
Human Health Effects

9. Human Health Effects

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The idea that CO₂-induced global warming is harmful to people's health has become entrenched in popular culture, with the reports of the Intergovernmental Panel on Climate Change (IPCC) being the source of much of this concern. In the Working Group II contribution to the Fourth Assessment Report, the authors claim to have "very high confidence" that "climate change currently contributes to the global burden of disease and premature deaths" (IPCC, 2007-II, p. 393). They also claim climate change will "increase malnutrition and consequent disorders ... increase the number of people suffering from death, disease and injury from heatwaves, floods, storms, fires and droughts ... continue to change the range of some infectious disease vectors ... increase the burden of diarrhoeal diseases ... increase cardio-respiratory morbidity and mortality associated with ground-level ozone ... [and] increase the number of people at risk of dengue." The IPCC admits that warming weather would "bring some benefits to health, including fewer deaths from cold," but says those benefits "will be outweighed by the negative effects of rising temperatures worldwide, especially in developing countries" (Ibid.).

Some of these claims have been shown in previous chapters to be counterfactual. For example, research cited in Chapter 6 showed the global warming that occurred in the twentieth century did not cause more "heatwaves, floods, storms, fires and droughts," and that a warmer world is likely to see fewer episodes of these extreme weather events than a cooler world. We will not repeat that analysis in this chapter.

This chapter reviews data on the relationships between temperature and CO₂ and diseases, heat-related mortality, nutrition, and human longevity. We find in each case that global warming is likely to improve human health. Section 9.4 explains how rising CO₂ concentrations in the air will play a positive role in solving the conflict between the need to raise food for a growing population and the need to protect natural ecosystems. Section 9.5 describes the negative role played by increased use of biofuels, which the IPCC advocates in the Working Group III contribution to the Fourth Assessment Report (IPCC, 2007-III), in this same conflict.

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9.1. Diseases

Which is more deadly: heat or cold? Rising temperatures or falling temperatures? The IPCC claims warming is the primary danger to be avoided at all costs. Real-world data, however, indicate the opposite.

Systematic research on the relationship between heat and human health dates back to the 1930s (Gover, 1938; Kutschenreuter, 1950; Kutschenreuter, 1960; Oechsli and Buechley, 1970). Early studies by Bull (1973) and Bull and Morton (1975a,b) in England and Wales, for example, demonstrated that normal changes in temperature typically are inversely associated with death rates, especially in older subjects. That is, when temperatures rise, death rates fall; when temperatures fall, death rates rise. Bull and Morton (1978) concluded “there is a close association between temperature and death rates from most diseases at all temperatures,” and it is “very likely that changes in external temperature cause changes in death rates.”

Since this early research was published, a large number of studies have confirmed the original findings. Contrary to the IPCC’s highly selective reading of the literature, the overwhelming majority of researchers in the field have found that warmer weather reduces rather than increases the spread and severity of many diseases and weather-related mortality rates. We review this literature in the following order: cardiovascular diseases, respiratory diseases, malaria, tick-borne diseases, and finally cold- and heat-related mortality from all diseases.

Additional information on this topic, including reviews on the health effects of CO₂ not discussed here, can be found at http://www.co2_science.org/subject/h/subject_h.php under the heading Health Effects.

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9.1.1. Cardiovascular Diseases

A good place to begin a review of temperature-related mortality is a cold location ... like Siberia. Feigin *et al.* (2000) examined the relationship between stroke occurrence and weather parameters in the Russian city of Novosibirsk, which has one of the highest incidence rates of stroke in the world. Analyzing the health records of 2,208 patients with a sex and age distribution similar to that of the whole of Russia over the period 1982-93, they found a statistically significant association between stroke occurrence and low ambient temperature. For ischemic stroke (IS), which accounted for 87 percent of all strokes recorded, they report that the risk of IS occurrence on days with low ambient temperature is 32 percent higher than on days with high ambient temperature. They recommend implementing “preventive measures ... such as avoiding low temperature.”

Hong *et al.* (2003) studied weather-related death rates in Incheon, Korea over the period January 1998 to December 2000, reporting that “decreased ambient temperature was associated with risk of acute ischemic stroke,” with the strongest effect being seen on the day after exposure to cold weather. They found that “even a moderate decrease in temperature can increase the risk of ischemic stroke.” In addition, “risk estimates associated with decreased temperature were greater in winter than in the summer,” suggesting that “low temperatures as well as temperature changes are associated with the onset of ischemic stroke.”

Nafstad *et al.* (2001) studied weather-related death rates in Oslo, Norway. Thanks to a Norwegian

law requiring all deaths to be examined by a physician who diagnoses cause and reports it on the death certificate, they were able to examine the effects of temperature on mortality due to all forms of cardiovascular disease for citizens of the country's capital over the period 1990 to 1995. They found that the average daily number of cardiovascular-related deaths was 15 percent higher in the winter months (October-March) than in the summer months (April-September), leading them to conclude that "a milder climate would lead to a substantial reduction in average daily number of deaths."

Hajat and Haines (2002) set out to determine if cardiovascular-related doctor visits by the elderly bore a similar relationship to cold temperatures. Based on data obtained for registered patients aged 65 and older from several London, England practices between January 1992 and September 1995, they found the mean number of general practitioner consultations was higher in the cool-season months (October-March) than in the warm-season months (April-September) for all cardiovascular diseases.

Of course, one might say, such findings are only to be expected in cold climates. What about warm climates, where summer maximum temperatures are often extreme, but summer minimum temperatures are typically mild? Research conducted by Green *et al.* (1994) in Israel revealed that between 1976 and 1985, mortality from cardiovascular disease was 50 percent higher in mid-winter than in mid-summer, both in men and women and in different age groups, in spite of the fact that summer temperatures in the Negev, where much of the work was conducted, often exceed 30°C, while winter temperatures typically do not drop below 10°C. These findings were substantiated by other Israeli studies reviewed by Behar (2000), who states that "most of the recent papers on this topic have concluded that a peak of sudden cardiac death, acute myocardial infarction and other cardiovascular conditions is usually observed in low temperature weather during winter."

Evidence of a seasonal variation in cardiac-related mortality has been found in the mild climate of southern California in the United States. In a study of all 222,265 death certificates issued by Los Angeles County for deaths caused by coronary artery disease from 1985 through 1996, Kloner *et al.* (1999) found that death rates in December and January were 33 percent higher than those observed in the period June through September.

Likewise, based on a study of the Hunter region of New South Wales, Australia that covered the

period 1 July 1985 to 30 June 1990, Enquselassie *et al.* (1993) determined that "fatal coronary events and non-fatal definite myocardial infarction were 20-40 percent more common in winter and spring than at other times of year." Regarding daily temperature effects, they found that "rate ratios for deaths were significantly higher for low temperatures," noting that "on cold days coronary deaths were up to 40 percent more likely to occur than at moderate temperatures."

In a study of "hot" and "cold" cities in the United States—where Atlanta, Georgia; Birmingham, Alabama; and Houston, Texas comprised the "hot" group, and Canton, Ohio; Chicago, Illinois; Colorado Springs, Colorado; Detroit, Michigan; Minneapolis-St. Paul, Minnesota; New Haven, Connecticut; Pittsburgh, Pennsylvania; and Seattle and Spokane, Washington comprised the "cold" group—Braga *et al.* (2002) determined the acute effects and lagged influence of temperature on cardiovascular-related deaths. They found that in the hot cities, neither hot nor cold temperatures had much impact on mortality related to cardiovascular disease (CVD). In the cold cities, on the other hand, they report that both high and low temperatures were associated with increased CVD deaths, with the effect of cold temperatures persisting for days but the effect of high temperatures restricted to the day of the death or the day before. Of particular interest was the finding that for all CVD deaths the hot-day effect was *five times smaller* than the cold-day effect. In addition, the hot-day effect included some "harvesting," where the authors observed a deficit of deaths a few days later, which they did not observe for the cold-day effect.

Gouveia *et al.* (2003), in a study conducted in Sao Paulo, Brazil using data from 1991-1994, found that the number of cardiovascular-related deaths in adults (15-64 years of age) increased by 2.6 percent for each 1°C decrease in temperature below 20°C, while there was no evidence for any heat-induced deaths due to temperatures rising above 20°C. In the elderly (65 years of age and above), however, a 1°C warming above 20°C led to a 2 percent increase in deaths; but a 1°C cooling below 20°C led to a 6.3 percent increase in deaths, or more than three times as many cardiovascular-related deaths due to cooling than to warming in the elderly.

Similar results have been found in Australia (Enquselassie *et al.*, 1993), Brazil (Sharovsky *et al.*, 2004), England (McGregor, 2005; Carder *et al.*, 2005; McGregor *et al.*, 2004; and Kovats *et al.*, 2004), Greece (Bartzokas *et al.*, 2004), Japan (Nakaji *et al.*, 2004), the United States (Cagle and Hubbard, 2005),

and parts of Africa, Asia, Europe, Latin America and the Caribbean (Chang *et al.*, 2004).

These studies demonstrate that global warming *reduces* the incidence of cardiovascular disease related to low temperatures and wintry weather by a much greater degree than it increases the incidence associated with high temperatures and summer heat waves.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/healtheffectscardio.php>.

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9.1.2. Respiratory Diseases

As was true of cardiovascular-related mortality, deaths due to respiratory diseases are more likely to be associated with cold conditions in cold countries. In Oslo, where Nafstad *et al.* (2001) found winter deaths due to cardiovascular problems to be 15 percent more numerous than similar summer deaths, they also determined that deaths due to respiratory diseases were fully 47 percent more numerous in winter than in summer. Likewise, the London study of Hajat and Haines (2002) revealed that the number of doctor visits by the elderly was higher in cool-season than warm-season months for all respiratory diseases. At mean temperatures below 5°C, in fact, the relationship between respiratory disease consultations and temperature was linear, and stronger at a time lag of six to 15 days, such that a 1°C decrease in mean temperature below 5°C was associated with a 10.5 percent increase in all respiratory disease consultations.

Gouveia *et al.* (2003) found that death rates in Sao Paulo, Brazil due to a 1°C cooling were twice as great as death rates due to a 1°C warming in adults, and 2.8 times greater in the elderly. Donaldson (2006) studied the effect of annual mean daily air temperature on the length of the yearly respiratory syncytial virus (RSV) season in England and Wales for 1981-2004 and found “emergency department admissions (for 1990-2004) ended 3.1 and 2.5 weeks earlier, respectively, per 1°C increase in annual central England temperature (P = 0.002 and 0.043, respectively).” He concludes that “the RSV season has become shorter” and “these findings imply a health benefit of global warming in England and Wales associated with a reduction in the duration of the RSV season and its consequent impact on the health service.”

The study of hot and cold cities in the United States by Braga *et al.* (2002) found that increased temperature variability is the most significant aspect of climate change with respect to respiratory-related deaths in the U.S. Why is this finding important? Because Robeson (2002) has clearly demonstrated, from a 50-year study of daily temperatures at more than 1,000 U.S. weather stations, that temperature variability *declines* with warming, and at a very substantial rate. The reduced temperature variability in a warmer world would lead to reductions in temperature-related deaths at both the high and low ends of the daily temperature spectrum at all times of the year.

These studies show that a warming world would improve people’s health by reducing deaths related to respiratory disease.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/healtheffectspresp.php>.

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9.1.3. Malaria

Rogers and Randolph (2000) note that “predictions of global climate change have stimulated forecasts that vector-borne diseases will spread into regions that are at present too cool for their persistence.” Such predictions are a standard part of the narrative of those who believe global warming would have catastrophic effects. However, even the IPCC states “there is still much uncertainty about the potential impact of climate change on malaria in local and global scales” and “further research is warranted” (IPCC, 2007-II, p. 404).

According to Reiter (2000), claims that malaria resurgence is the product of CO₂-induced global warming ignore the disease’s history and an extensive literature showing factors other than climate are

known to play more important roles in the disease's spread. For example, historical analysis reveals that malaria was an important cause of illness and death in England during the Little Ice Age. Its transmission began to decline only in the nineteenth century, during a warming phase when, according to Reiter, "temperatures were already much higher than in the Little Ice Age."

Why was malaria prevalent in Europe during some of the coldest centuries of the past millennium? And why have we only recently witnessed malaria's widespread decline at a time when temperatures are warming? Other factors are at work, such as the quality of public health services, irrigation and agricultural activities, land use practices, civil strife, natural disasters, ecological change, population change, use of insecticides, and the movement of people (Reiter, 2000; Reiter, 2001; Hay *et al.*, 2002). Models employed by the IPCC predict widespread future increases in malaria because nearly all of the analyses they cite used only one, or at most two, climate variables to make predictions of the future distribution of the disease over the earth, and they generally do not include any non-climatic factors.

In one modeling study that used more than just one or two variables, Rogers and Randolph (2000) employed five climate variables and obtained very different results. Briefly, they used the present-day distribution of malaria to determine the specific climatic constraints that best define that distribution, after which the multivariate relationship they derived from this exercise was applied to future climate scenarios derived from state-of-the-art climate models, in order to map potential future geographical distributions of the disease. They found only a 0.84 percent increase in potential malaria exposure under the "medium-high" scenario of global warming and a 0.92 percent decrease under the "high" scenario. They state that their quantitative model "contradicts prevailing forecasts of global malaria expansion" and "highlights the use [we would say superiority] of multivariate rather than univariate constraints in such applications." This study undercuts the claim that any future warming of the globe will allow malaria to spread into currently malaria-free regions.

Hay *et al.* (2002) investigated long-term trends in meteorological data at four East African highland sites that experienced significant increases in malaria cases over the past couple decades, reporting that "temperature, rainfall, vapour pressure and the number of months suitable for *P. falciparum*

transmission have not changed significantly during the past century or during the period of reported malaria resurgence." Therefore, these factors could not be responsible for the observed increases in malaria cases. Likewise, Shanks *et al.* (2000) examined trends in temperature, precipitation, and malaria rates in western Kenya over the period 1965-1997, finding no linkages among the variables.

Also working in Africa, Small *et al.* (2003) examined trends in a climate-driven model of malaria transmission between 1911 and 1995, using a spatially and temporally extensive gridded climate data set to identify locations where the malaria transmission climate suitability index had changed significantly over this time interval. Then, after determining areas of change, they more closely examined the underlying climate forcing of malaria transmission suitability for those localities. This protocol revealed that malaria transmission suitability did increase because of climate change in specific locations of limited extent, but in Southern Mozambique, which was the only region for which climatic suitability consistently increased, the cause of the increase was increased precipitation, not temperature.

In fact, Small *et al.* say that "climate warming, expressed as a systematic temperature increase over the 85-year period, does *not* appear to be responsible for an increase in malaria suitability over any region in Africa." They concluded that "research on the links between climate change and the recent resurgence of malaria across Africa would be best served through refinements in maps and models of precipitation patterns and through closer examination of the role of nonclimatic influences." The great significance of this has recently been demonstrated by Reiter *et al.* (2003) for dengue fever, another important mosquito-borne disease.

