Rising Carbon Dioxide Is Great for Plants

by Sylvan H. Wittwer

From the Fall 1992 issue of Policy Review

To subscribe to Policy Review, call (800) 544-4843.

One of the best-kept secrets in the global warming debate is that the plant life of Planet Earth would benefit greatly from a higher level of carbon dioxide (CO2) in the atmosphere.

You read that correctly. Flowers, trees, and food crops love carbon dioxide, and the more they get of it, the more they love it. Carbon dioxide is the basic raw material that plants use in photosynthesis to convert solar energy into food, fiber, and other forms of biomass. Voluminous scientific evidence shows that if CO2 were to rise above its current ambient level of 360 parts per million, most plants would grow faster and larger because of more efficient photosynthesis and a reduction in water loss. There would also be many other benefits for plants, among them greater resistance to temperature extremes and other forms of stress, better growth at low light intensities, improved root/top ratios, less injury from air pollutants, and more nutrients in the soil as a result of more extensive nitrogen fixation.

This good news about carbon dioxide has been all but ignored in alarmist discussions about possible global climate changes. CO2-related benefits were barely mentioned at the Earth Summit in Rio de Janeiro in June, where the rising level of carbon dioxide and other "greenhouse gases" was decried as the world's greatest environmental threat. The Rio Summit ended with the United States and over 150 other nations signing a Framework Convention on Climate Change, committing themselves to stabilizing emissions of CO2 and other greenhouse gases at 1990 levels.

Indeed, the conventional wisdom in public policy circles is that carbon dioxide is a terrible pollutant that threatens the fate of the earth. Senator Albert Gore, the Democratic vice-presidential candidate, calls for stiff "carbon taxes" on the burning of fossil fuels, and has written in his book Earth in the Balance that the process of "filling the atmosphere with carbon dioxide and other pollutants...is a willful expansion of our dysfunctional civilization into ulnerable parts of the natural world."

On the Republican side, William K. Reilly, President Bush's administrator of the Environmental Protection Agency, defends the $20 billion in costs that the Clean Air Act of 1990 has imposed on the U.S. economy, in part on the grounds that it "will eliminate 56 billion pounds of pollutants annually, many of them greenhouse gases."

And yet, for over 100 years, nurserymen have been adding carbon dioxide to their greenhouses to raise the yields of vegetables, flowers, and ornamental plants. And for decades, it has been well known among botanists, biochemists, agriculturalists, and foresters that a shortage of carbon dioxide is the most common limiting factor preventing photosynthesis from proceeding more efficiently.

The Global Warming Debate

There is no question that the carbon dioxide level in the atmosphere has been rising, and that this rise is due primarily to the burning of fossil fuels and to deforestation. Measured in terms of volume, there were about 280 parts of CO2 in every million parts of air at the beginning of the Industrial Revolution, and there are 360 parts per million (ppm) today, a 30 percent rise. The annual increase is 2 ppm, and rising. If present trends continue, the concentration of CO2 in the atmosphere will double to about 700 ppm in the latter half of the 21st century. This increase would not be a direct threat to human life; the threshold in mine-safety regulations is 5,000 ppm of carbon dioxide. But a man-made change of this magnitude in the atmosphere requires careful efforts to understand its consequences.

A number of climatologists have used computer models to predict a rise in global temperatures of 2 to 9 degrees Fahrenheit over the next century as a result of this projected rise in CO2 and other greenhouse gases, such as methane. The global warming hypothesis is disputed by many climate scientists. Even so, it is understandable that so many environmentalists and citizens would be concerned by a doubling of atmospheric carbon dioxide levels. In so changing the composition of the air, humans are inadvertently conducting a global and environmental experiment without a clear knowledge of the outcome.

While scientists disagree about the likely effects of additional carbon dioxide on global temperature, they generally agree on another important effect of a rise in the CO2 level. A doubling of the carbon dioxide concentration in the atmosphere, as is projected, would increase plant productivity by almost one-third. Most plants would grow faster and bigger, with increases in leaf size and thickness, stem height, branching, and seed production. The number and size of fruits and flowers would also rise. Root/top ratios would increase, giving many plants better root systems for access to water and nutrients.

