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WESTERN FUELS ASSOCIATION INC.
The National Fuel Supply Cooperative

Ned Leonard
Manager of Communications and Governmental Affairs

March 17, 1992

Anthony Socci
Senate Commerce, Science &
Transportation Committee
427 Hart Senate Office Building
Washington, DC 20510

Dear Mr. Socci:

I am enclosing the transcript of "The Greening of Planet Earth" which reflects the differences between the 27:50 original and 15:30 edited versions of the videotape. You will also find enclosed a copy of the edited production which is being distributed as a "presenter's copy" for use in extremely time-limited situations such as service club luncheons. The longer version is in general circulation.

Regarding the curriculum vitae of the scientists who appear in "The Greening of Planet Earth," they had not previously been collected. I am contacting each of them and requesting that they send it to me for forwarding to you.

If I can be of further assistance, please let me know.

Sincerely,

Ned Leonard

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Transcript of
THE GREENING OF PLANET EARTH
("Redlining" denotes text edited from 15:30 version)

NARRATOR:

Dawn of the Industrial Revolution. Western society is primarily agricultural and commercial. The concentration of carbon dioxide in the atmosphere is 270 parts per million.

And then, factories spring up across the countryside and industrial towns grow around them. We begin to burn fossil fuels in large quantities — and then burn more. The carbon dioxide level of the air rises. The level rises again. Then again.

The 1950s. The concentration of carbon dioxide in the air is 315 parts per million. Still more fossil fuels are burned. More and more carbon dioxide is emitted into the atmosphere. More industrialization — then more. More carbon dioxide — then more.

The year 2085. The atmospheric level of carbon dioxide has doubled to 540 parts per million. What kind of world have we created?

DR. HERMAN MAYEUX:

A better world, a more productive world. Plants are the basis for all productivity on earth. They're the only organisms that can utilize the sun's energy and create matter, food. And they're going to do that much more effectively, much more efficiently.

DR. BRUCE KIMBALL:

With a doubling of CO_2, why cotton growers can look forward to yields that are 60 percent and more greater than what they are at present-day levels.

DR. MARY BRAKKE:

For citrus it would be a very, very positive thing.

DR. GERD-RAINER WEBER:

Our world will be a much better one.

DR. KENNETH BOOTE:

In terms of plant growth it's nothing but beneficial.

DR. HARTWELL ALLEN:

We would expect a world in which crop plants would produce about 30 to 40 percent more than they are currently producing.

DR. SHERWOOD IDSO:

A doubling of the CO_2 content of the atmosphere, will produce a tremendous greening of planet earth.

NARRATOR:

Carbon dioxide is the major building block of life. Plants extract it from the atmosphere during photosynthesis and transform it into the food we need to survive. As a by-product of this process, oxygen is released.

Throughout the history of life on earth, there has generally been much more CO_2 in the atmosphere than there is today.

These higher levels of carbon dioxide encouraged life. Vegetation in prehistoric eras was lush and grew profusely over wide areas.

As this vegetation died and decayed, much of its trapped carbon was transformed into the coal, oil, and natural gas the world depends on today.

The carbon dioxide that was in the atmosphere is now being returned to it by the burning of fossil fuels, a natural by-product of man's industrial evolution. And, as more and more scientists are confirming, our world is deficient in carbon dioxide, and a doubling of atmospheric CO_2 is very beneficial.

"AGRICULTURE"

DR. LEON ALLEN:
Agronomy Department,
University of Florida

We are investigating the effects of elevated levels of atmospheric carbon dioxide on plants using controlled environment chambers wherein we can control CO_2 levels very precisely. We are interested in this because we want to know how C_3 crop species such as rice and soy bean may respond to future levels of atmospheric carbon dioxide.

What we are finding is that these species respond quite nicely to a doubling of carbon dioxide and give increased yields up to 30 to 40 percent.

DR. KENNETH BOOTE:
Agronomy Department,
University of Florida

Most of the temperate plants grown in the United States — the temperate cool season cereals, soy bean, peanut — are plants that respond to carbon dioxide. The temperate plants will respond with about a 35 percent increase in growth and yield in response to a doubling of CO_2.

We have done a simulation of a doubling of CO_2 effect on soy bean dry matter accumulation and seed yield and I have an example of that with this simulation. This shows the 330 part per million CO_2 dry matter and this shows a doubling of CO_2 at 660 parts per million.

If I run another example here of just the seed weight, this shows the seed dry weight increase over time until final maturity for a normal 330 part per million CO_2 and a doubling of CO_2 (660 parts per million) showing about a 35 to 40 percent increase in seed yield.

DR. JEFFREY BAKER:
Agronomy Department,
University of Florida

With our work with soy beans we have found that soy bean also responds favorably to elevated CO_2 concentration. The net benefit in grain yield is similar to that for what we're seeing for rice. With rice, elevated CO_2 levels stimulate growth and ultimately this translates into increased grain yield.

We're getting, typically, anywhere from 30 to 40 percent increases in grain yield. We get increased carbon uptake through photosynthesis. We get a decline in carbon loss during nighttime respiration. We also get a decline in total water use, and all this translates into an increase in grain yield which is the useful portion of the plant with rice.

DR. HERMAN MAYEUX:
Agricultural Research Service,
USDA

We grew a wheat crop, two varieties of wheat, across a CO_2 gradient from well below what it was in pre-industrial times, up to what it is now. And we found that both of those varieties increased their yield by a factor of three.

DR. HYRUM JOHNSON
Agricultural Research Service,
USDA

Earlier, we did an experiment with oats. At the time we took the oats out, then we did measure the biomass, the total increase in stem and leaf weight and so on. It was on the same order of increase as we found with the wheat.

DR. BRUCE KIMBALL:
US Water Conservation Laboratory, USDA

Elevated CO_2 levels have greatly increased the growth of our cotton crops. We found that enriching the crop to about 550 parts per million (which is 200 parts per million above our control plots) that the growth is increased by about 40 percent or more.

A world in which the CO_2 concentration has doubled is one in which the plants will enjoy it a lot more. They have been, in effect, eating the CO_2 out of the air for a long time and they're rather starved for CO_2. So the plants are really going to like this high CO_2 world that we're going into now.

DR. ALLEN:

The increase in atmospheric CO_2 is a benefit that will occur around the globe, regardless of where you're located. There'll always be some benefit for somebody, for everybody perhaps.

"WATER-USE EFFICIENCY"

NARRATOR:

Enriched levels of atmospheric carbon dioxide not only enhance plant growth, but they also make plants more water efficient. In fact, a doubling of CO_2 would also double most plants' water use efficiency.

Plants exposed to higher levels of CO_2 do not open the stomates, or pores, in the leaves as widely as when there is less CO_2 in the air. And the smaller the openings, the less water is lost by evaporation into the atmosphere.

But what does this imply?

DR. MARY BRAKKE:
Agronomy Department
University of Florida

The idea of increased water use efficiency for citrus is very, very positive and it's a good sign for areas such as Florida which are facing severe reductions in the water use for agricultural purposes, even at present.

DR. MAYEUX:

The marvelous thing about the increase in water use efficiency is that all plants experience it to some degree or another. And most plants experience it to a significant degree. The research shows that when CO_2 levels double from what they are to now, there'll be some large response. Our research shows that the 30 percent increase we've already experienced in CO_2 has already had an effect on plants in this regard.

DR. KIMBALL: Another question comes up is: what happens to the yield of the crop when it's water stressed and you have higher CO_2? And an interesting thing happens. We find, that for the most part, it appears that there is a greater stimulation of growth under conditions of water stress at high CO_2, so to some extent the higher CO_2 compensates somewhat for water stress.

DR. ALLEN: As CO_2 rises in the atmosphere we expect more crop production per unit land area and slightly decreased water use per unit land area, so we expect this to lead to overall production with less water requirements.

In areas that are irrigated we expect there to be maybe 40 percent, at least 40 percent greater productivity per unit of water applied. This could lead to either greater areas being irrigated, but more likely to a very nice increase in crop yield with no further inputs into the agricultural system.

DR. SHERWOOD IDSO:
US Water Conservation Laboratory, USDA

As the efficiency with which plants utilize water increases in the years ahead as the CO_2 content rises, plants will obviously be able to grow and survive in areas where they currently cannot because of a lack of water. That means that you should see a tremendous redistribution of plants on the face of the earth.

In very general terms, you should see a real greening of the desert. You should see grasses and small shrubs moving out onto areas where they could not live, survive and reproduce before. Then there should also be a tendency for bushes and shrubs to grow where only grasses have grown in the past. And of course, forests should greatly expand their ranges.

"COMPUTER SIMULATIONS"

NARRATOR:

This real-world evidence of CO_2's positive effects has been challenged over the years by theoretical computer models. Some of these models say that the earth is warming to a frightening degree due to the man-made "greenhouse effect" — a phenomenon in which CO_2, plus harmful greenhouse gases, trap the heat escaping into the atmosphere and send it back to earth.

The models say that this will cause the polar icecaps to melt, drought to grip the heartland of the U.S., and superstorms to ravage the planet. But are these models accurate? What role does CO_2 play? Has there actually been any global warming? What are the computer simulations trying to do?

DR. GERD-RAINER WEBER:
German National Coal Association

What computer models are doing is they are trying to simulate the physics and the chemistry that is going on in our atmosphere. However, the chemistry and the physics are so complex that even if we knew all the processes that have a bearing on climate, it would be very hard to model it, to simulate it, with a set of physical or chemical equations.

DR. RICHARD LINDZEN:
Center for Meteorology and Physical Oceanography, Massachusetts Institute of Technology

An easy way of describing their inability is to note that there are all sorts of things like cloud cover, water vapor, heat transport, that in present models have errors on the order of 50 percent. And such errors absolutely swamp the effects of a doubling of carbon dioxide. As long as the models have errors that can swamp the effect you're looking for, you cannot regard the models as credible.

DR. WEBER:

We don't know even know all the processes, for instance, that are taking place between the biosphere of the earth and the atmosphere. We do not know all the processes that are taking place between the oceans and the atmosphere — clouds and the atmosphere.

DR. LINDZEN:

The same models that, for instance, predict 5 degrees for a doubling are predicting we should have seen 2 degrees or at least one degree Centigrade in the last century. Nobody claims we've seen anything more than about a half degree. The number often centers on something a little smaller than that. And that is overtly inconsistent with the models. Moreover, there is virtually no one who believes that the half degree is due to greenhouse gases, because climate has always varied by itself without man's intervention.

DR. WEBER: So the reality falls about at least 50 percent short of what the models predict. Now this is really one of the major issues. We simply don't see, at this point, the warming the models predict.

DR. LINDZEN: It's garbage in, garbage out. If you put in a bad parameterization, if you put in inadequate resolution, you do not have credible answers coming out. It's not as though I would believe the models if they only gave me that it would get colder. There's no basis for believing them.

We've gone from ice ages to warm periods. We had a Little Ice Age until almost the 18th Century. We're warming since then, but we're not as warm as it was in the Medieval Period when you had grape growths in Scotland, you know, and so on. So the climate is always fluctuating and there is nothing in what we have seen in the last 100 years that looks any different from these fluctuations.

DR. WEBER: Now as we move into the late 1980s and early 1990s, oceanic models have become much more sophisticated. And there have been several attempts by major modeling groups to couple realistic oceans to atmospheric models. And some of those models show that, indeed, the warming that people expect for coming decades is considerably less than what older models had expected.

DR. LINDZEN: I probably share the puzzlement of a lot of people in trying to understand why modest warming is treated as one of the gravest dangers facing mankind. I simply do not know why. I do know what I have seen, as have most other people, on television. You know, pictures of palm trees in Boston, Washington under water. And those indeed are part of what I suppose one could call a cataclysmic scenario. But to the best of my knowledge, they have nothing to do with what any scientist has predicted, regardless of which side of the issue he is on.

"THE SYSTEM"

NARRATOR: But even if the earth does warm a certain amount, what effect will this have?

DR. IDSO: If there ever were to be a warming of the world, there would be a warming of the oceans. And this would increase the productivity of the unicellular algae or phytoplankton that live there. This would increase their production of various substances that when they die are released to the surface waters of the ocean. One of these substances is something we call dimethylsulfide, or DMS. It makes its way into the atmosphere as a gas, where it is converted into particles around which water vapor condenses, to create more cloud particles. With more cloud particles you have brighter clouds. This reflects more of the incoming solar radiation back to space, and it cools the planet.

On land very much the same thing would happen. If you have an increase in temperature on land, you have an increase in the productivity of many soil micro-organisms. When this happens, they give off sulfur gases in greater quantities. One of these is also dimethylsulfide.

You even have a situation where you don't need an increase in temperature to kick this mechanism into operation. That is, just the increased activity of plant life caused by enriching the air with CO_2 will put ultimately more organic matter into the soil. This is the food for microbes. You give them more food, they produce more. More evolution of dimethylsulfide. More cloud condensation particles. And you could have a situation whereby there could be a cooling of the planet, due to the increase in CO_2 content of the atmosphere that could overpower the greenhouse effect.

"TREES AND ANCIENT FORESTS"

NARRATOR:

Trees account for about three-quarters of all photosynthesis done by land plants, and two-thirds of all photosynthesis done globally. What effect will a doubling of CO_2 have on them?

Part of the answer comes from an experiment being conducted with sour orange trees and another part from Bristlecone pines — the oldest living organisms in the world.

DR. DONALD GRAYBILL:
Laboratory of Tree Ring Research, USDA

We're here at eleven thousand feet in the White Mountains of eastern California to discuss the growth of Bristlecone pine. It has shown some phenomenal increases in the past one hundred years or so, that we can't attribute to temperature or to precipitation. We think that the increasing carbon dioxide may have had a very important effect on this growth.

Now the Bristlecone pine is very important in this respect — and especially at these elevations — because it's the only natural laboratory where we've seen this effect. And so we've begun to study this all over the dry, arid mountain ranges of the western United States. And we've found that it's quite widespread, again, only at these very high elevations, where a little bit more carbon dioxide is very helpful for growth.

DR. IDSO:

The experiment that we have been conducting here for four years deals with growing sour orange trees under normal conditions of atmospheric CO_2 concentration. And then, where the CO_2 content of the air has been enriched to an approximate doubling, not quite a doubling, of the current concentration.

And we have followed these trees, as I said, for about four years now, and the enriched trees have almost tripled their biomass. That is they have grown approximately three times faster than the trees growing in normal air.

Now this response is so incredible. It suggests that were the CO_2 content of the atmosphere to double, the growth rates of earth's trees would triple. And the studies that we have done over the past couple of months, looking at the photosynthetic response of these trees to atmospheric CO_2 enrichment, suggest that it does not stop there. In other words, if we tripled or quadrupled the CO_2 content of the atmosphere, it looks like the growth response of the trees would just continue to increase linearly.

DR. GRAYBILL: One of the very important points that must be understood and is crucial to this story, is that we see a tremendous growth spurt in the past one hundred or so years, that we have not seen in the past few thousand years in these trees. Now, this corresponds precisely with the tremendous increases in carbon dioxide that are even now measured from Mauna Loa in Hawaii, from ice cores, and from other places.

DR. IDSO: Most recently we have put in several new chambers, where we are looking at five other species of trees. We are looking at them under a range of CO_2 concentrations that actually go far above what we have looked at with the large sour orange trees over the past few years. And we find that these other trees appear to respond exactly the same way as the sour orange trees to atmospheric CO_2 enrichment. And as the CO_2 content continues to rise beyond what we've looked at in the past, the response seems to be linear. It continues to go up and up and up.

We have gone out to a level of twelve hundred parts per million of CO_2 and there seems to be no drop off in the response. It means that we may have way more than a tripling of the growth of these trees. A quadrupling. Maybe five or six times more. It's absolutely incredible.

DR. GRAYBILL: If carbon dioxide levels continue to increase, and it is critical to the growth of plants (as we know it is) then we might well begin to see increases in productivity — forest productivity, wood production — as we go down the mountainside, as carbon dioxide levels increase. And again, we might see increased efficiency in use of water in those forests as well. This might have another ramification in that, over large areas, we might see a surplus of water over time.

DR. IDSO:

As the CO_2 content of the air continues to rise in the future, the planet's trees will become more and more stimulated. That is they will grow at greater and greater rates. And as they do this, they will extract more and more CO_2 from the atmosphere. As time goes on and their growth rates are doubled or tripled or even quadrupled, which is a real likelihood as far as our experiments indicate, you will have so much CO_2 being removed from the atmosphere, that there will come a point where the CO_2 content of the atmosphere will rise no further, because the trees of the planet will be yearly extracting as much CO_2 from the atmosphere as mankind yearly puts into it.

"WETLANDS"

NARRATOR:

Since 1986, the Smithsonian Institution in Washington, D.C. has sponsored research into the effects of enriched levels of CO_2 on marshland plants. Co-sponsored by the U.S. Department of Energy, these experiments are being conducted near the Chesapeake Bay in Edgewater, Maryland.

In this field, plants are growing in open-topped chambers. Some are being exposed to twice today's level of CO_2. For comparison, others are growing in chambers with current levels of CO_2. Both C_3 and C_4 plants are being studied.

C_3 plants comprise about 95 percent of all plant species on earth, and the enriched C_3 plants react very positively. They take in more CO_2 during the day and release less at night. They don't decay as quickly. They increase their growth rate dramatically, both above ground and below it. They use water more efficiently and they use less of it.

So what do these Smithsonian experiments suggest? Will the earth's huge areas of marshland become a depository where excess CO_2 can be stored? What about the possibility of food crops doubling or even tripling, worldwide?

What if areas of the world unable to support crops or forests can one day do so? And what if more productive plant life can ultimately stop the rise of atmospheric CO_2 completely?

The research continues.

"THE CO_2 CYCLE"

NARRATOR: Every spring, vegetation awakens and takes in vast quantities of CO_2 for the growing season. Then, in the fall and winter, the vegetation dies and decays, and the CO_2 is put back into the air. We have about a 30-year record of this cycle.

DR. IDSO: Scientists that have looked in detail at this record have determined that each year the difference between the high and low points of the seasonal oscillation is getting greater and greater. The only explanation that anybody has ever been able to come up with that explains the magnitude of this rise, has to do with the fact that the plant life of the planet must be becoming more and more robust each year in response to the gradually rising CO_2 content of the atmosphere.

DR. JOHNSON: Undoubtedly there has been already a considerable increase in the yields that are coming from the fields, because of the CO_2 enrichment that's in the atmosphere.

DR. BOOTE: In the last 30 years we should have had a 5 to 6 percent yield increase from the CO_2 increase that already has happened.

DR. MAYEUX: We know from historical records and from personal observations that crop productivity has increased dramatically, especially since World War II. Three, four, five times more cotton, corn, wheat, soybeans, rice, and we think we know why this is. We have better crop varieties. The plant breeders have come up with hybrids and much more productive, better-adapted strains of these crops.

We've learned to do a much better job applying fertilizers, controlling diseases, controlling insects, and our cultural practices are fairly well-developed in the world today.

But it also makes sense that many of these crops are the kind that respond dramatically to increasing CO_2. So it makes sense that the 30 percent increase in CO_2 that we've experienced since pre-industrial time should have increased crop growth.

"THE FUTURE"

NARRATOR:

What does the future hold? In great measure, it holds a variety of questions:

Questions about the wholesale destruction of our tropical rain forests, about becoming the most efficient energy users we can, and questions about how we intend to feed our exploding global population.

In addition to these questions, however, the future also holds great promise. And contributing to this promise is the positive effect that carbon dioxide has on our world.

As we have seen, enriched levels of CO_2 in the air greatly enhance growth and water use efficiency in almost all the world's vegetation. Crop plants will continue to grow more productively, contributing ever greater supplies of food. Forests will extend their ranges, grasses will grow where none grow now, and great tracts of barren land will be reclaimed.

In fact, it is not inconceivable that the vitality of our entire biosphere could rise by a full order of magnitude over next few centuries to a new greening of planet earth.

