie (2005) and Liao *et al.* (2006). In their own investigation into such changes, Springsteen *et al.* examined near-surface (upper 15 cm) soil biogeochemistry along a 42-year (1963-2005) chronosequence, which encompassed grassland, woodland, and grassland-woodland transition zones in a *northern* Great Plains grassland at the USDA-ARS Northern Great Plains Research Laboratory near Mandan, North Dakota (USA), in order to determine the influence of woody plant

expansion on soil carbon and nitrogen contents.

According to the four researchers, total soil carbon content rose by 26% across the chronosequence from grassland to woodland within the 0-15 cm soil depth, while total soil nitrogen content rose by 31%. And they add that the *rate of woody shrub expansion* from 1963 to 1988 (25 years) was $\sim 1,800 \text{ m}^2$ per year at their study site, while from 1988 to 2005 (17 years) it was $\sim 3,800 \text{ m}^2$ per year, or just a little more than doubled. It would thus appear that soil carbon sequestration driven by woody-plant invasions of grasslands (which are driven to a significant degree by the ongoing rise in the air's CO_2 content), as well as the increases in soil nitrogen content required to sustain them, are growing ever greater with the passage of time.

Lastly, in a vastly different type of study based on a 48-year record derived from an average of 17 measurements per year, Raymond and Cole (2003) demonstrated that the export of *alkalinity*, in the form of bicarbonate ions, from the USA's Mississippi River to the Gulf of Mexico had increased by approximately 60% since 1953. "This increased export," as they described it, was "in part the result of increased flow resulting from higher rainfall in the Mississippi basin," which had led to a 40% increase in annual Mississippi River discharge to the Gulf of Mexico over the same time period. The remainder, however, had to have been due to increased rates of chemical weathering of soil minerals.

What factors might have been responsible for this phenomenon? The two researchers

noted that potential mechanisms included "an increase in atmospheric CO_2 , an increase [in] rainwater throughput, or an increase in plant and microbial production of CO_2 and organic acids in soils due to biological responses to increased rainfall and temperature." But it has also likely changed as a result of the increase in terrestrial plant productivity that is produced by the increase in the aerial fertilization effect provided by the historical rise in the air's CO_2 content, which also leads to an increase in plant and microbial production of CO_2 and organic acids in soils. And this phenomenon should have led to an increase in Mississippi River alkalinity equivalent to that which Raymond and Cole observed since 1953.

In light of the findings presented above, it would appear that the late 20th-century rise in temperature and CO_2 has also improved the productivity of plant communities in the central region of the U.S., notwithstanding climate-alarmist concerns to the contrary.

WESTERN USA

Moving on to the western United States, we begin with a discussion of two studies taking a model-based approach to the issue.

In an attempt to evaluate the consequences of a doubling of the air's CO_2 content and 2 to 4°C increases in air temperature on ecosystem performance in a high-elevation Rocky Mountain watershed, Baron *et al.* (2000) utilized an empirically-based hydro-ecological simulation model. Their results indicated that "both photosynthesis and transpiration were highly responsive to doubled CO_2 ." It was also determined that the positive effects of the 4°C temperature increase "were additive, so a warmer and

carbon-rich environment increased plant growth by 30%.” Hence, the authors concluded that “forests will expand at the expense of tundra in a warmer, wetter, and enriched CO₂ world,” and that observed increases in tree height and density in recent decades illustrate “the rapidity with which vegetation can respond to climate change.”

Because *urban environments* are affected by urban heat islands, carbon dioxide domes, and high-level nitrogen deposition, Shen *et al.* (2008) say that “to some extent they portend the future of the global ecosystem,” and that they “provide a unique ‘natural laboratory’ to study potential ecosystem responses to anthropogenic environmental changes.” Against this backdrop, therefore, the team of four authors used a version of the *Patch Arid Land Simulator-Functional Types* (PALSF-T) process-based ecosystem model -- originally developed for the Chihuahuan Desert but modified to represent the *Larrea tridentata*-dominated ecosystem characteristic of the Sonoran Desert within which Phoenix is located -- to investigate the impacts of previously documented city-to-desert gradients of atmospheric CO₂ concentration, air temperature (TA), and nitrogen deposition (Ndep) on *aboveground net primary productivity* (ANPP) and *soil organic matter* (SOM).

In response to the mean maximum rural-to-urban increases in CO₂ (160 ppm), Ndep (24 kg per ha/year) and TA (4.0°C) characteristic of Phoenix, mean ANPP changes of +52.5, +42.7 and -7.8 g dry matter (DM) per m²/year were obtained, respectively, from the 76.3 g DM per m²/year characteristic of desert conditions, when each of the three factors was increased individually. And

when all three parameters were increased together, the net increase in ANPP was found to be even greater than the sum of the three individual results: 108 vs. 87.4 g DM per m²/year, which numbers translate to respective percentage increases of 142% vs. 115%. In the case of SOM, increases of 18.5, 12.3 and 1.2 g C per m²/year were obtained for mean maximum individual increases in CO₂, Ndep and TA, respectively, while the combined increase was 30.9 g C per m²/year. Given such findings, it should be abundantly clear that even in a desert region as hot as Phoenix, the types of CO₂, temperature and nitrogen deposition increases predicted for the years ahead portend huge increases in indigenous ecosystem productivity and soil organic matter buildup.

Transitioning from model- to empirical-based studies, Zavaleta and Kettley (2006) examined patterns of production, standing biomass, carbon (C) and nitrogen (N) storage, community composition, and soil moisture along a 25-year chronosequence of sites within an annual, exotic-dominated grassland at Stanford University’s Jasper Ridge Biological Preserve in the interior foothills of the central coast range south of San Francisco, California (USA), various parts of which had been invaded at a number of different times over the past quarter-century by *Baccharis pilularis* shrubs.

According to the two researchers, increasing above- and below-ground biomass along the chronosequence “drove increases in ecosystem N sequestration of ~700% and in C storage of over 125%,” including a 32% increase in total soil C over the 25-year period. What is more, they found that “increases in carbon storage also

did not appear to be saturating at 25 years after shrub establishment in any pool, suggesting the potential for additional carbon gains beyond 25 years.” In addition, they found that *Baccharis* shrubs began to decline in prominence after about 20 years, as native oaks “with life spans of centuries” and the potential to drive even *larger* ecosystem changes began to grow in the shrub-dominated areas.

Of further interest, the two researchers say they “initially hypothesized that *Baccharis*-invaded sites would experience increasing N limitation as N was immobilized in biomass and litter.” *However*, as they continue, they found that “total soil N increased rapidly with shrub age” and that “the magnitude of increase in total soil nitrogen was much larger than the increase in nitrogen immobilization in biomass and litter over time.”

Zavaleta and Kettley conclude their analysis by saying that their findings “illustrate the potential for important vegetation-mediated ecosystem responses and feedbacks to atmospheric CO₂ and climate change,” as indeed they do. In particular, they highlight the great potential for a CO₂-induced range expansion of trees; and they pretty much lay to rest the claim (Hungate *et al.*, 2003) that the availability of nitrogen, in forms usable by plants, will probably be too low for large future increases in carbon storage driven by CO₂-induced increases in plant growth and development.