More Efficient Photosynthesis

There are two important reasons for this productivity boost at higher CO2 levels. One is superior efficiency of photosynthesis. The other is a sharp reduction in water loss per unit of leaf area.

Photosynthesis converts the renewable energy of sunlight into energy that living creatures can use. In the presence of chlorophyll, plants use sunlight to convert carbon dioxide and water into carbohydrates that, directly or indirectly, supply almost all animal and human needs for food; oxygen and some water are released as by-products of this process. The principal factors affecting the rate of photosynthesis are a favorable temperature, the level of light intensity, and the availability of carbon dioxide. Most green plants respond quite favorably to concentrations of CO_2 well above current atmospheric levels.

A related benefit comes from the partial closing of pores in leaves that is associated with higher CO_2 levels. These pores, known as stomata, admit air into the leaf for photosynthesis, but they are also a major source of transpiration or moisture loss. By partially closing these pores, higher CO_2 levels greatly reduce the plants' water loss--a significant benefit in arid climates.

There are marked variations in response to CO_2 among plant species. The biggest differences are among three broad categories of plants--C3, C4, and Crassulacean Acid Metabolism or CAM--each with a different pathway for photosynthetic fixation of carbon dioxide.

Most green plants, including trees, algae, and most major food crops, use the C3 pathway, so named because the first products of photosynthesis (called photosynthate) have three carbon atoms per molecule. C3 plants respond most dramatically to higher levels of CO_2 . At current atmospheric levels of CO_2, up to half of the photosynthate in C3 plants is typically lost and returned to the air by a process called photo-respiration, which occurs simultaneously with photosynthesis in sunlight. Elevated levels of atmospheric CO_2 virtually eliminate photo-respiration in C3 plants, making photosynthesis much more efficient. High CO_2 levels also sharply reduce dark respiration (the partial destruction of the products of photosynthesis during nighttime) among C3 plants.

Corn, sugarcane, sorghum, millet, and some tropical grasses use the C4 pathway, so named because the first products of photosynthesis have four carbon atoms per molecule. C4 plants also experience a boost in photosynthetic efficiency in response to higher carbon dioxide levels, but because there is little photo-respiration in C4 plants, the improvement is smaller than in C3 plants. Instead, the largest benefit C4 plants receive from higher CO_2 levels comes from reduced water loss. Loss of water through leaf pores declines by about 33 percent in C4 plants with a doubling of the CO_2 concentration from its current atmospheric level. Since corn and other C4 plants are frequently grown under drought conditions of high temperatures and limited soil moisture, this superior efficiency in water use may improve yields when rainfall is even lower than normal.

The lowest response to higher CO_2 levels is usually from the CAM plants, which include pineapples, agaves, and many cacti and other succulents. Like the C4 plants, CAM plants do not undergo photo-respiration. CAM plants are also already well adapted for efficient water use. Under arid conditions they fix carbon dioxide at night, when the stomata are open and water loss is minimal. During the day their stomata are closed, and stored CO_2 is released so photosynthesis can proceed. However, some CAM plants follow the C3 pathway when they are not under water stress; thus, succulents that receive plenty of water experience higher productivity at elevated levels of carbon dioxide.

Thousands of Experiments

Thousands of scientific experiments have been conducted to measure the effects of carbon dioxide enrichment on specific plants. In most green plants, productivity continues to rise up to CO_2 concentrations of 1,000 ppm and above. For rice, the optimal CO_2 level is between 1,500 and 2,000 ppm. For unicellular algae, the optimal level is 10,000 to 50,000 ppm.