END

With special thanks to:

Dr. Leon H. Allen, Jr., Agronomy Department, University of Florida

Dr. Jeffrey T. Baker, Agronomy Department, University of Florida

Dr. Kenneth J. Boote, Agronomy Department, University of Florida

Dr. Mary Brakke, Agronomy Department, University of Florida

Dr. Donald A. Graybill, Laboratory of Tree Ring Research, University of Arizona

Dr. Sherwood B. Idso, United States Water Conservation Laboratory, United States Department of Agriculture

Dr. Hyrum B. Johnson, Agricultural Research Service, United States, Department of Agriculture

Dr. Bruce A. Kimball, United States Water Conservation Laboratory, United States Department of Agriculture

Dr. Richard S. Lindzen, Center for Meteorology and Physical Oceanography, Massachusetts Institute of Technology

Dr. Herman S. Mayeux, Jr., Agricultural Research Service, United States Department of Agriculture

Dr. Gerd-Rainer Weber, German National Coal Association

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Analysis of:

"The Greening of Planet Earth: The Effects of Carbon Dioxide on the Biosphere"

produced by: The Biosphere Institute (1991)

distributed by: The Western Fuels Association

Analysis by: Christopher B. Field
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Summary

The biosphere is now responding and will continue to respond to increased CO_2. The responses are potentially important and certainly worthy of further study. They will almost certainly, however, be much more modest than the dramatic greening of the earth presented in the video.

The video makes a number of valid points and a number of unjustified arguments. Below is a summary of both kinds of conclusions, followed by a more detailed analysis of each.

Summary of Valid Points

- Increasing CO_2 is a reality, and the increases are very likely to continue.

- Direct effects of CO_2 on the biosphere are potentially important and probably deserve a level of emphasis comparable to that invested in studying effects mediated through climate change.

- Most plants respond to increasing CO_2 with modest increases in photosynthesis and growth, but only under some conditions.

- Increased CO_2 tends to lead to modest increases in water use efficiency, and these may lead to increased plant production in dry habitats, including extensions in the ranges of some species.

Summary of Unjustified Conclusions and Errors

- The video argues that increased CO_2 may lead to dramatic increases in the productivity of agricultural and natural ecosystems. Actual increases are likely to be much more modest and perhaps insignificant. In general, the production increases resulting from elevated CO_2 in controlled environment studies (typically 30 - 40 %) probably represent the upper range of responses in agricultural and natural ecosystems.

- The video puts little emphasis on factors, other than CO_2, that limit plant production. In both agricultural and natural ecosystems, production increases resulting from increased CO_2 are limited, both by the characteristics of individual plant species and by the availability of light, water, and mineral nutrients, which are the other resources required for plant growth.

- The video argues that production will increase so much that the rate of carbon storage in the biosphere will eventually equal the rate of emission from anthropogenic effects. The video fails to distinguish between the controls on carbon fixation and carbon storage. Neither terrestrial nor ocean ecosystems can dramatically increase carbon storage, because neither has sufficient available mineral nutrients to allow large increases in storage.

- The video argues that rings of high-altitude trees and the increasing seasonal cycle in atmospheric CO_2 demonstrate that the biosphere is already responding to elevated CO_2. In fact, results of the tree-ring studies are controversial, and the increasing seasonal cycle is consistent with other explanations.

- The video takes an unjustifiably skeptical perspective on the role of atmospheric CO_2 in climate change

"The Greening of Planet Earth: The Effects of Carbon Dioxide on the Biosphere" develops the argument, at a level accessible to non-scientists, that increasing atmospheric carbon dioxide (CO_2) is and will continue to be a major benefit, stimulating plant growth, increasing agricultural production, and vegetating the deserts. The basic biology that forms the video's starting point is largely correct. CO_2 is the primary substrate for photosynthesis and hence for plant growth, and photosynthesis or CO_2 uptake in most plants does increase in response to increased CO_2. These basic facts underlie the potential that global plant productivity will rise with increases in the CO_2 concentration in the atmosphere. The video builds on these basic facts by presenting a number of experimental and theoretical results indicating significant yield increases in response to elevated CO_2. These results are the work of respected scientists, and most have been published in the peer-reviewed literature.

Does this mean that elevated CO_2 will lead to the video's dramatic greening of the planet Earth? Certainly not. While many of the video's technical points are correct, most of the conclusions drawn from them represent extrapolations that not only reach well beyond the available data but also ignore a number of well-understood and clearly-documented processes that are acting and will continue to act to limit the biosphere's response to increasing atmospheric CO_2.

Analysis of Valid Points

1) **The Reality of Increasing CO_2:** The concentration of CO_2 in the atmosphere is clearly increasing. It is currently higher that it has been for the last 160,000 years, about 25% higher than it was at the start of the Industrial Revolution. The recent increase has been driven by fossil fuel combustion and deforestation. Growth of human populations and economic development will continue to exert strong pressure for further increases, unless governments act to limit CO_2 emissions. The video is justified in making the point that increased atmospheric CO_2 is a fact, while it is not yet possible to categorically prove that increased concentrations of CO_2 and other greenhouse gases have or will ever cause significant changes in the global climate.

2) **Direct CO_2 Effects on the Biosphere Deserve Focus:** To date, the public attention, scientific discussion, and research funding concerning increasing atmospheric CO_2 have emphasized predicted changes in global climate rather than direct effects on the biosphere. This emphasis is unfortunate, both because direct effects of CO_2 on the biosphere are virtually certain and because the potential impacts of direct and climate-mediated effects on the biosphere are potentially comparable in magnitude. If the video had stopped short of unjustified extrapolation, it could make a contribution in shifting attention on CO_2 to a more balanced emphasis on its role in both climate change and direct effects on the biosphere.

3) **Yield Increases are a Real Possibility:** Several of the researchers who appear on the video describe results of empirical and modeling studies indicating that doubling atmospheric CO_2 can increase yields of agricultural crops up to 30 - 40 %. I consider responses of this magnitude typical of responses reported in the peer-reviewed literature for growth chamber, greenhouse, and open-top chamber studies. Of the two published studies on natural ecosystems, one reported somewhat larger and the other reported smaller increases in production. One important feature of many of the studies using controlled environments is that the cultural conditions, especially nutrient availability and planting density, were adjusted to encourage the maximum response to increased CO_2. In commercial agricultural systems and in natural ecosystems, the CO_2 responses of production will tend to be less.

4) Range Extensions Into Drier Sites are a Real Possibility: The video argues that increased water use efficiency (growth or photosynthesis per unit of water used) resulting from elevated CO_2 will allow plants to extend their ranges into drier regions. This possibility has not been studied empirically, but it is reasonable and potentially important. Realized increases in water use efficiency will probably tend to be relatively small, however, and are more likely to result in changes in the abundance of plants already on a site than in the invasion of whole new ecosystems. Factors like decreased soil moisture associated with global warming and constraints of energy balance on water use will tend to minimize increases in water use efficiency.

Analysis of Unjustified Conclusions and Errors

The video's unfounded or incorrect conclusions all result from unjustified extrapolation of valid empirical and theoretical results. Three classes of misinterpretation underlie most of the errors. These are (1) a failure to recognize the full range of production limiting factors in agricultural and natural ecosystems, (2) a failure to distinguish carbon fixation from carbon storage in terms of consequences for the atmosphere, and (3) an unjustifiably extreme skepticism about greenhouse-gas induced climate change. In addition, the video makes a misleading analysis of evidence consistent with current responses of the biosphere to elevated CO_2, and it fails to mention potentially important problems that may result from direct responses of the biosphere to increased atmospheric CO_2. Below, I consider each of these points in more detail.

1) Production-limiting factors in agricultural and natural ecosystems: Several speakers on the video report production increases of 30 - 40 % in agricultural species exposed to doubled CO_2. One speaker reports much larger increases in sour orange trees. In commercial greenhouses, production increases of 30 - 40 % are common, and increases in this range are likely to be possible in field crops, especially when planting densities are low. The much larger responses discussed in the video are possible under experimental conditions, but are unlikely under commercial or natural conditions. The video's extrapolation from the modest yield increases discussed by most of the speakers to suggestions about two-fold increases in water use efficiency and several-fold increases in the production of natural ecosystems is very tenuous. It seems to be based on the assumption that since trees dominate the production of the terrestrial biosphere, then the CO_2 responses of experimental trees in pots should be used to project the CO_2 responses of natural ecosystems. The critical issue in developing extensions from experimental to natural ecosystems is not the stature of the plants, but the ability of individual species to respond and the status of the habitat with respect to water, mineral nutrients, and light, the other resources (in addition to CO_2) required for plant growth. Most natural ecosystems are characterized by plant species unlikely to have high potential to accelerate growth and resource availabilities that will tend to make them no more than modestly responsive to elevated CO_2.

All plants need light, water, mineral nutrients, and CO_2 to grow. When they use all of the available pool of any of these resources, growth stops. Elevated CO_2 can increase growth through three mechanisms. When all other resources are abundant, most plants, especially those with the C_3 photosynthetic pathway, are carbon limited, and elevated CO_2 gives plants the potential to capture more of the available pools of the other resources. Elevated CO_2 also increases the efficiency, defined as growth or photosynthesis per unit of resource use, with which plants can use water, mineral nutrients, and light. In experimental studies, water use efficiency often increases by about the same amount as production (30 - 40 %), but constraints of canopy energy balance will tend to make this effect smaller in the field. The responses of nutrient and light use efficiency are also smaller than the 30 - 40 % range.

Finally, elevated CO_2 can potentially allow plants to access additional resources, for example through growing deeper roots or facilitating biological nitrogen fixation.

Several factors indicate that growth responses in the range of 30 - 40 % are probably higher than the average response in natural ecosystems. First, many laboratory studies indicate that the biochemical potential for photosynthesis decreases in plants grown under elevated CO_2. These decreases, perhaps reflecting limits on the plants' ability to utilize additional carbohydrate, may constrain ecosystem level-growth responses. Second, increased CO_2 is likely to lead to decreased nutrient availability at the ecosystem level. As plants produce biomass with a higher ratio of carbon to nitrogen, the dead plant matter becomes more resistant to decomposition, resulting in a situation in which a larger pool of nutrients is bound in decaying plant matter and less is available to support new plant growth. Third, nutrient use efficiency is probably much less responsive to elevated CO_2 in ocean than in terrestrial ecosystems. Thus, ocean ecosystems essentially lack one of the major response mechanisms of terrestrial ecosystems. It is unlikely that elevated CO_2 will lead to any significant increase in the productivity of nutrient-limited ocean ecosystems, or all ocean ecosystems except coastal zones and high latitude upwelling zones.

In commercial agriculture, production increases resulting from elevated CO_2 may be substantial, but the increase in economic yield will often be much smaller. Especially in forage crops, where the priority is on protein production, elevated CO_2 will tend to increase biomass accumulation while decreasing protein content, such that the total yield in protein per unit area of cropland is largely unaffected by the increased CO_2. Where the primary product is carbohydrate-rich fruits or tubers, the impact of elevated CO_2 is likely to be larger. Legume crops may be able to increase nitrogen fixation under elevated CO_2, but only if fertilization with phosphorus and the other minerals necessary for nitrogen fixation is increased.

The video strongly suggests that plant production is likely to continue to increase as CO_2 levels rise well above two times the current level. The data addressing this point are minimal, but three factors indicate that production responses will begin to saturate as CO_2 rises above the ambient level. First, the biochemical response of photosynthesis to CO_2 is a saturating function. In plants with the C_4 photosynthetic pathway (e.g. corn and sugarcane), photosynthesis is typically CO_2 saturated at current ambient levels. In plants with the C_3 photosynthetic pathway (90% of all plant species), photosynthesis saturates gradually with elevated CO_2, with the saturation beginning near ambient levels. Second, as increasing CO_2 leads to increasing carbohydrate availability, intrinsic limitations on plants' abilities to use the carbohydrates are likely to become increasingly important. Third, as the availability of carbohydrates continues to increase, limitations imposed by other resources will become increasingly important.

In summary, the CO_2 induced production increases described by the video clearly occur under some conditions. The range of these conditions is a matter of scientific uncertainty, but a number of well established principles indicate that the production responses in natural ecosystems will usually be smaller than the 30 - 40 % discussed by the video and certainly smaller than the 3-fold to 10-fold suggested in the video's final minutes.

2) Carbon fixation vs. carbon storage: Results of only two studies on the responses of natural ecosystems to elevated CO_2 have been published, making generalization very difficult at this point. There is, however, no doubt that the video makes a serious error in suggesting that increasing CO_2 will increase the rate of carbon storage in the biosphere up to the point at which the biosphere stores all of the anthropogenic CO_2, stabilizing the CO_2 concentration in the atmosphere. The limitations on the magnitude of the production response of natural ecosystems (discussed above) will tend to limit increases in the rate of carbon storage. More important, however, increasing carbon fixation does not necessarily lead to increases in carbon storage. If decomposition or carbon loss increases at the same rate as carbon fixation, carbon storage remains unchanged.

In examining the likely responses of carbon storage to increased CO_2, three issues are critical. First, the biosphere has a very limited capacity to sequester carbon without also sequestering nutrients such as nitrogen and phosphorus. The capacity to sequester carbon without nutrients is effectively zero in terrestrial ecosystems and is very small in ocean ecosystems. If carbon storage occurs, it will lead to nutrient depletion, and nutrient depletion tends to limit production. If the limiting nutrient is already completely utilized (as is the case in most ocean and many terrestrial ecosystems) the capacity for increased carbon storage is limited to the change in nutrient use efficiency (usually 20% or less). Storing one unit of carbon in soil organic matter entails also storing 0.1-0.2 units of nitrogen, while storing the same amount of carbon in stems or wood requires losing 0.02 - 0.01 units of nitrogen from circulation. Nitrogen fixation may increase under elevated CO_2, but biological fixation of one unit of nitrogen releases approximately the same amount of carbon as could be stored with that unit of nitrogen in the soil. Industrial nitrogen fixation based on fossil fuel is comparable in efficiency, with the carbon release required to drive the process approximately equal to the carbon that the could be stored with the nitrogen as soil organic matter. In summary, increases in carbon storage in the biosphere as a result of increased atmospheric CO_2 will almost certainly be modest, because nutrient availability places an upper limit on potential storage.

Second, the response of decomposition to increased atmospheric CO_2 will depend on several factors, and the overall direction of the change is likely to differ among ecosystems. Increases in the carbon content of plant litter will tend to slow decomposition, but increased soil moisture (a possible result of increased water use efficiency), increased temperature, and increased root allocation will all tend to increase decomposition. Increases in the size of the pool of decomposing material will also tend increase the amount of material decomposed per unit of time and will insure that the pool of stored carbon cannot increase indefinitely.

Third, as discussed above, biosphere responses are very likely to saturate with respect to CO_2 as concentrations rise higher and higher. In contrast to the video's description of the biosphere as an ever increasing carbon sink, it is much more likely that increases in the size of the carbon pool in the biosphere will act as negative feedbacks on the annual increment, potentially increasing the fraction of the anthropogenic CO_2 that remains in the atmosphere.

3) Greenhouse-gas induced climate change: The atmosphere is complex and incompletely understood, but the video's emphasis on the uncertainty concerning the role of CO_2 in climate change is an extreme position in no way representative of a current scientific consensus on this issue. The IPCC (Intergovernmental Panel on Climate Change) prediction of a 1.5 - 4 °C global warming resulting from a doubling of atmospheric CO_2 is closer to a consensus position. Recent data indicating that changes in ozone and sulfate aerosols have offset some of the radiative forcing due to to CO_2 help explain why the evidence for recent warming is inconclusive.

The prediction that increased atmospheric CO_2 will lead to some global warming is, in my opinion, much more likely to be correct than indicated by the speakers on the video. The basic physical principles underlying the greenhouse effect are quite simple and broadly accepted. The earth must maintain energy balance. If more solar radiation is absorbed, then the temperature must increase until reradiation to space increases enough to compensate for the increased absorption. The uncertainties concern other processes with the potential to either amplify or suppress the initial response to CO_2. Quantitatively, the most important of these is a water vapor feedback. Increased temperature should lead to increased water vapor in the air, and, since water vapor is a potent greenhouse gas, increased water vapor should amplify the tendency toward warming. On the other hand, increased water vapor could lead to increased cloudiness, and clouds may either amplify or suppress the greenhouse effect, depending on their structure and location. Recent satellite data indicate that the water vapor feedback tends to amplify CO_2 induced warming, as predicted by most of the climate models.

The video argues that increased atmospheric CO_2 is likely to increase the emission of DMS and other sulfur compounds from ocean and terrestrial ecosystems and that these compounds should offset global warming or even produce a future cooling. This argument is probably incorrect. Ocean photosynthesis is rarely carbon limited (as discussed above) and it is unlikely that elevated CO_2 would stimulate DMS emissions if it fails to stimulate photosynthesis. Increased CO_2 should produce some stimulation of terrestrial photosynthesis, but the consequences of this for sulfate aerosol formation and cloud reflectivity are unclear, especially since cloud condensation nuclei are much more abundant over land than over the oceans.

More remains to be learned about the role of CO_2 in global warming, but a modest warming resulting from a CO_2 doubling is likely enough that it should be considered in any serious evaluation of the CO_2 issue. Research designed to identify and reduce the uncertainties in global climate models, for example EPRI's MECCA program, should continue to narrow the uncertainty in the coming years.

4) Evidence of current biosphere responses to elevated CO_2: The video argues that two kinds of data, (1) recent increases in the width of tree rings from high altitude trees and (2) recent increases in the amplitude of the seasonal cycle in the atmospheric CO_2 concentration can be attributed only to increased plant growth resulting from increased CO_2. Neither argument is sound. With the high altitude tree ring studies, the analysis is simply unclear. Some studies indicate that all the patterns appear to be consistent with responses to climate while others find evidence for a pattern not explained by climate and perhaps due to increased CO_2. The recent change in the amplitude of the seasonal cycle in the atmosphere is consistent with increased plant production, but it is also consistent with a small change in seasonality.

5) Other problems: Direct effects of CO_2 on the biosphere may result in a number of problems. These include changes in the nutritional value of crops, increased aggressiveness of weeds with the C_3 (CO_2 sensitive) photosynthetic pathway in crops with the C_4 (CO_2 insensitive) photosynthetic pathway (e.g. corn and sugarcane), increased crop losses to herbivores, and changes in species composition resulting in the disappearance or decreased abundance of desirable species.

Editorial Forum

Atmospheric Carbon Dioxide: A Plant Fertilizer?

Boyd R. Strain

Horticulturists and greenhouse managers have long known that increasing the carbon dioxide concentration in greenhouses would give larger plants with more and larger flowers and more crop yield.[1] Twenty years ago, agronomists speculated from field experiments and simulation modeling[2] that enriching the atmosphere around crops in the field would give a fertilizer effect, causing more plant growth and greater crop yield. Recent measurements[3] with citrus trees suggest that a doubling or tripling of tree growth might be brought about with a doubling of the atmospheric concentration of carbon dioxide. All of these observations were made under controlled agricultural conditions in which all other environmental requirements were maintained at optimal levels. In other words, when temperature, light, soil water, and mineral fertilizers are present in optimal ranges and when plants are not suffering from disease, weed competition, or herbivory, adding carbon dioxide to the atmosphere generally increases plant growth and crop yield.

Realizing that the global atmosphere is steadily increasing in carbon dioxide and believing that the gas has the properties of a plant fertilizer, some individuals have proposed that this increase is a good thing. They suggest that we should not be concerned about carbon dioxide enhancement because the fertilization effect is going to help us feed the increasing human population. This argument is usually offered with expressions of doubt that such increases in carbon dioxide will result in significant global warming. The purveyors of this idea argue that if the greenhouse effect were going to occur the thermal effect of the 25% increase observed in carbon dioxide concentration during the past century would be detectable in the global climate record. We have all been treated to the pros and cons of this argument in the pages of our scientific journals and more frequently in the popular press. Newspapers, news magazines, television commentators, and popular movie idols have all entered into the fray. Is it any wonder that our legislators and citizens remain in a state of uncertainty and confusion?