In a laboratory-based study, Peterson and Neofotis (2004) grew velvet mesquite (*Prosopis velutina* Woot.) seedlings for six weeks from their time of planting (as seeds) in small pots within environmentally controlled growth chambers that were

maintained at atmospheric CO₂ concentrations of 380 and 760 ppm and two levels of water availability (high and low). Although they did not see a significant CO₂-induced increase in plant growth, the authors say that by the end of their six-week study, they observed a highly significant reduction of approximately 41% in the volume of water transpired by *P. velutina* in response to the experimental doubling of the air’s CO₂ content. “This large reduction in whole-plant water use,” as they describe it, “occurred because the reduction in transpiration per unit leaf area at elevated CO₂ was not offset by a proportional increase in total leaf area.”

The pair of scientists from the Biosphere 2 Center near Oracle, Arizona, USA, say their findings suggest that “under a future [high-CO₂] scenario, seedlings may deplete soil moisture at a slower rate than they do currently,” and that “this could facilitate seedling survival between intermittent rain events,” noting that their work “corroborates the conclusions of Polley *et al.* (1994, 1999, 2003) that increasing levels of atmospheric CO₂ may facilitate the establishment of mesquite seedlings through a reduction in soil water depletion.” That such has indeed occurred is suggested by the fact, again quoting Peterson and Neofotis, that “mesquites and other woody species in the semiarid southwestern United States have shown substantial increases in population density and geographic range since Anglo-American settlement of the region approximately 120 years ago,” in support of which statement they cite the studies of Van Auken and Bush (1990), Gibbens *et al.* (1992), Bahre and Shelton (1993), Archer (1995), Boutton *et al.* (1999), Van Auken (2000), Ansley *et al.*

(2001), Wilson *et al.* (2001) and Biggs *et al.* (2002).

Among such studies could also be listed the work of Feng (1999), who derived variations in plant intrinsic water-use efficiency over the preceding two centuries from 23 carbon isotope tree-ring chronologies. These results were nearly identical to the historical trend in the air's CO₂ content, with plant intrinsic water-use efficiency rising by 10 to 25% from 1750 to 1970, during which time the air's CO₂ concentration rose by approximately 16%. Feng thus concluded that "in arid environments where moisture limits the tree growth, biomass may have increased with increasing transpiration efficiency," noting that the enhanced growth of trees in arid environments may "have operated as a carbon sink for the anthropogenic CO₂" emitted over that time span.

Finally, working at eight different sites within the Pacific Northwest of the United States, Soule and Knapp (2006) studied ponderosa pine trees to see how they may have responded to the increase in the atmosphere's CO₂ concentration that occurred after 1950. The two geographers say the sites they chose "fit several criteria designed to limit potential confounding influences associated with anthropogenic disturbance." In addition, they selected locations with "a variety of climatic and topo-edaphic conditions, ranging from extremely water-limiting environments ... to areas where soil moisture should be a limiting factor for growth only during extreme drought years." They also say that all sites were located in areas "where ozone concentrations and nitrogen deposition are typically low."

At all eight of the sites that met all of these criteria, Soule and Knapp obtained core samples from about 40 mature trees that included "the potentially oldest trees on each site," so that their results would indicate, as they put it, "the response of mature, naturally occurring ponderosa pine trees that germinated before anthropogenically elevated CO₂ levels, but where growth, particularly post-1950, has occurred under increasing and substantially higher atmospheric CO₂ concentrations." Utilizing meteorological evaluations of the Palmer Drought Severity Index, they thus compared ponderosa pine radial growth rates during matched wet and dry years pre- and post-1950.

So what did they find? Overall, the two researchers discovered a post-1950 radial growth enhancement that was "more pronounced during drought years compared with wet years, and the greatest response occurred at the most stressed site" (see Figure 25). As for the magnitude of the response, they determined that "the relative change in growth [was] upward at seven of our [eight] sites, ranging from 11 to 133%".

With respect to the significance of their observations, Soule and Knapp say their results show that "radial growth has increased in the post-1950s period ... while climatic conditions have generally been unchanged," which further suggests that "nonclimatic driving forces are operative." In addition, they say the "radial growth responses are generally consistent with what has been shown in long-term open-top chamber (Idso and Kimball, 2001) and FACE studies (Ainsworth and Long, 2005)." Hence, they conclude that their findings "suggest that elevated levels of

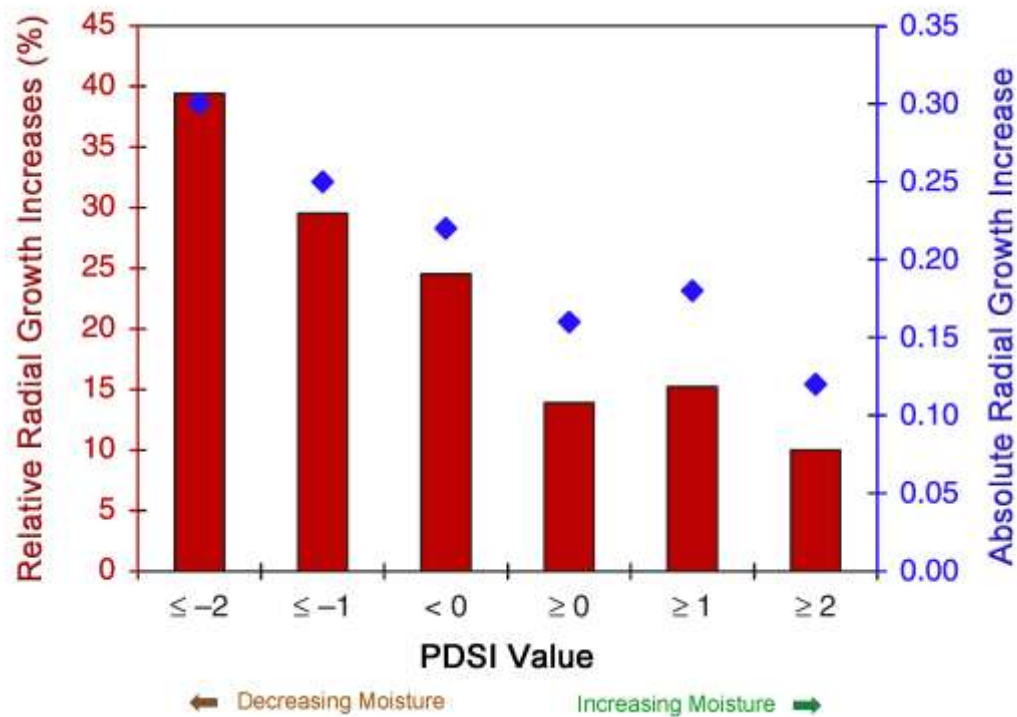


Figure 25. Relative and absolute radial growth increases of Ponderosa pine (Pinus ponderosa) in the Pacific Northwest, USA, post-1950 compared with pre-1950 during years falling into various Palmer Drought Severity Index (PDSI) categories of drought (moist) severity. Adapted from Soule and Knapp (2006).

atmospheric CO₂ are acting as a driving force for increased radial growth of ponderosa pine, but that the overall influence of this effect may be enhanced, reduced or obviated by site-specific conditions.”