Examining the reemergence of malaria in the East African highlands, Zhou *et al.* (2004) conducted a nonlinear mixed-regression model study that focused on the numbers of monthly malaria outpatients of the past 10-20 years in seven East African highland sites and their relationships to the numbers of malaria outpatients during the previous time period, seasonality and climate variability. They say that "for all seven study sites, we found highly significant nonlinear, synergistic effects of the interaction between rainfall and temperature on malaria incidence, indicating that the use of either temperature or rainfall alone is not sensitive enough

for the detection of anomalies that are associated with malaria epidemics.” This has also been found by Githeko and Ndegwa (2001), Shanks *et al.* (2002) and Hay *et al.* (2002). Climate variability—not just temperature or warming—contributed less than 20 percent of the temporal variance in the number of malaria outpatients, and at only two of the seven sites studied.

In light of their findings, Zhou *et al.* concluded that “malaria dynamics are largely driven by autoregression and/or seasonality in these sites” and that “the observed large among-site variation in the sensitivity to climate fluctuations may be governed by complex interactions between climate and biological and social factors.” This includes “land use, topography, *P. falciparum* genotypes, malaria vector species composition, availability of vector control and healthcare programs, drug resistance, and other socioeconomic factors.” Among these are “failure to seek treatment or delayed treatment of malaria patients, and HIV infections in the human population,” which they say have “become increasingly prevalent.”

Kuhn *et al.* (2003) say “there has been much recent speculation that global warming may allow the reestablishment of malaria transmission in previously endemic areas such as Europe and the United States.” To investigate the robustness of this hypothesis, they analyzed the determinants of temporal trends in malaria deaths within England and Wales from 1840-1910. Their analysis found that “a 1°C increase or decrease was responsible for an increase in malaria deaths of 8.3 percent or a decrease of 6.5 percent, respectively,” which explains “the malaria epidemics in the ‘unusually hot summers’ of 1848 and 1859.” Nevertheless, the long-term near-linear temporal decline in malaria deaths over the period of study, in the words of the researchers, “was probably driven by nonclimatic factors.” Among these they list increasing livestock populations (which tend to divert mosquito biting from humans), decreasing acreages of marsh wetlands (where mosquitoes breed), as well as “improved housing, better access to health care and medication, and improved nutrition, sanitation, and hygiene.” They additionally note that the number of secondary cases arising from each primary imported case “is currently minuscule,” as demonstrated by the absence of any secondary malaria cases in the UK since 1953.

Although simplistic model simulations may suggest that the increase in temperature predicted for Britain by 2050 is likely to cause an 8-14 percent

increase in the potential for malaria transmission, Kuhn *et al.* say “the projected increase in proportional risk is clearly insufficient to lead to the reestablishment of endemicity.” Expanding on this statement, they note that “the national health system ensures that imported malaria infections are detected and effectively treated and that gametocytes are cleared from the blood in less than a week.” For Britain, they conclude that “a 15 percent rise in risk might have been important in the 19th century, but such a rise is now highly unlikely to lead to the reestablishment of indigenous malaria,” since “socioeconomic and agricultural changes” have greatly altered the cause-and-effect relationships of the past.

Zell (2004) states that many people “assume a correlation between increasing disease incidence and global warming.” However, “the factors responsible for the emergence/reemergence of vector-borne diseases are complex and mutually influence each other.” He cites as an example the fact that “the incidence and spread of parasites and arboviruses are affected by insecticide and drug resistance, deforestation, irrigation systems and dams, changes in public health policy (decreased resources of surveillance, prevention, and vector control), demographic changes (population growth, migration, urbanization), and societal changes (inadequate housing conditions, water deterioration, sewage, waste management).” Therefore, as he continues, “it may be over-simplistic to attribute emergent/re-emergent diseases to climate change and sketch the menace of devastating epidemics in a warmer world.” Indeed, Zell states that “variations in public health practices and lifestyle can easily outweigh changes in disease biology,” especially those that might be caused by global warming.

Rogers and Randolph (2006) ask if climate change could be responsible for recent upsurges of malaria in Africa. They demonstrate that “evidence for increasing malaria in many parts of Africa is overwhelming, but the more likely causes for most of these changes to date include land-cover and land-use changes and, most importantly, drug resistance rather than any effect of climate,” noting that “the recrudescence of malaria in the tea estates near Kericho, Kenya, in East Africa, where temperature has not changed significantly, shows all the signs of a disease that has escaped drug control following the evolution of chloroquine resistance by the malarial parasite.” They then go on to explain that “malaria waxes and wanes to the beat of two rhythms: an

annual one dominated by local, seasonal weather conditions and a *ca.* 3-yearly one dominated by herd immunity,” noting that “effective drugs suppress both cycles before they can be expressed,” but that “this produces a population which is mainly or entirely dependent on drug effectiveness, and which suffers the consequence of eventual drug failure, during which the rhythms reestablish themselves, as they appear to have done in Kericho.”

Childs *et al.* (2006) present a detailed analysis of malaria incidence in northern Thailand from January 1977 through January 2002 in the country’s 13 northern provinces. Over this time period, when the IPCC claims the world warmed at a rate and to a level that were unprecedented over the prior two millennia, Childs *et al.* report a decline in total malaria incidence (from a mean monthly incidence of 41.5 to 6.72 cases per hundred thousand people. Noting “there has been a steady reduction through time of total malaria incidence in northern Thailand, with an average decline of 6.45 percent per year,” they say this result “reflects changing agronomic practices and patterns of immigration, as well as the success of interventions such as vector control programs, improved availability of treatment and changing drug policies.”

Finally, some researchers have studied the effect of rising CO₂ concentrations on the mosquitos that transmit malaria. Tuchman *et al.* (2003) took leaf litter from *Populus tremuloides* (Michaux) trees that had been grown out-of-doors in open-bottom root boxes located within open-top above-ground chambers maintained at atmospheric CO₂ concentrations of either 360 or 720 ppm for an entire growing season, incubated the leaf litter for 14 days in a nearby stream, and fed the incubated litter to four species of detritivorous mosquito larvae to assess its effect on their development rates and survivorship. This work revealed that larval mortality was 2.2 times higher for *Aedes albopictus* (Skuse) mosquitos that were fed leaf litter that had been produced in the high-CO₂ chambers than it was for those fed litter that had been produced in the ambient-air chambers.

In addition, Tuchman *et al.* found that larval development rates of *Aedes triseriatus* (Say), *Aedes aegypti* (L.), and *Armigeres subalbatus* (Coquillett) were slowed by 78 percent, 25 percent, and 27 percent, respectively, when fed litter produced in the high-CO₂ as opposed to the ambient-CO₂ chambers, so that mosquitos of these species spent 20, 11, and nine days longer in their respective larval stages when feeding on litter produced in the CO₂-enriched as

compared to the ambient-CO₂ chambers. As for the reason behind these observations, the researchers suggest that “increases in lignin coupled with decreases in leaf nitrogen induced by elevated CO₂ and subsequent lower bacterial productivity [on the leaf litter in the water] were probably responsible for [the] decreases in survivorship and/or development rate of the four species of mosquitos.”

What is the significance of these findings? In the words of Tuchman *et al.*, “the indirect impacts of an elevated CO₂ atmosphere on mosquito larval survivorship and development time could potentially be great,” because longer larval development times could result in fewer cohorts of mosquitos surviving to adulthood; and with fewer mosquitos around, there should be lower levels of mosquito-borne diseases.

In conclusion, research that takes into account more than one or two variables typically shows little or no relationship between the incidence of malaria and temperature. Many factors are more important than temperature, and those that are subject to human control are being used to steadily reduce the incidence of deaths from this disease. In the words of Dye and Reiter (2000), “given adequate funding, technology, and, above all, commitment, the campaign to ‘Roll Back Malaria,’ spearheaded by the World Health Organization, will have halved deaths related to [malaria] by 2010” - independent of whatever tack earth’s climate might take in the interim.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/m/malaria.php>

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9.1.4. Tick-Borne Diseases

The IPCC claims that one of the likely consequences of the increase in temperature would be expanded geographic ranges of tick-borne diseases, although once again this prediction is highly qualified. "Climate change alone is unlikely to explain recent increases in the incidences of tick-borne disease in Europe or North America," the IPCC admits, and "other explanations cannot be ruled out" (IPCC 2007-II, p. 403).

Randolph and Rogers (2000) reported that tick-borne encephalitis (TBE) "is the most significant vector-borne disease in Europe and Eurasia," having "a case morbidity rate of 10-30 percent and a case mortality rate of typically 1-2 percent but as high as 24 percent in the Far East." The disease is caused by a flavivirus (TBEV), which is maintained in natural rodent-tick cycles; humans may be infected with it if bitten by an infected tick or by drinking untreated milk from infected sheep or goats.

Early writings on the relationship of TBE to global warming predicted it would expand its range and become more of a threat to humans in a warmer world. However, Randolph and Rogers indicate that "like many vector-borne pathogen cycles that depend on the interaction of so many biotic agents with each other and with their abiotic environment, enzootic cycles of TBEV have an inherent fragility," so that "their continuing survival or expansion cannot be predicted from simple univariate correlations." The two researchers decided to explore the subject in greater detail than had ever been done before.

Confining their analysis to Europe, Randolph and Rogers first correlated the present-day distribution of TBEV to the present-day distributions of five climatic variables: monthly mean, maximum, and minimum temperatures, rainfall and saturation vapor pressure, "to provide a multivariate description of present-day areas of disease risk." Then, they applied this understanding to outputs of a general circulation model of the atmosphere that predicted how these five climatic variables may change in the future. The results of these operations indicated that the

distribution of TBEV might expand both north and west of Stockholm, Sweden in a warming world. For most other parts of Europe, however, the two researchers say “fears for increased extent of risk from TBEV caused by global climate change appear to be unfounded.” They found that “the precise conditions required for enzootic cycles of TBEV are predicted to be disrupted” in response to global warming, and that the new climatic state “appears to be lethal for TBEV.” This finding, in their words, “gives the lie to the common perception that a warmer world will necessarily be a world under greater threat from vector-borne diseases.” In the case of TBEV, in fact, they report that the predicted change “appears to be to our advantage.”

Similarly, Estrada-Peña (2003) evaluated the effects of various abiotic factors on the habitat suitability of four tick species that are major vectors of livestock pathogens in South Africa. This work revealed “year-to-year variations in the forecasted habitat suitability over the period 1983-2000 show a clear decrease in habitat availability, which is attributed primarily to increasing temperature in the region over this period.” In addition, when climate variables were projected to the year 2015, Estrada-Peña found that “the simulations show a trend toward the destruction of the habitats of the four tick species.” This is the opposite of what is predicted by those who warn of catastrophic consequences from global warming.

Zell (2004) determined that “the factors responsible for the emergence/reemergence of vector-borne diseases are complex and mutually influence each other,” citing as an example that “the incidence and spread of parasites and arboviruses are affected by insecticide and drug resistance, deforestation, irrigation systems and dams, changes in public health policy (decreased resources of surveillance, prevention, and vector control), demographic changes (population growth, migration, urbanization), and societal changes (inadequate housing conditions, water deterioration, sewage, waste management).”

In light of these many complicating factors, Zell says “it may be over-simplistic to attribute emergent/re-emergent diseases to climate change and sketch the menace of devastating epidemics in a warmer world.” Indeed, he concludes that “variations in public health practices and lifestyle can easily outweigh changes in disease biology,” especially those that might be caused by global warming.

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9.1.5. Heat-related Mortality

Keatinge and Donaldson (2001) analyzed the effects of temperature, wind, rain, humidity, and sunshine during high pollution days in the greater London area over the period 1976-1995 to determine what weather and/or pollution factors have the biggest influence on human mortality. Their most prominent finding was that simple plots of mortality rate versus daily air temperature revealed a linear increase in deaths as temperatures fell from 15°C to near 0°C. Mortality rates at temperatures above 15°C were, in the words of the researchers, “grossly ailinear,” showing no trend. Days with high pollutant concentrations were colder than average, but a multiple regression analysis revealed that no pollutant was associated with a significant increase in mortality among people over 50 years of age. Indeed, only low temperatures were shown to have a significant effect on both immediate (one day after the temperature perturbation) and long-term (up to 24 days after the temperature perturbation) mortality rates.

Keatinge *et al.* (2000) examined heat- and cold-related mortality in north Finland, south Finland, southwest Germany, the Netherlands, Greater London, north Italy, and Athens, Greece in people aged 65-74. For each of these regions, they determined the 3°C temperature interval of lowest mortality and then evaluated mortality deviations

from that base level as temperatures rose and fell by 0.1°C increments. The result, according to the researchers, was that “all regions showed more annual cold related mortality than heat related mortality.” Over the seven regions studied, annual cold-related deaths were nearly 10 times greater than annual-heat related deaths. The scientists also note that the very successful adjustment of the different populations they studied to widely different summer temperatures “gives grounds for confidence that they would adjust successfully, with little increase in heat related mortality, to the global warming of around 2°C predicted to occur in the next half century.” Indeed, they say their data suggest “any increases in mortality due to increased temperatures would be outweighed by much larger short term declines in cold related mortalities.” For the population of Europe, therefore, an increase in temperature would appear to be a climate change for the better.

Gouveia *et al.* (2003) conducted a similar study in Sao Paulo, Brazil, where they tabulated the numbers of daily deaths from all causes (excepting violent deaths and deaths of infants up to one month of age), which they obtained from the city’s mortality information system for the period 1991-1994. They then analyzed these data for children (less than 15 years of age), adults (ages 15-64), and the elderly (age 65 and above) with respect to the impacts of warming and cooling. For each 1°C increase above the minimum-death temperature of 20°C for a given and prior day’s mean temperature, there was a 2.6 percent increase in deaths from all causes in children, a 1.5 percent increase in deaths from all causes in adults, and a 2.5 percent increase in deaths from all causes in the elderly. For each 1°C decrease below the 20°C minimum-death temperature, however, the cold effect was greater, with increases in deaths from all causes in children, adults, and the elderly registering 4.0 percent, 2.6 percent, and 5.5 percent, respectively. These cooling-induced death rates are 54 percent, 73 percent, and 120 percent greater than those attributable to warming.

Kan *et al.* (2003), in a study conducted in Shanghai, China from June 1, 2000 to December 31, 2001, found a V-like relationship between total mortality and temperature that had a minimum mortality risk at 26.7°C. Above this temperature, they note that “total mortality increased by 0.73 percent for each degree Celsius increase; while for temperatures below the optimum value, total mortality decreased by 1.21 percent for each degree Celsius increase.” The net effect of a warming of the climate of

Shanghai, therefore, would likely be reduced mortality on the order of 0.5 percent per degree Celsius increase in temperature, or perhaps even more, in light of the fact that the warming of the past few decades has been primarily due to increases in daily minimum temperatures.

Goklany and Straja (2000) studied deaths in the United States due to all causes over the period 1979-97. They found deaths due to extreme cold exceeded those due to extreme heat by 80 percent to 125 percent. No trends were found due to either extreme heat or cold in the entire population or, remarkably, in the older, more susceptible, age groups, i.e., those aged 65 and over, 75 and over, and 85 and over. Goklany and Straja say the absence of any trend “suggests that adaptation and technological change may be just as important determinants of such trends as more obvious meteorological and demographic factors.”