Let us consider the evidence that atmospheric carbon dioxide might, under average agricultural field conditions, serve as a fertilizer and stimulate plant growth. An extensive review of the literature[4] disclosed that much of the evidence for large increases (>80%) in carbon fixation from a doubling of carbon dioxide concentration comes from short-term measurements of net photosynthesis rates. The few long-term experiments that have been made of total plant growth and economic crop yield indicate that a doubling of carbon dioxide would increase economic crop yield in ten of the world's leading crops by an average of 30%. This discovery led to my statement[5] that some fraction (2.5 to 10%) of the increases in crop yield realized in this century could have been due to carbon dioxide fertilization rather than to genetic improvement and the application of mineral fertilizers and pesticides.

One possible complication that must be taken into account in estimating future agricultural productivity is that plants require a balanced supply of essential mineral elements from the soil (e.g., nitrogen, phosphorus, sulfur, calcium, iron, and many others) to maintain maximum growth rates. If the atmosphere is supplemented with carbon dioxide but the soil fertility is not raised, plant tissues will become carbon rich but the maximum possible growth response will not occur because of mineral nutrient limitations. Agriculturists in developed countries may have the means to add the required soil fertilizers but third-world farmers will experience new problems in maintaining yields. Likewise, rangeland and forest managers may not observe significant growth increases because available nutrients become incorporated into plant and litter material and are not recycled in rates sufficient to meet the demand resulting from the carbon fertilization. The ecological recycling of mineral nutrients requires fun-

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gal and bacterial decomposition of dead plant materials. If these materials have high carbon to protein (C/N) ratios microbial decomposers may be inhibited and the rate of elemental recycling may decline. At current rates of nitrogen and phosphorus addition in agricultural and urban settings we are experiencing ground and surface water pollution. It must be assumed that these pollution problems would be intensified if it became necessary to increase the concentrations, or rates of application, of soil fertilizers. The expense of food production would increase if nitrogen and phosphorus demands were to escalate. Since both nitrogen and phosphorus fertilizer production are energy intensive industries, one may also predict that the energy requirement of intensive agriculture will increase.

Another positive benefit from carbon dioxide enhancement has been suggested by observations that plants lose less water by transpiration when they are growing in atmospheres containing increased carbon dioxide. This is because the stomatal pores in the epidermis of plant leaves, through which water vapor is lost to the atmosphere by transpiration, are partially constricted in the presence of high concentrations of carbon dioxide. It is frequently observed, in fact, that a doubling of atmospheric carbon dioxide can halve the conductance of water vapor through the stomatal pores. With more carbon fixed from increasing net photosynthesis but decreasing water lost by transpiration, the water-use-efficiency (WUE) ratio (CO_2 fixed in photosynthesis/H_2O lost in transpiration) increases. Thus, it has been speculated that crop water use would decrease, with the plants requiring less irrigation water in irrigated fields and less soil water in dry-land agriculture. On the other hand, it has been pointed out that most crops produce greater leaf area under high carbon dioxide concentrations and that greater leaf area per plant would consume the water saved by increasing WUE. The interaction between temperature, precipitation, and atmospheric humidity drives evaporation and transpiration, so this issue will remain unresolved until future climates can be more accurately predicted.

It is clear that plant species and varieties respond differentially to carbon dioxide increase.[6] In fact, plants respond in differential fashion to essentially any environmental change. In the case of carbon dioxide, plants with the carbon-three (C-3) photosynthetic pathway (most vascular plants of the world) increase in photosynthesis and growth up to at least double the current atmospheric carbon dioxide concentration if other potentially limiting resources remain available. Carbon-four (C-4) pathway plants (some important crops, including corn and sorghum, and some aggressive weeds, including Johnson grass) are nearly carbon dioxide saturated at the current atmospheric carbon dioxide concentration. Thus, we can predict that C-3 crops and weeds will be stimulated by carbon dioxide enhancement while C-4 crops and weeds will be less stimulated. Thus, while C-3 weeds will be more of an agricultural problem in the future C-4 weeds may decrease in importance. Likewise, C-3 crops (e.g., wheat, rice, barley, soybean, cotton) may experience significant gains while C-4 crops (e.g., corn, sorghum, sugar cane) may not be so stimulated. As stated above, however, the degree of stimulation will be dependent on other environmental factors remaining optimal for the new carbon dioxide level. It is probable that agriculturists will seek to optimize future productivity by selecting the most responsive varieties and species dependent upon the overall environmental conditions realized in their area.

In addition to the argument that more atmospheric carbon dioxide will be beneficial and therefore fossil fuel releases do not have to be restrained, some individuals maintain that restraints on fossil fuel consumption may not have to be applied because carbon is sequestered in forests and other carbon storing ecosystems (e.g., peatlands). It has been estimated that the rate of carbon dioxide enrichment of the global atmosphere could be slowed by the extensive planting of trees.[7] The hope is that, when the current rates of carbon fixation are supplemented with carbon fertilization due to atmospheric enrichment with carbon dioxide, much of the carbon dioxide will be scrubbed from the atmosphere and stored in wood. The concept is even being applied commercially by the Applied Energy Services utility company, which plans to reforest 400 square miles of degraded tropical forest in Guatemala with the aim of exactly compensating for the estimated 15.5 billion tons of carbon that will be emitted during the 40-year life time of a new power plant the company is constructing in Connecticut.

Ecologists pointed out several years ago,[8] however, that biological productivity in unmanaged ecosystems is limited by the natural recycling of mineral elements in conjunction with periodic physical environmental stresses (e.g., high and low temperature, drought,

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salinity, insufficient or excess light) and biological stresses (e.g., herbivory, parasitism, competition). Occasional catastrophic events, such as hurricanes, floods, and epidemic herbivory or disease in many tropical ecosystems and drought, fire, and erosion in temperate ecosystems, occur with sufficient frequency to reduce net ecosystem productivity and the potential of ecosystems to sequester carbon over the long term. For the Guatemalan forest to do its part it will have to sequester carbon at an average annual rate of almost 1000 tons per square mile per year for 40 uninterrupted years. Although this rate is only 0.4 of estimated maximum tropical forest sequestration rates, it is probable that the degraded state of the land to be reforested in Guatemala will prevent the required rate of carbon storage. It must also be realized that carbon sequestration only occurs in young and recovering forests. Mature forests, like mature people, reach a steady state of growth at which carbon intake equals carbon loss on an annual basis. Thus, the millions of square miles that would be required to sequester a significant portion of the annual global carbon dioxide injection would only have a temporary scrubbing effect. Once the forests became mature it would be necessary to harvest the trees and to plant new forests to maintain sequestration. Of course, the timber could not be used for firewood or short-term paper products. It would be necessary to save all of the organic matter produced by the forest and to keep it locked up forever to prevent it from reentering the atmosphere as carbon dioxide.

On the basis of the evidence now available I conclude that although carbon dioxide is definitely a plant fertilizer and humans may ultimately benefit from some increase in the concentration of the gas in the atmosphere, the accelerating rate of change predicted to occur if fossil fuel consumption continues to grow unabated may not be tolerable. It will obviously require a certain amount of time for the effects of the carbon dioxide increase on plant growth to be incorporated into the agricultural technology of developed countries but, at current or reduced rates of injection, I believe such adjustments will be possible. However, the agricultural systems of third-world countries or the ecological systems of non-agricultural regions of the earth cannot accomodate the current rate of injection. These non-managed areas will undergo significant ecological modification if restrictions are not applied to future carbon dioxide injection rates. Carbon sequestration as a result of tree planting will not be important in reducing carbon dioxide concentrations in the long term. In the short term, tree planting will undoubtedly be beneficial in terms of decreased erosion and decreased mineral nutrient loss to the rivers and oceans. For the longer term, in addition to fossil fuel conservation, the development of non-carbon energy alternatives will be essential both to reduce the risk of global warming and to prevent over-fertilization of plant crops.

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Editorial Forum

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[8]Strain BR, Bazzaz FA (1983): Terrestrial plant communities. In Lemon ER (ed) CO_2 and Plants: The Response of Plants to Rising Levels of Atmospheric CO_2. Boulder, CO, Westview Press, pp 172-222.

salinity, insufficient or excess light) and biological stresses (e.g., herbivory, parasitism, competition). Occasional catastrophic events, such as hurricanes, floods, and epidemic herbivory or disease in many tropical ecosystems and drought, fire, and erosion in temperate ecosystems, occur with sufficient frequency to reduce net ecosystem productivity and the potential of ecosystems to sequester carbon over the long term. For the Guatemalan forest to do its part it will have to sequester carbon at an average annual rate of almost 1000 tons per square mile per year for 40 uninterrupted years. Although this rate is only 0.4 of estimated maximum tropical forest sequestration rates, it is probable that the degraded state of the land to be reforested in Guatemala will prevent the required rate of carbon storage. It must also be realized that carbon sequestration only occurs in young and recovering forests. Mature forests, like mature people, reach a steady state of growth at which carbon intake equals carbon loss on an annual basis. Thus, the millions of square miles that would be required to sequester a significant portion of the annual global carbon dioxide injection would only have a temporary scrubbing effect. Once the forests became mature it would be necessary to harvest the trees and to plant new forests to maintain sequestration. Of course, the timber could not be used for firewood or short-term paper products. It would be necessary to save all of the organic matter produced by the forest and to keep it locked up forever to prevent it from reentering the atmosphere as carbon dioxide.

On the basis of the evidence now available I conclude that although carbon dioxide is definitely a plant fertilizer and humans may ultimately benefit from some increase in the concentration of the gas in the atmosphere, the accelerating rate of change predicted to occur if fossil fuel consumption continues to grow unabated may not be tolerable. It will obviously require a certain amount of time for the effects of the carbon dioxide increase on plant growth to be incorporated into the agricultural technology of developed countries but, at current or reduced rates of injection, I believe such adjustments will be possible. However, the agricultural systems of third-world countries or the ecological systems of non-agricultural regions of the earth cannot accomodate the current rate of injection. These non-managed areas will undergo significant ecological modification if restrictions are not applied to future carbon dioxide injection rates. Carbon sequestration as a result of tree planting will not be important in reducing carbon dioxide concentrations in the long term. In the short term, tree planting will undoubtedly be beneficial in terms of decreased erosion and decreased mineral nutrient loss to the rivers and oceans. For the longer term, in addition to fossil fuel conservation, the development of non-carbon energy alternatives will be essential both to reduce the risk of global warming and to prevent over-fertilization of plant crops.

? t 3/5/1-28

3/5/1
01891840 GEOREF NO.: 90-26544 BIBL. INDEX GEOLOGY NO.: 90-23390
MONOGRAPH TITLE: Carbon dioxide and global change; Earth in transition
AUTHOR(S): Idso, Sherwood B.
PUBLISHER: IBR Press, Tempe, AZ, United States
DATE: 1989 292 p.
COUNTRY OF PUBLICATION: United States
ISBN: 0-9623489-1-0
SUBFILE: B
DOCUMENT TYPE: Book BIBLIOGRAPHIC LEVEL: Monographic
ILLUSTRATIONS: illus.
LANGUAGE: English
MAJOR DESCRIPTORS: *ecology
DESCRIPTORS: changes; greenhouse effect; carbon dioxide; climate; atmosphere; drought; ozone; soils; plants
SECTION HEADINGS: 22 (Engineering & Environmental Geology)

3/5/2
01834743 GEOREF NO.: 89-49775 BIBL. INDEX GEOLOGY NO.: 89-43049
TITLE: A problem for paleoclimatology?
AUTHOR(S): Idso, S. B.
CORPORATE SOURCE: U. S. Water Conserv. Lab., Phoenix, AZ, United States
SOURCE: Quaternary Research (New York) vol. 31 no. 3 p. 433-434
DATE: 1989
COUNTRY OF PUBLICATION: United States
CODEN: QRESAV ISSN: 0033-5894 REFS.: 21
SUBFILE: B
DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
LANGUAGE: English
MAJOR DESCRIPTORS: *paleoclimatology
DESCRIPTORS: methods; interpretation; indicators; plants; carbon dioxide; palynomorphs; microfossils
SECTION HEADINGS: 24 (Surficial Geology, Quaternary Geology)

3/5/3
01819415 GEOREF NO.: 89-33608 BIBL. INDEX GEOLOGY NO.: 89-24494
TITLE: Historical temperature trends in the United States and the effect of urban population growth
AUTHOR(S): Balling, R. C., Jr.; Idso, S. B.
CORPORATE SOURCE: Ariz. State Univ., Dep. Geogr., Tempe, AZ, United States; U. S. Water Conserv. Lab., United States
SOURCE: Journal of Geophysical Research, D, Atmospheres vol. 94 no. 3 p. 3359-3363
DATE: 1989
COUNTRY OF PUBLICATION: United States
ISSN: 0747-7309 REFS.: 22
SUBFILE: B
DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
ILLUSTRATIONS: 4 tables; sketch maps
LANGUAGE: English
MAJOR DESCRIPTORS: *United States; *ecology
DESCRIPTORS: stratigraphy; Holocene; observations; terrestrial environment; environmental geology; land use; Quaternary; upper Holocene; climate;

urbanization; conterminous regions; paleoclimatology; human activity; temperature; paleotemperature; modern; changes; regression analysis; statistical analysis; environment
SECTION HEADINGS: 22 (Engineering & Environmental Geology); 24 (Surficial Geology, Quaternary Geology)

3/5/4
01615546 GEOREF NO.: 88-05742 BIBL. INDEX GEOLOGY NO.: 88-04019
TITLE: Detection of global carbon dioxide effects
AUTHOR(S): Idso, S. B.
CORPORATE SOURCE: U. S. Water Conserv. Lab., Phoenix, AZ, United States
SOURCE: Nature (London) vol. 329 no. 6137 p. 293
DATE: 1987
COUNTRY OF PUBLICATION: United Kingdom
CODEN: NATUAS ISSN: 0028-0836
SUBFILE: B
DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
LANGUAGE: English
MAJOR DESCRIPTORS: *atmosphere; *ecology
DESCRIPTORS: geochemistry; carbon dioxide; observations; greenhouse effect; global; seasonal variations
SECTION HEADINGS: 22 (Engineering & Environmental Geology); 02 (Geochemistry)

3/5/5
01388671 GEOREF NO.: 85-32598 BIBL. INDEX GEOLOGY NO.: 85-34058
TITLE: Rising atmospheric carbon dioxide concentrations may increase streamflow
AUTHOR(S): Idso, S. B.; Brazel, A. J.
CORPORATE SOURCE: U. S. Water Conserv. Lab., Phoenix, AZ, United States ; Ariz. State Univ., United States
SOURCE: Nature (London) vol. 312 no. 5989 p. 51-53
DATE: 1984
COUNTRY OF PUBLICATION: United Kingdom
CODEN: NATUAS ISSN: 0028-0836 REFS.: 12
SUBFILE: B
DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
ILLUSTRATIONS: illus.; 2 tables
LANGUAGE: English
MAJOR DESCRIPTORS: *atmosphere; *Western U.S.; *hydrology
DESCRIPTORS: composition; changes; hydrogeology; hydrologic cycle; carbon dioxide; geochemistry; atmospheric precipitation; rivers and streams; stream flow; United States
SECTION HEADINGS: 21 (Hydrogeology & Hydrology)

3/5/6
01356529 GEOREF NO.: 84-57433 BIBL. INDEX GEOLOGY NO.: 84-52729
TITLE: ''Greenhouse effect'' may be beneficial
AUTHOR(S): Idso, S. B.
CORPORATE SOURCE: U. S. Water Conserv. Lab. Agric. Res. Serv., Phoenix, AZ, United States
SOURCE: Geotimes vol. 29 no. 7 p. 7
DATE: 1984
COUNTRY OF PUBLICATION: United States
CODEN: GEOTAJ ISSN: 0016-8556
SUBFILE: B

DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
LANGUAGE: English
MAJOR DESCRIPTORS: *atmosphere
DESCRIPTORS: changes; carbon dioxide; fossil fuels; analysis
SECTION HEADINGS: 22 (Engineering & Environmental Geology)

3/5/7
01281003 GEOREF NO.: 83-43248 BIBL. INDEX GEOLOGY NO.: 83-41077
TITLE: Climatic effects of atmospheric carbon dioxidediscussions and reply
AUTHOR(S): MacCracken, M. C.; Idso, S. B.; Hansen, J.; Johnson, D.; Lacis, A.; Lebedeff, S.; Lee, P.; Rind, D.; Russell, G.
CORPORATE SOURCE: Lawrence Livermore Lab., Atmos. and Geophys. Sci. Div., Livermore, CA, United States; U. S. Water Conserv. Lab., United States, Goddard Space Flight Cent., United States
SOURCE: Science vol. 220 no. 4599 p. 873-875
DATE: 1983
COUNTRY OF PUBLICATION: United States
CODEN: SCIEAS ISSN: 0036-8075 REFS.: 10
SUBFILE: B
DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
ILLUSTRATIONS: illus.
LANGUAGE: English
NOTE: For reference to article by Hansen, J., et al., see Science, Vol. 213, p. 957, 1981
MAJOR DESCRIPTORS: *atmosphere
DESCRIPTORS: composition; carbon dioxide; climate effects; temperature; global; paleoclimatology
SECTION HEADINGS: 02 (Geochemistry)

3/5/8
01205119 GEOREF NO.: 82-33896 BIBL. INDEX GEOLOGY NO.: 82-30747
TITLE: Climatic change; desert-forming processes
AUTHOR(S): Idso, Sherwood B.
CORPORATE SOURCE: U. S. Water Conserv. Lab., Phoenix, AZ, United States
MONOGRAPH TITLE: Desert dust; origin, characteristics, and effect on man
EDITOR(S): Pewe, Troy L. (editor)
CORPORATE SOURCE: Ariz. State Univ., Dep. Geol., Tempe, AZ, United States
CONFERENCE TITLE: Desert dust; origin, characteristics, and effect on man
CONFERENCE LOCATION: Denver, CO, United States
CONFERENCE DATE: Feb. 22-23, 1977
SOURCE: Special Paper - Geological Society of America no. 186 p. 217-222
DATE: 1981
COUNTRY OF PUBLICATION: United States
ISBN: 0-8137-2186-5
CODEN: GSAPAZ ISSN: 0072-1077 REFS.: 34
SUBFILE: B
DOCUMENT TYPE: Serial; Conference BIBLIOGRAPHIC LEVEL: Analytic
LANGUAGE: English SUMMARY LANGUAGE: German; French; Russian; Chinese
MAJOR DESCRIPTORS: *ecology; *geomorphology; *sedimentation
DESCRIPTORS: changes; climate; eolian features; deserts; transport; wind transport; desertification; landform evolution; solar radiation
SECTION HEADINGS: 22 (Engineering & Environmental Geology)

3/5/9
01205118 GEOREF NO.: 82-33895 BIBL. INDEX GEOLOGY NO.: 82-30746

TITLE: Climatic change; the role of atmospheric dust
AUTHOR(S): Idso, Sherwood B.
CORPORATE SOURCE: U. S. Water Conserv. Lab., Phoenix, AZ, United States
MONOGRAPH TITLE: Desert dust; origin, characteristics, and effect on man
EDITOR(S): Pewe, Troy L. (editor)
CORPORATE SOURCE: Ariz. State Univ., Dep. Geol., Tempe, AZ, United States
CONFERENCE TITLE: Desert dust; origin, characteristics, and effect on man
CONFERENCE LOCATION: Denver, CO, United States
CONFERENCE DATE: Feb. 22-23, 1977
SOURCE: Special Paper - Geological Society of America no. 186 p. 207-215
DATE: 1981
COUNTRY OF PUBLICATION: United States
ISBN: 0-8137-2186-5
CODEN: GSAPAZ ISSN: 0072-1077 REFS.: 95
SUBFILE: B
DOCUMENT TYPE: Serial; Conference BIBLIOGRAPHIC LEVEL: Analytic
ILLUSTRATIONS: illus.
LANGUAGE: English SUMMARY LANGUAGE: German; French; Russian; Chinese
MAJOR DESCRIPTORS: *atmosphere; *pollution; *ecology
DESCRIPTORS: composition; aerosols; air; dust; changes; climate; clastic sediments; solar radiation; temperature; climate effects; human ecology
SECTION HEADINGS: 22 (Engineering & Environmental Geology)