Summarizing their findings, Soule and Knapp recount how they had “hypothesized that ponderosa pine ... would respond to gradual increases in atmospheric CO₂ over the past 50 years, and that these effects would be most apparent during drought stress and on environmentally harsh sites,” and in the following sentence of their paper they say their results “support these hypotheses.” Hence, they conclude by stating that “an atmospheric CO₂-driven growth-enhancement effect exists for

ponderosa pine growing under specific natural conditions within the interior Pacific Northwest,” providing yet another important example of the ongoing CO₂-induced *greening of the Earth*.

It would thus appear, given the findings of all studies presented in this section above, that the late 20th-century rise in temperature and CO₂ has improved the productivity of plant communities in the western region of the U.S., notwithstanding climate-alarmist concerns of unprecedented ecological disaster due to rising temperatures and drought.

SOUTH AMERICA

Focusing on vegetative trends in South America, we begin with the long view of the situation provided by Beerling and Mayle (2006), who investigated the nature of Amazonian ecosystem response to the large-scale environmental changes experienced during glacial-interglacial cycles via a series of 21,000-year simulations. This they accomplished using a dynamic process-based ecosystem model for three scenarios: (1) real-world glacial-to-interglacial changes in CO₂ concentration and climate, (2) the real-world change in CO₂ with a constant preindustrial climate, and (3) the real-world change in climate with a constant preindustrial CO₂ concentration. So what did they learn?

During the last glacial maximum, according to the authors, the model suggested that “total above-ground carbon storage in Amazonia was half preindustrial values, indicative of rain forests with markedly lower canopy densities and simpler structures due to lowered CO₂ levels, corroborating modeling studies by Cowling (2004) and Cowling *et al.* (2001).” Thereafter, they say that “biome shifts in ecotonal areas since the last glacial maximum [“the competitive replacement of drought-adapted vegetation (e.g. savanna or deciduous/semideciduous dry forest) by rain forest”] were driven predominantly by climate change, while coincident, increased ecosystem carbon storage throughout the Amazon Basin was driven largely by CO₂.”

What do these findings have to do with today? In answering this question, Beerling and Mayle say “the underlying cause for the observed trend of increasing biomass in long-term Amazonian forest plots over

recent years, despite drought-induced El Niño events (Phillips *et al.*, 1998; Baker *et al.*, 2004a), has been a subject of considerable debate (Baker *et al.*, 2004a; Wright, 2005),” and in this regard they conclude that “this biomass increase is part of a long-term historical trend driven by anthropogenically induced rising CO₂ levels since the 19th century.”

In another model-based study, but covering only the late 20th century, Ichii *et al.* (2005) “simulated and analyzed 1982-1999 Amazonian, African, and Asian carbon fluxes using the Biome-BGC prognostic carbon cycle model driven by National Centers for Environmental Prediction reanalysis daily climate data,” after which they “calculated trends in gross primary productivity (GPP) and net primary productivity (NPP).” In doing so, they found solar radiation variability to be the primary factor responsible for interannual *variations* in GPP, followed by temperature and precipitation variability. In terms of GPP *trends*, however, they report that “recent changes in atmospheric CO₂ and climate promoted terrestrial GPP increases with a significant linear trend in all three tropical regions.” In the Amazonian region, for which we are most interested in terms of the present discussion, the rate of GPP increase was the highest at 0.67 PgC year⁻¹ per decade, while in Africa and Asia it was about 0.3 PgC year⁻¹ per decade. Likewise, as with Beerling and Mayle, carbon dioxide was determined to be the major cause of increased growth, as Ichii *et al.* report that “CO₂ fertilization effects strongly increased recent NPP trends in regional totals.”

Such a finding, to say the least, is especially interesting, because for most of the past century it was believed that old-growth

forests, such as those of Amazonia, should be close to dynamic equilibrium. Just the opposite, however, has been repeatedly observed by several different groups of researchers over the past two decades.

In one of the first studies to illuminate this reality, Phillips and Gentry (1994) analyzed the turnover rates – which are close correlates of net productivity (Weaver and Murphy, 1990) – of forty tropical forests from all around the world. And in doing so, they found that the growth rates of these already highly productive forests have been rising ever higher since at least 1960, and that they have experienced an apparent acceleration in growth rate sometime after 1980. Commenting on these findings, Pimm and Sugden (1994) reported that the consistency and simultaneity of the forest growth trends that Phillips and Gentry had documented on several continents led them to conclude that “enhanced productivity

induced by increased CO₂ is the most plausible candidate for the cause of the increased turnover.”

A few years later, Phillips *et al.* (1998) analyzed forest growth rate data for the period 1958 to 1996 for several hundred plots of mature tropical trees scattered around the world, finding that tropical forest biomass, as a whole, increased substantially over the period of record (Figure 26). In fact, the increase in the Neotropics (tropical Central and South America) was equivalent to approximately 40% of the missing terrestrial carbon sink of the entire globe. And, again, they identified the aerial fertilization effect of the ongoing rise in the air’s CO₂ content as one of the primary factors likely to be responsible for this phenomenon.

More recently, Laurance *et al.* (2004a) reported accelerated growth in the 1990s

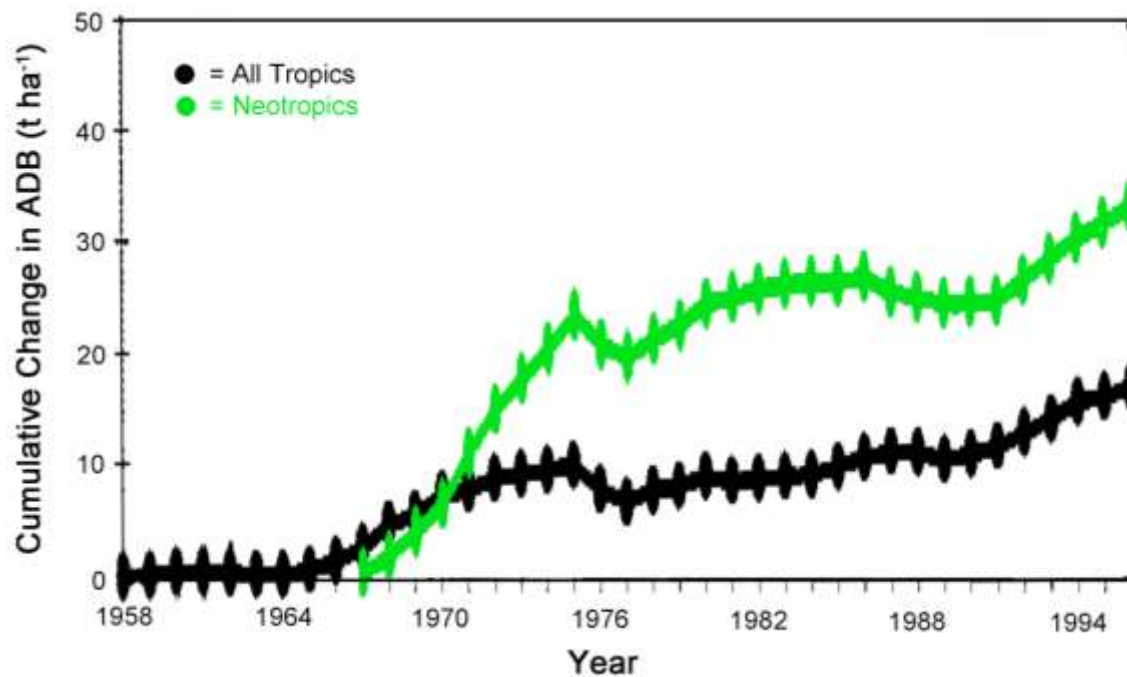


Figure 26. Cumulative aboveground dry biomass change (ADB) per year in humid forests in the entire Tropics since 1958 and in the Neotropics (tropical Central and South America) since 1967. Adapted from Phillips *et al.* (1998).