Bruce Kimball, a research leader of the Water Conservation Laboratory of the U.S. Department of Agriculture in Phoenix, Arizona, has pulled together nearly 800 scientific observations from around the world measuring the response of food and flower crops to elevated CO_2 concentrations. The mean (average) response to a doubling of the CO_2 concentration from its current level of 360 ppm is a 32 percent improvement in plant productivity, with varied manifestations in different species.

Greenhouse-grown vegetables, including tomatoes, cucumbers, and lettuce, show earlier maturity, larger fruit size, greater numbers of fruit, a reduction in cropping time, and yield increases ranging from 10 to 70 percent, averaging 20 to 50 percent.

Greenhouse-grown flower crops, including roses, carnations, and chrysanthemums, grow to earlier maturity, and have longer stems and larger, longer-lived, more colorful flowers. Yield increases range from 9 to 15 percent, with a mean of 12 percent.

Flowers and ornamental plants propagated by cuttings, such as geraniums and a number of herbaceous and woody species, show faster and more extensive rooting, with greater plant heights and dry weight. There are also significant reductions in the time needed to grow a marketable product.

Cereal grains with C3 metabolism, including rice, wheat, barley, oats, and rye, show yield increases ranging from 25 to 64 percent, resulting from a rise in carbon fixation and reduction in photo-respiration. Flag leaves, the ones closest to grain panicles or heads, show a 60 percent increase in photosynthetic rates.

Food crops with C4 metabolism, including corn, sorghum, millet, and sugarcane, show yield increases ranging from 10 to 55 percent, resulting primarily from superior efficiency in water use.

Tuber and root crops, including potatoes and sweet potatoes, show dramatic increase in tuberization (potatoes) and growth of roots (sweet potatoes). Yield increases range from 18 to 75 percent.

Legumes, including peas, beans, and soybeans, show yield increases of 28 to 46 percent.

For soybeans, frequently planted not only for their food value but because they naturally fertilize the soil, there is a spectacular increase in biological nitrogen fixation, as will be shown below.

Aquatic plants are commonly limited in their growth by a shortage of carbon dioxide. CO2 enrichments induce three- to five-fold increases in algal biomass when light and mineral nutrients, especially phosphorus, are plentiful. In lakes and ponds with severe pollution, a higher CO2 concentration may therefore accentuate the danger of oxygen depletion through a buildup in algae population. This could lead to the death of fish, as happened in Lake Erie until there was a major reduction in pollutants, including phosphates. Aquatic species with foliage above the water, such as the water hyacinth, produce about 40 percent more biomass when the CO2 concentration is doubled. Such an increase could aggravate an already serious weed problem in fresh water lakes and streams.

Flower Power

The benefits of carbon dioxide enrichment are well-known among commercial growers of flowers and vegetables. Paul Nielsen, a rose grower in Santa Barbara, California, puts carbon dioxide into his greenhouse every morning before the vents are opened. "We find that roses respond well to carbon dioxide levels of 1,000 to 1,100 ppm," says Nielsen. "The stems are larger and thicker, and there are more stems per plant."

Dick Oglevee, of Connellsville, Pennsylvania, is America's largest grower of geraniums. From the beginning of September through the middle of May, he burns natural gas in his greenhouses to keep the CO2 concentration at 1,000 ppm. "More carbon dioxide gives us stronger stalks, better breaking, and more cuttings per week," says Oglevee. "I wish we could do this in the summer too, but it's too hot to keep the vents closed."

Richard Gerhart, a cucumber and tomato grower in North Ridgeville, Ohio, is also a big fan of CO2 enrichment: "Half the dry matter in a tomato or cucumber is carbon, and the only place that comes from is carbon dioxide in the air." Gerhart maintains a 600 ppm concentration in his greenhouses, except on cloudy days, when he gets even better results by raising the concentration to 800-1,000 ppm.

American commercial greenhouses have used carbon dioxide fertilization for tomatoes, lettuce, cucumbers, flower and foliage plants, and bedding plants for at least 30 years. The benefits of this enrichment were first discovered by nurserymen in Germany 100 years ago, and the practice is widely used in Sweden, Denmark, Holland, Germany, Australia, and Japan, as well as the United States and Canada. Carbon dioxide enrichment is economical when greenhouse vents can be closed. It is therefore used most often in winter in northern areas and in the southerly latitudes of the Southern Hemisphere.