3/5/10
01069763 GEOREF NO.: 81-64436 BIBL. INDEX GEOLOGY NO.: 81-60594
TITLE: Human actions and nature's reactions
AUTHOR(S): Idso, S. B.
CORPORATE SOURCE: U. S. Water Conserv. Lab., Phoenix, AZ, United States
MONOGRAPH TITLE: American Quaternary Association; sixth biennial meeting, abstracts and program
AUTHOR(S): Anonymous
CONFERENCE TITLE: American Quaternary Association; Sixth biennial meeting
CONFERENCE LOCATION: Orono, Maine, United States
CONFERENCE DATE: Aug. 18-20, 1980
SOURCE: Am. Quat. Assoc., Natl. Conf., Abstr. no. 6 p. 105-106
DATE: 1980
COUNTRY OF PUBLICATION: United States
CODEN: AMQUAM
SUBFILE: B
DOCUMENT TYPE: Abstract; Serial; Conference BIBLIOGRAPHIC LEVEL: Analytic
LANGUAGE: English
MAJOR DESCRIPTORS: *atmosphere
DESCRIPTORS: temperature; greenhouse effect; carbon dioxide; mathematical models; models; composition; heat balance; experimental studies; pollution; human ecology
SECTION HEADINGS: 24 (Surficial Geology, Quaternary Geology)

3/5/11
01019546 GEOREF NO.: 81-12154
TITLE: Net radiation received by a horizontal surface at the earth, by B. de Jong
AUTHOR(S): Idso, S. B.
SOURCE: J. Hydrol. vol. 24 no. 3-4 p. 351-352
DATE: 1975
COUNTRY OF PUBLICATION: International
CODEN: JHYDA7 ISSN: 0022-1694

SUBFILE: B
DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
LANGUAGE: English
MAJOR DESCRIPTORS: *book reviews
DESCRIPTORS: hydrogeology; title
SECTION HEADINGS: 15 (Miscellaneous & Mathematical Geology)

3/5/12
00978444 GEOREF NO.: 80-25856 BIBL. INDEX GEOLOGY NO.: 80-22802
TITLE: The climatological significance of a doubling of Earth's atmospheric carbon dioxide concentration
AUTHOR(S): Idso, S. B.
CORPORATE SOURCE: U. S. Water Conserv. Lab., Phoenix, Ariz., United States
SOURCE: Science (AAAS) vol. 207 no. 4438 p. 1462-1463
DATE: 1980
COUNTRY OF PUBLICATION: United States
CODEN: SCIEAS ISSN: 0036-8075 REFS.: 11
SUBFILE: B
DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
LANGUAGE: English
MAJOR DESCRIPTORS: *atmosphere
DESCRIPTORS: composition; carbon dioxide; abundance; climate; theoretical studies; mathematical models; models
SECTION HEADINGS: 02 (Geochemistry)

3/5/13
00931060 GEOREF NO.: 79-18541 BIBL. INDEX GEOLOGY NO.: 79-18072
TITLE: Duststorms of Mars
AUTHOR(S): Idso, S. B.
SOURCE: Astronomy vol. 5 no. 3 p. 34-39
DATE: 1977
COUNTRY OF PUBLICATION: United States
SUBFILE: B
DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
ILLUSTRATIONS: illus.
LANGUAGE: English
MAJOR DESCRIPTORS: *Mars
DESCRIPTORS: observations; duststorms; 1973; Viking
SECTION HEADINGS: 04 (Extraterrestrial Geology)

3/5/14
00899953 GEOREF NO.: 78-36002 BIBL. INDEX GEOLOGY NO.: 78-35738
TITLE: Atmospheric dust; climatological consequencesdiscussion and reply
AUTHOR(S): Herman, B. M.; Twomey, S. A.; Staley, D. O.; Idso, S. B.; Brazel, A. J.
CORPORATE SOURCE: Univ. Ariz., Inst. Atmos. Phys., Tucson, Ariz., United States; U. S. Water Conserv. Lab., United States, Ariz. State Univ., United States
SOURCE: Science (AAAS) vol. 201 no. 4353 p. 378-379
DATE: 1978
COUNTRY OF PUBLICATION: United States
CODEN: SCIEAS REFS.: 1
SUBFILE: B
DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
LANGUAGE: English

NOTE: For reference to article by Idso, S. B., and Brazel, A. J., see Science, Vol. 198, p. 731, 1977
MAJOR DESCRIPTORS: *atmosphere; *pollution
DESCRIPTORS: composition; dust; air; effects; aerosols; climate; temperature; solar radiation; Arizona; global; Phoenix
SECTION HEADINGS: 22 (Engineering & Environmental Geology)

3/5/15
00898826 GEOREF NO.: 78-34875 BIBL. INDEX GEOLOGY NO.: 78-35753
TITLE: Climatological effects of atmospheric particulate pollution
AUTHOR(S): Idso, S. B.; Brazel, A. J.
CORPORATE SOURCE: U. S. Water Conserv. Lab., Phoenix, Ariz., United States; Ariz. State Univ., United States
SOURCE: Nature vol. 274 no. 5673 p. 781-782
DATE: 1978
COUNTRY OF PUBLICATION: United Kingdom
CODEN: NATUAS REFS.: 17
SUBFILE: B
DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
ILLUSTRATIONS: illus.
LANGUAGE: English
COORDINATES: Latitude: N331500 ; N334500 ; Longitude: W1130000 ; W1122000
MAJOR DESCRIPTORS: *atmosphere; *pollution; *ecology; *volcanology
DESCRIPTORS: composition; particulate materials; effects; temperature; changes; volcanism; dust clouds; Maricopa County; pollutants; climate; human ecology; dust; experimental studies; cooling; anthropogenic materials; warming; Arizona; Phoenix; South Mountain; observations; conservation
SECTION HEADINGS: 22 (Engineering & Environmental Geology)

3/5/16
00880363 GEOREF NO.: 78-16393 BIBL. INDEX GEOLOGY NO.: 78-21187
TITLE: A perspective on the role of atmospheric dust in climatic change theory
AUTHOR(S): Idso, S. B.
CORPORATE SOURCE: U. S. Water Conserv. Lab., Phoenix, Ariz., United States
MONOGRAPH TITLE: Abstracts of the Fourth biennial meeting of the American Quaternary Association
AUTHOR(S): Andrews, J. T.; Barry, R. G. (chairperson; chairperson)
CONFERENCE TITLE: Fourth biennial meeting of the American Quaternary Association
CONFERENCE LOCATION: Tempe, Ariz., United States
CONFERENCE DATE: Oct. 9-10, 1976
SOURCE: Am. Quat. Assoc., Natl. Conf., Abstr. no. 4 p. 59-60
DATE: 1976
COUNTRY OF PUBLICATION: United States
CODEN: AMQUAM
SUBFILE: B
DOCUMENT TYPE: Abstract; Serial; Conference BIBLIOGRAPHIC LEVEL: Analytic
LANGUAGE: English
MAJOR DESCRIPTORS: *paleoclimatology; *geomorphology
DESCRIPTORS: Quaternary; global; landform evolution; deserts; changes; dust ; thermal radiation; albedo; genesis; mechanism; Holocene
SECTION HEADINGS: 24 (Surficial Geology, Quaternary Geology)

3/5/17
00871683 GEOREF NO.: 78-07713 BIBL. INDEX GEOLOGY NO.: 78-06469
TITLE: Solar and thermal radiation as estimators of soil water content
AUTHOR(S): Jackson, R. D.; Reginato, R. J.; Idso, S. B.
CONFERENCE TITLE: American Geophysical Union; 1976 fall annual meeting
CONFERENCE LOCATION: San Franc., Calif., United States
CONFERENCE DATE: Dec. 6-10, 1976
SOURCE: Eos (Am. Geophys. Union, Trans.) vol. 57 no. 12 p. 913
DATE: 1976
COUNTRY OF PUBLICATION: United States
CODEN: EOSTAJ
SUBFILE: B
DOCUMENT TYPE: Abstract; Serial; Conference BIBLIOGRAPHIC LEVEL: Analytic
LANGUAGE: English
MAJOR DESCRIPTORS: *remote sensing; *soils
DESCRIPTORS: methods; infrared methods; water regimes; moisture; storage; albedo; thermal radiation
SECTION HEADINGS: 21 (Hydrogeology & Hydrology)

3/5/18
00868664 GEOREF NO.: 78-04692 BIBL. INDEX GEOLOGY NO.: 78-06838
TITLE: Planetary radiation balance as a function of atmospheric dust; climatological consequences
AUTHOR(S): Idso, S. B.; Brazel, A. J.
CORPORATE SOURCE: U. S. Water Conserv. Lab., Phoenix, Ariz., United States; Ariz. State Univ.
SOURCE: Science (AAAS) vol. 194 no. 4318 p. 731-733
DATE: 1977
COUNTRY OF PUBLICATION: United States
CODEN: SCIEAS REFS.: 6
SUBFILE: B
DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
ILLUSTRATIONS: illus.
LANGUAGE: English
NOTE: U. S. Agric. Res. Serv.; Contrib.
MAJOR DESCRIPTORS: *environmental geology; *atmosphere
DESCRIPTORS: concepts; human ecology; observations; heat balance; dust; solar radiation; aerosols; thermal radiation; troposphere; temperature; paleoclimatology; climate; Phoenix; Arizona; pollution
SECTION HEADINGS: 22 (Engineering & Environmental Geology)

3/5/19
00848385 GEOREF NO.: 77-33470 BIBL. INDEX GEOLOGY NO.: 77-34764
TITLE: An evaluation of total solar reflectance and spectral band ratioing techniques for estimating soil water content
AUTHOR(S): Reginato, R. J.; Vedder, J. F.; Idso, S. B.; Jackson, R. D.; Blanchard, M. B.; Goettelman, R.
SOURCE: J. Geophys. Res. vol. 82 no. 15 p. 2101-2104
DATE: 1977
COUNTRY OF PUBLICATION: United States
CODEN: JGREA2 REFS.: 8
SUBFILE: B
DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
ILLUSTRATIONS: illus.
LANGUAGE: English
NOTE: Paper No. 6C0925

COORDINATES: Latitude: N333000 ; N333000 ; Longitude: W1120300 ; W1120300
MAJOR DESCRIPTORS: *Arizona; *geophysical methods
DESCRIPTORS: Maricopa County; geophysical surveys; remote sensing; Phoenix; applications; solar radiation; reflectance; soils; moisture content; techniques; airborne; United States
SECTION HEADINGS: 20 (Geophysics, Applied)

3/5/20
00828324 GEOREF NO.: 77-13409 BIBL. INDEX GEOLOGY NO.: 77-15594
TITLE: Soil water content and evaporation determined by thermal parameters obtained from ground-based and remote measurements
AUTHOR(S): Idso, S. B.; Reginato, R. J.; Vedder, J. F.; Jackson, R. D.; Blanchard, M. B.; Goettelman, R.
CORPORATE SOURCE: U. S. Dep. Agric., U. S. Water Conserv. Lab., Phoenix, Ariz., United States; NASA, Ames Res. Cent., United States
SOURCE: Eos (Am. Geophys. Union, Trans.) vol. 56 no. 12 Fall annual meeting p. 985
DATE: 1975
COUNTRY OF PUBLICATION: United States
CODEN: EOSTAJ REFS.: 0
SUBFILE: B
DOCUMENT TYPE: Abstract; Serial BIBLIOGRAPHIC LEVEL: Analytic
LANGUAGE: English
MAJOR DESCRIPTORS: *hydrology; *soils; *geophysical methods
DESCRIPTORS: surveys; water regimes; evaporation; methods; applications; remote sensing; airborne; infrared methods; ground; moisture
SECTION HEADINGS: 25 (Surficial Geology, Soils)

3/5/21
00805212 GEOREF NO.: 76-35798
TITLE: Soil water content and evaporation determined by thermal parameters obtained from ground-based and remote measurements
AUTHOR(S): Reginato, R. J.; Idso, S. B.; Vedder, J. F.; Jackson, R. D.; Blanchard, M. B.; Goettelman, R.
SOURCE: J. Geophys. Res. vol. 81 no. 9 p. 1617-1620
DATE: 1976
CODEN: JGREA2
SUBFILE: B
DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
ILLUSTRATIONS: illus.
LANGUAGE: English
MAJOR DESCRIPTORS: *soils; *Arizona; *engineering geology; *geophysical surveys
DESCRIPTORS: water regimes; moisture content; evaporation; loam; measurement; temperature; methods; instruments; Phoenix; surveys; infrared surveys; remote sensing; comparison; ground; thermocouples; United States; satellite
SECTION HEADINGS: 22 (Engineering & Environmental Geology)

3/5/22
00804579 GEOREF NO.: 76-35165
TITLE: Timing of ground truth acquisition during remote assessment of soil-water content
AUTHOR(S): Jackson, R. D.; Reginato, R. J.; Idso, S. B.
CORPORATE SOURCE: U. S. Water Conserv. Lab., Phoenix, Ariz., United States

SOURCE: Remote Sensing Environ. vol. 4 no. 4 p. 249-255
DATE: 1976
CODEN: RSEEA7
SUBFILE: B
DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
ILLUSTRATIONS: illus.
LANGUAGE: English
MAJOR DESCRIPTORS: *soils; *Arizona
DESCRIPTORS: Avondale Loam; water regimes; water content; loam; remote sensing; sampling; ground truth; United States; Phoenix
SECTION HEADINGS: 25 (Surficial Geology, Soils)

3/5/23
00792180 GEOREF NO.: 76-22766
TITLE: The utility of surface temperature measurements for the remote sensing of surface soil water status
AUTHOR(S): Idso, S. B.; Schmugge, T.; Jackson, R. D.; Reginato, R. J.
CORPORATE SOURCE: U. S. Water Conserv. Lab., Phoenix, Ariz., United States; NASA Goddard Space Flight Cent., United States
SOURCE: J. Geophys. Res. vol. 80 no. 21 p. 3044-3049
DATE: 1975
CODEN: JGREA2
SUBFILE: B
DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
ILLUSTRATIONS: illus.
LANGUAGE: English
MAJOR DESCRIPTORS: *geophysical surveys; *Arizona; *soils
DESCRIPTORS: infrared surveys; United States; Phoenix; thermal; remote sensing; satellite; applications; measurement; moisture content; Avondale ; Gran; Cashion; Navajo; water regimes; methods; temperature; surface
SECTION HEADINGS: 25 (Surficial Geology, Soils)

3/5/24
00780833 GEOREF NO.: 76-11419
TITLE: Assessing soil-water status via albedo measurements
AUTHOR(S): Idso, S. B.; Reginato, R. J.
CORPORATE SOURCE: USDA, U. S. Water Conserv. Lab., Phoenix, Ariz., United States
SOURCE: Hydrol. Water Resour. Ariz. Southwest vol. 4 p. 41-54
DATE: 1974
SUBFILE: B
DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
ILLUSTRATIONS: illus.; tables
LANGUAGE: English
MAJOR DESCRIPTORS: *soils; *Arizona
DESCRIPTORS: water regimes; storage; moisture content; evaporation; measurement; methods; albedo; United States; Phoenix
SECTION HEADINGS: 25 (Surficial Geology, Soils)

3/5/25
00778253 GEOREF NO.: 76-08839
TITLE: Surface albedo and desertification
AUTHOR(S): Jackson, R. D.; Idso, S. B.; Otterman, J.
SOURCE: Science (AAAS) vol. 189 no. 4207 p. 1012-1015
DATE: 1975
COUNTRY OF PUBLICATION: United States

CODEN: SCIEAS
SUBFILE: B
DOCUMENT TYPE: Serial BIBLIOGRAPHIC LEVEL: Analytic
ILLUSTRATIONS: illus.
LANGUAGE: English
NOTE: Discussion and reply; for reference to article by Otterman, J., see Science, Vol. 186, p. 531, 1974
MAJOR DESCRIPTORS: *geomorphology
DESCRIPTORS: processes; desertification; mechanism; denudation; vegetation; removal; soils; albedo; increase; interpretation; temperature; surface; United States; Mediterranean region; Africa; Egypt; Middle East; Israel
SECTION HEADINGS: 23 (Surficial Geology, Geomorphology)

3/5/26
00731383 GEOREF NO.: 75-01105
TITLE: Thermal Blanketing: A Case for Aerosol-Induced Climatic Alteration
AUTHOR(S): Idso, Sherwood B.
SOURCE: Science (AAAS) Vol. 186, No. 4158, p. 50-51, illus.
DATE: 1974
CODEN: SCIEAS
SUBFILE: B
DOCUMENT TYPE: Serial
JOURNAL ANNOUNCEMENT: 1975
LANGUAGE: English
NOTE: Lower atmosphere pollution buildup, post-1946 warming trend, greenhouse effect, Phoenix, Arizona
MAJOR DESCRIPTORS: *Arizona; *Environmental geology
DESCRIPTORS: Pollution; Maricopa County; Phoenix; Atmosphere; lower; climate; temperature; changes; observations; United States
SECTION HEADINGS: 22 (Engineering & Environmental Geology)

3/5/27
00595308 GEOREF NO.: 71-22893
TITLE: Evaporation suppression by solar radiation reflection
AUTHOR(S): Idso, Sherwood B.
SOURCE: J. Geophys. Res. Vol. 76, No. 12, p. 2900
DATE: 1971
CODEN: JGREA2
SUBFILE: B
DOCUMENT TYPE: Serial
JOURNAL ANNOUNCEMENT: 1971
LANGUAGE: English
NOTE: For reference to original paper, see J. Geophys. Res. Vol. 75, No. 27, p. 5155-5163, 1970
MAJOR DESCRIPTORS: *Hydrology
DESCRIPTORS: Evaporation; Reflectance; solar radiation; monolayers; discussion
SECTION HEADINGS: 17 (Geophysics, General)

3/5/28
00582916 GEOREF NO.: 71-10445
TITLE: Seasonal changes in the vertical distribution of dust in the lower troposphere
AUTHOR(S): Idso, Sherwood B.; Kangieser, Paul C.
SOURCE: J. Geophys. Res. Vol. 75, No. 12, p. 2179-2184, illus.
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41 Pages

The Greenhouse Effect and Its Implications Regarding Global Agriculture

Research Bulletin Number 724 / April 1989

The Greenhouse Effect and Its Implications Regarding Global Agriculture

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BIOTIC INFLUENCES AS THE EARTH WARMS:
WARMER AND WARMER, FASTER....and faster...and..?([1])

George M. Woodwell

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I am a biologist with more than thirty years' experience in ecology addressing various aspects of the global carbon cycle, especially the interactions between life and environment. I have specialized in research on units of landscape such as forests and estuaries. I believe that we know enough now to anticipate great difficulties with the capacity of the earth for supporting us over the next years unless we move rapidly to correct the series of trends outlined in the scientific presentations today. The failure of the current US leadership to acknowledge this problem and offer the leadership that the rest of the world expects of us has made the United States an international pariah. To emphasize the seriousness of that unflattering perspective I am enclosing a copy of a recent editorial in The Guardian ([2]). I would also call attention to the recent report of the Office of Technology Assessment that shows clearly that the nation could reduce its reliance on fossil fuels by as much as 20% almost immediately at a net saving in dollars and with many ancillary environmental, economic, international and military advantages ([3]).