relative to the 1980s for the large majority (87%) of tree genera in 18 one-hectare plots spanning an area of about 300 km² in central Amazonia, while Laurance *et al.* (2004b) observed similarly accelerated tree community dynamics in the 1990s relative to the 1980s. And once again, it was suggested, in the words of Laurance *et al.* (2005), that these “pervasive changes in central Amazonian tree communities were most likely caused by global- or regional-scale drivers, such as increasing atmospheric CO₂ concentrations (Laurance *et al.*, 2004a,b).”

Expanding upon this theme, Laurance *et al.* (2005) say they “interpreted these changes as being consistent with an ecological ‘signature’ expected from increasing forest productivity (cf., Phillips and Gentry, 1994; Lewis *et al.* 2004a,b; Phillips *et al.*, 2004).” They note, however, that they have been challenged in this conclusion by Nelson (2005), and they thus go on to consider his arguments in some detail, methodically dismantling them one by one.

Next on the scene was Lewis (2006), who reports that the increasing dynamism and productivity of intact tropical forests has had a long history, noting that “across the paleotropics forest dynamism has been steadily increasing for five decades (Phillips and Gentry, 1994).” Among 50 old-growth plots scattered across tropical South America, for example, he notes that “stem recruitment, stem mortality, and biomass growth, and loss, *all* increased significantly (Lewis *et al.*, 2004a).” In addition, he reports that “over approximately the last 20 years, long-term monitoring of 59 plots showed that above-ground biomass increased by 0.6 ± 0.2 tonnes C ha⁻¹ a⁻¹, or a relative increase of $0.50 \pm 0.17\%$ a⁻¹ (mean \pm

95% confidence interval; Baker *et al.*, 2004a).” This rate of increase, to quote him again, “is slightly higher than that documented by Phillips *et al.* (1998).” Thus, there is no question that “over the past two decades,” according to Lewis, “these forests have shown concerted changes in their ecology, becoming, on average, faster growing – more productive – and more dynamic, and showing a net increase in above-ground biomass,” all of which rates of increase are greater than the previously documented increases in the rates of these phenomena.

As for what might be causing this suite of changes, Lewis states that “the results appear to show a coherent fingerprint of increasing net primary productivity across tropical South America, caused by a long-term increase in resource availability (Lewis *et al.*, 2004a,b).” And as for what “resources” might be involved, Lewis gives four possibilities: increases in solar radiation, air temperature, nutrient deposition and atmospheric CO₂ concentration. But after analyzing each of them in detail, he concludes that “the most parsimonious explanation is the increase in atmospheric CO₂, because of the undisputed long-term historical increase in CO₂ concentrations, the key role of CO₂ in photosynthesis, and the demonstrated positive effects of CO₂ fertilization on plant growth rates including experiments on whole temperate-forest stands (Ainsworth and Long, 2005),” or as he states in another place in his review, the explanation resides in “the anthropogenic increase in atmospheric carbon dioxide concentrations, increasing forest net primary productivity leading to accelerated forest growth and dynamics.”

In spite of the forest growth optimism inherent in the studies cited above, some pessimists remained. As background for discussing their reservations, Gloor *et al.* (2009) wrote that “analysis of earlier tropical plot data has suggested that large-scale changes in forest dynamics are currently occurring in Amazonia (Phillips and Gentry, 1994; Phillips *et al.*, 2004a), and that an increase in aboveground biomass has occurred, with increases in mortality tending to lag increases in growth (Phillips *et al.*, 1998; Baker *et al.*, 2004a,b; Lewis *et al.*, 2004a).” And they state that this conclusion had been challenged by an overzealous application of the “Slow in, Rapid out” dictum, which relates to the fact that forest growth is a slow process, whereas mortality can be dramatic and singular in time, such that sampling over relatively short observation periods may miss these more severe events, leading to positively-biased estimates of aboveground biomass trends, when either no trend or negative trends actually exist.

In an attempt to resolve this debate, Gloor *et al.* statistically characterized the disturbance process in Amazon old-growth forests as recorded in 135 forest plots of the RAINFOR network up to 2006, as well as other independent research programs, exploring the consequences of sampling artifacts using a data-based stochastic simulator. Their results indicated that “over the observed range of annual aboveground biomass losses, standard statistical tests show that the distribution of biomass losses through mortality follow an exponential or near-identical Weibull probability distribution and not a power law as assumed by others.” In addition, they say that “the simulator was parameterized using both an exponential disturbance

probability distribution as well as a mixed exponential-power law distribution to account for potential large-scale blow-down events,” and that “in both cases, sampling biases turn out to be too small to explain the gains detected by the extended RAINFOR plot network.” And based on these findings, Gloor *et al.* concluded that their results lend “further support to the notion that currently observed biomass gains for intact forests across the Amazon are actually occurring over large scales at the current time, presumably as a response to climate change,” which in many of their earlier papers is explicitly stated to include the aerial fertilization effect of the historical increase in the air’s CO₂ content.

Introducing their work on the subject, Bonal *et al.* (2011) write that “the impact of global change during the last century on the biology of tropical rainforest trees is largely unknown,” but they say that “an increase in tree radial growth increment over recent decades in Amazonian tropical rainforests has been observed, leading to increased above-ground biomass at most study sites,” citing the studies of Phillips *et al.* (1998, 2009) and Malhi *et al.* (2004) in this regard, while subsequently noting that “the stimulating impact on photosynthesis of increased CO₂ concentrations in the air (Ca) could explain these growth patterns (Lloyd and Farquhar, 2008).”

In further investigating this phenomenon, Bonal *et al.* additionally assessed the impacts of historical environmental changes on leaf morphological (stomatal density, stomatal surface, leaf mass per unit area) and physiological traits (carbon isotope composition, $\delta^{13}\text{C}_{\text{leaf}}$, and discrimination, $\Delta^{13}\text{C}_{\text{leaf}}$, oxygen isotope composition, $\delta^{18}\text{O}_{\text{leaf}}$) of two tropical rainforest species

(*Dicorynia guianensis*; *Humiria balsamifera*) that are abundant in the Guiana shield (Northern Amazonia),” working with leaf samples from different international herbariums that covered a 200-year time period (AD 1790-2004). So what did they learn?