Davis *et al.* (2003) examined daily mortality rates for 28 major U.S. cities over 29 years between 1964 and 1998. In order to control for changes in the age structure of each city’s population that might bias temporal comparisons, they standardized each day’s mortality count relative to a hypothetical standard city with a population of one million people, with the demographics of that city based on the age distribution of the entire U.S. population in the year 2000. They found “heat-related mortality rates declined significantly over time in 19 of the 28 cities. For the 28-city average, there were 41.0+/- 4.8 (mean +/- SE) excess heat-related deaths per year (per standard million) in the 1960s and 1970s, 17.3 +/- 2.7 in the 1980s, and 10.5 +/- 2.0 in the 1990s.” This 74 percent drop in heat-related deaths occurred despite an average increase in temperature of 1.0°C during the same period. They interpret this to mean that “the U.S. populace has become systematically less affected by hot and humid weather conditions,” and they say this “calls into question the utility of efforts linking climate change forecasts to future mortality responses in the United States,” something the IPCC explicitly does. The four scientists conclude that “there is no simple association between increased heat wave duration or intensity and higher mortality rates in the United States.”

Donaldson *et al.* (2003) determined the mean daily May-August 3°C temperature bands in which deaths of people aged 55 and above were at a minimum for three areas of the world—North Carolina, USA; South Finland; and Southeast England. They then compared heat- and cold-related

deaths that occurred at temperatures above and below this optimum temperature interval for each region, after which they determined how heat-related deaths in the three areas changed between 1971 and 1997 in response to: (1) the 1.0°C temperature rise that was experienced in North Carolina over this period (from an initial temperature of 23.5°C), (2) the 2.1°C temperature rise experienced in Southeast England (from an initial temperature of 14.9°C), and (3) the unchanging 13.5°C temperature of South Finland.

First, it was determined that the 3°C temperature band at which mortality was at its local minimum was lowest for the coolest region (South Finland), highest for the warmest region (North Carolina), and intermediate for the region of intermediate temperature (Southeast England). This suggests these three populations were somewhat acclimated to their respective thermal regimes. Second, in each region, cold-related mortality (expressed as excess mortality at temperatures below the region's optimum 3°C temperature band) was greater than heat-related mortality (expressed as excess mortality at temperatures above the region's optimum 3°C temperature band).

Third, the researchers found that in the coldest of the three regions (South Finland, where there was no change in temperature over the study period), heat-related deaths per million inhabitants in the 55-and-above age group declined from 382 to 99. In somewhat warmer Southeast England, where it warmed by 2.1°C over the study period, heat-related deaths declined but much less, from 111 to 108. In the warmest of the three regions (North Carolina, USA, where mean daily May-August temperature rose by 1.0°C over the study period), heat-related deaths fell most dramatically, from 228 to a mere 16 per million.

From these observations we learn that most people can adapt to both warmer and cooler climates and that cooling tends to produce many more deaths than warming, irrespective of the initial temperature regime. As for the reason behind the third observation—the dramatic decline in heat-related deaths in response to warming in the hottest region of the study (North Carolina)—Donaldson *et al.* attribute it to the increase in the availability of air conditioning in the South Atlantic region of the United States, where they note that the percentage of households with some form of air conditioning rose from 57 percent in 1978 to 72 percent in 1997. With respect to the declining heat-related deaths in the other two areas, they say “the explanation is likely to lie in the

fact that both regions shared with North Carolina an increase in prosperity, which could be expected to increase opportunities for avoiding heat stress.”

Huynen *et al.* (2001) analyzed mortality rates in the entire population of Holland. For the 19-year period from January 1979 through December 1997, the group of five scientists compared the numbers of deaths in people of all ages that occurred during well-defined heat waves and cold spells. They found a total excess mortality of 39.8 deaths per day during heat waves and 46.6 deaths per day during cold spells. These numbers indicate that a typical cold-spell day kills at a rate that is 17 percent greater than a typical heat-wave day in the Netherlands.

The researchers note that the heat waves they studied ranged from 6 to 13 days in length, while the cold spells lasted 9 to 17 days, making the average cold spell approximately 37 percent longer than the average heat wave. Adjusting for this duration differential makes the number of deaths per cold spell in the Netherlands fully 60 percent greater than the number of deaths per heat wave. What is more, excess mortality continued during the whole month *after* the cold spells, leading to even more deaths, while there appeared to be mortality deficits in the month following heat waves, suggesting, in the words of the authors, “that some of the heat-induced increase in mortality can be attributed to those whose health was already compromised” or “who would have died in the short term anyway.” This same conclusion has been reached in a number of other studies (Kunst *et al.*, 1993; Alberdi *et al.*, 1998; Eng and Mercer, 1998; Rooney *et al.*, 1998). It is highly likely, therefore, that the 60 percent greater death toll we have calculated for cold spells in the Netherlands as compared to heat waves is an underestimate of the true differential killing power of these two extreme weather phenomena.

The Dutch could well ask themselves, therefore, “Will global climate change reduce climate-related mortalities in the Netherlands?” ... which is exactly what the senior and second authors of the Huynen *et al.* paper did in a letter to the editor of *Epidemiology* (Martens and Huynen, 2001). Based on the predictions of nine different GCMs for an atmospheric CO₂ concentration of 550 ppm in the year 2050—which implied a 50 percent increase in Dutch heat waves and a 67 percent drop in Dutch cold spells—they calculated a total mortality *decrease* for Holland of approximately 1,100 people per year at that point in time.

Data from Germany tell much the same story. Laschewski and Jendritzky (2002) analyzed daily mortality rates of the population of Baden-Württemberg, Germany (10.5 million inhabitants) over the 30-year period 1958-1997 to determine the sensitivity of the people living in this moderate climatic zone of southwest Germany to long- and short-term episodes of heat and cold. They found the mortality data “show a marked seasonal pattern with a minimum in summer and a maximum in winter” and “cold spells lead to excess mortality to a relatively small degree, which lasts for weeks,” and that “the mortality increase during heat waves is more pronounced, but is followed by lower than average values in subsequent weeks.” The authors’ data demonstrate that the mean duration of above-normal mortality for the 51 heat episodes that occurred from 1968 to 1997 was 10 days, with a mean increase in mortality of 3.9 percent, after which there was a mean *decrease* in mortality of 2.3 percent for 19 days. Hence, the net effect of the heat waves was a calculated overall decrease in mortality of 0.2 percent over the full 29-day period.

We end with the work of Thomas Gale Moore, an economist at Stanford University USA. In his first publication reviewed here (Moore, 1998), Moore reported the results of two regression analyses he conducted to estimate the effect on the U.S. death rate of a 4.5°F increase in average temperature, the IPCC’s “best estimate” at the time (1992) of likely warming over the course of the next century. For the first analysis, Moore “regressed various measures of warmth on deaths in Washington, DC, from January 1987 through December 1989,” a period of 36 months, and then extrapolated the results for the entire country. He used Washington, DC because temperatures are recorded for major urban areas, not states, while monthly data on deaths is available from the National Center for Health Statistics only for states, but the center treats the nation’s capital as a state. This analysis found a 4.5°F rise “would cut deaths for the country as a whole by about 37,000 annually.”

For his second analysis, Moore regressed the death rates in 89 large U.S. counties with various weather variables, including actual average temperatures in 1979, highest summer temperature, lowest winter temperature, number of heating degree days, and number of cooling degree days, and several other variables known to affect death rates (percent of the population over age 65, percent black, percent with 16 years or more of schooling, median

household income, per-capita income, air pollution, and health care inputs such as number of hospital beds and physicians per 100,000 population.) He found “the coefficient for average temperature implies that if the United States were enjoying temperatures 4.5 degrees warmer than today, mortality would be 41,000 less. This savings in lives is quite close to the number estimated based on the Washington, DC data, for the period 1987 through 1989.” Moore notes that “a warmer climate would reduce mortality by about the magnitude of highway deaths.”

Two years later, in a report published by the Hoover Institution, Moore estimated the number of deaths that would be caused by the costs associated with reducing U.S. greenhouse gas emissions (Moore, 2000). “Economists studying the relationship of income and earnings to mortality have found that the loss of \$5 million to \$10 million in the U.S. GDP [gross domestic product] leads to one extra death,” Moore writes. Since the Energy Information Administration (EIA) estimated that meeting the Kyoto Protocol’s goal of reducing greenhouse gas emissions to 7 percent below 1990 levels by 2010-2012 would cost \$338 billion annually (without emissions trading), “the EIA estimates imply that somewhere between 33,800 and 67,000 more Americans will die annually between 2008 and 2012.”

These studies of the effects of temperature on human mortality show that cooling, not warming, kills the largest number of people each year. The number of lives saved by warmer weather, if the IPCC’s forecasts of future warming are correct (and we doubt that they are), would far exceed the number of lives lost. The margin in the United States is enormous, with the number of prevented deaths exceeding the number of deaths that occur on the nation’s highways each year. Conversely, attempting to stop global warming by reducing emissions would cost lives—between 33,800 and 67,000 a year in the U.S. alone, according to Moore (2000). These staggering numbers leave little doubt that global warming does not pose a threat to human health.

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9.2. Nutrition

Rising concentrations of CO₂ in the atmosphere affect human health indirectly by enhancing plant productivity, a topic examined at length in Chapter 7. In this section we review the scientific literature on CO₂-induced changes to the quantity and quality of food crops—in particular the protein and antioxidants present in grains and fruits—and on the medicinal properties of some plants. We find the overwhelming weight of evidence indicates a positive effect of global warming on human health.

9.2.1. Food Quantity

The concentration of CO₂ in the earth's atmosphere has risen approximately 100 ppm since the inception of the Industrial Revolution. To measure the effect this increase had on wheat, Mayeux *et al.* (1997) grew two cultivars of commercial wheat in a 38-meter-long soil container topped with a transparent tunnel-like polyethylene cover within which a CO₂ gradient was created that varied from approximately 350 ppm at one end of the tunnel to about 200 ppm at the other end. Both wheat cultivars were irrigated weekly over the first half of the 100-day growing season, to maintain soil water contents near optimum conditions. Over the last half of the season, this regimen was maintained on only half of the wheat of each cultivar, in order to create both water-stressed and well-watered treatments.

At the conclusion of the experiment, the scientists determined that the growth response of the wheat was a linear function of atmospheric CO₂ concentration in both cultivars under both adequate and less-than-adequate soil water regimes. Based on the linear regression equations they developed for grain yield in these situations, we calculate that the 100-ppm increase in atmospheric CO₂ concentration experienced over the past century-and-a-half probably

increased the mean grain yield of the two wheat cultivars by about 72 percent under well-watered conditions and 48 percent under water-stressed conditions, for a mean yield increase on the order of 60 percent under the full range of moisture conditions likely to have existed in the real world. In other words, the historical rise in CO₂ concentrations may have increased wheat yields by 60 percent, clearly a benefit to a growing population.

This CO₂-induced yield enhancement to wheat production also has been documented by Alexandrov and Hoogenboom, 2000a; Brown and Rosenberg, 1999; Cuculeanu *et al.*, 1999; Dijkstra *et al.*, 1999; Eitzinger *et al.*, 2001; Harrison and Butterfield, 1996; Masle, 2000; Southworth *et al.*, 2002; and van Ittersum *et al.*, 2003. Nor is wheat the only food crop that benefits from CO₂-fertilization. Research reviewed in Chapter 7 showing increased production by other crops exposed to enhanced CO₂, includes the following:

- Alfalfa (De Luis *et al.*, 1999; Luscher *et al.*, 2000; Morgan *et al.*, 2001; Sgherri *et al.*, 1998)
- Cotton (Booker, 2000; Booker *et al.*, 2000; Leavitt *et al.*, 1994; Reddy *et al.*, 1999; Reddy *et al.*, 1998. Tischler *et al.*, 2000)
- Corn (maize) (Baczek-Kwinta and Koscielniak, 2003; Bootsma *et al.*, 2005; Conway and Toenniessen, 2003; Leakey *et al.*, 2004; Magrin *et al.*, 2005; Maroco *et al.*, 1999; Shen *et al.*, 2005; Watling and Press, 1997; Watling and Press, 2000)
- Peanuts (Alexandrov and Hoogenboom, 2000b; Prasad *et al.*, 2003; Stanciel *et al.*, 2000; Vu, 2005)
- Potatoes (Bunce, 2003; Chen and Setter, 2003; Fangmeier and Bender, 2002; Kauder *et al.*, 2000; Lawson *et al.*, 2001; Louche-Tessandier *et al.*, 1999; Ludewig *et al.*, 1998; Magliulo *et al.*, 2003; Miglietta *et al.*, 1998; Olivo *et al.*, 2002; Pruski *et al.*, 2002; Schapendonk, *et al.*, 2000; Sicher and Bunce, 1999; Wolf and van Oijen, 2002; Wolf and van Oijen, 2003)
- Rice (Baker *et al.*, 2000; De Costa *et al.*, 2003a; De Costa *et al.*, 2003b; Gesch *et al.*, 2002; Kim *et al.*, 2003; Kim *et al.*, 2001; Kobayashi *et al.*, 2001; Tako, *et al.*, 2001; Watling and Press, 2000; Weerakoon *et al.*, 2000; Widodo *et al.*, 2003; Ziska *et al.*, 1997)

- Sorgham (Ainsworth and Long, 2005; Ottman *et al.*, 2001; Prior *et al.*, 2005; Watling and Press, 1997)
- Soybeans (Alexandrov and Hoogenboom, 2000b; Allen *et al.*, 1998; Bernacchi *et al.*, 2005; Birt *et al.*, 2001; Bunce, 2005; Caldwell *et al.*, 2005; Ferris *et al.*, 1999; Heagle *et al.*, 1998; Messina, 1999; Nakamura *et al.*, 1999; Rogers *et al.*, 2004; Serraj *et al.*, 1999; Thomas *et al.*, 2003; Wittwer, 1995; Ziska, 1998; Ziska and Bunce, 2000; Ziska *et al.*, 2001a; Ziska *et al.*, 2001b)
- Strawberries (Bunce, 2001; Bushway and Pritts, 2002; Deng and Woodward, 1998)

Based on this voluminous data and much more, Idso and Idso (2000) calculated that the increase in atmospheric CO₂ concentration during the past 150 years probably caused mean yield increases on the order of 70 percent for wheat and other C₃ cereals, 28 percent for C₄ cereals, 33 percent for fruits and melons, 62 percent for legumes, 67 percent for root and tuber crops, and 51 percent for vegetables.

Such major increases in production by important food plants due to the historical increase in the air's CO₂ content have undoubtedly benefitted human health. In fact, it is safe to say that some of the people reading these words would not be alive today were it not for the CO₂ enrichment caused by human industry since the beginning of the Industrial Revolution.

What does the IPCC say about this extraordinary benefit to human health made possible by rising CO₂ levels? Incredibly, it is not mentioned anywhere in the contribution of Working Group I to the Fourth Assessment Report of the IPCC (IPCC 2007-I) or in the chapter on the impact of global warming on human health in the contribution of Working Group II (IPCC 2007-II). It is treated dismissively in the chapter on agriculture in the contribution of Working Group III (IPCC 2007-III), even though the proposals justified in the first two volumes and advanced in the third would *reduce* CO₂ emissions and therefore have a negative impact on crop yields. To call this a gross oversight is to be kind to the authors of these reports.

In view of these observations, it is indisputable that the ongoing rise in the air's CO₂ content has bestowed a huge benefit to human health by expanding the yields of food crops.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/agriculture.php>.