The accumulation of carbon dioxide and methane in the atmosphere is causing, and will cause, more than three quarters of the warming anticipated from heat-trapping gasses over the next several decades. Both are products of the exploitation of fossil fuels and products of biotic activity. For brevity I shall

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[1]. Testimony of G.M. Woodwell before the Subcommittee on Health and Environment, Committee on Energy and Commerce, U.S. House of Representatives, February 21, 1991.

[2]. Jeremy Leggett in The Guardian, Feb 1, 1991 (appended).

[3]. OTA, 1991. Changing by Degrees: Steps to Reduce Greenhouse Gasses. Congress of the United States, Office of Technology Assessment. 42pp.

emphasize carbon dioxide.

My most important conclusion is that evidence is accumulating that we are observing and can expect a continuing acceleration of the rate of accumulation of carbon dioxide and methane as the earth warms, an acceleration that will probably speed the warming ([4]).

I shall also emphasize that the primary control of the concentration of carbon dioxide in the atmosphere over years to decades is on land, not the oceans. Forests are the most important vegetation type on land because they are large in area, contain about three times as much carbon as the atmosphere currently contains, and because their annual metabolism involves an exchange with the atmosphere of at least 100 billion tons of carbon (Fig 1). This exchange is highly vulnerable to changes in the environment.

The two most powerful factors that affect the influence of forests on the composition of the atmosphere are their areal extent and their metabolism.

The area of forested lands in the world is declining. The magnitude of the decline is in question, but the pattern and direction of change globally are not. The pattern is now almost classical, if over-simplified here: in this world that adds 90 million new people annually, forests, especially in the tropics, are displaced by agriculture. The agriculture survives for a time, may be replaced by low-density grazing, and the land gradually lapses into impoverishment. It falls out of the economy and the records. Such land is accumulating globally, but there little attempt to measure it. One third of the land area of India is now recognized officially by Indian officials as impoverished to the point where it is outside agriculture and non-forested. Most is barren, salinized, or rock from which the soil has been lost through erosion by wind and monsoonal rains. The accumulation of impoverished land is the most important land-use change currently underway in the world. Most of that land was

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[4]. Woodwell, G.M. 1983. Biotic effects on the concentration of atmospheric carbon dioxide: A review and projection. in <u>Changing Climate</u>, NAS Press, Washington, D.C., pp 216-241

------- 1986. Testimony of G.M.Woodwell in hearings before the U.S. Senate Subcommittee on Environmental Pollution, of the Committee on Environment and Public Works, June 10-11, 1986. Congressional Record Special Printing, pp 98-106

WMO/UNEP 1990. Climate Change: The IPCC Scientific Assessment. 365pp. Geneva.

once forested and its impoverishment constitutes a major transfer of carbon from forest and soil to the atmosphere. The transfer continues. It can and will be measured, but only by applications of satellite imagery whose use, although technically advanced, is not yet being applied to this purpose with sufficient vigor to produce progress in proportion to the growth of the problem. There is, of course, question as to how the warming of the earth will affect climates globally, but the first assumption must be that a warming in the range of tenths of a degree C to one degree or more C per decade will cause an acceleration of the trend toward impoverishment.

The implications are seen most clearly by considering a forest such as the eastern deciduous forest of North America. At its warmer and drier limit it yields to grassland; at its wetter and colder limit it is replaced by coniferous or mixed hardwoods and softwoods in a transition zone to the boreal forest. Throughout its broad range it is made up of populations of trees of several species, but each population has existed through several generations and been selected for a genetic constitution appropriate for that place and climate. As the earth warms and climates change, plants at the warmer and drier limits of their distribution first, fail to reproduce, then succumb to pests of disease or fire. The forest is replaced by shrubland, later, by grassland. The transition may be accelerated by fire or disease as the trees are weakened. At the wetter and colder margin a similar transition occurs except that while climates may be appropriate to support forest, mortality of trees will far outstrip the capacity of the trees to regenerate and the interim community will be shrubland or some other stage of impoverished forest. These are conspicuous changes at the margins of the distribution of a plant community. There are parallel changes throughout the community. Each population of plants has been selected through several generations for the particular site and climate of its place. As climate changes, each population becomes maladapted to that place and each organism becomes more vulnerable to disease, to competition, to parasites or other disturbance. The community as a whole is weakened and, ultimately, impoverished as longer lived species die and are replaced but slowly if at all. The impoverishment will be accompanied by accelerated decay of dead and dying plants, adding to the release of carbon as carbon dioxide and methane into the atmosphere.

The changes in the metabolism of forests as our earthly habitat is modified under the human caress are also difficult to discern. A close acquaintance with the physiology of forests will lead in almost any direction: some have suggested that the increased precipitation and temperature in the higher latitudes associated with a warming of the earth and combined with the increased carbon dioxide in the atmosphere will cause a surge in the fixation and storage of carbon that will be a boon to life and tend to check the accumulation of carbon dioxide in the atmosphere. Such an effect may occur, possibly in a lesser degree than some of the more optimistic have asserted ([5]). But others will argue that whatever advantages there may be to gross photosynthesis will be lost through the acceleration of respiration in response to warmer temperatures ([6]). The issue is vital, for it contains the potential for diminishing or greatly aggravating the warming of the earth far beyond the current calculations of the climatologists. The question hinges on whether the changes in climate can be expected to stimulate the removal of carbon from the atmosphere through photosynthesis or the release of carbon as carbon dioxide and methane through the stimulation of the respiration of decay.

I suggest that the evidence for a resolution of that question sufficient to provide a basis for governmental action is available. The evidence was alluded to in the recent report of the Intergovernmental Panel on Climate Change (see note 4 above) which provided an international consensus on the seriousness of the problem. The IPCC called attention to the probability that the warming would proceed more rapidly than estimations based on emissions from fossil fuels have suggested.

Three lines of evidence show that the dominant influence on forests will be the changes in temperature and that a warming will cause a net release of carbon from the land into the atmosphere.

One is first principles of physiology and ecology: rates of respiration, including the respiration of decay, are highly sensitive to temperature. A one degree C. increase in temperature will increase rates of respiration by 5-30%, sometimes more. Rates of photosynthesis are much less sensitive to temperature and can be increased by as much as 10% only with difficulty. Virtually any disturbance of a forest stimulates respiration over

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[5]. The topic has been reviewed at length in Strain, B.R. and J.D. Cure. (eds) 1985. Direct Effects of Increasing Carbon Dioxide on Vegetation. U. S. Dept of Energy. National Technical Information Service, Springfield, Virginia 22161. 286 pp. and summarized in Woodwell, G.M. 1988. The warming of the industrialized middle latitudes 1985-2050: causes and consequences. Prepared for the Symposium: **Developing Policies for Responding to Future Climatic Change** held in Villach, Austria, September, 1987. Climatic Change, 15:31-50, 1989.

[6]. Houghton, R.A. and G.M. Woodwell, 1989. Global Climatic Change. Scientific American. April. pp36-44.

photosynthesis. Specific data addressing this issue are few and difficult to obtain.

But the most persuasive data we have are the observations of variations in temperature and carbon dioxide over time. We have the now well-known data from the Vostoc Core that show concentrations of both carbon dioxide and methane varying with temperature over 160,000 years of recent glacial history (Fig 2). While these data offer little insight into cause and effect, they do show that there is no basis, at least in that record, for defending the hypothesis that as temperature and carbon dioxide rise photosynthesis will be stimulated enough to reduce the concentration of carbon dioxide in the atmosphere and cure the problem. The carbon dioxide record seems to suggest that, at least during declining temperatures, the carbon dioxide concentrations lagged the changes in temperature.

We also have a set of data from Mauna Loa accumulated and analyzed by David Keeling and his colleagues, who have shown that there is a correlation between the temperature and carbon dioxide concentrations when the upward trend and the pronounced annual oscillation are removed (Fig. 3). The carbon dioxide concentration lags the temperature, a relationship that suggests that the temperature changes cause the changes in carbon dioxide. The shorter term oscillations are ascribed by Keeling et al ([7]) to changes in the surface temperature of the oceans; the longer term oscillations to changes in the metabolism on land. A more recent analysis of these same data by Oppenheimer and others shows that there are longer-term cycles of temperature and carbon dioxide that follow the same pattern with the carbon dioxide lagging temperature.

The third line of evidence is what is happening at the moment. We have had since 1980 seven of the warmest years for the globe in 130 years of record. If the observations above hold, we should see the accumulation of additional carbon in the atmosphere as carbon dioxide as the large pools of carbon in forests warm and respiration is accelerated. Such a change appears to be underway. Keeling and his colleagues (6) again have provided us with a set of data on the accumulation of carbon dioxide in the atmosphere (Fig 4). Two aspects of this curve are important. Firstly, after 1973 there was a sharp drop in the rate of expansion of global use of fossil fuels. In fact the rate of use stabilized through the first half of the 1980's. There was,

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[7]. Keeling, C.D., R.B. Bacastow, A.F. Carter, S.C. Piper, T. P. Whorf, M. Heimann, W.G. Mook, and H. Roeloffzen. 1989. A three dimensional model of atmospheric CO^2 transport based on observed winds: 1. Analysis of observational data. Geophysical Monograph 55. American Geophysical Union (pp165-236).

however, no obvious reduction in the rate of accumulation of carbon dioxide in the atmosphere. In subsequent years, in fact, with no appreciable increase in the use of fossil fuels globally, the rate of accumulation accelerated above the rate that had prevailed for more than 15 years. During the fifteen years prior to 1986 the rate of accumulation was about 1.5 ppm/yr, equivalent to about 3 billion tons of carbon. Since that year the rate of increase has varied up to 2.6 ppm or about 5 billion tons of carbon without any equivalent change in the use of fossil fuels. Keeling and colleagues examined this issue themselves in 1989 and prepared the graph shown here. Their conclusion was that the release is a biotic release. The conclusion was substantiated by considering the isotopic ratio of carbon in air. The rate of accumulation heat trapping gasses, especially carbon dioxide, has risen as might be expected from the experience summarized above.

The most important point here is that the warming of the earth can be expected to release additional carbon into the atmosphere and to speed the warming. The process appears to be underway. The seriousness of it becomes apparent only when one compares the magnitudes of the flows of carbon that contribute to the accumulation of 3-5 billion tons of carbon in the atmosphere as carbon dioxide.

The release from fossil fuels is about 5.6 billion tons of carbon. There is an additional release from deforestation currently estimated as between 0.5 and 3.0 billion tons, possibly more. Presumably these two fluxes are under human control and have been the major cause of the long-term accumulation of carbon in the atmosphere in heat-trapping gasses. A third net flux is appearing, if these analyses are correct. It is a shift in the formerly approximately balanced two-way flow of carbon through gross photosynthesis and total respiration in favor of respiration. The magnitude of such shift is potentially large, enough to swamp human capacities at control in a short time.

There is urgency in moving with deliberate and effective speed to stabilize the heat-trapping gas content of the atmosphere before we lose the capacity for affecting it and commit the earth to a cycle of warming of unknown severity, speed, duration and effects. While we may be able to anticipate with reasonable accuracy the effects of a warming of 1-2 degrees C, we are not able to anticipate the effects of a greater warming and the complex changes that will accompany it.

The steps to correct this circumstance are well known. The reasons for our failure to take them have nothing to do with science or knowledge or lack of insight as to the consequences.

Figure Captions:

Fig. 1. The global carbon cycle. Units are in billions of tons of carbon (10^{15} grams). The important point is the flux of carbon between the atmosphere and biotic pools on land. These flows are affected heavily by climate and by the management of vegetation, especially forests.

Fig. 2. Data on carbon dioxide and methane concentrations with estimations of temperature over 160,000 years of recent history of the earth. Adapted from IPCC, 1990.

Fig. 3. Temperature and carbon dioxide concentrations in air at Mauna Loa. The annual increase and the seasonal oscillation have been removed. (From Keeling et al. 1989)

Fig. 4. The accumulation of carbon dioxide in the atmosphere. During the late 1970's and early 1980's there was a levelling of the global use of fossil fuels. This levelling did not appear in the rate of accumulation of carbon dioxide in the atmosphere as shown in this graph. Later, during the late 1980's, the rate of accumulation has increased without any concomitant increase in the rate of consumption of fossil fuels. (From Keeling et al 1989)

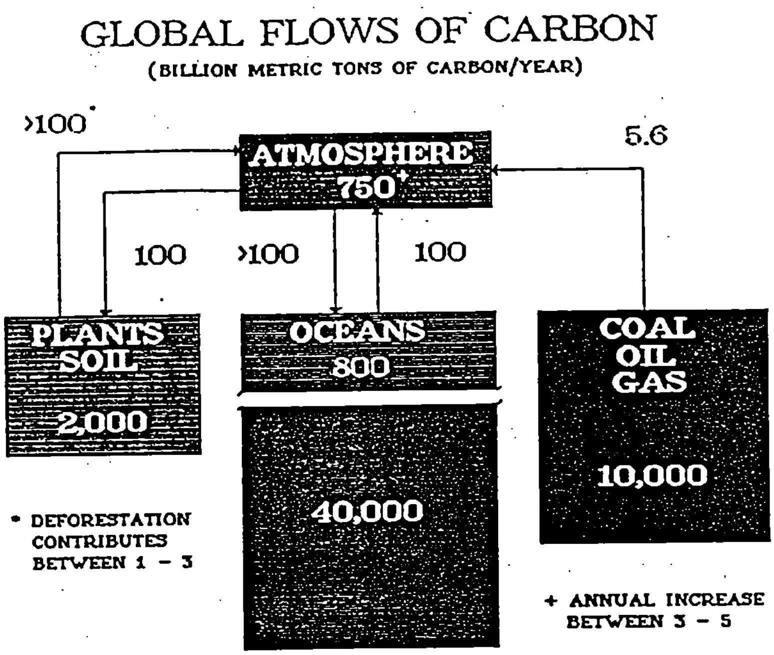


FIG. 1

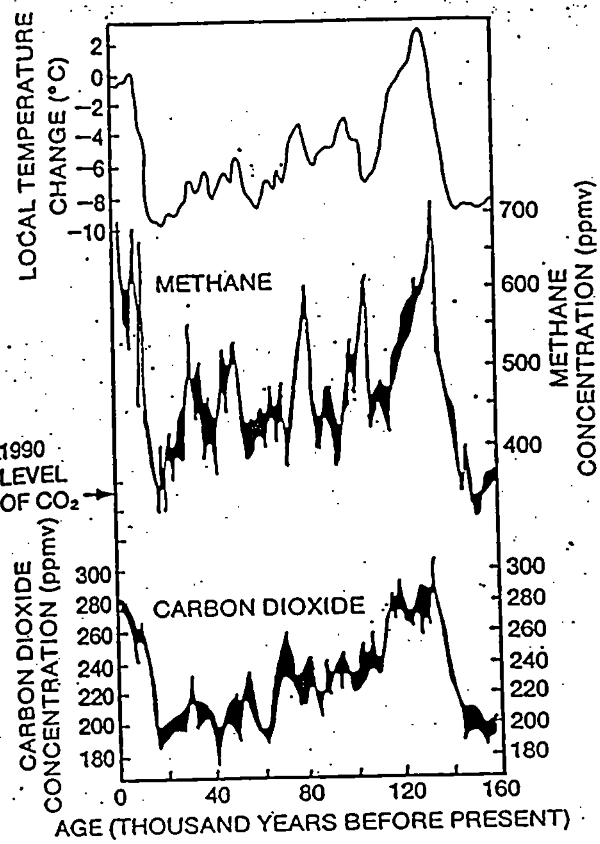


FIG. 2

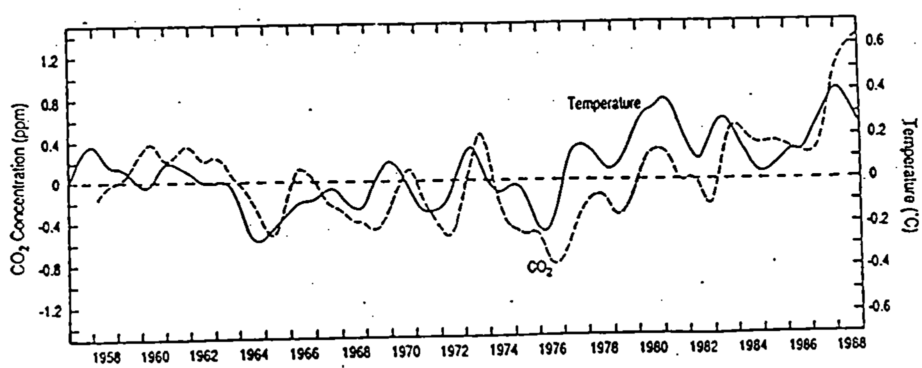


FIG. 3

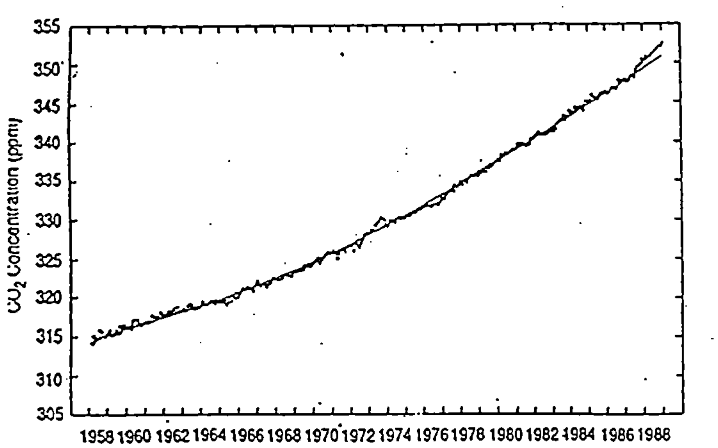


FIG. 4

THE GUARDIAN
Friday February 1 1991

Face the facts, George

Gulf war: as the oil slick widens, the rhetoric thickens. On the eve of a major conference on global warming, **Jeremy Leggett** asks who are the world's greatest carbon criminals

NO ONE can forgive the poisoning of the Gulf with more than 11 million barrels of oil. A criminal environmental act, right enough — a restricted, shallow sea, an already fragile ecosystem: a grotesque environmental tragedy. But as the rhetoric of war flows thick, parallel acts of carbon criminality are passing without comment.

● **23,000 million barrels:** the amount of oil burnt each year worldwide, more than a quarter of it in the US. These 23 billion barrels contribute 40 per cent of all energy-related carbon dioxide which mankind puts into the atmosphere each year, there to contribute — along with the products of coal and gas burning — almost 60 per cent of the human-enhanced greenhouse effect.

Remaining addicted to fossil fuels in this way will, within decades, unleash rates of temperature and sea-level rise unprecedented in human history. This is not doom-mongering: it is the prediction of every big climate-modelling centre in the world, and the opinion of hundreds of climate scientists who urged cuts in CO_2 emissions at last year's UN World Climate Conference. Yet, having located more than a million million barrels of oil under the ground (more than two thirds in the Gulf), oil companies are still looking for more.

● **7,500 million barrels:** transport's share of oil consumption. Transport consumes around one third of all the energy used in the world each year. The 24 leading industrialised countries of the OECD (Organisation for Economic Co-operation and Development) consume more than half the world's oil, and transport consumes more than half of the OECD's oil. Each year, the average car puts more than four times its body weight of CO_2 into the atmosphere.

● **2,500 million barrels:** the amount of gasoline burnt in one year in the US. America's share of oil used in world transport is more than one third. Small wonder: of the 400 million cars on the planet, Americans drive one third. Their fleet fuel-efficiency average is one of inefficiency unparalleled in the OECD: 20 mpg, at a time when Ford, General Motors, and Chrysler have the capability to mass-produce cars which do more than 100 mpg. Or to make battery- and hydrogen-powered cars charged by solar photovoltaic, so producing no direct greenhouse gas emissions.

● **1,900 million barrels:** the amount of oil imported to the US each year from the Gulf. And this is only 24 per cent of all US oil imports. By how much would fuel efficiency of the US car fleet have to improve to remove the need for these 1,900 million barrels? One third would more than do the trick. Average fuel efficiency of *new* US cars *decreased* from 1985 to 1989 (from 27.5 to 26 mpg), when the Reagan Administration slackened auto industry efficiency requirements. In the UK, fuel efficiency — after improving in the early eighties — has stalled, the Government having refused to introduce mandatory standards.