The eleven researchers say their study revealed “a clear response of leaf physiological characteristics to increasing C_a for both species,” consistent with the findings of previous studies “from different ecosystems (Penuelas and Azcon-Bieto, 1992; Beerling *et al.*, 1993; Van de Water *et al.*, 1994; Pedicino *et al.*, 2002; Penuelas *et al.*, 2008), and with data from tree rings in Europe (Bert *et al.*, 1997; Duquesnay *et al.*, 1998; Saurer *et al.*, 2004), Africa (Gebrekirstos *et al.*, 2009) and in tropical rainforests (Hietz *et al.*, 2005; Silva *et al.*, 2009; Nock *et al.*, 2011).” More specifically, they say their results pointed to “an increase in water-use efficiency over recent decades of about 23.1 and 26.6% for *Humiria* and *Dicorynia*, respectively,” driven mostly by increases in leaf photosynthesis. And they indicate that “the range of change in water-use efficiency for these two species was consistent with many results observed not only in tropical forests (Hietz *et al.*, 2005; Nock *et al.*, 2011), but in boreal (Saurer *et al.*, 2004) and temperate forests (Francey and Farquhar, 1982; Penuelas and Azcon-Bieto, 1992; Bert *et al.*, 1997; Duquesnay *et al.*, 1998).” Bonal *et al.* further state that the responses of the two tree species they studied to increasing C_a appear to be “simply related to the availability of CO_2 in the air (fertilization effect),” and they say that “this trend seems to be consistent with recent tree growth patterns in the Amazonian region,” and indeed it is, as plants exposed to elevated

CO_2 concentrations are likely to lose less water via transpiration. Hence, the amount of carbon gained per unit of water lost per unit leaf area -- or *water-use efficiency* -- tends to increase dramatically as the air’s CO_2 content rises. As a result, at higher CO_2 concentrations, plants can better cope under conditions of drought, thereby vastly improving their productivity and growth as opposed to conditions experienced under lower CO_2 .

This situation is further illustrated by Silva *et al.* (2009), who, working with various types of tree-ring data obtained from *A. angustifolia* trees growing in both forest and grassland sites in southern Brazil, compared changes in *intrinsic water use efficiency* – iWUE, defined as the ratio of the rate of CO_2 assimilation by the trees’ needles to their stomatal conductance – with concomitant historical changes in temperature, precipitation and atmospheric CO_2 concentration that occurred over the past century. And based on this analysis, the four researchers found that during the past several decades, “iWUE increased over 30% in both habitats” (see Figure 27), and that “this increase was highly correlated with increasing levels of CO_2 in the atmosphere.” Over this latter period, however, tree growth remained rather stable, due to lower-than-normal precipitation and higher-than-normal temperatures, which would normally tend to *depress* the growth of this species, as Katinas and Crisci (2008) describe *A. angustifolia* as being “intolerant of dry seasons and requiring cool temperatures.” As a result, Silva *et al.* concluded that the “climatic fluctuations during the past few decades,” which would normally be expected to have been *deleterious* to the growth of *A. angustifolia*, seem to have had

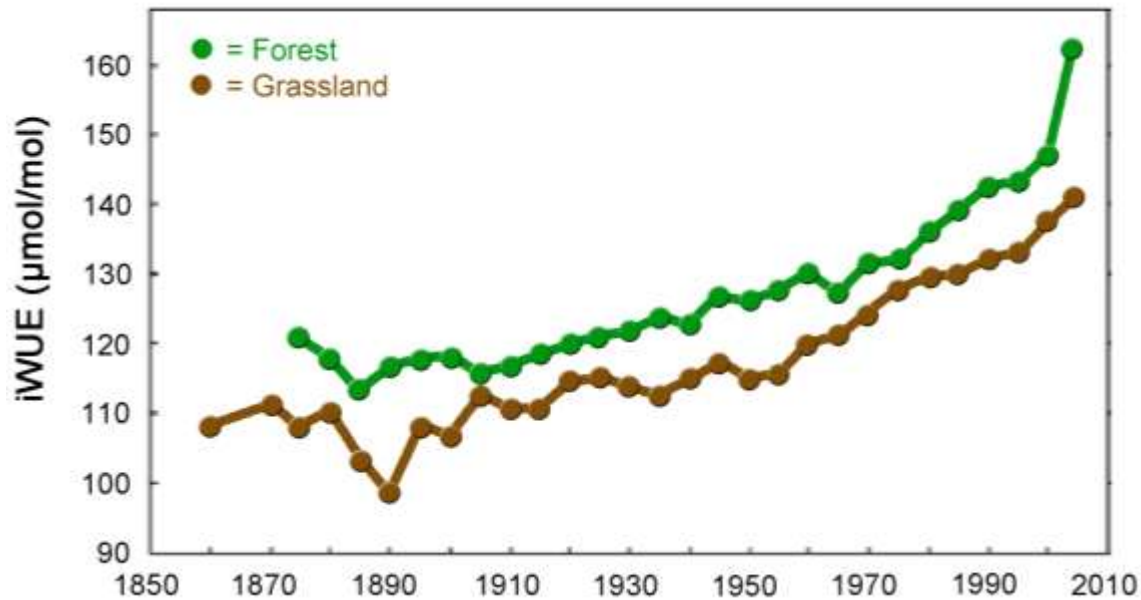


Figure 27. Intrinsic water-use efficiency (iWUE) in *Araucaria angustifolia* trees established into forest and grassland in southern Brazil (means of individuals per site in 5-years total values). Adapted from Silva *et al.* (2009).

their growth-retarding effects “compensated by increases in atmospheric CO₂ and changes [i.e., *increases*] in iWUE.”

Also working along this line of examination was Phillips *et al.* (2009), who set out to investigate what *negative* effect a severe drought might have on South America’s surprisingly-spry-for-its-age tropical mega-forest, especially a drought of the type that the world’s climate alarmists predict will occur if anthropogenic CO₂ emissions are not significantly abated. More specifically, what the international team of scientists wanted to know was whether such a decline in the availability of water might wipe out the super ecosystem’s biomass gains of prior decades, thereby fulfilling one of the climate alarmists’ worst-case catastrophic scenarios.

Focusing their attention on the Amazonian drought of 2005, which they describe as “one of the most intense droughts of the

past 100 years,” as well as “a possible analog of future events,” the 66 researchers (who had monitored a host of forest plots across the Amazon basin over the prior quarter-century) utilized tree diameter, wood density, and allometric models to compute the basin’s woody biomass at each time of measurement, both before and after the drought, deriving the results that are plotted in the Figure 28 below.