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9.2.2. Food Quality

The quantity of food is mankind's primary concern when it comes to survival. But after survival is assured, the *quality* of food rises to the fore. What role does the ongoing rise in the air's CO₂ content play here? In this section we survey the literature on the effects of higher CO₂ air concentration on plant protein and antioxidant content.

9.2.2.1. Protein Content

Idso and Idso (2001) and Idso *et al.* (2001) cited studies where elevated levels of atmospheric CO₂ either increased, decreased, or had no effect on the protein concentrations of various agricultural crops.

The relationship, as we will see, is complex, though in the end it appears that enhanced atmospheric CO₂ has a positive effect on the protein content of most crops.

Pleijel *et al.* (1999) analyzed the results of 16 open-top chamber experiments that had been conducted on spring wheat in Denmark, Finland, Sweden, and Switzerland between 1986 and 1996. In addition to CO₂ enrichment of the air, these experiments included increases and decreases in atmospheric ozone (O₃). The scientists found that while increasing O₃ pollution reduced wheat grain yield it simultaneously increased the protein concentration of the grain. Removing O₃ from the air led to higher grain yield but lower protein concentration. The opposite relationship was found for atmospheric CO₂ enrichment, which increased grain yield but lowered protein concentration. Water stress, which was also a variable in one of the experiments, reduced yield and increased grain protein concentrations.

In an earlier study of CO₂ and O₃ effects on wheat grain yield and quality, Rudorff *et al.* (1996) found that “flour protein contents were increased by enhanced O₃ exposure and reduced by elevated CO₂” but that “the combined effect of these gases was minor.” They conclude that “the concomitant increase of CO₂ and O₃ in the troposphere will have no significant impact on wheat grain quality.”

Earlier, Evans (1993) had found several other crops to be greatly affected by soil nitrogen availability. Rogers *et al.* (1996) observed CO₂-induced reductions in the protein concentration of flour derived from wheat plants growing at low soil nitrogen concentrations, but no such reductions were evident when the soil nitrogen supply was increased. Pleijel *et al.* concluded that the oft-observed negative impact of atmospheric CO₂ enrichment on grain protein concentration would probably be alleviated by higher applications of nitrogen fertilizers.

The study of Kimball *et al.* (2001) confirmed their hypothesis. Kimball *et al.* studied the effects of a 50 percent increase in atmospheric CO₂ concentration on wheat grain nitrogen concentration and the baking properties of the flour derived from that grain throughout four years of free-air CO₂ enrichment experiments. In the first two years of their study, soil water content was an additional variable; in the last two years, soil nitrogen content was a variable. The most influential factor in reducing grain nitrogen concentration was determined to be low soil nitrogen.

Under this condition, atmospheric CO₂ enrichment further reduced grain nitrogen and protein concentrations, although the change was much less than that caused by low soil nitrogen. When soil nitrogen was not limiting, however, increases in the air’s CO₂ concentration did not affect grain nitrogen and protein concentrations; neither did they reduce the baking properties of the flour derived from the grain. Hence, it would appear that given sufficient water and nitrogen, atmospheric CO₂ enrichment can significantly increase wheat grain yield without sacrificing grain protein concentration in the process.

There are some situations where atmospheric CO₂ enrichment has been found to *increase* the protein concentration of wheat. Agrawal and Deepak (2003), for example, grew two cultivars of wheat (*Triticum aestivum* L. cv. Malviya 234 and HP1209) in open-top chambers maintained at atmospheric CO₂ concentrations of 350 and 600 ppm alone and in combination with 60 ppb SO₂ to study the interactive effects of elevated CO₂ and this major air pollutant on crop growth. They found that exposure to the elevated SO₂ caused a 13 percent decrease in foliar protein concentrations in both cultivars; but when the plants were concomitantly exposed to an atmospheric CO₂ concentration of 600 ppm, leaf protein levels decreased only by 3 percent in HP1209, while they actually increased by 4 percent in Malviya 234.

In the case of rice—which according to Wittwer (1995) is “the basic food for more than half the world’s population,” supplying “more dietary energy than any other single food”—Jablonski *et al.* (2002) conducted a wide-ranging review of the scientific literature, finding that it too appeared to suffer no reduction in grain nitrogen (protein) concentration in response to atmospheric CO₂ enrichment. Likewise, they found no CO₂-induced decrease in seed nitrogen concentration in the studies of legumes they reviewed. This finding is also encouraging, since according to Wittwer (1995) legumes “are a direct food resource providing 20 percent of the world’s protein for human consumption,” as well as “about two thirds of the world’s protein concentrate for livestock feeding.” What is more, the biomass of the CO₂-enriched wheat, rice, and legumes was found by Jablonski *et al.* to be significantly increased above that of the same crops grown in normal air. Hence, there will likely be a large increase in the total amount of protein made available to humanity in a future CO₂-enriched world, both directly via food crops and indirectly via livestock.

With respect to the leguminous soybean, Thomas *et al.* (2003) additionally note that “oil and protein comprise ~20 and 40 percent, respectively, of the dry weight of soybean seed,” which “unique chemical composition,” in their words, “has made it one of the most valuable agronomic crops worldwide.” In addition, they say “the intrinsic value of soybean seed is in its supply of essential fatty acids and amino acids in the oil and protein, respectively,” and they report that Heagle *et al.* (1998) “observed a positive significant effect of CO₂ enrichment on soybean seed oil and oleic acid concentration.”

Legumes and their responses to atmospheric CO₂ enrichment also figure prominently in a number of studies of mixed forage crops. In a study of nitrogen cycling in grazed pastures on the North Island of New Zealand, for example, Allard *et al.* (2003) report that under elevated CO₂, leaves of the individual species exhibited lower nitrogen concentrations but higher water-soluble carbohydrate (WSC) concentrations. They also say “there was a significantly greater proportion of legume in the diet at elevated CO₂,” and that this “shift in the botanical composition towards a higher proportion of legumes counterbalanced the nitrogen decrease observed at the single species scale, resulting in a nitrogen concentration of the overall diet that was unaffected by elevated CO₂.” They further report that “changes at the species level and at the sward level appeared to combine additively in relation to WSC,” and “as there was a significant correlation between WSC and digestibility (as previously observed by Dent and Aldrich, 1963 and Humphreys, 1989), there was also an increase in digestibility of the high CO₂ forage,” which result, in their words, “matches that found in a Mini-FACE experiment under cutting (Teyssonneyre, 2002; Picon-Cochard *et al.*, 2004),” where “digestibility also increased in response to CO₂ despite reduced crude protein concentration.” These data, plus the strong relationship between soluble sugars (rather than nitrogen) and digestibility, led them to suggest that “the widespread response to CO₂ of increased soluble sugars might lead to an increase in forage digestibility.”

Luscher *et al.* (2004) found much the same thing in their review of the subject, which was based primarily on studies conducted at the Swiss FACE facility that hosts what has become the world’s longest continuous atmospheric CO₂ enrichment study of a naturally occurring grassland. In response to an approximate two-thirds increase in the air’s CO₂ concentration, leaf nitrogen (N) concentrations of

white clover (*Trifolium repens* L.) and perennial ryegrass (*Lolium perenne* L.) were reduced by 7 percent and 18 percent, respectively, when they were grown separately in pure stands. However, as Luscher *et al.* report, “the considerably lower concentration of N under elevated CO₂, observed for *L. perenne* leaves in pure stands, was found to a much lesser extent for *L. perenne* leaves in the bi-species mixture with *T. repens* (Zanetti *et al.*, 1997; Hartwig *et al.*, 2000).” Furthermore, as they continue, “under elevated CO₂ the proportion of N-rich *T. repens* (40 mg N g⁻¹ dry matter) increased in the mixture at the expense of the N-poor *L. perenne* (24 mg N g⁻¹ dry matter when grown in monoculture),” the end result being that “the concentration of N in the harvested biomass of the mixture showed no significant reduction.”

Campbell *et al.* (2000) analyzed research conducted between 1994 and 1999 by a worldwide network of 83 scientists associated with the Global Change and Terrestrial Ecosystems (GCTE) Pastures and Rangelands Core Research Project 1 (CRP1) that resulted in the publication of more than 165 peer-reviewed scientific journal articles. Campbell *et al.* determined from this massive collection of data that the legume content of grass-legume swards was typically increased by approximately 10 percent in response to a doubling of the air’s CO₂ content.

Luscher *et al.* (2004) state that “the nutritive value of herbage from intensively managed grassland dominated by *L. perenne* and *T. repens* ... is well above the minimum range of the concentration of crude protein necessary for efficient digestion by ruminants (Barney *et al.*, 1981).” They conclude that “a small decrease in the concentration of crude protein in intensively managed forage production systems [which may never occur, as noted above] is not likely to have a negative effect on the nutritive value or on the intake of forage.”

One final forage study is Newman *et al.* (2003), who investigated the effects of two levels of nitrogen fertilization and an approximate doubling of the air’s CO₂ content on the growth and chemical composition of tall fescue (*Festuca arundinacea* Schreber cv. KY-31), both when infected and uninfected with a mutualistic fungal endophyte (*Neotyphodium coenophialum* Morgan-Jones and Gams). They found that the elevated CO₂ reduced the crude protein content of the forage by an average of 21 percent in three of the four situations studied: non-endophyte-infected plants in both the low and high nitrogen treatments, and endophyte-infected plants in the high nitrogen treatment. However, there was no protein

reduction for endophyte-infected plants in the low nitrogen treatment.

As noted by Newman *et al.*, “the endophyte is present in many native and naturalized populations and the most widely sown cultivars of *F. arundinacea*,” so the first two situations in which the CO₂-induced protein reduction occurred (those involving non-endophyte-infected plants) are not typical of the real world. In addition, since the dry-weight biomass yield of the forage was increased by fully 53 percent under the low nitrogen regime, and since the 10-times-greater high nitrogen regime boosted yields only by an additional 8 percent, there would appear to be no need to apply any extra nitrogen to *F. arundinacea* in a CO₂-enriched environment. Consequently, under best management practices in a doubled-CO₂ world of the future, little to no nitrogen would be added to the soil and there would be little to no reduction in the crude protein content of *F. arundinacea*, but there would be more than 50 percent more of it produced on the same amount of land.

With respect to the final plant quality studied by Newman *et al.*—i.e., forage digestibility—increasing soil nitrogen lowered *in vitro* neutral detergent fiber digestibility in both ambient and CO₂-enriched air; this phenomenon was most pronounced in the elevated CO₂ treatment. Again, however, under low nitrogen conditions there was no decline in plant digestibility. Hence, there is a second good reason not to apply extra nitrogen to *F. arundinacea* in a high CO₂ world of the future and, of course, little to no need to do so. Under best management practices in a future CO₂-enriched atmosphere, therefore, the results of this study suggest much greater quantities of good-quality forage could be produced without the addition of any, or very little, extra nitrogen to the soil.

But what about the unmanaged world of nature? Increases in the air’s CO₂ content often—but not always (Goverde *et al.*, 1999)—lead to greater decreases in the concentrations of nitrogen and protein in the foliage of C₃ as compared to C₄ grasses (Wand *et al.*, 1999); as a result, in the words of Barbehenn *et al.* (2004a), “it has been predicted that insect herbivores will increase their feeding damage on C₃ plants to a greater extent than on C₄ plants” (Lincoln *et al.*, 1984, 1986; Lambers, 1993).

To test this hypothesis, Barbehenn *et al.* (2004a) grew *Lolium multiflorum* Lam. (Italian ryegrass, a common C₃ pasture grass) and *Bouteloua curtipendula* (Michx.) Torr. (sideoats gramma, a

native C₄ rangeland grass) in chambers maintained at either the ambient atmospheric CO₂ concentration of 370 ppm or the doubled CO₂ concentration of 740 ppm for two months, after which newly molted sixth-instar larvae of *Pseudaletia unipuncta* (a grass-specialist noctuid) and *Spodoptera frugiperda* (a generalist noctuid) were allowed to feed upon the grasses. As expected, foliage protein concentration decreased by 20 percent in the C₃ grass, but by only 1 percent in the C₄ grass, when grown in the CO₂-enriched air. However, and “contrary to our expectations,” according to Barbehenn *et al.*, “neither caterpillar species significantly increased its consumption rate to compensate for the lower concentration of protein in [the] C₃ grass,” noting that “this result does not support the hypothesis that C₃ plants will be subject to greater rates of herbivory relative to C₄ plants in future [high-CO₂] atmospheric conditions (Lincoln *et al.*, 1984).” In addition, and “despite significant changes in the nutritional quality of *L. multiflorum* under elevated CO₂,” they report that “no effect on the relative growth rate of either caterpillar species on either grass species resulted” and there were “no significant differences in insect performance between CO₂ levels.”

In a similar study with the same two plants, Barbehenn *et al.* (2004b) allowed grasshopper (*Melanoplus sanguinipes*) nymphs that had been reared to the fourth instar stage to feed upon the grasses; once again, “contrary to the hypothesis that insect herbivores will increase their feeding rates disproportionately in C₃ plants under elevated atmospheric CO₂,” they found that “*M. sanguinipes* did not significantly increase its consumption rate when feeding on the C₃ grass grown under elevated CO₂,” suggesting this observation implies that “post-ingestive mechanisms enable these grasshoppers to compensate for variable nutritional quality in their host plants,” and noting that some of these post-ingestive responses may include “changes in gut size, food residence time, digestive enzyme levels, and nutrient metabolism (Simpson and Simpson, 1990; Bernays and Simpson, 1990; Hinks *et al.*, 1991; Zanutto *et al.*, 1993; Yang and Joern, 1994a,b).” In fact, their data indicated that *M. sanguinipes* growth rates may have actually *increased*, perhaps by as much as 12 percent, when feeding upon the C₃ foliage that had been produced in the CO₂-enriched air.

In conclusion, the ongoing rise of the air’s CO₂ concentration is not reducing the protein concentration in, or digestibility of, most important

plant crops. In cases where protein concentration might be reduced, the addition of nitrogen fertilizer appears to offset the effect.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/p/protein.php>.

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9.2.2.2. Antioxidant Content

Antioxidants are chemical compounds that inhibit oxidation. Some antioxidants found in the human diet, such as vitamin E, vitamin C, and beta carotene, are thought to protect body cells from the damaging effects of oxidation. Scurvy—a condition characterized by general weakness, anemia, gum disease (gingivitis), and skin hemorrhages—is induced by low intake of vitamin C. There is some evidence that the condition may be resurgent in industrial countries, especially among children (Dickinson *et al.*, 1994; Ramar *et al.*, 1993; Gomez-Carrasco *et al.*, 1994). Hampl *et al.* (1999) found that 12-20 percent of 12- to 18-year-old school children in the United States “drastically under-consume” foods that supply vitamin C. Johnston *et al.* (1998) determined that 12-16 percent of U.S. college students have marginal plasma concentrations of vitamin C.

Since vitamin C intake correlates strongly with the consumption of citrus juice (Dennison *et al.*, 1998), and since the only high-vitamin-C juice consumed in any quantity by children is orange juice (Hampl *et al.*, 1999), even a modest role played by the ongoing rise in the air's CO₂ content in increasing the vitamin C concentration of orange juice could prove to be of considerable significance for public health in the United States and elsewhere. Thus, determining if rising CO₂ concentrations increase or

hinder the production of antioxidants in human food is relevant to the issue of what effect the historical rise in CO₂ concentrations is having on human health.