● **500 million barrels:** the approximate amount of oil afloat at any one time in supertankers, each one running the gauntlet of an Amoco Cadiz disaster (approximately two million barrels spilt). Over the last 16 years, 160 accidents have spilt more than 10,000 barrels each.

● **8 million to 20 million barrels:** the amount of oil spilt each year *deliberately* from tankers cleaning out tanks, terminal operations, dry docking, bilge and fuel oil dumping. The "low" estimate is from the International Maritime Organisation. For a high estimate, try the US Department of the Interior Minerals Management Service's best guess of around 20 million.

● **5 million to 11 million barrels:** Saddam's alleged act of environmental terrorism — as estimated so far. Five million barrels represents less than a tenth of 1 per cent of all oil into which Kuwait's oil wells tap.

● **1.6 million barrels:** the average daily oil production in Kuwait in 1989 — less than 3 per cent of the world total. By how much would the average fuel efficiency of the American car have to increase to shed the need of the US share of this *and* of Iraq's production in a normal year? Just 3 mpg — from 20 to 23 mph — according to the US Government's Lawrence Berkeley laboratory.

● **260,000 barrels:** the amount spilt by the Exxon Valdez. That "clean-up" involved 11,000 people, cost over $1 billion, and "cleared" only 20 per cent of the 1,000 miles-plus of beaches affected. The spill's short-term impacts on wildlife are well known. The scientific jury is still out on the long-term effects. It involved a finite source of oil (20 per cent of the contents of a supertanker). And it didn't take place in a war zone.

● **1 barrel:** the amount of oil needed for an oil-fuelled US aircraft carrier to steam 238 yards, or an M-1 tank to chug 23 miles (over that distance each puts 400 kilograms of CO_2 into the atmosphere).

The Global Climate Convention negotiations start on Monday, with more than 100 governments round the table. The low-lying island countries queuing up to plead for their physical and cultural survival are likely to be disappointed with the response.

George Bush, hoping to defer flak (along with Turkey, his is the only OECD government not to have promised stabilising or cutting greenhouse emissions in the years to come), offered to host the talks in Washington. Appropriately for the world's largest consumer and importer of oil, the world's largest producer of coal, and the world's largest emitter of CO_2 and total greenhouse gases (nearly a quarter of all world emissions), the US government has moved the talks to a Virginia backwater. As Bob Hall of the US Petroleum Institute said recently: "Burning hydrocarbons is a way of life."

The question is just who are the carbon criminals, George?

Dr Jeremy Leggett is director of science in Greenpeace International's Atmosphere and Energy Campaign.

APPENDIX A.

October 15, 1991

To: Katie McGinty

From: Tony Socci

Re: Plants, Crops and CO-2 Fertilization Effects

First of all, I have done much reading, much research and much phone-calling regarding the relationship between nutrients and plant/crop/tree yield (fluxes in biomass = organic carbon fluxes). My initial brief discussion with you does indeed, appear to have been correct, all around.

Needless to say, logically, intuitively, plants/crops/trees cannot simply grow (add mass) without the addition of nutrients. The basis for this biogeochemical relationship goes something like this: in the biosphere carbon is a slave to the availability, or lack thereof, of nutrients (mostly P). Stated otherwise, nutrients are biolimiting. CO-2 is not a nutrient even though certain biotic species can store extra carbon for a while. But without additional nutrients to support the extra mass, in time, the biota cannot survive or maintain that mass in the absence of sufficient nutirents.

Nitrogen, because it is readily available to plants at all times due to it's atmospheric abundance, is not as biolimiting as say P. All a plant has to do is sequester it. There is more N than plants are currently using in photosynthesis. P (phosphorous), on the other hand, is truly biolimiting because it's availability to the biosphere is governed by the weathering of continental crust, the only source of additional P on the planet. Hence, it's scarcity limits biomass production. It's availability enhances it. The same arguments would apply, in part, to potassium as well.

Even in a doubled CO-2 atmosphere, plants cannot increase mass, and sustain it, in the absence of additional nutrients. So, the real bottom line is that more nutrients/fertilizer will be needed to accomodate extra mass/biomass in higher CO-2 environments. And although there are great differences among species with respect to rates of photosynthesis, etc., the nutrient/carbon relationship or dependency maintains. It is the basis of many models, particularly with respect to oceanic productivity.

As I mentioned to you before, there is an apparent (real) prevailing misconception that CO-2 alone has a sustainable fertilization effect on the biosphere. In other words, what these people are really saying is that the biosphere has inexplicably (and in very short order, timewise) become evolutionarily efficient in a truly Darwinian sense. In other words, without understanding the important subtleties here, people are alleging that the biosphere can add mass in a higher C)-2 environment without an additional source or supply of nutrients. This is bullshit, of course. This would be true evolutionary efficiency were it the case, which it is not.

Please note as well, increases in C/N ratios and decreases in N content of plant leaves grown in high CO-2 environments reflect potentially lowered nutritive value to herbivores and so on down the food chain. In some studies, insect larvae responded by increasingly higher consumption of plants from higher CO-2 environments. Thus increased herbivory could reduce or eliminate any potential gains in plant carbon storage expected from CO-2 fertilization. According to Woodwell, "At this time there is no direct evidence that net ecosystem production has responded to increasing CO-2, either regionally or globally (Woodwell, 1983; in: Atmospheric Carbon Dioxide and the Global Carbon Cycle, p. 264, 1985).

From Strain and Cure: "...the relative CO-2 simulation is smaller when nutrients are in short supply. Therefore, if farmers are to obtain maximum benefit from the future higher atmospheric CO-2 concentration, soil nutrient levels must not be depleted. Fertilization (with nutrients) will probably become even more important....because the plant yield response will reflect a greater relative increase from CO-2 as well as the normal absolute increase from the fertilizer (see accompanying papers)."

Any questions or comments?

Tony

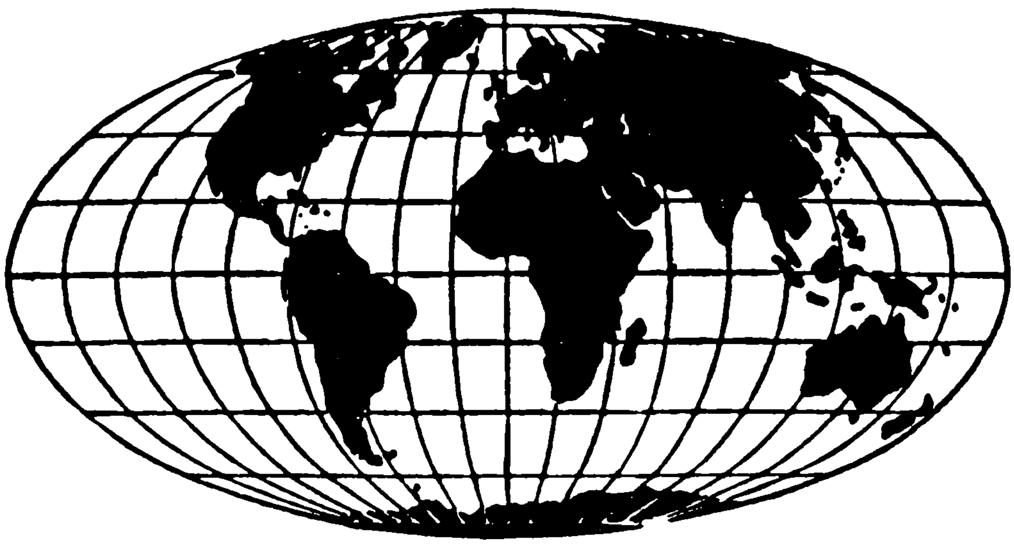
DOE/ER-0239

December 1985

United States Department of Energy

Office of Energy Research
Office of Basic Energy Sciences
Carbon Dioxide Research Division

ATMOSPHERIC CARBON DIOXIDE AND THE GLOBAL CARBON CYCLE



CO2

are sufficiently large, the climate can be altered, with a subsequent feedback effect on the dynamics of terrestrial plant communities.

There is also an indirect effect resulting from changes in the composition of radiatively active atmospheric gases and other pollutants produced by burning of fossil fuels and by changes in the terrestrial landscape (e.g., Crutzen et al. 1979; Logan et al. 1981). The contribution to atmospheric CO_2 concentration because of decreases in terrestrial carbon storage and a potential reverse effect from CO_2 fertilization are indirect influences. A CO_2-induced climate change could influence the land cover and also alter the dynamic responses of terrestrial ecosystems to human disturbance.

The response of this highly interactive system is inextricably linked to understanding the dynamics of the Earth's forests over periods ranging from decades to centuries (Solomon et al. 1984). These dynamics are currently being investigated using simulation models (e.g., Lieth 1984; Shugart 1984). Model simulations allow us to explore hypotheses about the effects on the terrestrial carbon cycle of potentially important phenomena, such as CO_2 fertilization and climate change, in the current absence of needed field data on these effects. Such exercises provided the few estimates of geographic shifts in ecosystem distribution and of alterations in carbon storage using climate model scenarios of CO_2 warming.

Tree-ring records also have the potential for revealing these dynamics. Besides the carbon isotopic history of atmospheric CO_2, tree rings may record past climates (Fritts 1976; Blasing et al. 1981; LaMarche and Hirschboek 1984) and air pollution effects (Baes and McLaughlin 1984), including effects on carbon isotope fractionation (Freyer 1979).

10.3.2.1 *Effects of CO_2 Fertilization*

Tree-ring data are being used to examine the relationship between growth and CO_2 fertilization (e.g., LaMarche et al. 1984). However, a multitude of potential interferences can produce unaccounted-for variability (noise) in any given signal, and this limits the use of tree-ring data (Section 10.2.5). Thus, existing data are often contradictory (Woodwell 1983) or otherwise equivocal. A case in point is the growth enhancement observed in high-altitude tree rings over the period 1850–1859 to 1974–1983 attributed by LaMarche et al. (1984) to a CO_2 fertilization effect. The magnitude of the observed growth enhancement (7 to 11 times the level of a maximal response expected, considering the approximate 20% increase in atmospheric CO_2 over the same interval) indicates that factors other than increased CO_2 must be considered to account for the total effect (e.g., climate change).

The increase in phytomass simulated by seven different forest ecosystem models (temperate deciduous to subtropical rain forest) ranged from 20 to 60% when the growth rate for all trees was uniformly increased by 100% (i.e., less than a 1 to 1 correspondence between phytomass and individual growth stimulation [Shugart 1984; Shugart et al. 1984]). The increase was not due to an elevated maximum phytomass at any point in the landscape, but rather was caused by an increased rate of filling of gaps made in the canopy. For this reason, simulated forests with a high rate of disturbance (e.g., fire, selective timber harvesting) and more growth associated with gap-filling produced a larger landscape-scale fertilization response. This observation might be significant in light of the previous discussion in Section 10.2.9 (i.e., *the growth response is greatest for disturbed systems*). However, as the following discussion suggests, the gulf that separates model simulations and field validation is great indeed.

If changes in growth rates are not uniform across all the species involved (more likely case), the potential expression of CO_2-induced fertilization could involve changes in the community composition and could be very complex, resulting in even smaller increases in forest biomass (Shugart et al. 1984). Another critical uncertainty is whether limitations on growth imposed by current water or nutrient deficiencies, or by changes in plant morphology, will preclude a positive growth response to CO_2 (Kramer 1981). Consideration of the interrelationships between carbon, water, and nutrient pathways in soil-plant systems has led to the opposed hypothesis that stimulation of root and rhizosphere processes by elevated levels of CO_2 could increase both water-use efficiency and nutrient availability, and thus allow an increase in plant growth (Luxmoore 1981; Rosenberg 1981). This hypothesis is supported by the initial results of studies where plants were grown under apparent nutrient limitation in a forest soil (Norby et al. 1984). However, other research on plant-herbivore interactions under conditions of elevated CO_2 (Lincoln et al. 1984) suggests that any increases in carbon storage may be offset by increased consumption.

Increases in carbon-nitrogen ratios and decreases in nitrogen content of plant leaves grown in elevated CO_2 regimes reflect potentially lowered nutritive value to herbivores and, ultimately, to microbes important in leaf litter decomposition, nutrient cycling, and soil formation. In laboratory studies, insect larvae responded by increasingly higher consumption of plants from higher CO_2 atmospheres (Lincoln et al. 1984). Thus, in a field situation, increased herbivory could reduce or eliminate any potential gains in plant carbon

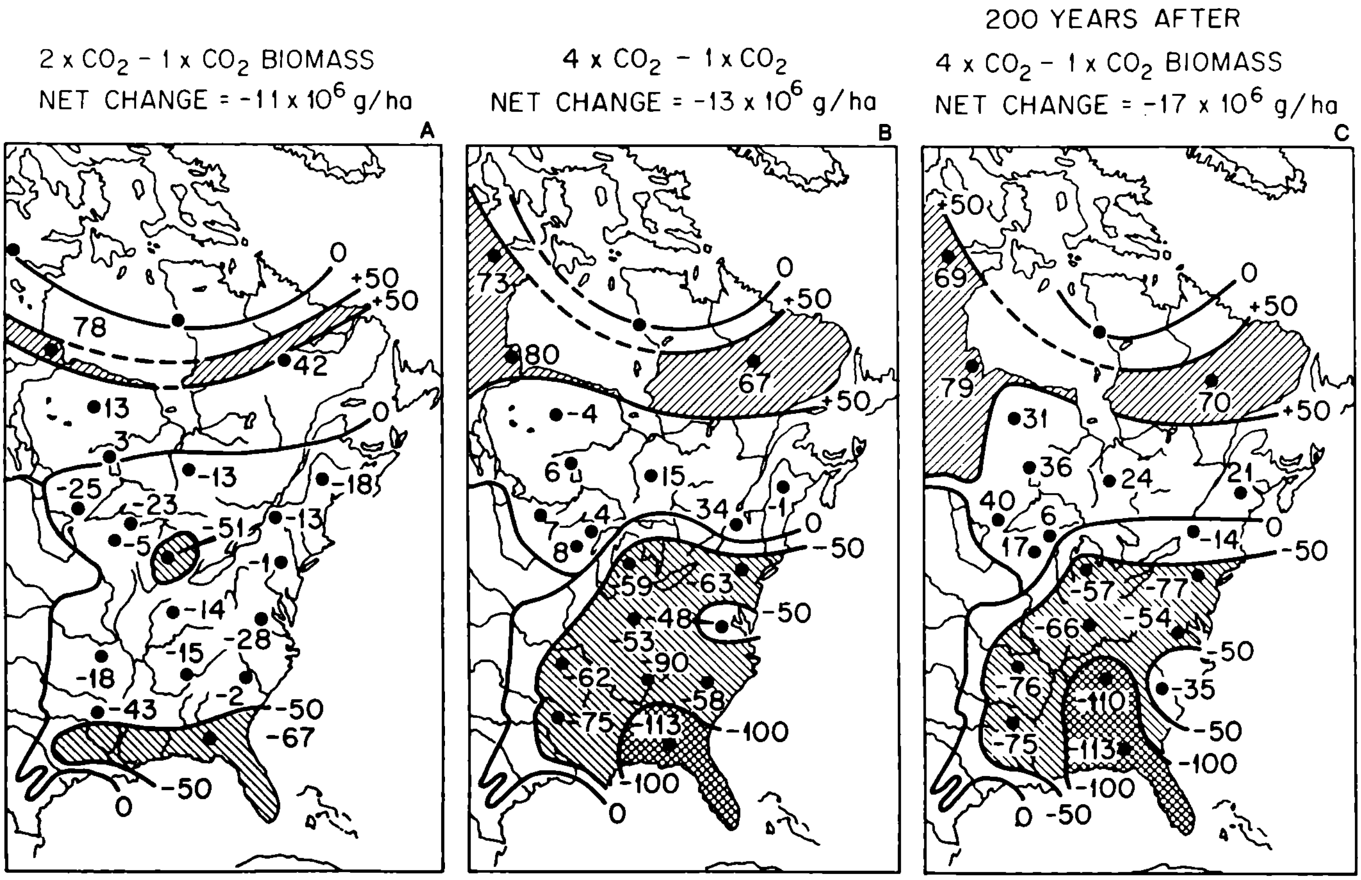


Figure 10.6. Carbon storage dynamics simulated at 21 sites in eastern North America. Maps show carbon storage differences between contemporary climate and (A) 2-x-CO_2 climate, (B) 4-x-CO_2 climate, (C) 200 years after 4-x-CO_2 climate stabilizes. Tree species of Florida, Cuba, and other Gulf islands may be important in the southern United States in the future, but were not simulated (Source: Solomon and Tharp 1985).

storage expected from CO_2 fertilization. Reduced rates of litter decomposition and nutrient cycling caused by lowered litter quality could also terminate an increased growth response to elevated CO_2 without increased herbivory. The role of consumers and decomposers (heterotrophs) in mediating the effects of CO_2 fertilization is potentially very important, but again, very poorly characterized (see Section 8.5.4; Strain 1985). Significant conclusions about the effects of elevated atmospheric CO_2 levels on the global carbon cycle are precluded by the current lack of information (Strain 1985), and thus the parameterization of a CO_2 fertilization response in global carbon cycle models (see Chapter 7) is currently a hypothetical exercise. At this time, there is no direct evidence that net ecosystem production has responded to increasing CO_2, either regionally or globally (Woodwell 1983).

10.3.2.2 *Effects of Climate Change*

Our understanding of potential ecosystem responses to climate change is also rather crude (Sections 8.5.4 and 8.6.1), but some of the factors identified above (ecosystem-specific responses, importance of heterotrophs, sensitivity of nutrient cycles) appear to be common threads binding the interpretation of CO_2 and climatic effects together. The forest stand simulation model approach suggested large decreases in carbon storage in eastern U.S. forests from CO_2-induced climate warming not completely compensated for by increased storage in Canadian boreal forests under generic model-projected climates, which included seasonality (Solomon and Tharp 1985). The projected carbon storage losses (Figure 10.6) amounted to 10 to 20% of the average standing biomass in these systems (Olson et al. 1983). Such losses could offset potentially enhanced carbon storage from CO_2 fertilization. Losses of carbon and changes in forest community structure were still occurring 200 years after a 4-x-CO_2 climate change scenario had been established (Solomon and Tharp 1985). The modifying effects of soil characteristics or heterotrophs are not yet considered in such simulations.

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DoE & EPRI

DIRECT EFFECTS OF INCREASING CARBON DIOXIDE ON VEGETATION

Trees

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MASTER

tissue culture may provide the means to multiply that genetic potential into the large numbers of plants needed for commercial crop production. As the CO_2 content of the atmosphere increases, selection for desirable productivity responses to the high CO_2 will undoubtedly be made, whether automatically in field plots exposed to the higher atmospheric concentration or consciously in growth chambers with controlled CO_2 concentrations.

9.3.2 Changes in Cultural Practices

9.3.2.1 *Fertilizer*

Experiments to test the interaction between nutrient concentration and atmospheric CO_2 concentration as it affects plant yield and growth have fairly consistently shown that the relative CO_2 stimulation is smaller when nutrients are in short supply (Kimball, in press; Table 5.5 in Chapter 5). Therefore, if farmers are to obtain maximum benefit from the future higher atmospheric CO_2 concentration, soil nutrient levels must not be depleted. Fertilization will probably become even more important, therefore, because the plant yield response will reflect a greater relative increase from CO_2 as well as the normal absolute increase from the fertilizer.