It is also standard practice for laboratory scientists working with algae cultures to conduct their research in CO_2-enriched environments. "Most experiments with algae are conducted at CO_2 concentrations of up to 20,000 ppm," says N. E. Tolbert, professor emeritus of biochemistry at Michigan State University. "Cultures that can be grown in three days at high levels of CO_2 would require 10 to 14 days at the normal atmospheric concentration."

Phenomenal Response in Trees

Some of the most convincing evidence that the rising level of atmospheric carbon dioxide is good for plants comes from the response measurement of individual trees and overall forest growth. Forests cover approximately one-third of the earth's land area, and account for two-thirds of global photosynthesis. They have C3 metabolism, and, like other C3 plants, respond favorably to higher concentrations of carbon dioxide.

Trees and their seedlings grown under controlled environments or in open top chambers simulating the outdoors have shown remarkable growth responses to elevated levels of CO_2. Practically every species evaluated thus far in the seedling stage has shown a positive response. Addition of carbon dioxide to black walnut seedlings--at concentrations of 1,000 to 2,000 ppm for three months--increases dry weight by 80 percent, height by 96 percent, and leaf area by 79 percent. Similar results have been obtained for sugar maple, oak, ash, sweet gum, pine, and eucalyptus. The forestry department at Michigan State University has produced plantable trees in months, rather than years, by subjecting seedlings to 1,000 ppm CO_2 concentrations under optimal conditions of light, temperature, day length, and nutrients.

The Water Conservation Laboratory of the U.S. Department of Agriculture has compared the growth of orange trees under the current atmospheric CO_2 concentration of 360 ppm, and a concentration of 650 ppm. The trees at the elevated levels have accumulated 2.8 times more biomass in five years, and in their first two years of production produced 10 times more oranges.

Breath of the Biosphere

If plants respond so well to additional carbon dioxide, then we would expect to see positive responses to the substantial increase in atmospheric CO_2 over recent decades. Several pieces of evidence suggest exactly such a response.

A fascinating report was published by scientists with the Finnish Forest Research Institute in the April 3, 1992 issue of Science magazine. The researchers reported a 25 to 30 percent increase in the growing stock of forests in Austria, Finland, France, Sweden, Switzerland, and West Germany between 1971 and 1990, and attributed this growth in part to a 9 percent increase in atmospheric carbon dioxide during the same period.

Hartwell Allen, a plant scientist with the U.S. Department of Agriculture's Agricultural

Research Service in Gainesville, Florida, has estimated that soybean yields have increased by 13 percent because of a rise in global carbon dioxide concentration. Another source of dramatic evidence of rising biological productivity comes from the increasing amplitude of the atmosphere's CO2 cycle. The majority of the terrestrial vegetation of the earth is in the Northern Hemisphere, so more photosynthesis takes place in the spring and summer than in the fall and winter. The carbon dioxide level in the atmosphere begins to fall in the spring, and continues to fall through the summer months, as CO2 is removed by the vegetative cover of the north. In late autumn, at least in northern latitudes, much of this vegetation dies and decomposes, and photosynthetic activity drops to a low level; much of the carbon sequestered over the growing season is then returned to the air as CO2 .

This oscillation in the CO2 level is called the "biosphere's breath," and its amplitude is measured by the Mauna Loa recording station in Hawaii. When the first records were made in 1959, there was a 6.5 ppm difference in CO2 concentration between summer and winter. Last year, the difference was 7.5 ppm. What this means is astonishing: during their major growing seasons, the plants of the Northern Hemisphere have been able to sequester at least 15 percent more carbon than they did 33 years ago.

Other Important Benefits

Besides greater efficiency in photosynthesis and a reduction in water loss, higher levels of carbon dioxide provide other important benefits for plants.