As may readily be seen from these real-world measurement-based results, the great Amazonian drought of 2005 resulted in only a slight hiatus in the strong upward trend of tree biomass accumulation that was exhibited over the prior two decades, which had occurred, as Phillips *et al.* note, through a multi-decadal period spanning both wet *and dry* episodes, the latter of which are not even detectable in their wood biomass data. Hence, it would appear that although *extremely* severe drought conditions can indeed bring a halt

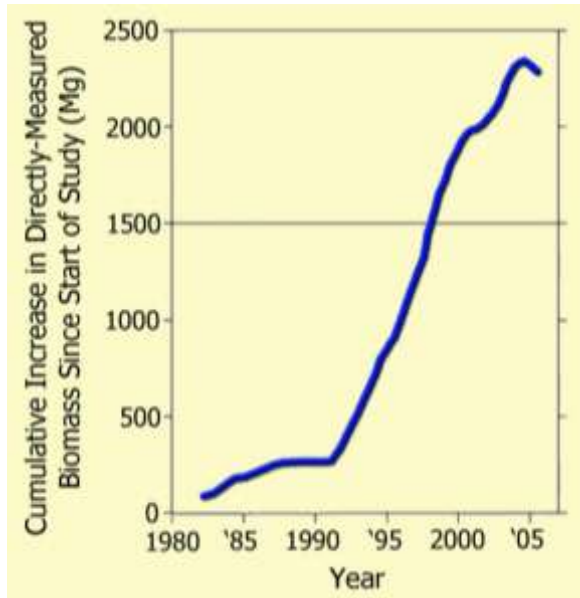


Figure 28. The post-1980 cumulative biomass increase of Amazon trees ≥ 10 cm in diameter as a function of the mid-date of each forest-plot census interval, portrayed as a 50-interval moving mean. Adapted from Phillips et al. (2009).

to biomass accumulation in old growth tropical forests -- and sometimes even lead to minor *reductions* in biomass due to selective tree mortality -- the vast majority of the aged trees are able to regain their photosynthetic prowess and add to their prior store of biomass once the moisture stress subsides, thanks in large measure to the enhanced *growth* (Lin et al., 1998) and *water use efficiency* (Hietz et al., 2005) that are experienced by nearly all woody plants as the air's CO₂ content rises.

Additional support for this attribution is provided by the work of Lloyd and Farquhar (2008), who concluded that "the magnitude and pattern of increases in forest dynamics across Amazonia observed over the last few decades are consistent with a CO₂-induced stimulation of tree growth," while still more support for the premise comes from the work of Phillips et al. (2008), who concluded

that the simplest explanation for the phenomenon is that "improved resource availability has increased net primary productivity, in turn increasing growth rates," and who further note that "the only change for which there is unambiguous evidence that the driver has widely changed *and* that such a change should accelerate forest growth is the increase in atmospheric CO₂," because of "the undisputed long-term increase in [its] concentration, the key role of CO₂ in photosynthesis, and the demonstrated effects of CO₂ fertilization on plant growth rates."

In light of the voluminous and undeniable real-world observations reported in the studies described above, it must be acknowledged that where tropical forests have not been decimated by the direct destructive actions of man, such as the felling and burning of trees, forest productivity has been growing ever greater with the passing of time, rising hand-in-hand with the increasing CO₂ content of the air; and it has been doing so in spite of all concomitant changes in atmospheric, soil, and water chemistry, as well as "dreaded" 20th-century global warming. Real-world evidence also suggests that the anthropogenic-induced increase in the air's CO₂ content is primarily responsible for this beneficent state of affairs, which further suggests that *if humanity will but cease its direct physical assaults upon Earth's tropical forests*, there is nothing to fear about their future well-being but ill-founded fear itself.

THE FUTURE

In spite of the overwhelming amount of evidence presented in the preceding sections of this report, demonstrating that

rising atmospheric CO₂ concentrations and warmer temperatures have enhanced the productivity of the biosphere, concerns have been expressed that these trends will gradually decline -- and eventually *reverse* -- if temperatures rise toward the upper limits projected in future model-based scenarios of global warming.

In all likelihood, however, the greening of the planet will *continue* in the years and decades to come, even if the largest temperature increases predicted by the models happen to occur. This is because the *optimum temperature for plant growth and development* typically *rises* with increasing levels of atmospheric CO₂; and this response, coupled with expected increases in plant photosynthetic rates from the rise in the air's CO₂ concentration, has been shown to be more than enough to

totally compensate for any temperature-induced plant stress caused by the worst-case scenario of climate-model-predicted CO₂-induced global warming.

This phenomenon was demonstrated years ago by Jurik *et al.* (1984), who exposed bigtooth aspen leaves to atmospheric CO₂ concentrations of 325 and 1935 ppm and measured their photosynthetic rates at a number of different temperatures. Figure 29 below reproduces their results and slightly extends the two relationships defined by their data to both warmer and cooler conditions.

As can be seen in that figure, at 10°C, elevated CO₂ has essentially no effect on net photosynthesis in this particular species, as Idso and Idso (1994) have demonstrated is characteristic of plants in