As mentioned previously, yields are likely to increase by a third, on the average, for a doubling of atmospheric CO_2 concentration. Therefore, if a third more nutrient is removed from the soil each year, it is only logical that soil nutrient levels will more rapidly become depleted if they are not replenished. There is some uncertainty, however, whether the increased fertilizer needs will bear a 1:1 relationship to increased yields (see Chapter 5 for discussion). Randall and Engelstad (1983) predict that increased amounts of fertilizers will be needed to exploit the higher future yield potential from improved plant varieties and production systems. They did not explicitly consider the effects of elevated levels of CO_2, but certainly it will be one of the factors in the improved future production system.

Phosphorus and potassium. Phosphorus (P) and potassium (K) will be considered first because their inorganic transformations are better understood. Soils naturally vary considerably in P and K contents and in the rates at which weathering processes break down minerals to make the P and K available to plants. If a crop now obtains 50% of its P and K from the soil and 50% from applied fertilizers, and if CO_2-induced growth requires 33% more P and K to sustain yields and avoid depletion, then the fertilizer application might have to be increased as much as 66%. However, Randall and Engelstad (1983) predict that improvements will be forthcoming in the efficiency of fertilizer use, which will tend to decrease this figure.

The increased atmospheric CO_2 concentration may improve the efficiency of nutrient uptake and fertilizer use. One reason is that there may be an increased extent of soil exploration due to increased root-to-shoot ratios. Another possibility is that the high-CO_2 plants may exude greater amounts of carbohydrates and other organic compounds from their roots, thereby stimulating the growth of mycorrhizal fungi. These fungi form symbiotic associations with roots of some plant species and are known to help plants obtain P. If they have a greater supply of carbohydrates, it is plausible that they will in turn make more P available to the plants (Lamborg et al. 1983). Preliminary results for trees, reported by Norby et al. (1984), support the hypothesis that stimulation of tree-root and rhizosphere processes by elevated CO_2 increases nutrient availability.

As already mentioned, soils vary greatly in their natural fertility, and crops vary in their requirements for P and K and in their response to CO_2. Localized testing of soil nutrient levels and of the various crop responses to applied fertilizer will have to continue into the future for farmers to adapt to the higher CO_2 world.

Nitrogen. Nitrogen (N) is not an abundant element in soil-forming minerals, so the supply of this most important nutrient must come from external or fertilizer sources for sustained production. Many fertile soils such as the midwestern mollisols have high levels of organic matter from the remains of decaying plant and animal material from previous years and centuries. As this organic material decays, some N becomes available for plant growth, analogous to the release of available P and K from weathering of soil-forming minerals just discussed. Because plants will be larger in the higher CO_2 world, there probably will be a greater quantity of plant material available for decomposition each year, which in turn is likely to increase the organic matter content of the soil (Larson et al. 1984), and more soil nitrogen will become available each year. Although quantities of plant material will be larger, the quality of the material may be lower in the sense that its higher C:N and C:P ratios may somewhat inhibit decomposer organisms (Strain and Bazzaz 1983). For sustained agricultural production, therefore, most N will have to come from external sources.

The primary source of N is from N_2 in the atmosphere. Nitrogen-fixing bacteria live in the soil and in symbiotic association with legumes and a few other plants. These bacteria obtain energy for metabolism from decaying organic material, or directly from their hosts in the case of symbionts, and they have the ability to reduce atmospheric nitrogen and transform it into other forms that can be metabolized by themselves and their host plants.

CO_2 enrichment has increased the amount of N_2 fixed by leguminous crops rather dramatically, with a doubling of CO_2 concentration producing a doubling of N fixation in several experiments (Hardy and Havelka 1977). More recent studies have shown substantial, although more modest, increases (Williams et al. 1981). Thus, we can surmise that leguminous crops will probably not be limited by a lack of N in the future high-CO_2 world, or at least not any more than they are now.

Leguminous crops are often grown in crop rotations because their residue contains high levels of N that remain in the soil for the succeeding crop. In CO_2-enrichment experiments, the yield and growth of legumes on the average have been increased by the same 32% as other crops (Kimball 1983b; Table 5.3 in Chapter 5). Therefore, legume rotation should be at least as good a method for obtaining N for the nonlegume crops in the future high-CO_2 world as it is now. However, Randall and Engelstad (1983), without considering CO_2 enrichment, predict that biological nitrogen fixation will have little effect on fertilizer needs by 2030.

Most nonleguminous crops in developed countries are grown with additions of N from commercial fertilizer. To sustain yields that are 32% higher in the future, it seems logical that applications of N will have to be increased by roughly the same average percentage, remembering of course that crops vary in their requirements, that soils vary in their organic matter content, and that adjustments will have to be made for residual N from previous legume crops. Currently the efficiency of nitrogen fertilizer use is only about 50% (the proportion of applied fertilizer taken up by the crop), at least for corn (Randall and Engelstad 1983). Improvements in the efficiency of nitrogen use are forecast for the future, so this increase in efficiency could possibly provide some of the extra nitrogen needed to sustain higher yields in the future higher CO_2 world. As with P and K, the increased CO_2 concentrations may cause some increase in efficiency through increases in root exploration and through stimulation of microbial activity.

Supply and demand. The amounts of fertilizers that will be applied in the future per unit area will be determined by the marginal product value/fertilizer cost ratio that brings the most profit. Although yields are likely to increase about 32% on the average with a doubling of CO_2 levels, as discussed previously, the price of the agricultural product cannot be predicted with any certainty.

Population increase was predicted to outpace food production increase even before the days of Malthus (Heady 1984). Instead, however, increases in agricultural production have led to food surpluses in the United States and other developed countries, and the world hunger problem has in fact been a distribution and economic problem, albeit severe and deadly to some, rather than a shortage of production. Heady (1984) predicts that a slower rate of population growth will cause the demand for agricultural products to grow very slowly until about the year 2000, and after that time demand will be close to production, so increased food prices and increased profitability of fertilizer application will result.

The fertilizer cost part of the ratio is also influenced by population pressures and the size of available reserves. Engelstad (1984) said that ample supplies of potash exist in Canada. However, the supply of high-grade phosphate ore is limited, so progressively lower grades of phosphate rock will have to be mined. On the other hand, there are ample reserves of the lower grade rock, so costs for P and K should not drastically change. Nitrogen fertilizer production requires large amounts of fossil fuel energy and a hydrocarbon feedstock, so in recent years the price of nitrogen fertilizer has been tied to the price of natural gas (Engelstad 1984). Coal may substitute for natural gas in the future, but nitrogen fertilizer from coal will be more than twice as expensive as that from natural gas. Increasing population brings increasing demand for energy, and industrial development in Third World countries also increases energy demand. Thus, for the short term it certainly appears that the optimal rates of N application will be lower, but they are likely to increase in the distant future as food prices increase more rapidly than energy prices.

9.3.2.2 *Pest Control*

Weeds. Increasing CO_2 concentration has increased growth, on the average, of all species of plants that have been studied. The growth increase of the 770 observations analyzed by Kimball (1983b) averaged 36%, but the range of individual responses was from about −40 to +700%. Obviously there is a huge amount of variability, so those plants that can gain a larger relative advantage from the higher CO_2 level will have a competitive edge over their neighbors. If the plants that gain the most from the CO_2 happen to be weeds, then greater weed control problems loom ahead in the future.

However, as noted by Wittwer (in press), of the 20 most important food crops, 16 have the C_3 photosynthetic pathway. On the other hand, of the world's 18 most noxious weeds, 14 have the C_4 photosynthetic pathway. As already noted, C_3 plants generally have a greater growth response to CO_2 than

June '91

Climate News Around the World

Europe

Drought, landslides, stressed plants, more frequent severe storms, and salt marsh changes are among the impacts in store for Europe if climate change materializes. A series of workshops has studied the impacts of climate and land-use changes in Europe and a summary of the findings and recommendations, Potential Impacts of Climatic Change in Europe, has been published.

The Netherlands government has worked with the World Climate Program, the International Institute for Applied Systems Analysis and the European Community Climate Program in conducting the workshops and has published a summary of the findings and recommendations in a report entitled, Potential Impacts of Climatic Change in Europe. Some of the many conclusions, recommendations and research proposals delineated in this slim volume are listed below:

- More drought will hamper river navigation, soils will become more prone to erosion and, in Southeastern Europe, to salinization, and air and water pollution will place further stress on forests, according to the conclusions of a workshop, "Interrelated Bioclimatic and Land-Use Changes."

- A conference on "Landscape-Ecological Impact of Climatic Change" concluded that rapid shifts of vegetation in decades instead of centuries will force plants and animals onto soils and under daylight regimes to which they cannot adapt. Weeds and pests will take advantage of destabilization and spread rapidly. While the disappearance of glaciers is estimated to have only minor effects, more unstable moraine slopes will contribute to landslides, mud-flows and sediment in rivers and reservoirs. Natural fires may accelerate permafrost degradation.

- Coasts will be subject to possible changes of ocean currents, changes in frequency and duration of storms and other extreme events, and shifts in sediment discharge, according to a workshop, "Expected Effects of Climatic Change on Marine Coastal Systems." Erosion, sedimentation, soil chemistry and changes in competitive ability will affect salt-marsh vegetation. Diatoms and animals in tidal pools may receive higher UV-B radiation.

- In a session on "The Greenhouse Effect and Primary Productivity in European Agro-Ecosystems," the participants urged a clear distinction between the beneficial, neutral, and detrimental effects of warming and of increased CO2 concentrations. While the direct plant-physiological effect of CO2 concentration on annual agricultural plants can be assessed with some confidence, models of perennials are much more uncertain. Glass-house experiments with some species suggest that CO2 enrichment fades away after prolonged exposure.

- IIASA held a meeting on "Future Environments for Europe: Some Implications of Alternative Development Paths" at which a major issue for consideration was climate and chemical time bombs. A chemical time bomb is a phenomenon in which certain man-made chemicals accumulate in ecological systems with no apparent adverse effects for a number of years until a threshold is reached. Then a sudden explosion into the wider environment may occur. Climatic change may provide the trigger: increased storm strength may stir sediments in which toxic chemicals have been stored for years, or dessication of the soil can lead to aeration and oxidation and mobilization of substances hidden in it. IIASA with support of the Netherlands government has started a project on "Chemical Time Bombs in Europe"; climate change and land-use changes are among the forcing factors considered.

India

The Government of India has invested in a major research study of the impacts of possible sea level rise due to global warming along the Indian coast and islands. The study is expected to be completed in December 1991 and will be particularly pertinent for the 25 percent of the population living along the coast, according to a paper prepared by Dr. Kalipada Chatterjee, Ministry of Environment and Forests, Government of India, for a January conference in Nagoya, Japan, the Asian Pacific Seminar on Climate Change.

The entire west coast and some parts of the eastern coast are subject to erosion which is acute along the coast of Orissa, Bengal and Kerala. A one meter rise of sea level would cause shore recession of from about 270 to 615 meters in various east and west coat areas. On the Kerala coast, about three to five meters a year have been lost because of a lack of sediment deposition. Other coasts have suffered because of the removal of sands for construction materials. The Arabian Sea islands are particularly vulnerable to sea level rise as they have an elevation of three to five meters.

Many of the areas vulnerable to erosion are subject to repeated hazards of surging sea waves and heavy rainfall accompanying cyclonic winds. Possible sea level rise would also accentuate the problem of increased salt water intrusion, especially in the estuarine regions and deltas of the east coast, already a problem in some areas.

Most of the floods in the country occur during the monsoons and are associated with either the monsoon itself or tropical storms or depressions. The lower reaches of the rivers generally overflow their banks during heavy rainfalls.

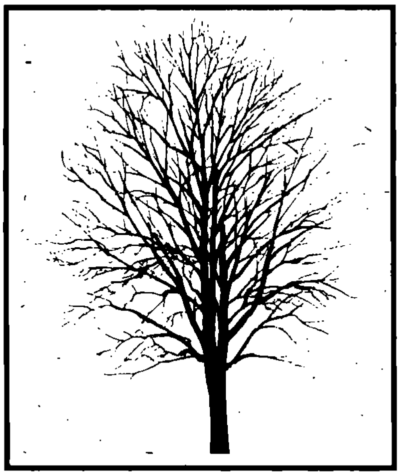
Although a strong base exists for management and control of flood damage, there has been an upward trend in damages during recent years because of a number of factors. The population explosion has put a severe stress on housing and sanitation facilities.

In the unplanned growth of large and medium-sized cities, housing has been built in river beds and catchment areas, causing heavy loss of life and property damage when waters rise. These settlements have also blocked the natural drainage channels of flood waters which then sweep away habitations in their way. Although expenditures on flood control have increased over the years, they are not sufficient and much more effort will be needed in the future, especially under a climate change regime, according to Chatterjee.

Reprinted from the *University Record*
Kate Kellogg, News and Information Services

Elevated CO2 Accelerates Tree Growth at UM Biological Station

Dr. James Teeri, Director of the University of Michigan Biological Station and professor of biology, has found new evidence that elevated levels of carbon dioxide CO_2 increase growth and modify senescence of native Michigan trees. Pine, red maple, and aspen grown at Biological Station, responded significantly to elevated (CO_2) levels in one of the first experiments to simulate predicted effects of global warming outside of a greenhouse.



The seedlings were grown in open-top chambers and exposed to a constant 700 parts per million of CO_2 supplied by a computerized delivery system. This concentration is approximately double the current CO_2 content of air, and simulates atmospheric conditions predicted for the year 2050 if fossil fuel emissions continue at their present rate. A control group in identical chambers received air with 355 parts per million of CO_2, the current worldwide average, and bare plots were monitored for possible chamber effects.

After a summer of growth, big tooth aspen (*Populus grandidentata*) in the CO_2-elevated chambers weighed 30 percent more than aspen grown nearby in untreated chambers and had 25 percent more leaf area. Over the same period, white pine (*Pinus strobus*) and red maple (*Acer rubrum*) had both weighed about 20 percent more than their untreated counterparts. "We were amazed at the large response of the treated trees," says Teeri, "because they were grown in such nutrient-poor soil. Similar experiments conducted elsewhere in the country also have shown large growth response to elevated CO_2 but most of those were conducted in greenhouses using fertilized soil. Ours is one of the first to study the response of indigenous trees—grown out in the open in unaltered soil—to elevated CO_2."

The researchers do not know exactly why elevated CO_2 has triggered the unusual rate of growth but hypothesize that, in addition to raising the temperature of the surrounding air, it may accelerate both the photosynthetic rates of the trees and nutrient cycling in the soil. Don Zak, assistant professor of natural resources at UM explains that, as root growth and leaf production increase, the plant releases more carbon below ground, which in turn stimulates growth of microbes in the soil. Soil bacteria then convert nitrogen in the soil to nitrate, in effect creating a natural fertilizer and the growth cycle continues.

An apparent delay of senescence in the treated plants was an unexpected result of the elevated CO_2. Under normal conditions, plants prepare for cold weather by drawing nitrogen from leaves back to their stems, Teeri explains. The leaves change color and eventually drop off while the nitrogen is recycled for new shoots the following year. But as of late September last year, when photosynthesis usually declines in northern Michigan trees, the leaves of the treated plants were still fully active, Teeri says. "About one-third of the leaves on each control plant had turned yellow, representing a normal 30 percent decline in photosynthesis. "We don't know to what extent CO_2 might block metabolic events that help prepare a plant for winter, last year we had to harvest all plants for data comparison."

This year, some of the trees were left in the ground until the first killing frost in late October. The trees exposed to elevated CO_2 remained active until the frost and did not appear to be any more sensitive to the cold than those exposed to normal CO_2 concentrations.

Although the U-M scientists have documented strong growth responses to CO_2 in three different species native to northern Michigan, Teeri cautions against drawing broad conclusions based on this particular experiment's results. "We have seen great variation within those responses and still have much to learn about the different ways that the thousands of untested species will respond," says Teeri. "Less

hardy species might decrease over a period of atmospheric warming and some might disappear entirely. "But there is no question that predicted atmospheric changes will have a profound effect on the function and composition of both natural and agricultural ecosystems. We are certain the forests in northern Michigan will look substantially different 100 years from now."

? = direct increase in CO_2 v. an ? in the troposphere . . .

The Role of the University in Global Change Research: Structural Constraints and the Potential for Change

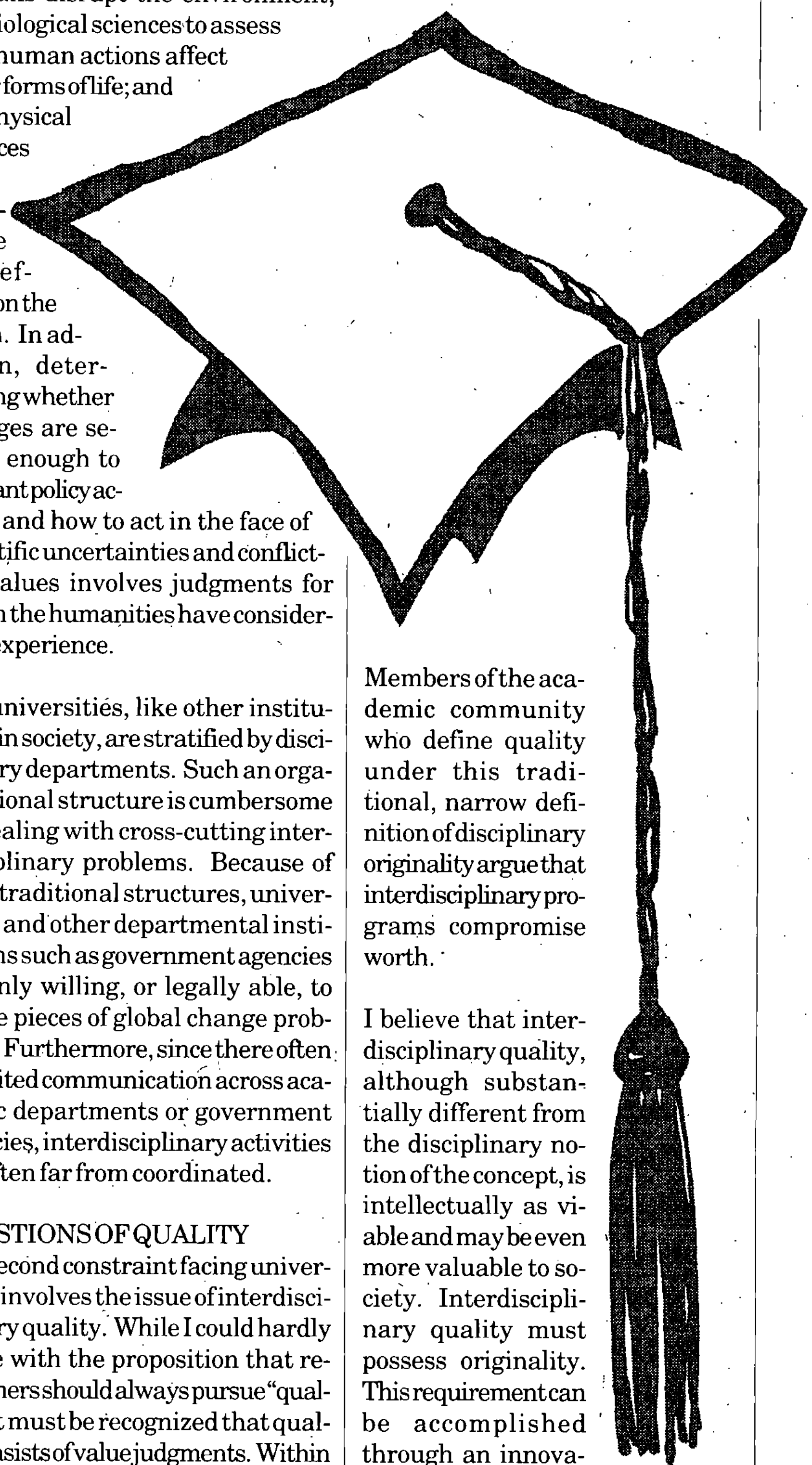
Dr. Stephen Schneider

Global change problems, many in desperate need of solutions, rarely fall within the intellectual boundaries traditionally associated with university departments. Structural characteristics of most universities constrain their abilities to address global change issues. Yet the expertise and facilities found in the large research university today are imperative for this process. Three particular constraints impede most universities efforts in this area. First, universities are typically divided into disciplinary fields which concentrate on traditionally defined areas of study. In addition, universities are in conflict concerning their attitudes towards the place of scholars as policy advocacy. And, some faculty at some universities also tend to discount interdisciplinary work, considering it of lower intellectual quality than that of rigorous disciplinary studies.