Antioxidant concentrations in plants are generally observed to be high when environmental stresses are present, such as exposure to pollutants, drought, intense solar radiation, and high air or water temperatures. Stress generates highly reactive oxygenated compounds that damage plants, and ameliorating these stresses typically involves the production of antioxidant enzymes that scavenge and detoxify the highly reactive oxygenated compounds. In a study of two soybean genotypes, Pritchard *et al.* (2000) reported that three months' exposure to twice-ambient CO₂ concentrations reduced the activities of superoxide dismutase and catalase by an average of 23 and 39 percent, respectively. Likewise, Polle *et al.* (1997) showed that two years of atmospheric CO₂ enrichment reduced the activities of several key antioxidative enzymes, including catalase and superoxide dismutase, in beech seedlings. Moreover, Schwanz and Polle (1998) demonstrated this phenomenon can persist indefinitely, as they discovered similar reductions in these same enzymes in mature oak trees that had been growing near natural CO₂-emitting springs for 30 to 50 years.

The standard interpretation of these results is that the observed reductions in the activities of antioxidative enzymes under CO₂-enriched conditions imply that plants exposed to higher-than-current atmospheric CO₂ concentrations experience less oxidative stress and thus have a reduced need for antioxidant protection. This conclusion further suggests that "CO₂-advantaged" plants will be able to funnel more of their limited resources into the production of other plant tissues or processes essential to their continued growth and development.

On the other hand, when oxidative stresses do occur under high CO₂ conditions, the enhanced rates of photosynthesis and carbohydrate production resulting from atmospheric CO₂ enrichment generally enable plants to better deal with such stresses by providing more of the raw materials needed for antioxidant enzyme synthesis. Thus, when CO₂-enriched sugar maple seedlings were subjected to an additional 200 ppb of ozone, Niewiadomska *et al.* (1999) reported that ascorbate peroxidase, which is the first line of enzymatic defense against ozone, significantly increased. Likewise, Schwanz and Polle (2001) noted that poplar clones grown at 700 ppm CO₂ exhibited a much greater increase in superoxide dismutase activity upon chilling induction than clones

grown in ambient air. In addition, Lin and Wang (2002) observed that activities of superoxide dismutase and catalase were much higher in CO₂-enriched wheat than in ambiently grown wheat following the induction of water stress.

In some cases, the additional carbon fixed during CO₂-enrichment is invested in antioxidative compounds, rather than enzymes. One of the most prominent of these plant products is *ascorbate* or vitamin C. In the early studies of Barbale (1970) and Madsen (1971, 1975), a tripling of the atmospheric CO₂ concentration produced a modest (7 percent) increase in this antioxidant in the fruit of tomato plants. Kimball and Mitchell (1981), however, could find no effect of a similar CO₂ increase on the same species, although the extra CO₂ of their study stimulated the production of vitamin A. In bean sprouts, on the other hand, a mere one-hour-per-day doubling of the atmospheric CO₂ concentration actually *doubled* plant vitamin C contents over a seven-day period (Tajiri, 1985).

Probably the most comprehensive investigation of CO₂ effects on vitamin C production in an agricultural plant—a tree crop (sour orange)—was conducted by Idso *et al.* (2002). In an atmospheric CO₂ enrichment experiment begun in 1987 and still ongoing, a 75 percent increase in the air's CO₂ content was observed to increase sour orange juice vitamin C concentration by approximately 5 percent in run-of-the-mill years when total fruit production was typically enhanced by about 80 percent. In aberrant years when the CO₂-induced increase in fruit production was much greater, however, the increase in fruit vitamin C concentration also was greater, rising to a CO₂-induced enhancement of 15 percent when fruit production on the CO₂-enriched trees was 3.6 times greater than it was on the ambient-treatment trees.

Wang *et al.* (2003) evaluated the effects of elevated CO₂ on the antioxidant activity and flavonoid content of strawberry fruit in field plots at the U.S. Department of Agriculture's Beltsville Agricultural Research Center in Beltsville, Maryland, where they grew strawberry plants (*Fragaria x ananassa* Duchesne cv. Honeoye) in six clear-acrylic open-top chambers, two of which were maintained at the ambient atmospheric CO₂ concentration, two of which were maintained at ambient + 300 ppm CO₂, and two of which were maintained at ambient + 600 ppm CO₂ for a period of 28 months (from early spring of 1998 through June 2000). The scientists harvested the strawberry fruit, in their words, "at the

commercially ripe stage” in both 1999 and 2000, after which they analyzed them for a number of different antioxidant properties and flavonol contents.

Before reporting what they found, Wang *et al.* provide some background by noting that “strawberries are good sources of natural antioxidants (Wang *et al.*, 1996; Heinonen *et al.*, 1998).” They further report that “in addition to the usual nutrients, such as vitamins and minerals, strawberries are also rich in anthocyanins, flavonoids, and phenolic acids,” and that “strawberries have shown a remarkably high scavenging activity toward chemically generated radicals, thus making them effective in inhibiting oxidation of human low-density lipoproteins (Heinonen *et al.*, 1998).” In this regard, they note that previous studies (Wang and Jiao, 2000; Wang and Lin, 2000) “have shown that strawberries have high oxygen radical absorbance activity against peroxyl radicals, superoxide radicals, hydrogen peroxide, hydroxyl radicals, and singlet oxygen.”

They determined, first, that strawberries had higher concentrations of ascorbic acid (AsA) and glutathione (GSH) “when grown under enriched CO₂ environments.” In going from ambient to ambient + 300 ppm CO₂ and ambient + 600 ppm CO₂, for example, AsA concentrations increased by 10 and 13 percent, respectively, while GSH concentrations increased by 3 and 171 percent, respectively. They also learned that “an enriched CO₂ environment resulted in an increase in phenolic acid, flavonol, and anthocyanin contents of fruit.” For nine different flavonoids, for example, there was a mean concentration increase of 55 ± 23 percent in going from the ambient atmospheric CO₂ concentration to ambient + 300 ppm CO₂, and a mean concentration increase of 112 ± 35 percent in going from ambient to ambient + 600 ppm CO₂. In addition, they report that the “high flavonol content was associated with high antioxidant activity.” As for the significance of these findings, Wang *et al.* note that “anthocyanins have been reported to help reduce damage caused by free radical activity, such as low-density lipoprotein oxidation, platelet aggregation, and endothelium-dependent vasodilation of arteries (Heinonen *et al.*, 1998; Rice-Evans and Miller, 1996).”

In summarizing their findings, Wang *et al.* say “strawberry fruit contain flavonoids with potent antioxidant properties, and under CO₂ enrichment conditions, increased the[ir] AsA, GSH, phenolic acid, flavonol, and anthocyanin concentrations,” further noting that “plants grown under CO₂

enrichment conditions also had higher oxygen radical absorbance activity against [many types of oxygen] radicals in the fruit.”

Deng and Woodward (1998) reported that after growing strawberry plants in air containing an additional 170 ppm of CO₂, total fresh fruit weights were 42 and 17 percent greater than weights displayed by control plants grown at high and low soil nitrogen contents, respectively. Bushway and Pritts (2002) reported that a two- to three-fold increase in the air’s CO₂ content boosted strawberry fruit yield by an average of 62 percent. In addition, Campbell and Young (1986), Keutgen *et al.* (1997), and Bunce (2001) reported positive strawberry photosynthetic responses to an extra 300 ppm of CO₂ ranging from 9 percent to 197 percent (mean of 76 percent \pm 15 percent); and Desjardins *et al.* (1987) reported a 118 percent increase in photosynthesis in response to a 600 ppm increase in the air’s CO₂ concentration.

Other researchers have found similar enhancements of antioxidative compounds under enriched levels of atmospheric CO₂. Estiarte *et al.* (1999), for example, reported that a 180-ppm increase in the air’s CO₂ content increased the foliar concentrations of flavonoids, which protect against UV-B radiation damage, in field-grown spring wheat by 11 to 14 percent. Caldwell *et al.* (2005) found that an ~75 percent increase in the air’s CO₂ content increased the total isoflavone content of soybean seeds by 8 percent when the air temperature during seed fill was 18°C, by 104 percent when the air temperature during seed fill was 23°C, by 101 percent when the air temperature was 28°C, and by 186 percent and 38 percent, respectively, when a drought-stress treatment was added to the latter two temperature treatments.

Lastly, in an experiment conducted under very high atmospheric CO₂ concentrations, Ali *et al.* (2005) found that CO₂ levels of 10,000 ppm, 25,000 ppm, and 50,000 ppm increased total flavonoid concentrations of ginseng roots by 228 percent, 383 percent, and 232 percent, respectively, total phenolic concentrations by 58 percent, 153 percent, and 105 percent, cysteine contents by 27 percent, 65 percent, and 100 percent, and non-protein thiol contents by 12 percent, 43 percent, and 62 percent, all of which substances are potent antioxidants.

In summary, as the CO₂ content of the air rises, plants typically experience less oxidative stress, and since they thus need fewer antioxidants for protection, antioxidant levels in their leaves decline, which

enables them to use more of their valuable resources for other purposes. However, elevated CO₂ also provides more of the raw materials needed for oxidant enzyme synthesis, leading to higher levels of antioxidative compounds—such as *ascorbate*, or vitamin C. Research shows this happens with enough frequency that higher CO₂ levels will lead to higher concentrations of antioxidants, leading to better health.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/a/antioxidants.php>.

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9.2.3. Medicinal Constituents

Primitive medical records indicate that extracts from many species of plants have been used for treating a variety of human health problems for perhaps the past 3,500 years (Machlin, 1992; Pettit *et al.*, 1993, 1995). In modern times the practice has continued, with numerous chemotherapeutic agents being isolated (Gabrielsen *et al.*, 1992a). Until recently, however, no studies had investigated the effects of atmospheric CO₂ enrichment on specific plant compounds of direct medicinal value.

Stuhlfauth *et al.* (1987) studied the individual and combined effects of atmospheric CO₂ enrichment and water stress on the production of secondary metabolites in the woolly foxglove (*Digitalis lanata* EHRH), which produces the cardiac glycoside *digoxin* that is used in the treatment of cardiac insufficiency. Under controlled well-watered conditions in a phytotron, a near-tripling of the air's CO₂ content increased plant dry weight production in this medicinal plant by 63 percent, while under water-stressed conditions the CO₂-induced dry weight increase was 83 percent. In addition, the concentration of digoxin within the plant dry mass was enhanced by 11 percent under well-watered conditions and by 14 percent under conditions of water stress.

In a subsequent whole-season field experiment, Stuhlfauth and Fock (1990) obtained similar results. A near-tripling of the air's CO₂ concentration led to a 75 percent increase in plant dry weight production per unit land area and a 15 percent increase in digoxin yield per unit dry weight of plant, which combined to produce a doubling of total digoxin yield per hectare of cultivated land.

Idso *et al.* (2000) evaluated the response of the tropical spider lily (*Hymenocallis littoralis* Jacq. Salisb.) to elevated levels of atmospheric CO₂ over four growing seasons. This plant has been known since ancient times to possess anti-tumor activity; in modern times it has been shown to contain constituents that are effective against lymphocytic leukemia and ovary sarcoma (Pettit *et al.*, 1986). These same plant constituents also have been proven to be effective against the U.S. National Cancer Institute's panel of 60 human cancer cell lines, demonstrating greatest effectiveness against melanoma, brain, colon, lung, and renal cancers (Pettit *et al.*, 1993). In addition, it exhibits strong anti-viral activity against Japanese encephalitis and

yellow, dengue, Punta Tora, and Rift Valley fevers (Gabrielsen *et al.*, 1992a,b).

Idso *et al.* determined that a 75 percent increase in the air's CO₂ concentration produced a 56 percent increase in the spider lily's below-ground bulb biomass, where the disease-fighting substances are found. In addition, for these specific substances, they observed a 6 percent increase in the concentration of a two-constituent (1:1) mixture of 7-deoxynarciclasine and 7-deoxy-trans-dihydronarciclasine, an 8 percent increase in pancratistatin, an 8 percent increase in trans-dihydronarciclasine, and a 28 percent increase in narciclasine. Averaged together and combined with the 56 percent increase in bulb biomass, these percentage concentration increases resulted in a total mean active-ingredient increase of 75 percent for the plants grown in air containing 75 percent more CO₂.

Other plant constituents that perform important functions in maintaining human health include sugars, lipids, oils, fatty acids, and macro- and micro-nutrients. Although concerns have been raised about the availability of certain of the latter elements in plants growing in a CO₂-enriched world (Loladze, 2002), the jury is still out with respect to this subject as a consequence of the paucity of pertinent data.

Literally thousands of studies have assessed the impact of elevated levels of atmospheric CO₂ on the quantity of biomass produced by agricultural crops, but only a tiny fraction of that number have looked at any aspect of food quality. From what has been learned about plant protein, antioxidants, and the few medicinal substances that have been investigated in this regard, there is no reason to believe these other plant constituents would be present in lower concentrations in a CO₂-enriched world and ample evidence that they may be present in significantly higher concentrations and greater absolute amounts.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/co2healthpromoting.php>.

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9.3. Human Longevity

The past two centuries have witnessed a significant degree of global warming as the earth recovered from the Little Ice Age and entered the Current Warm Period. Simultaneously, the planet has seen an increase in its atmospheric CO₂ concentration. What effect have these trends had on human longevity? Although no one can give a precise quantitative answer to this question, it is possible to assess their relative importance by considering the history of human longevity.

Tuljapurkar *et al.* (2000) examined mortality over the period 1950-1994 in Canada, France, Germany (excluding the former East Germany), Italy, Japan, the United Kingdom, and the United States, finding that “in every country over this period, mortality at each age has declined exponentially at a roughly constant rate.” In discussing these findings, Horiuchi (2000) notes that the average lifespan of early humans was about 20 years, but that in the major industrialized countries it is now about 80 years, with the bulk of this increase having come in the past 150 years. He then notes that “it was widely expected that as life expectancy became very high and approached the ‘biological limit of human longevity,’ the rapid ‘mortality decline’ would slow down and eventually level off,” but “such a deceleration has not occurred.” “These findings give rise to two interrelated questions,” says Horiuchi: (1) “Why has mortality decline not started to slow down?” and (2) “Will it continue into the future?”

Some points to note in attempting to answer these questions are the following. First, in Horiuchi’s words, “in the second half of the nineteenth century and the first half of the twentieth century, there were large decreases in the number of deaths from infectious and parasitic diseases, and from poor nutrition and disorders associated with pregnancy and childbirth,” which led to large reductions in the deaths of infants, children, and young adults. In the second half of the twentieth century, however, Horiuchi notes that “mortality from degenerative diseases, most notably heart diseases and stroke, started to fall,” and the reduction was most pronounced among the elderly. Some suspected this latter drop in mortality might have been achieved “through postponing the deaths of seriously ill people,” but data from the United States demonstrate, in his words, that “the health of the elderly greatly improved in the 1980s and 1990s, suggesting that the extended length of life in old age is mainly due to better health rather than prolonged survival in sickness.”