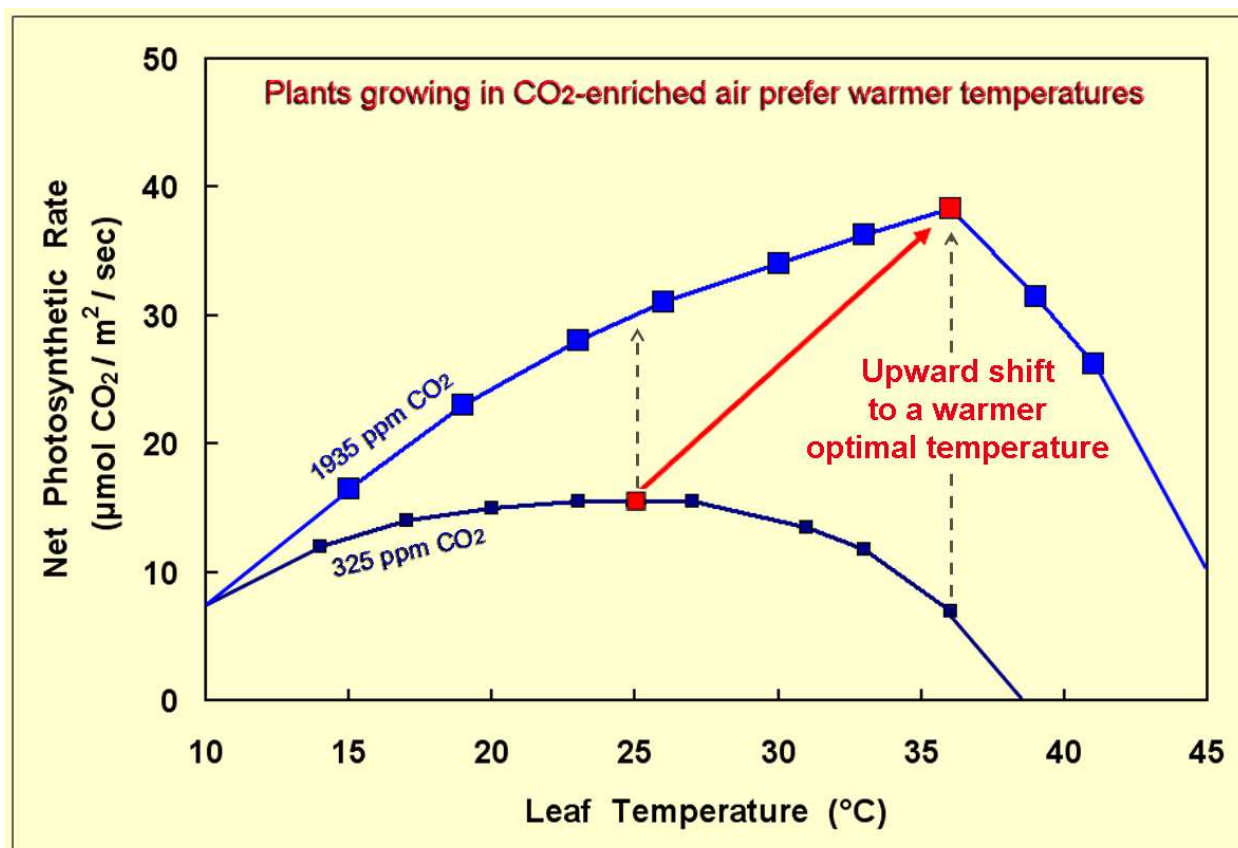


Figure 29. Net photosynthesis of big tooth aspen leaves growing under two concentrations of atmospheric carbon dioxide at various temperatures. Adapted from Jurik *et al.* (1984).

general. At 25°C, however, where the net photosynthetic rate of the leaves exposed to 325 ppm CO₂ is maximal, the extra CO₂ of this study boosts the net photosynthetic rate of the foliage by nearly 100%; and at 36°C, where the net photosynthetic rate of the leaves exposed to 1935 ppm CO₂ is maximal, the extra CO₂ boosts the net photosynthetic rate of the foliage by 450%. In addition, it is readily seen that the extra CO₂ increases the optimum temperature for net photosynthesis in this species by about 11°C: from 25°C in air of 325 ppm CO₂ to 36°C in air of 1935 ppm CO₂.

In viewing the warm-temperature *extensions* of the two relationships at the right-hand side of the figure, it can also be seen that the transition from positive to negative net photosynthesis – which denotes a change from life-sustaining to life-depleting conditions – likely occurs somewhere in the vicinity of 39°C in air of 325 ppm CO₂ but somewhere in the vicinity of 50°C in air of 1935 ppm CO₂. Thus, not only was the *optimum* temperature for the growth of bigtooth aspen greatly increased by the extra CO₂ of this experiment, so too was the temperature above which life cannot be sustained also increased, and by about the same amount, i.e., 11°C.

Other researchers have also documented this important CO₂-induced plant benefit in numerous other agricultural, grassland and woody plant species, nearly all of which studies indicate that a 300 ppm increase in the air's CO₂ content increases a plant's optimum temperature for growth and development by a mean of approximately 6°C (Bjorkman *et al.*, 1978; Berry and Bjorkman, 1980; Nilsen *et al.*, 1983; Jurik *et al.*, 1984; Seeman *et al.*, 1984; Harley *et al.*, 1986; Stuhlfauth and Fock, 1990;

McMurtrie *et al.*, 1992; McMurtrie and Wang, 1993; Idso *et al.*, 1995; Cowling and Sykes, 1999; Gutierrez *et al.*, 2009). And this response is *more* than enough to *totally compensate* for any temperature-induced plant stress caused by the worst-case scenario of climate-model-predicted CO₂-induced global warming. And *additional* research indicates that plants may be able to boost their optimum temperature for photosynthesis as the temperature warms, even in the *absence* of a concurrent increase in atmospheric CO₂.

Such can be concluded from the work of Gunderson *et al.* (2010), who investigated the “photosynthetic sensitivity to temperature and the potential for acclimation in relation to the climatic provenance of five species of deciduous trees, *Liquidambar styraciflua* [sweetgum], *Quercus rubra* [northern red oak], *Quercus falcata* [southern red oak], *Betula alleghaniensis* [yellow birch] and *Populus grandidentata* [bigtooth aspen].” Their experiment was conducted out-of-doors within open-top chambers that were maintained at three different temperature regimes – ambient, ambient plus 2, and 4°C above ambient – for a period of three years. Based on their analysis, the five scientists report that “warming treatments resulted in a shift in the temperature response curves for CO₂ assimilation, such that leaves in warmer treatments had higher temperature optima [T_{opt}],” an example of which phenomenon is depicted in the figure below for *Q. rubra* seedlings during one specific month.

As may be seen from Figure 30, the trees growing in progressively warmer environments had progressively higher T_{opt} values; and there was a tendency for the

net CO₂ assimilation rates at those higher T_{opt} values to be a bit higher as well. Gunderson *et al.* additionally found that this adjustment in photosynthetic response was typically accomplished over a period of as little as *two days*; while indicating that “others have found all or most acclimation within 2-6 days (Veres and Williams, 1984; Hill *et al.*, 1988; Battaglia *et al.*, 1996; Turnbull *et al.*, 2002; Froux *et al.*, 2004).” They also state that a similar “adjustment of thermal optima was confirmed in all species, whether temperatures varied with season or treatment, and regardless of climate in the species’ range or provenance of the plant material,” and they say that the observed “responses to the temperature manipulation were not different from the seasonal acclimation observed in mature indigenous trees,” which they also investigated locally.

In light of all these observations, it would indeed appear that Earth’s plants will be able to successfully adjust their physiology to accommodate a warming of the *magnitude* and *rate-of-rise* that is typically predicted by climate alarmists to accompany the projected future increase in the air’s CO₂ content. In fact, if the planet’s flora can adjust their physiology to not only *survive* a modest instantaneous warming of 2-4°C, but to actually *benefit* from it, as has been demonstrated to be the case in several trees examined by Gunderson *et al.*, there is little reason not to believe that they would respond to a similar warming projected to develop over a *century* or more. And when one factors in the *aerial fertilization effect* of the rising atmospheric CO₂ concentration, plus its *transpiration-reducing effect* that boosts plant water use efficiency, as well as CO₂’s ability to *also*