Rising levels of CO2 compensate for the deficiencies in light that frequently occur in the winter months in northern Europe, Canada, and the United States. Indeed, flowers and vegetables grown in CO2 -enriched greenhouses experience an even higher-percentage boost in plant productivity under very low light intensities than under normal light.

Enrichment of the air by carbon dioxide also appears to offer some protection to plants against both extremely hot and cold temperatures. There is also evidence that high atmospheric levels of CO2 raise the optimal temperature for plant growth. The implication of this for the global warming debate is significant: if the higher-CO2 world of the future leads to higher temperatures, plants will respond favorably both to increases in carbon dioxide and to the warmer conditions.

Plant responses to a higher carbon dioxide concentration do appear to be limited by deficiencies in nitrogen and other mineral nutrients. If plants are to take full advantage of future CO2 -enriched atmospheres, it may be necessary to apply more fertilizer in many parts of the world. Even so, higher CO2 levels have a remarkably stimulatory effect on biological nitrogen fixation by legumes, such as soybeans. A classic study by Ralph Hardy and U. D. Havelka, published in Science in 1975, showed that a tripling of atmospheric CO2 results in a six-fold increase in biological nitrogen fixation--from 75 to 425 kilograms of nitrogen per hectare--by rhizobial bacteria in nodules attached to the roots of soybeans.

Elevated concentrations of CO2 also offer protection against air pollutants. The partial closing of the stomata at higher CO2 levels reduces the exposure of both C3 and C4 plants to ozone, sulfur dioxide, nitrous oxides, and other harmful substances in the air. The benefits are particularly pronounced for soybeans and other legumes that are especially sensitive to air pollutants.

Good News for the Planet

The benefits to plants that would result from a doubling of the carbon dioxide concentration do not necessarily mean that such a doubling is good for the planet. We do not know what the optimal level of atmospheric carbon dioxide should be. So many variables could be affected by a major increase in CO2 including temperature and a redistribution of water resources, that the honest observer has to conclude he does not really know what will happen. Even so, the good news about plant growth makes it possible to project a number of features of the global ecosystem in the next century.

First, we can expect a rapid expansion of food production that may offset some of the presumed adverse climate effects. As crop yields rise with higher CO2 levels, the amount of land devoted to agriculture can decline. It will be much easier to protect environmentally sensitive land areas from over-cultivation for crops.

Since C3 plants will benefit somewhat more than C4 plants from higher CO2 levels, there will be some shift in the mix of plants. Trees are C3 plants, so we can expect more rapid reforestation and an enormous expansion in forest biomass. Of the 21 most important food crops, 17 have C3 pathways. They include rice, wheat, barley, oats, rye, soybeans, field beans, mung beans, cowpeas, chickpeas, pigeonpeas, potatoes, sweet potatoes, cassava-yams, sugar beets, bananas, and coconuts. The exceptions are corn, sorghum, millet, and sugarcane, which have C4 pathways, and which will probably decline in relative production. On the other hand, since 14 of the 18 most noxious weeds are C4 plants, rising levels of atmospheric CO2 will generally favor crop production over weeds.

Plants, directly or indirectly, provide 95 percent of the total food of the earth. Since plants are at the bottom of the food chain, a boost in plant production should lead to major increases in bird, fish, and mammal populations as well.

The rising carbon dioxide concentration in the atmosphere must be viewed with caution. But it is inappropriate for public discussion of the issue to focus only on the hypothetical dangers of global warming that might result from higher carbon dioxide levels. It is important to stress as well the known benefits of a higher carbon dioxide concentration for the productivity of food crops, trees, and other plants.

SYLVAN H. WITTWER, professor emeritus of horticulture at Michigan State

University, directed the Michigan Agricultural Experiment Station for 20 years, and chaired the Board on Agriculture of the National Research Council. He is the author of the world's leading textbook on greenhouse vegetables, and is co-author, most recently, of Feeding a Billion: Frontiers in Chinese Agriculture.