Additional support for this conclusion comes from the study of Manton and Gu (2001). With the completion of the latest of the five National Long-Term Care Surveys of disability in U.S. citizens over 65 years of age—which began in 1982 and extended to 1999 at the time of the writing of their paper—these researchers were able to discern two trends: (1) disabilities in this age group decreased over the entire period studied, and (2) disabilities decreased at a rate that grew ever larger with the passing of time. Over

the 17-year period of record, the percentage of the group that was disabled dropped 25 percent, from 26.2 percent in 1982 to 19.7 percent in 1999. The percentage disability decline rate per year for the periods 1982-1989, 1989-1994, and 1994-1999 was 0.26, 0.38, and 0.56 percent per year, respectively. Commenting on the accelerating rate of this disability decline, the authors say “it is surprising, given the low level of disability in 1994, that the rate of improvement accelerated” over the most recent five-year interval.

Looking outside the United States, Oeppen and Vaupel (2002) reported that “world life expectancy more than doubled over the past two centuries, from roughly 25 years to about 65 for men and 70 for women.” They noted that “for 160 years, best-performance life expectancy has steadily increased by a quarter of a year per year,” and they emphasized that this phenomenal trend “is so extraordinarily linear that it may be the most remarkable regularity of mass endeavor ever observed.”

These observations demonstrate that if the increases in air temperature and CO₂ concentration of the past two centuries were bad for our health, their combined negative influence was minuscule compared to whatever else was at work in promoting this vast increase in worldwide human longevity. It is that “whatever else” to which we now turn our attention.

It is evident that in developed countries, the elderly are living longer with the passing of time. This phenomenon is likely due to ever-improving health in older people, which in turn is likely the result of continuing improvements in the abilities of their bodies to repair cellular damage caused by degenerative processes associated with old age, i.e., stresses caused by the reactive oxygen species that are generated by normal metabolism (Finkel and Holbrook, 2000).

Wentworth *et al.* (2003) report they found “evidence for the production of ozone in human disease,” specifically noting that “signature products unique to cholesterol ozonolysis are present within atherosclerotic tissue at the time of carotid endarterectomy, suggesting that ozone production occurred during lesion development.” According to Marx (2003), “researchers think that inflammation of blood vessels is a major instigator of plaque formation,” that “ozone contributes to plaque formation by oxidizing cholesterol,” and that the new findings “suggest new strategies for preventing

atherosclerosis.” Also according to Marx, Daniel Steinberg of the University of California, San Diego, says that although it’s still too early to definitively state whether ozone production in plaques is a major contributor to atherosclerosis, he expresses his confidence that once we know for sure, we’ll know which antioxidants will work in suppressing plaque formation.

Reactive oxygen species (ROS) generated during cellular metabolism or peroxidation of lipids and proteins also play a causative role in the pathogenesis of cancer, along with coronary heart disease (CHD), as demonstrated by Slaga *et al.* (1987), Frenkel (1992), Marnett (2000), Zhao *et al.* (2000) and Wilcox *et al.* (2004). However, as noted by Yu *et al.* (2004), “antioxidant treatments may terminate ROS attacks and reduce the risks of CHD and cancer, as well as other ROS-related diseases such as Parkinson’s disease (Neff, 1997; Chung *et al.*, 1999; Wong *et al.*, 1999; Espin *et al.*, 2000; Merken and Beecher, 2000).” As a result, they say that “developing functional foods rich in natural antioxidants may improve human nutrition and reduce the risks of ROS-associated health problems.”

Consider, in this regard, the common strawberry. Wang *et al.* (2003) report that strawberries are especially good sources of natural antioxidants. They say that “in addition to the usual nutrients, such as vitamins and minerals, strawberries are also rich in anthocyanins, flavonoids, and phenolic acids,” and that “strawberries have shown a remarkably high scavenging activity toward chemically generated radicals, thus making them effective in inhibiting oxidation of human low-density lipoproteins (Heinonen *et al.*, 1998).” They also note that Wang and Jiao (2000) and Wang and Lin (2000) “have shown that strawberries have high oxygen radical absorbance activity against peroxy radicals, superoxide radicals, hydrogen peroxide, hydroxyl radicals, and singlet oxygen.” And they say that “anthocyanins have been reported to help reduce damage caused by free radical activity, such as low-density lipoprotein oxidation, platelet aggregation, and endothelium-dependent vasodilation of arteries (Heinonen *et al.*, 1998; Rice-Evans and Miller, 1996).”

Our reason for citing all of this information is that Wang *et al.* (2003) have recently demonstrated that enriching the air with carbon dioxide increases both the concentrations and activities of many of these helpful substances. They determined, for example, that strawberries had higher concentrations of

ascorbic acid and glutathione when grown in CO₂-enriched environments. They also learned that “an enriched CO₂ environment resulted in an increase in phenolic acid, flavonol, and anthocyanin contents of fruit.” For nine different flavonoids there was a mean concentration increase of 55 percent in going from the ambient atmospheric CO₂ concentration to ambient + 300 ppm CO₂, and a mean concentration increase of 112 percent in going from ambient to ambient + 600 ppm CO₂. Also, they report that “high flavonol content was associated with high antioxidant activity.”

There is little reason to doubt that similar concentration and activity increases in the same and additional important phytochemicals in other food crops would occur in response to the same increases in the air’s CO₂ concentration. Indeed, the aerial fertilization effect of atmospheric CO₂ enrichment is a near-universal phenomenon that operates among plants of all types, and it is very powerful (e.g., Mayeux *et al.*, 1997; Idso and Idso, 2000). There must have been significant concomitant increases in the concentrations and activities of the various phytochemicals in these foods that act as described by Wang *et al.* (2003).

Could some part of the rapid lengthening of human longevity reported by Oeppen and Vaupel (2002) be due to enhanced CO₂ in the air putting more antioxidants in our diets? Two recent experiments showing the positive effects of antioxidants on animal lifespan provide some additional evidence that this may be the case.

Melov *et al.* (2000) examined the effects of two superoxide dismutase-/catalase-like mimetics (EUK-8 and EUK-134) on the lifespan of normal and mutant *Caenorhabditis elegans* worms that ingested various concentrations of the mimetics. In all of their experiments, treatment of normal worms with the antioxidant mimetics significantly increased both mean and maximum lifespan. Treatment of normal worms with only 0.05 mM EUK-134, for example, increased their mean lifespan by fully 54 percent. In mutant worms whose lifespan had been genetically shortened by 37 percent, treatment with 0.5 mM EUK-134 restored their lifespan to normal by increasing their mutation-reduced lifespan by 67 percent. It also was determined that these effects were not due to a reduction in worm metabolism, which could have reduced the production of oxygen radicals, but “by augmenting natural antioxidant defenses without having any overt effects on other traits.” In the words of the authors, “these results suggest that

endogenous oxidative stress is a major determinant of the rate of aging,” the significance of which statement resides in the fact that antioxidants tend to reduce such stresses in animals, including man.

Another study addressing the subject was conducted by Larsen and Clarke (2002), who fed diets with and without coenzyme Q to wild-type *Caenorhabditis elegans* and several mutants during the adult phases of their lives, while they recorded the lengths of time they survived. This work revealed that “withdrawal of coenzyme Q from the diet of wild-type nematodes extends adult life-span by ~60 percent.” In addition, they found that the lifespans of the four different mutants they studied were extended by a Q-less diet. More detailed experiments led them to conclude that the life-span extensions were due to reduced generation and/or increased scavenging of reactive oxygen species, leading them to conclude in the final sentence of their paper that “the combination of reduced generation and increased scavenging mechanisms are predicted to result in a substantial decrease in the total cellular ROS and thereby allow for an extended life-span.”

In light of these many diverse observations of both plants and animals, there is some reason to believe that the historical increase of CO₂ in the air has helped lengthen human lifespans since the advent of the Industrial Revolution, and that its continued upward trend will provide more of the same benefit.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/h/humanlifespan.php>.

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9.4. Food vs. Nature

Norman Borlaug, the father of the Green Revolution, recently expressed in a *Science* editorial his concern over the challenge of “feeding a hungry world” by noting that “some 800 million people still experience chronic and transitory hunger each year,” and that “over the next 50 years, we face the daunting job of

feeding 3.5 billion additional people, most of whom will begin life in poverty” (Borlaug, 2007). He described how the scientific and technological innovations he played a major role in discovering and implementing helped reduce the proportion of hungry people in the world “from about 60% in 1960 to 17% in 2000.” Had that movement failed, he says, environmentally fragile land would have been brought into agricultural production and the resulting “soil erosion, loss of forests and grasslands, reduction in biodiversity, and extinction of wildlife species would have been disastrous.”

Rising CO₂ concentrations in the air helped make it possible to feed a growing global population in the past without devastating nature, but what of the future? The world’s population in 2008 was estimated to be 6.7 billion and is projected to reach between 9.1 and 9.7 billion by 2050 (United Nations, 2009; U.S. Census Bureau, 2008). There is real concern about our ability to feed the world’s population a mere 50 years hence.

Tilman *et al.* (2001) analyzed the global environmental impacts likely to occur if agriculture is to keep pace with population growth. They report that “humans currently appropriate more than a third of the production of terrestrial ecosystems and about half of usable freshwaters.” They estimate that the amount of land devoted to agriculture by the year 2050 will have to increase 18 percent to meet the rising demand for food. Because developed countries are expected to withdraw large areas of land from farming over the next 50 years for recreation, open space, and reforestation, the net loss of natural ecosystems to cropland and pasture in developing countries will amount to about half of all potentially suitable remaining land, which would “represent the worldwide loss of natural ecosystems larger than the United States.” Similar warnings of a coming food vs. nature conflict have been expressed by other scientists, for example, Wallace (2000) and Raven (2002).

What, if anything, can be done to address this conflict between the need to produce food and the wish to preserve nature? And what role, if any, will climate change play in averting the crisis or making it even worse?

We begin by observing that the fear that there isn’t enough land to support a growing population’s food needs is a very old one, dating at least to Thomas Malthus (1798) and expressed in our day by popular writers such as Paul Ehrlich (2008) and Al Gore (1992). Predictions of widespread famine have

been wrong before, as trends in food production and daily intake of calories per capita, while not linear in the short term, show long-term positive trends that are driven primarily by gains in yields per acre, not expansion of the area under cultivation (Alexandratos, 1995; Goklany, 1999; Waggoner and Ausubel, 2001). Malthusian concerns are misplaced because, as Max Singer once explained, “multiplying food production by five times over the next one hundred or two hundred years will be easier than multiplying it by over seven times as we did in the last two hundred years. No miracles, no scientific breakthroughs, no unknown lands or unexpected new resources, and no reforms of human character or government are required. All that is required is a continuing use of current evolutionary processes in technology and in economic development, and as much peace as we have had in the last century” (Singer, 1987).

We also agree with the sensible assessment of science writer Gregg Easterbrook that “the whole notion that there is a proper level of population for *Homo sapiens*, or for any species, would be nonsensical to nature” and “there is no reason in principle that the Earth cannot support vastly more human beings than live upon it today, with other species preserved and wild habitats remaining intact” (Easterbrook, 1995). Similar sentiments have been expressed by Waggoner (1995, 1996), Waggoner *et al.* (1996), and Meyer and Ausubel (1999).

Regardless of whether the goal of feeding a growing population while protecting nature is attainable, the question remains about global warming’s role in this very real conflict. Tilman and a second set of collaborators, writing a year after their previously cited analysis, said “raising yields on existing farmland is essential for ‘saving land for nature’” (Tilman *et al.* (2002). They proposed a three-part strategy: (1) increasing crop yield per unit of land area, (2) increasing crop yield per unit of nutrients applied, and (3) increasing crop yield per unit of water used.

With respect to the first of these efforts—increasing crop yield per unit of land area—the researchers note that in many parts of the world the historical rate-of-increase in crop yield is declining as the genetic ceiling for maximal yield potential is being approached. This “highlights the need for efforts to steadily increase the yield potential ceiling.” With respect to the second effort—increasing crop yield per unit of nutrients applied—they note that “without the use of synthetic fertilizers, world food

production could not have increased at the rate [that it did in the past] and more natural ecosystems would have been converted to agriculture.” Hence, they say the solution “will require significant increases in nutrient use efficiency, that is, in cereal production per unit of added nitrogen.” With respect to the third effort—increasing crop yield per unit of water used—Tilman *et al.* note that “water is regionally scarce,” and that “many countries in a band from China through India and Pakistan, and the Middle East to North Africa either currently or will soon fail to have adequate water to maintain per capita food production from irrigated land.”

The ongoing rise in the atmosphere’s CO₂ concentration will help the world’s farmers achieve all three parts of the Tilman strategy. First, since atmospheric CO₂ is the basic “food” of nearly all plants, the more of it there is in the air, the better they function and the more productive they become. As discussed in Section 9.2, a 300 ppm increase in the atmosphere’s CO₂ concentration would increase the productivity of earth’s herbaceous plants by 30 to 50 percent (Kimball, 1983; Idso and Idso, 1994) and the productivity of its woody plants by 50 to 80 percent (Saxe *et al.*, 1998; Idso and Kimball, 2001). These increases will be in addition to whatever yield gains are made possible by advances in plant genetics, pest control, and other agricultural practices. Consequently, as the air’s CO₂ content continues to rise, so too will the land-use efficiency and productive capacity of the planet improve.

Regarding the second strategy, of increasing crop yield per unit of nutrients applied, many studies have investigated the effects of an increase in the air’s CO₂ content on plants growing in soils with different nitrogen concentrations. (See Chapter 7, Section 7.3.7, for a thorough review of these studies.) These studies found that many plants increase their photosynthetic nitrogen-use efficiency when atmospheric CO₂ concentration is raised. For example, Smart *et al.* (1998) found wheat grown in controlled-environment chambers maintained at an atmospheric CO₂ concentration of 1,000 ppm increased average plant biomass by approximately 15 percent, irrespective of soil nitrogen content.

Zerihun *et al.* (2000) studied the effects of CO₂ enrichment on sunflowers using three different soil nitrogen concentrations and found whole plant biomass values that were 44, 13 and 115 percent greater than those of the plants growing in ambient air at low, medium and high levels of soil nitrogen,

respectively. Deng and Woodward (1998) found that strawberries grown in high CO₂ environments produced 17 percent greater fresh fruit weight even when receiving the lowest levels of nitrogen fertilization. Newman *et al.* (2003) investigated the effects of two levels of nitrogen fertilization and an approximate doubling of the air's CO₂ concentration on the growth of tall fescue, an important forage crop. They found the plants grown in the high-CO₂ air and under low N conditions photosynthesized 15 percent more and produced 53 percent more dry matter (DM).

Demmers-Derks *et al.* (1998) grew sugar beets at atmospheric CO₂ concentrations of 360 and 700 ppm and high and low nitrogen treatment levels, and found the extra CO₂ enhanced total plant biomass by 13 percent even in plants receiving the low nitrogen treatments. Also working with sugar beets, Romanova *et al.* (2002) doubled atmospheric CO₂ concentrations while fertilizing plants with three different levels of nitrate-nitrogen. The plants exhibited rates of net photosynthesis that were approximately 50 percent greater than those displayed by the plants grown in ambient air, regardless of soil nitrate availability.