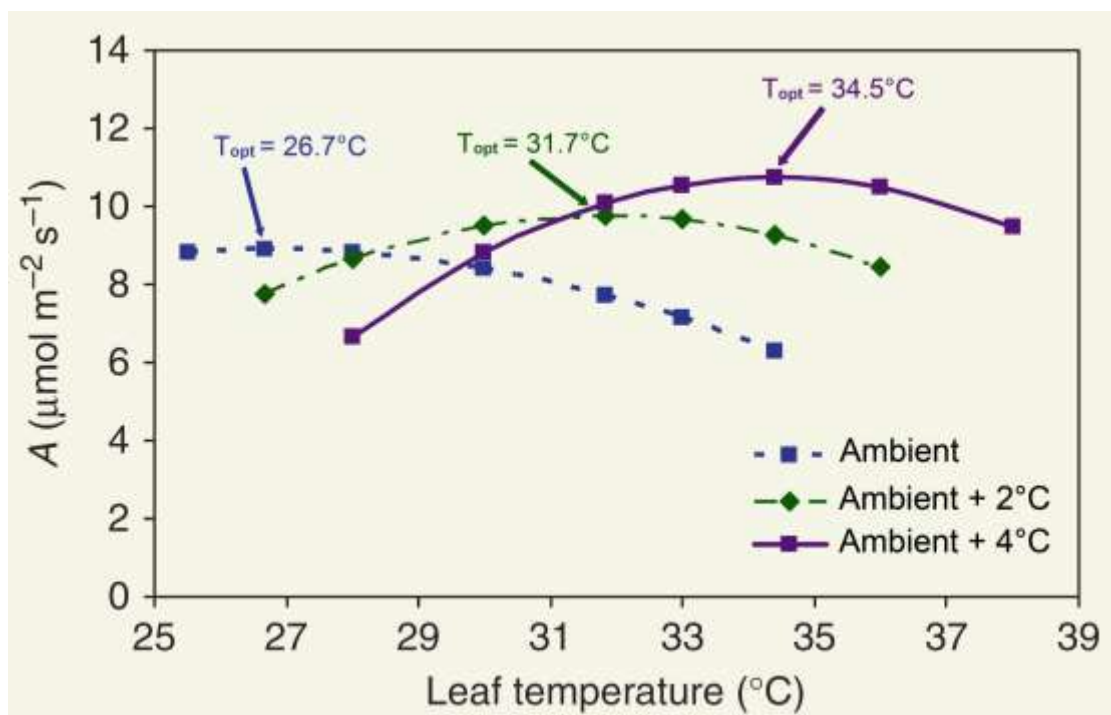


Figure 30. Net CO₂ assimilation rate vs. leaf temperature in *Quercus rubra* seedlings during June of 2003 in the ambient (A) and elevated (A+2°C and A+4°C) temperature treatments. Adapted from Gunderson *et al.* (2010).

raise the T_{opt} values of most plants, the world's vegetation is seen to possess the *ideal mix of ingredients* to reap a *tremendous* benefit. As such, we expect that the recent greening of the planet

observed by so many scientists will continue in the years and decades to come, notwithstanding alarmist concerns to the contrary.

FINDINGS AND CONCLUSIONS

In the *Introduction* of this report we outlined two conflicting views that are held with respect to the potential effects of rising atmospheric CO₂ concentration and warmer temperatures on the productivity of Earth's biosphere. One view, held by climate alarmists and based primarily on computer model projections, posits that increases in CO₂ and global temperature will have devastating effects on terrestrial vegetation, potentially causing the extinction of numerous species of plants. The opposing view, offered by climate skeptics, maintains that the alarmist projections are *wholly incorrect* and that rising temperatures and atmospheric CO₂ concentrations will lead to significant *increases* in the growth and productivity of Earth's plants *everywhere they are found*.

In evaluating the relative correctness of these two contradictory viewpoints, we have presented a metaanalysis of the peer-reviewed scientific literature to see how the planet's vegetation has responded to the recent century-long increases in both atmospheric CO₂ and temperature, which increases should be providing some indication as to what the future holds, *right now!* And based on that analysis, we conclude the following:

1. The vigor of Earth's terrestrial biosphere has been increasing with time, revealing a great *greening of the planet* that extends throughout the entire globe.
 - Satellite-based analyses of net terrestrial primary productivity (NPP) reveal an increase of around 6-13% since the 1980s.
2. There is no empirical evidence to support the model-based claim that future carbon uptake will diminish on a global scale due to rising temperatures.
 - Earth's land surfaces were a net *source* of CO₂-carbon to the atmosphere until about 1940. From 1940 onward, however, the terrestrial biosphere has become, in the mean, an *increasingly greater sink* for CO₂-carbon.
 - Over the past 50 years, global carbon uptake has *doubled* from 2.4 ± 0.8 billion tons in 1960 to 5.0 ± 0.9 billion tons in 2010.

3. The observed greening of the Earth has occurred *in spite of* all the many real and imagined assaults on Earth's vegetation over this time period, including fires, disease, outbreaks of pests, deforestation, and climatic changes, primarily in temperature and precipitation.
4. The atmosphere's rising CO₂ content – which alarmists consider to be the chief culprit behind all of their concerns about the future of the biosphere (via the indirect threats they claim it poses as a result of CO₂-induced climate change) – is most likely the primary *cause* of the observed greening trends.
5. Looking to the future, Earth's plants should be able to successfully adjust their physiology to accommodate a warming of the *magnitude* and *rate-of-rise* that is typically predicted by climate alarmists to accompany the projected future increase in the air's CO₂ content. Factoring in the plant productivity gains expected to occur as a result of the *aerial fertilization effect* of the rising atmospheric CO₂ concentration, plus its *transpiration-reducing effect* that boosts plant water use efficiency, the world's vegetation is seen to possess the *ideal mix of ingredients* to reap a *tremendous* benefit.

Considering all of the above, the recent “greening of the Earth” observed by a host of scientists will likely continue in the years and decades to come.



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ABOUT THE AUTHOR



CRAIG D. IDSO is the founder and former President of the Center for the Study of Carbon Dioxide and Global Change and currently serves as Chairman of the Center's board of directors. Dr. Idso received his B.S. in Geography from Arizona State University, his M.S. in Agronomy from the University of Nebraska - Lincoln, and his Ph.D. in Geography from Arizona State University, where he studied as one of a small group of University Graduate Scholars.

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Dr. Idso is a member of the American Association for the Advancement of Science, American Geophysical Union, American Meteorological Society, Association of American Geographers, Ecological Society of America, and The Honor Society of Phi Kappa Phi. He also serves as co-editor of the Assessment Reports for the Nongovernmental International Panel on Climate Change (NIPCC) and he is the former Director of Environmental Science at Peabody Energy in St. Louis, Missouri.

ABOUT THE CENTER

The *Center for the Study of Carbon Dioxide and Global Change* was founded as a non-profit organization in 1998 to provide regular reviews and commentary on new developments in the world-wide scientific quest to determine the climatic and biological consequences of the ongoing rise in the air's CO₂ content. It achieves this objective primarily through the weekly online publication of 'CO₂ Science,' which is freely available on the Internet at www.co2science.org, and contains reviews of recently published peer-reviewed scientific journal articles, original research, and other educational materials germane to the debate over carbon dioxide and global change.

The Center's main focus is to separate reality from rhetoric in the emotionally-charged debate that swirls around the subject of carbon dioxide and global change and to avoid the stigma of biased advocacy by utilizing sound science. It has a stated commitment to empirical evidence and its position on global warming may be summarized as follows. There is little doubt the carbon dioxide concentration of the atmosphere has risen significantly over the past 100 to 150 years from humanity's use of fossil fuels and that the Earth has warmed slightly over the same period; but there is no compelling reason to believe that the rise in temperature was caused primarily by the rise in carbon dioxide. Moreover, real world data provide no compelling evidence to suggest that the ongoing rise in the carbon dioxide concentration of the atmosphere will lead to significant global warming or changes in Earth's climate.

In the 15-year period since its creation, the Center has published over 4300 timely and objective reviews of scientific research reports on both the biological and climatological effects of atmospheric CO₂ enrichment. Accompanying each review is the full peer-reviewed scientific journal reference from which the review was derived, so that patrons may independently obtain the original journal articles and verify the information for themselves.