Fangmeier *et al.* (2000) grew barley plants in containers at atmospheric CO₂ concentrations of either 360 or 650 ppm and either a high or low nitrogen fertilization regime. The elevated CO₂ had the greatest relative impact on yield when the plants were grown under the less-than-optimum low-nitrogen regime, i.e., a 48 percent increase vs. 31 percent under high-nitrogen conditions.

Finally, the review and analysis of Kimball *et al.* (2002) of most FACE studies conducted on agricultural crops since the introduction of that technology back in the late 1980s found that in response to a 300-ppm increase in the air's CO₂ concentration, rates of net photosynthesis in several C₃ grasses were enhanced by an average of 46 percent under conditions of ample soil nitrogen supply and by 44 percent when nitrogen was limiting to growth. Clover experienced a 38 percent increase in belowground biomass production at ample soil nitrogen, and a 32 percent increase at low soil nitrogen. Wheat and ryegrass experienced an average increase of 18 percent at ample nitrogen, while wheat experienced only a 10 percent increase at low nitrogen.

Other studies have found that many species of plants respond to increases in the air's CO₂ content by increasing fine-root numbers and surface area, which tends to increase total nutrient uptake under CO₂-enriched conditions (Staddon *et al.*, 1999; Rouhier

and Read, 1998; BassiriRad *et al.*, 1998; and Barrett *et al.*, 1998). This once again advances the Tilman strategy of increasing crop yield per unit of available nutrient. (See Chapter 7, Section 7.8.2, for a thorough review of those studies.)

Tilman's third strategy—increasing crop yield per unit of water used—is also advanced by rising levels of CO₂ in the atmosphere. Plants exposed to elevated levels of atmospheric CO₂ generally do not open their leaf stomatal pores—through which they take in carbon dioxide and give off water vapor—as wide as they do at lower CO₂ concentrations and tend to produce fewer of these pores per unit area of leaf surface. Both changes tend to reduce most plants' rates of water loss by transpiration. The amount of carbon they gain per unit of water lost—or water-use efficiency—therefore typically rises, increasing their ability to withstand drought.

In the study of Serraj *et al.* (1999), soybeans grown at 700 ppm CO₂ displayed 10 to 25 percent reductions in total water loss while simultaneously exhibiting increases in dry weight of as much as 33 percent. Likewise, Garcia *et al.* (1998) determined that spring wheat grown at 550 ppm CO₂ exhibited a water-use efficiency that was about one-third greater than that exhibited by plants grown at 370 ppm CO₂. Hakala *et al.* (1999) reported that twice-ambient CO₂ concentrations increased the water-use efficiency of spring wheat by 70 to 100 percent, depending on experimental air temperature.

Hunsaker *et al.* (2000) reported CO₂-induced increases in water-use efficiency for field-grown wheat that were 20 and 10 percent higher than those displayed by ambiently grown wheat subjected to high and low soil nitrogen regimes, respectively. Also, pea plants grown for two months in growth chambers receiving atmospheric CO₂ concentrations of 700 ppm displayed an average water-use efficiency that was 27 percent greater than that exhibited by ambiently grown control plants (Gavito *et al.*, 2000). (See Chapter 7, Section 7.2, for a thorough review of those studies.)

An issue related to water-use efficiency that could become more important in the future is the buildup of soil salinity from repeated irrigations, which can sometimes reduce crop yields. Similarly, in natural ecosystems where exposure to brackish or salty water is commonplace, saline soils can induce growth stress in plants not normally adapted to coping with this problem. The studies reported below show that rising atmospheric CO₂ concentrations also can help to alleviate this problem.

Mavrogianopoulos *et al.* (1999) reported that atmospheric CO₂ concentrations of 800 and 1200 ppm stimulated photosynthesis in parson melons by 75 and 120 percent, respectively, regardless of soil salinity, which ranged from 0 to 50 mM NaCl. Atmospheric CO₂ enrichment also partially alleviated the negative effects of salinity on melon yield, which increased with elevated CO₂ at all salinity levels.

Maggio *et al.* (2002) grew tomatoes at 400 and 900 ppm in combination with varying degrees of soil salinity and noted that plants grown in elevated CO₂ tolerated an average root-zone salinity threshold value that was about 60 percent greater than that exhibited by plants grown at 400 ppm CO₂ (51 vs. 32 mmol dm⁻³ Cl). The review of Poorter and Perez-Soba (2001) found no changes in the effect of elevated CO₂ on the growth responses of most plants over a wide range of soil salinities, in harmony with the earlier findings of Idso and Idso (1994).

These various studies suggest that elevated CO₂ concentrations will help farmers achieve all three of the strategies Tilman *et al.* say are essential to addressing the conflict between feeding a growing human population and preserving space for nature. The actual degree of crop yield enhancement likely to be provided by the increase in atmospheric CO₂ concentration expected to occur between 2000 and 2050 has been calculated by Idso and Idso (2000) to be sufficient—but just barely—to close the gap between the supply and demand for food some four decades from now. Consequently, letting the evolution of technology take its course—which includes continued emissions of CO₂ into the atmosphere by industry—appears to be the only way we can grow enough food to support ourselves in the year 2050 without taking unconscionable amounts of land and freshwater resources from nature.

In spite of the dilemma described above and the fact that enhanced levels of CO₂, in the air are a necessary part of the solution, the IPCC calls for strict measures to reduce anthropogenic CO₂ emissions—a strategy that, if it has any effect at all on plant and animal life, would lead to lower land-use efficiency, lower nitrogen-use efficiency, and lower plant water-use efficiency, just the opposite of what Tilman *et al.* called for.

One might ask whose predictions are more reliable, the IPCC's computer-model-generated forecasts of catastrophic consequences due to rising temperatures a century or longer from now, or our projections of human population growth and

agricultural productivity just four decades into the future? In addition to the obvious time differential between the two sets of predictions, human population growth and agricultural productivity are much better-understood processes than is global climate change, which involves a host of complex phenomena that span a spatial scale of fully 14 orders of magnitude, ranging from the planetary scale of 10⁷ meters to the cloud microphysical scale of 10⁻⁶ meter.

Many of the component processes that comprise today's state-of-the-art climate models are so far from adequately understood (see Chapters 1 and 2) that even the *signs* of their impacts on global temperature change (whether positive or negative) are not yet known. Consequently, in light of the much greater confidence that can realistically be vested in demographic and agricultural production models, it would seem that much greater credence can be placed in our predictions than in the predictions of climate doom.

In conclusion, the aerial fertilization effect of the increase in the air's CO₂ content that is expected to occur by the year 2050 would boost crop yields by the amounts required to prevent mass starvation in many parts of the globe, without a large-scale encroachment on the natural world. Acting prematurely to reduce human CO₂ emissions, as urged by the IPCC, could interrupt this response, resulting in the death by starvation of millions of people, loss of irreplaceable natural ecosystems, or both.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/f/food.php>.

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9.5. Biofuels

Biofuels are liquid and gaseous fuels made from organic matter. They include ethanol, biodiesel, and methanol. Biofuels may have some advantages over gasoline and diesel fuels, but they are more expensive to produce and can supply only a small part of the world's total transportation energy needs. Because they compete with food crops and nature for land and nutrients, expanding the use of biofuels could negatively affect human health and natural ecosystems.

The IPCC does not discuss biofuels in the contributions of Group I (Science) or Group II (Impacts, Adaptation and Vulnerability) to the Fourth Assessment Report. When it finally does discuss them, in two sections of the contribution of Group III (Mitigation), it fails to address the likely adverse consequences of increased use of biofuels on human health and the natural environment. We discuss those consequences in this section.

9.5.1. About Biofuels

Biofuels are not new—Henry Ford's first vehicle was fueled by ethanol—and conversion technologies exist or are in development for converting biomass into a wide range of biofuels suitable for heating, electric production, and transportation. For example, residues from agriculture and forestry long have been used by the lumber and papermaking industries to generate heat and power. Methane from animal waste and composting is captured and used locally or sold in commercial markets.

Of particular interest, and the focus of this section, is the biochemical conversion using enzymes of corn, soybeans, sugarcane, and other food crops into ethanol, biodiesel, and other biofuels used mainly for transportation. The country with the most aggressive biofuels program in the world is Brazil. After the country launched its National Alcohol Program in 1975, ethanol production in Brazil rose dramatically and now accounts for approximately 40 percent of total fuel consumption in the country's passenger vehicles (EIA, 2008).

Ethanol became popular as a gasoline supplement in the U.S. during the 1990s, when Congress mandated that oil refiners add oxygenates to their product to reduce some emissions. Congress did not provide liability protection for the makers of methyl tertiary butyl ether (MTBE), ethanol's main

competitor in the oxygenate business, so most companies quickly switched from MTBE to ethanol (Lehr, 2006). Some states also began to mandate ethanol use for reasons discussed below.

Most ethanol made in the U.S. comes from corn. Its production consumed 13 percent of the U.S. corn crop (1.43 billion bushels of corn grain) in 2005 and an estimated 20 percent of the 2006 crop. E10 (a blend of 10 percent ethanol and 90 percent gasoline) is widely available. E85 is an alternative fuel (85 percent ethanol and 15 percent gasoline) available mainly in corn-producing states; vehicles must be modified to use this fuel.

The Energy Policy Act of 2005 mandated the use of 4 billion gallons of ethanol in 2006. The 2007 Energy Independence and Security Act (EISA) subsequently mandated the use of 36 billion gallons of renewable fuels by 2022—16 billion gallons of cellulosic ethanol, 15 billion gallons of corn ethanol, and 5 billion gallons of biodiesel and other advanced biofuels (U.S. Congress, 2007).

Federal subsidies to ethanol producers in the U.S. cost taxpayers about \$2 billion a year (Dirksen, 2006). Congress protects domestic ethanol producers by imposing a 2.5 percent tariff and 54 cents per gallon duty on imports. Ethanol producers with plants of up to 60 million gallons annual production capacity are eligible to receive a production incentive of 10 cents per gallon on the first 15 million gallons of ethanol produced each year. Ethanol is also subsidized by scores of other countries and by at least 19 U.S. states (Doornbosch and Steenblich, 2007, Annex 1, pp. 45-47).

U.S. ethanol output rose from 3.4 billion gallons from 81 facilities in 2004 to 9 billion gallons from 170 facilities in 2008 (RFA, 2009). According to a forecast by the Energy Information Administration (EIA), "total U.S. biofuel consumption rises from 0.3 quadrillion Btu (3.7 billion gallons) in 2005 to 2.8 quadrillion Btu (29.7 billion gallons) in 2030, when it represents about 11.3 percent of total U.S. motor vehicle fuel on a Btu basis" (EIA, 2008). In 2005 ethanol represented about 2 percent of total gasoline consumption, and biodiesel less than 0.2 percent of diesel consumption, in the U.S.

Doornbosch and Steenblich (2007), in a report produced for the Organization for Economic Cooperation and Development (OECD), reported that "global production of biofuels amounted to 0.8 EJ [exajoule] in 2005, or roughly 1% of total road transport fuel consumption. Technically, up to 20 EJ from conventional ethanol and biodiesel, or 11% of

total demand for liquid fuels in the transport sector, has been judged possible by 2050.” Also for the world as a whole, EIA predicts “alternative fuels [will] account for only 9 percent of total world liquids use in 2030, despite an average annual increase of 5.6 percent per year, from 2.5 million barrels per day in 2005 to 9.7 million barrels per day in 2030” (EIA, 2008).

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9.5.2. Costs and Benefits

Proponents of biofuels say their increased production will increase the supply of transportation fuels and therefore lead to lower prices. Critics of biofuels point out that ethanol often costs more, not less, than gasoline, either because of production costs or supplies that can’t keep pace with government mandates, and therefore leads to higher prices at least in the short run.

Ethanol has only two-thirds the energy content of gasoline, which makes it a poor value for most consumers. The production cost of ethanol (which is only one component in determining its price) has fallen as a result of technological innovation and economies of scale, but some properties of ethanol continue to make it expensive compared to gasoline. Transportation costs for ethanol, for example, are high because it picks up water if it travels through

existing pipelines, diluting the ethanol and corroding the pipelines. Therefore, it is being trucked to the Northeast and along the Gulf Coast. Ethanol must be kept in a different container at the terminal and is blended into the gasoline in the truck on its way to the retailer from the terminal. This has caused regional shortages, further increasing the retail prices in these areas (Dirksen, 2006).

Ethanol also has been promoted as a fuel additive to reduce emissions. It reduces carbon monoxide in older vehicles and dilutes the concentration of aromatics in gasoline, reducing emissions of toxins such as benzene. Because ethanol has only two-thirds the energy content per volume as gasoline, it increases volumetric fuel use (with small increases in energy efficiency.) Ethanol increases air emissions such as aldehydes. In some areas, the use of 10 percent ethanol blends may increase ozone due to local atmospheric conditions (Niven, 2004).

Ethanol also is promoted as a “homegrown” and renewable energy source, so using more of it could help reduce a country’s dependency on foreign oil, which in turn might benefit national security and international relations. But ethanol used in the U.S. mostly supplants oil from domestic suppliers, which is more expensive than foreign oil, and leaves the country’s dependency on foreign oil the same or even makes it higher (Yacobucci, 2006). Rural communities benefit from the economic boost that comes from higher prices for corn and the jobs created by ethanol plants, but those economic benefits come at a high price in terms of higher food prices and tax breaks financed by government debt or higher taxes on other goods and services.

Finally, biofuels are renewable resources, which advocates say makes them environmentally friendlier than fossil fuels. But the energy consumed to make biofuels—to plant, fertilize, irrigate, and harvest corn and other feedstocks as well as to generate the heat used during the fermentation process and to transport biofuels to markets by train or trucks—is considerable. Fossil fuels (natural gas or coal) are typically the source of that energy. This environmental impact is the focus of the rest of this section.

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9.5.3. Net Emissions

The US 2007 Energy Independence and Security Act (EISA) mandates that life-cycle greenhouse gas emissions of corn ethanol, cellulosic ethanol, and advanced biofuels achieve 20 percent, 60 percent, and 50 percent greenhouse gas (GHG) emission reductions relative to gasoline, respectively. But there is considerable controversy over whether these fuels do in fact reduce GHG emissions.

Numerous studies of GHG emissions produced during the life-cycle of ethanol (from the planting of crops to consumption as a fuel) have found them to be less than those of gasoline, with most estimates around 20 percent (Hill *et al.*, 2006; Wang *et al.*, 2007; CBO, 2009). Emissions vary considerably based on the choice of feedstock, production process, type of fossil fuels used, location, and other factors (ICSU, 2009). Liska *et al.* (2009), in their study of life-cycle emissions of corn ethanol systems, found the direct-effect GHG emissions of ethanol (without any offset due to changes in land use) to be “equivalent to a 48% to 59% reduction compared to gasoline, a twofold to threefold greater reduction than reported in previous studies,” largely because they incorporate a credit for the commercial use of dry distilled grain (DDG). They report that “in response to the large increase in availability of distillers grains coproduct from ethanol production and the rise in soybean prices, cattle diets now largely exclude soybean meal and include a larger proportion of distillers grains coproduct (Klopfenstein *et al.*, 2008). Thus, the energy and GHG credits attributable to feeding distillers grains must be based on current practices for formulating cattle diets.” They give corn ethanol systems DDG credits ranging from 19% to 38% depending on region and type of fossil fuels used.

None of these estimates, however, takes into account the emission increases likely to come about from land-use changes. Righelato and Spracklen (2007) wrote that using ethanol derived from crops as a substitute for gasoline, and vegetable oils in place of diesel fuel, “would require very large areas of land in

order to make a significant contribution to mitigation of fossil fuel emissions and would, directly or indirectly, put further pressure on natural forests and grasslands.” The two British scientists calculated that a 10 percent substitution of biofuels for gasoline and diesel fuel would require “43% and 38% of current cropland area in the United States and Europe, respectively,” and that “even this low substitution level cannot be met from existing arable land.”

Righelato and Spracklen add that “forests and grasslands would need to be cleared to enable production of the energy crops,” resulting in “the rapid oxidation of carbon stores in the vegetation and soil, creating a large up-front emissions cost that would, in all cases examined, out-weigh the avoided emissions.” They report further that individual life-cycle analyses of the conversion of sugar cane, sugar beet, wheat, and corn to ethanol, as well as the conversion of rapeseed and woody biomass to diesel, indicate that “forestation of an equivalent area of land would sequester two to nine times more carbon over a 30-year period than the emissions avoided by the use of the biofuel.” They conclude that “the emissions cost of liquid biofuels exceeds that of fossil fuels.”

Fargione *et al.* (2008), writing in *Science*, said “increasing energy use, climate change, and carbon dioxide (CO₂) emissions from fossil fuels make switching to low-carbon fuels a high priority. Biofuels are a potential low-carbon energy source, but whether biofuels offer carbon savings depends on how they are produced.” They explain that “converting native habitats to cropland releases CO₂ as a result of burning or microbial decomposition of organic carbon stored in plant biomass and soils. After a rapid release from fire used to clear land or from the decomposition of leaves and fine roots, there is a prolonged period of GHG release as coarse roots and branches decay and as wood products decay or burn. We call the amount of CO₂ released during the first 50 years of this process the ‘carbon debt’ of land conversion. Over time, biofuels from converted land can repay this carbon debt if their production and combustion have net GHG emissions that are less than the life-cycle emissions of the fossil fuels they displace. Until the carbon debt is repaid, biofuels from converted lands have greater GHG impacts than those of the fossil fuels they displace.”

Fargione *et al.* calculate the number of years required to repay carbon debts for six areas: Brazilian Amazon (319 years), Brazilian Cerrado wooded (17 years), Brazilian Cerrado grassland (37 years), Indonesian or Malaysian lowland tropical rainforest

(86 years), Indonesian or Malaysian peatland tropical rainforest (423 years), and U.S. central grassland (93 years). They observe that no carbon debt is incurred when abandoned cropland or marginal prairie in the U.S. is used without irrigation to produce ethanol. They conclude that “the net effect of biofuels production via clearing of carbon-rich habitats is to increase CO₂ emissions for decades or centuries relative to the emissions caused by fossil fuel use,” and “at least for current or developing biofuels technologies, any strategy to reduce GHG emissions that causes land conversion from native ecosystems to cropland is likely to be counterproductive.”

In a companion essay in the same issue of *Science*, Searchinger *et al.* (2008) also describe the carbon debt due to land-use conversion, but measure it as the difference between biofuels and gasoline in GHG emissions measured in grams per MJ (megajoule) of energy. They begin by explaining that “to produce biofuels, farmers can directly plow up more forest or grassland, which releases to the atmosphere much of the carbon previously stored in plants and soils through decomposition or fire. ... Alternatively, farmers can divert existing crops or croplands into biofuels, which causes similar emissions indirectly. The diversion triggers higher crop prices, and farmers around the world respond by clearing more forest and grassland to replace crops for feed and food.”

Searchinger *et al.* used the Greenhouse gases Regulated Emissions and Energy use in Transportation (GREET) computer program created by the Center for Transportation Research at Argonne National Laboratory to calculate the GHGs in grams of CO₂ equivalent emissions per MJ of energy consumed over the production and use life-cycles of gasoline, corn ethanol, and biomass ethanol fuels. They observe that “emissions from corn and cellulosic ethanol emissions exceed or match those from fossil fuels, and therefore produce no greenhouse benefits,” unless biofuels are given a “carbon uptake credit” for the amount of carbon dioxide removed from the air by the growing biofuels feedstocks. When that adjustment is made, they estimate that gasoline (which gets no carbon uptake credit) produces 92g/MJ; corn ethanol, 74g/MJ; and biomass ethanol, 27g/MJ.

Searchinger *et al.* then calculate the amount of land that would be converted from forest and grassland into cropland to support the biofuels and, like Fargione *et al.* (2008), apply the GHG emissions

due to land-use change to each type of fuel. The result is that total net GHG emissions from both kinds of biofuel *exceed* those from gasoline, 177g vs. 92g in the case of corn ethanol and 138g vs. 92g in the case of biomass ethanol. They conclude that “corn-based ethanol, instead of producing a 20% savings, nearly doubles greenhouse emissions over 30 years and increases greenhouse gases for 167 years. Biofuels from switchgrass, if grown on U.S. corn lands, increase emissions by 50%. This result raises concerns about large biofuels mandates and highlights the value of using waste products.”

Coming to much the same conclusion, Laurance (2007) observed that “tropical forests, in particular, are crucial for combating global warming, because of their high capacity to store carbon and their ability to promote sunlight-reflecting clouds via large-scale evapotranspiration,” which led him to conclude that “such features are key reasons why preserving and restoring tropical forests could be a better strategy for mitigating the effects of carbon dioxide than dramatically expanding global biofuel production.”

Doornbosch and Steenblik (2007), while reporting that biofuels could provide up to 11 percent of the total world demand for road transport fuel by 2050, say “an expansion on this scale could not be achieved, however, without significant impacts on the wider global economy. In theory there might be enough land available around the globe to feed an ever increasing world population and produce sufficient biomass feedstock simultaneously, but it is more likely that land-use constraints will limit the amount of new land that can be brought into production leading to a ‘food-versus-fuel’ debate.”

Looking at a different environmental impact of expanded biofuel production, Crutzen and three collaborators calculated the amount of nitrous oxide (N₂O) that would be released to the atmosphere as a result of using nitrogen fertilizer to produce the crops used for biofuels (Crutzen *et al.*, 2007). Their work revealed that “all past studies have severely underestimated the release rates of N₂O to the atmosphere, with great potential impact on climate warming” because, as they report, N₂O “is a ‘greenhouse gas’ with a 100-year average global warming potential 296 times larger than an equal mass of CO₂.” The consequence is that “when the extra N₂O emission from biofuel production is calculated in ‘CO₂-equivalent’ global warming terms, and compared with the quasi-cooling effect of ‘saving’ emissions of CO₂ derived from fossil fuel,

the outcome is that the production of commonly used biofuels, such as biodiesel from rapeseed and bioethanol from corn, can contribute as much or more to global warming by N₂O emissions than cooling by fossil fuel savings.”

Crutzen *et al.* concluded that “on a globally averaged basis the use of agricultural crops for energy production ... can readily be detrimental for climate due to the accompanying N₂O emissions.” Their concerns were confirmed by a 2009 report from the International Council for Science (ICSU), which found “the increased N₂O flux associated with producing ethanol from corn is likely to more than offset any positive advantage from reduced carbon dioxide fluxes (compared to burning fossil fuels). Even for ethanol from sugar cane or biodiesel from rapeseed, emissions of nitrous oxide probably make these fuels less effective as an approach for reducing global warming than has been previously believed” (ICSU, 2009).

Producing ethanol from crop residues, or stover, is often proposed as a way to avoid carbon emissions arising from land conversion. But as Lal (2007) points out, crop residues perform many vital functions. He reports that “there are severe adverse impacts of residue removal on soil and environmental degradation, and negative carbon sequestration as is documented by the dwindling soil organic carbon reserves.” He notes that “the severe and widespread problem of soil degradation, and the attendant agrarian stagnation/deceleration, are caused by indiscriminate removal of crop residues.” Lal concludes that “short-term economic gains from using crop residues for biofuel must be objectively assessed in relation to adverse changes in soil quality, negative nutrients and carbon budget, accelerated erosion, increase in non-point source pollution, reduction in agronomic production, and decline in biodiversity.”

Finally, while using abandoned or degraded lands to produce biomass, rather than converting existing cropland or forests, is often alleged to reduce carbon emissions (e.g., Fargione *et al.*, 2008), the ICSU report notes that “of course, if the lands have the potential to revert to forests, conversion to biofuels represents a lost opportunity for carbon storage. The environmental consequences of inputs (irrigation water, fertilizer) required to make degraded and marginal lands productive must also be considered” (ICSU, 2009).

In conclusion, the production and use of biofuels frequently does not reduce net GHG emissions relative to gasoline, the fossil fuel they are intended to

replace. Therefore, there is no basis from an environmental perspective for preferring them to fossil fuels.

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9.5.4. Impact on Food Prices

Biofuel refineries compete with livestock growers and food processors for corn, soybeans, and other feedstocks usually used to produce biofuels in the United States, leading to higher animal feed and ingredient costs for farmers, ranchers, and food manufacturers. Some of that cost is eventually passed on to consumers. A study by the Congressional Budget Office (CBO) found “the demand for corn for ethanol production, along with other factors, exerted upward pressure on corn prices, which rose by more than 50 percent between April 2007 and April 2008. Rising demand for corn also increased the demand for cropland and the price of animal feed” (CBO, 2009). The CBO estimated that increased use of ethanol “contributed between 0.5 and 0.8 percentage points of the 5.1 percent increase in food prices measured by the consumer price index (CPI).”

Johansson and Azar (2007) analyzed what they called the “food-fuel competition for bio-productive land,” developing in the process “a long-term economic optimization model of the U.S. agricultural and energy system,” wherein they found that the competition for land to grow crops for both food and fuel production leads to a situation where “prices for all crops as well as animal products increase substantially.” Similarly, Doornbosch and Steenblich (2007) say “any diversion of land from food or feed production to production of energy biomass will influence food prices from the start, as both compete for the same inputs. The effects on farm commodity prices can already be seen today. The rapid growth of the biofuels industry is likely to keep these prices high and rising throughout at least the next decade (OECD/FAO, 2007).”

Runge and Senauer (2007), writing in *Foreign Affairs*, reported that the production of corn-based ethanol in the United States “takes so much supply to keep ethanol production going that the price of corn—and those of other food staples—is shooting up around the world.” The rising prices caused food riots to break out in Haiti, Bangladesh, Egypt, and Mozambique in April 2008, prompting Jean Ziegler, the United Nations’ “special rapporteur on the right to food,” to call using food crops to create ethanol “a crime against humanity” (CNN, 2008). Jeffrey Sachs, director of Columbia University’s Earth Institute, said

at the time, “We’ve been putting our food into the gas tank—this corn-to-ethanol subsidy which our government is doing really makes little sense” (Ibid.). Former U.S. President Bill Clinton was quoted by the press as saying “corn is the single most inefficient way to produce ethanol because it uses a lot of energy and because it drives up the price of food” (Ibid.). Unfortunately, as the CBO report concluded a year later, corn is likely to remain the main source of ethanol for quite some time as “current technologies for producing cellulosic ethanol are not commercially viable” (CBO, 2009).

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9.5.5. Use of Water

The third strategy proposed by Tilman *et al.* (2002) to address the conflict between growing food and preserving natural ecosystems is finding ways to conserve water. Biofuels, as the following studies demonstrate, fail to advance this objective.

Elcock (2008) projects that 12.9 billion gallons per day of water will be consumed in the manufacture of ethanol by 2030. This “increase accounts for roughly 60% of the total projected nationwide increase in water consumption over the 2005-2030 period, and it is more than double the amount of water projected to be consumed for industrial and commercial use in 2030 by the entire United States.”

A 2009 study by Argonne National Laboratory estimated life-cycle water consumption for one gallon of four types of fuel: ethanol, gasoline from domestic conventional crude oil, gasoline from Saudi conventional crude oil, and gasoline from Canadian oil sands (Wu *et al.*, 2009). For ethanol, they estimated an average consumption of 3.0 gallon of water/gallon of corn ethanol during the production process in a corn dry mill, a yield of 2.7 gallons of ethanol per bushel of corn, and the average consumptive use of irrigation water for corn farming in three U.S. Department of Agriculture Regions (5, 6, and 7) representing the vast majority of corn production in the United States. They found “total groundwater and surface water use for corn growing vary significantly across the three regions, producing 1 gallon of corn-based ethanol consumes a net of 10 to 17 gallon of freshwater when the corn is grown in Regions 5 and 6, as compared with 324 gallon when the corn is grown in Region 7.” When these figures are adjusted to reflect the lower Btu/gallon of ethanol compared to gasoline (75,700 / 115,000, or .66), the amount of water consumed per gallon of gasoline equivalent ranges from 15.2 to 25.8 gallons in Regions 5 and 6 and 492 gallons in Region 7.

Wu *et al.* (2009) found the amount of water required to create a gallon of gasoline was dramatically less: 3.4-6.6 gallons of water to make one gallon of gasoline from U.S. conventional crude oil, 2.8-5.8 gallons to make one gallon of gasoline from Saudi conventional crude, and 2.6-6.2 gallons to make one gallon of gasoline from Canadian oil sands.

An even more recent review of the literature conducted by the International Council for Science (ICSU) found “the water requirements of biofuel-derived energy are 70 to 400 times larger than other energy sources such as fossil fuels, wind or solar.

Roughly 45 billion cubic meters of irrigation water were used for biofuel production in the [sic] 2007, or some 6 times more water than people drink globally” (ICSU, 2009). The authors also point out that “severe water pollution can result from runoff from agricultural fields and from waste produced during the production of biofuels,” and that “the increase in corn [production] to support ethanol goals in the United States is predicted to increase nitrogen inputs to the Mississippi River by 37%.”

In light of this evidence, there can be little doubt that biofuels are a much less efficient use of scarce water resources than are fossil fuels. This means increased reliance on fossil fuels would make it more difficult to increase food production per unit of water in the future, one of Tilman *et al.*'s three strategies to solve the food vs. nature conflict.

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9.5.6. Conclusion

The production and use of biofuels has increased dramatically in recent years, due largely to government mandates and taxpayer subsidies. But the alleged environmental benefits of these “renewable fuels” disappear upon close inspection. As Doornbosch and Steenblich (2007) say in their OECD report, “when such impacts as soil acidification,

fertilizer use, biodiversity loss and toxicity of agricultural pesticides are taken into account, the overall environmental impacts of ethanol and biodiesel can very easily exceed those of petrol and mineral diesel. The conclusion must be that the potential of the current technologies of choice—ethanol and biodiesel—to deliver a major contribution to the energy demands of the transport sector without compromising food prices and the environment is very limited.”

The decision by the IPCC and many environmental groups to embrace ethanol pits energy production against food production, making even worse the conflict between the two that this section has addressed. There can be little doubt that ethanol mandates and subsidies have made both food *and* energy more, not less, expensive, and therefore less

available to a growing population. The extensive damage to natural ecosystems already caused by this poor policy decision, and the much greater destruction yet to come, are a high price to pay for refusing to understand and utilize the true science of climate change.

Additional information on this topic, including reviews of newer publications as they become available, can be found at <http://www.co2science.org/subject/b/biofuels.php>

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