For a major institution such as a modern university to ignore global change problems simply because they do not conform to their historical organizational structure is intellectually derelict and socially irresponsible. Efforts to organize campuses to foster global change teaching and research opportunities are critical and overdue. This will be a difficult process: seeking solutions to global change problems will require research efforts and organizational changes commensurate with the scale of the problems. But it is a process worth undertaking. By recognizing and addressing such constraints, universities can set an examples of how interdisciplinary work should be done while maintaining quality standards essential to the success of that work.

DISCIPLINARY STRUCTURE OF THE UNIVERSITY

Global change issues do not fit neatly into disciplinary boxes. They are multidisciplinary in their very essence. Such problems require the social sciences to shed light on why humans disrupt the environment; the biological sciences to assess how human actions affect other forms of life; and the physical sciences to evaluate the effects on the earth. In addition, determining whether changes are serious enough to warrant policy actions and how to act in the face of scientific uncertainties and conflicting values involves judgments for which the humanities have considerable experience.



But universities, like other institutions in society, are stratified by disciplinary departments. Such an organizational structure is cumbersome for dealing with cross-cutting interdisciplinary problems. Because of their traditional structures, universities and other departmental institutions such as government agencies are only willing, or legally able, to tackle pieces of global change problems. Furthermore, since there often is limited communication across academic departments or government agencies, interdisciplinary activities are often far from coordinated.

QUESTIONS OF QUALITY

The second constraint facing universities involves the issue of interdisciplinary quality. While I could hardly argue with the proposition that researchers should always pursue "quality," it must be recognized that quality consists of value judgments. Within a university setting, quality generally is defined as ample production of original work that advances the discipline. This definition is perfectly appropriate for disciplinary efforts, but too narrow for global change research. Members of the academic community who define quality under this traditional, narrow definition of disciplinary originality argue that interdisciplinary programs compromise worth.

I believe that interdisciplinary quality, although substantially different from the disciplinary notion of the concept, is intellectually as viable and may be even more valuable to society. Interdisciplinary quality must possess originality. This requirement can be accomplished through an innovative method of combining materials from various fields rather than within the confines of one field. The materials from vari-

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INFO ON WATKINS SPEECH/CO_2 VIDEO — ALSO SOME OTHER COAL NEWS ARTICLES

Coal News

October 7, 1991 • No. 5064

good stuff...

Forced C02 Cuts Bad Policy Idea

Column I
By Barbara Keating

American environmental activists, demanding that the United States sign on to an international agreement, that would cut carbon dioxide (CO_2) emissions by at least 20 percent by 2005, find willing allies in France and Germany. It is obvious that some of the political forces in these and other nations have long resented U.S. economic dominance.

Is this alliance prompted by genuine environmental concern, or do our global neighbors view this as their chance to cut American competition down to size? How do we tell the difference?

Scientific opinion is split on the subject of global temperature change. Though scientists unanimously agree that greenhouse gases, principally CO_2, are steadily increasing, there is no consensus among impeccably credentialed atmospheric scientists as to the actual result.

Since the U.S. stands to lose the most, it is not at all surprising to hear envious nations lining up with environmental activists who call for a strict reduction of CO_2 emissions.

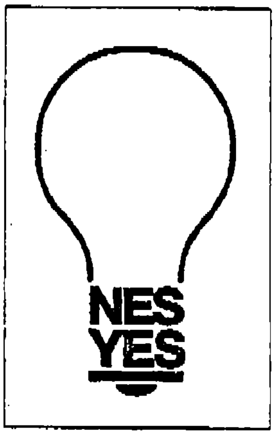
A study by Alan Manne of Stanford University and Richard Richels of the Electric Power Research Institute found that, to meet the goals

(See Column I, Page 3)

Barbara Keating is President of Consumer Alert, Modesto, Calif.

NES Week Plugged by Top Energy Official, Senators

Sens. J. Bennett Johnston (D-La.), Malcolm Wallop (R-Wyo.) and Secretary of Energy Adm. James D. Watkins kicked off National Energy Security Week Oct. 1. The three officials made presentations on the need for a comprehensive energy bill and expressed why they feel passing the National Energy Security Act of 1991, S. 1220, as written, is so important, rather than trying to pass energy legislation in piece-meal fashion.



Johnston, chairman of the Senate Energy and Natural Resources Committee, told the gathering of industry representatives from around the country who are involved with the newly formed National Energy Security Coalition that he has been a member of the committee for 19 years and "has seen most every mistake in the field of energy made."

Committee members as well as Americans in general, are very slow to learn, he noted.

However, S. 1220, introduced earlier this year by Johnston and Wallop, is the complete energy package the country needs, Johnston, Wallop and Watkins agreed.

Johnston noted that the bill is expected to be debated on the Senate floor beginning the week of Oct. 15. He plans to

(See NES, page 3)

U.S. Coal Should Benefit From New Overseas Markets

American coal producers may be facing an "extraordinary" business opportunity as Eastern Europe and other developing nations tackle monumental pollution and energy problems, an Interior Department (DOI) official said at NCA's Coal Lawyer's Conference.

Thomas Sansonetti, DOI

(See KEYNOTE, page 6)

WHAT'S INSIDE:

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Richard L. Lawson, President

COLUMN I– By Barbara Keating

(Continued from Page 1)

that are being seriously discussed, the U.S. would be penalized by approximately 3 percent of its gross national product, or about $160 billion a year, while China and the European Community (EC) would have to come up with less than half this amount.

If U.S. negotiators agree to the emission reduction, American consumers will be forced to undergo major shifts to lower living standards. A drastic reduction in the use of fossil-based fuels, means not only higher personal monthly utility bills, but rises in prices on virtually all goods and services, and a dramatic rise in gasoline for automobiles and other transportation costs.

No Significant Warming

Since U.S. consumers are the highest users of energy, the EC would like nothing better than a chance to bring us down to its per capita energy usage. Who can blame them? This might be plausible, and regretfully necessary, if it meant saving the planet from stir-fry, but sound scientific evidence discloses no significant warming to date and plenty of evidence that the political theory is just that.

Pressured by Germany's Helmut Kohl and by Frances' Francois Mitterrand, who heads a country where 70 percent of its electricity comes from nuclear power plants, on the one hand, and by domestic environmental activists, including his own Environmental Protection Agency head William Reilly on the other, President George Bush exhibits wise leadership in insisting on more thorough evaluation of the scientific and economic questions raised by half the scientific exports before committing U.S. consumer/taxpayers to exorbitant personal sacrifice.

No increase in overall global temperature has occurred in the past 10 years. The insignificant one-half of a degree Centigrade increase documented in the past 100 years occurred for the most part *before* heavy industrialization took place. There certainly is no cause for panic.

The earth has always undergone cooling and warming cycles, is coming out of a little ice age and is expected to experience a new cooling trend. Several global warming proponents in the scientific community warned of a coming ice age as recently as the mid 1990s.

Consumer Alert is a national, non-profit membership organization dedicated to the dissemination of accurate risk information to the general public.

Federal Lab, NOXSO Sign Tech Licensing Agreement

A new technique for controlling pollution is the subject of the first exclusive license agreement reached between a federal coal laboratory and a private firm.

Last week the Department of Energy (DOE) announced it had transferred the rights to a technology that significantly increases destruction of nitrogen oxides (N0x) to the NOXSO Corp. of Pittsburgh.

Developed by scientists at DOE's Pittsburgh Energy Technology Center, the new technique enhances the effectiveness of an advanced scrubbing system invented by NOXSO, now scheduled for demonstration under the agency's Clean Coal Technology Demonstration Program.

The new technique uses tiny alumina beads covered with sodium carbonate to capture both sulfur dioxide and N0x. The beads must be heated to regenerate their effectiveness. As a result of this and further processing, the captured sulfur compounds are converted to elemental sulfur, a marketable by-product.

The new development could play an important role in meeting new requirements set forth under the Clean Air Act Amendments of 1990.

NOXSO's process, without DOE's N0x control enhancement, currently is being tested on a 5-megawatt flue gas slipstream at an Ohio Edison power plant in Toronto, Ohio.

A full-scale demonstration of the technique is scheduled to begin in 1994.

NES – *(Continued from page 1)*

bring the bill up and debate it by title, with the Corporate Average Fuel Economy provision first, rather than debate the entire bill at once.

During the past few weeks, Johnston has made numerous visits to his fellow senators and said he has found a number of possible "swing votes" on S. 1220.

"I think we will be well above 50 votes," he said. "Maybe above 60."

As a result, in case of a filibuster, there is an excellent chance of getting a vote for cloture, he said.

Meanwhile, provisions regarding drilling in the Arctic National Wildlife Refuge will be the toughest portion to pass, Johnston told the group.

Johnston and Watkins said that if the Senate can pass the bill, it will be much more likely that the House will follow suit.

"If we go to the house with a very good bill, we're half way home," Johnston said.

As long as the NES legislation has been circulating, there have been a number of "naysayers," Wallop said. "Every step of the way we have proved the naysayers to be wrong" and no one in the environmental community has yet to offer any type of alternative.

Wallop noted that the committee has tried to keep the NES legislation from being "another environmental bill;" however, it is environmentally sound.

President George Bush believes the legislation is "one of the most important bills in the nation," Watkins said.

The president will be involved with the bill at the right time.

"We have everything in this bill," he said. Nobody else in the world has anything like it."

Entech's Berube Named CEO, Chairman of Montana Power

Daniel T. Berube, president and chief executive officer of Entech Inc., has been chosen to succeed Paul Schmechel as Montana Power Co.'s chairman and chief executive officer.

Schmechel plans to retire June 30, 1992.

Berube, 57, will take over the responsibilities as chief executive officer Jan. 1. Meanwhile, Schmechel will remain as chairman of the board until his retirement.

John J. Burke will continue in his position as Montana Power's vice chairman of the board.

As chief executive officer of Entech, Berube oversees Montana Power's group of non-utility companies involved in mining; oil and gas exploration, development and marketing; technology and waste management.

Berube, an NCA board member, joined Montana Power in 1964. Over the years Berube, an engineer, has served in engineering, construction and operation at all five of the company's coal-fired plants.

In 1987, Berube was named president of Western Energy, Montana Power's coal mining subsidiary, and a year later became the president of Entech. Since 1990, he has been Entech's chief executive officer and president.

A Boston native, he earned associate degrees in chemistry and mechanical engineering at Northeastern University, then served six years in the U.S. Air Force. Later, Berube earned a bachelor's degree in mechanical engineering from the University of Washington and a master's in engineering science from Montana College of Mineral Science and Technology.

Schmechel joined Montana Power in 1953, and is recognized for leading the company's diversification efforts into coal mining.

NCA's Finance, Tax Committees Hold First-Ever Joint Meeting

In the first-ever joint conference of the NCA's finance and tax committees, delegates heard discussions on national energy strategy and environmental realities, the impact of the Clean Air Act Amendments of 1990 and coal property and employee loss control.

Thomas Falkie, chairman of NCA's Accounting Committee and president of Berwind Natural Resources Co., gave the opening night keynote address at the conference, held Sept. 25-28 at the Ponte Vedra Inn & Club, Ponte Vedra Beach, Fla.

During the accounting session, consultants with The Wyatt Co. discussed the implementation of the Financial Accounting Statement 106 regarding post-employment benefits other than pensions and cost-control issues relating to employee benefits. An environmental accounting presentation was made by Price Waterhouse.

The tax session included discussions on recent developments in federal taxation, the current status of excess moisture with regard to black lung, reclamation taxes, foreign sales corporations and other issues. Paul Cox, a partner with Wyatt, Tarrant & Combs, was a guest speaker.

The 13th annual NCA Financial Executives Conference will be held at the Wigwam Resort, near Phoenix, Ariz. The meeting will be held Oct. 21-24, 1992 at which time the 1992 Survey of Coal Industry Accounting Practices will be released.

Watkins, Video Highlight ICCR

Energy Secretary James D. Watkins is scheduled to present a keynote address at the 9th International Conference on Coal Research on Tuesday, Oct. 15, during the luncheon.

Watkins' address falls on the second of three days of presentations on issues of international concern.

Delegates from 15 countries, including special guests from China, Korea, Bulgaria, Yugoslavia and Hungary, will be attending the conference at the Omni Shoreham in Washington, D.C., Oct. 13-16.

The world premiere of the "The Greening of Planet Earth" will be held on the evening of Oct. 15. The 30-minute video features several scientists discussing various benefits of increased levels of carbon dioxide on plants, trees and agriculture.

Other areas of discussion include power plant needs in the 21st century, clean use of coal though gasification and liquefaction and energy policies, research and development with regards to environmental concerns in various countries.

NCA, Bureau of Mines, and the Departments of Commerce, Energy and State are jointly sponsoring the conference along with the International Committee on Coal Research.

To register for this international event, call NCA's Gloria Runyon at 202-463-2656.

Meetings Set for Clean Coal Round V

The Department of Energy (DOE) plans to hold two public hearings in preparation for the agency's fifth round of the Clean Coal Technology Program, currently scheduled to be issued in 1992.

DOE's meetings will be in Cheyenne, Wyo. on Oct. 30, and in Louisville, Ky. on Nov. 12.

During the meetings, DOE will be hearing views on various issues of significance to the joint industry-government program.

WPOST 5/17/90 PA4

Global Heating Could Benefit U.S. Farmers

Prices Seen Rising As Production Falls

By William Booth
Washington Post Staff Writer

Farmers in the United States could benefit from global warming, according to the most elaborate analysis ever made of the impact of the greenhouse effect on U.S. agriculture.

While higher temperatures and reduced rainfall would cut production in many areas, higher concentrations of carbon dioxide in the air would make up for much of this loss by boosting plant growth. Because food prices would rise, farmers stand to earn more.

The detailed computer analysis, published today in the scientific journal Nature, finds U.S. farmers overall stand to gain as much as \$3.5 billion in annual revenue. American agriculture is a \$200 billion-a-year industry. In one scenario, consumers would also benefit from increased productivity.

But while U.S. farmers overall might enjoy higher prices, the effects of global warming could create dramatic regional shifts in agriculture, with some areas hard hit by climatic change. Some of the gains would be based on the higher prices that would accompany reduced productivity in some regions. Exports of American farm goods could also be reduced.

The researchers said, however, that they were somewhat surprised to find that the effects of global warming on agriculture seem less dire than once feared. While in the popular imagination, global warming is often associated with a return to Dust Bowl conditions, the scientists believe the United States will have little problem feeding itself in the next century, despite the possibility that average annual temperatures in the United States could increase as much as 10 degrees Fahrenheit.

"None of these scenarios predict mass starvation," said Bruce McCarl of the Department of Agricultural Economics at Texas A&M University, one of 10 authors of the report. "Food security is not an issue."

The research, which is based on an integration of economic, climate and crop-growth models, is the most detailed attempt to date on the possible effects of warmer weather on crops and prices in the United States. Much of the work was sponsored by the Environmental Protection Agency.

"Our results do not show catastrophe, but the effect of global warming is not a benign one for U.S. agriculture," said Cynthia Rosenzweig of the NASA Goddard Institute for Space Studies at Columbia University in New York, who also participated in the study.

Rosenzweig stressed that the effects of global warming on agriculture could still be profound, particularly for regions such as the Southeast and Southwest, where temperatures will be hottest and where water may be scarce.

The computer simulations predicted that, overall, crops would require more irrigation. The study factored in the increased costs of this but did not address the possibility that global warming will cause more variability in the climate, which could cause more flooding, drought and hail storms. Insect pests could also expand their range.

Carbon dioxide is accumulating in the atmosphere because of burning of coal, oil, gasoline, natural gas and wood. Scientists fear that the added gases will blanket the planet and trap heat close to the surface, causing global temperatures to increase about 4 degrees Fahrenheit by the year 2030. Temperatures in the United States could increase even more, since the effects of global warming would be greatest toward the poles and toward the centers of large land masses.

CLIMATE-VEGETATION INTERACTIONS

Edited by

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CONTENTS

Part II

Processes at the Plant Level-- Experimental Evidence

SUMMARY

Plant physiologists study the biological processes of vegetation at their most basic levels. These processes include the fluxes of carbon, water, and energy as they occur in and through plant cells, tissues, organs, and organisms. Atmospheric modelers should understand the basic aspects of plant physiology since the accumulations of these exchanges between plants and the atmosphere integrated over large vegetated areas affect climate. Thus, the second workshop session examined processes at the plant or canopy level, giving particular attention to the interactions of these processes with the atmosphere.

The session presentations concerned plant fluxes at varying levels of organization. Graham Farquhar discussed the physiology of stomatal conductance, photosynthetic capacity and carbon isotope studies. Paul Jarvis emphasized the importance of the coupling (or uncoupling) of a leaf or a plant canopy to the ambient air stream for the correct determination of evaporation rate especially when considering the effects of increased atmospheric CO_2. John Norman reviewed radiative transfer at the earth's surface and the information contained in spectral signatures of plant canopies.

Climate-Vegetation Interactions: Stomatal Conductance and Photosynthetic Capacity

Graham D. Farquhar

The effects of carbon dioxide on photosynthetic carbon assimiliation and on stomatal conductance (and water loss) vary with the time (and space) scale under consideration (Table 1). My own experience, like that of most of us, is with the shorter-term effects. The extension of observations at small scales--leaves, groups of plants, paddocks--to those at larger scales is easier than the extension through time scales, as the latter introduces completely new problems--changes in reproductive success, competition, species composition, etc.

Fortunately, there may be a need for short-term predictions, and I expect that simplified submodels of stomatal responses will be incorporated in global circulation models that are used for short-term meteorological predictions. Such submodels will ensure that the partition of radiation into fluxes of sensible (i.e., that which can be felt) and latent heat at the earth's surface is somewhat realistic. They may also serve as useful inputs for hydrological modeling. I hope that models of

Table 1. Effects of (CO_2) on photosynthesis and stomatal conductance. (Upward arrow indicates a likely increase.)

Time Scale	Photosynthesis	Stomatal Conductance
Seconds	Substrate ↗	
Minutes	Enzyme activation ↘	Aperture ↘
Hours	Triose phosphate (?) — Sink effects ↘	
	↘	
Days	Protein synthesis (?) Leaf area ↗	Superficial density (no./area) (?)
Months	Senescence (↗?) ↘ Reproduction (↗)	
Years	(↗) Presence/absence vegetation Species composition Fire frequency ↗	

photosynthesis will also be useful. First, stomatal conductance to the diffusion of water vapor and CO_2 appears impossible to predict without an understanding of the "demand" for CO_2 by the photosynthetic machinery. Secondly, large-scale short-term models of photosynthesis may be useful if future, sensitive measurements of, say, CO_2 concentration were to need correction of diurnal variations. Lest it appear that I am clutching at straws in an attempt to justify modeling photosynthesis in short-term, I should add that such models are now being incorporated in those predicting crop growth, and may be included in global circulation models (Sellers, 1985).

Certain relationships which emerge at the small time and space scales may be able to cross levels of organization relatively unscathed. I would hope that the discrimination by vegetation against $^{13}CO_2$ during photosynthesis (Farquhar *et al.*, 1982) is such an example, as its effects on atmospheric CO_2 are clearly apparent (Pearman and Hyson, 1985). The effects of leaves on the ^{18}O content of CO_2 in air passing across them may be another (Hubick *et al.*, 1986), as this, too, is seen in the atmosphere (Tans *et al.*, 1986).

I now summarize the mathematical description of photosynthesis of individual leaves, restricted to those with the C_3 pathway, because at the global level it is the most important form.

MODEL OF C_3 PHOTOSYNTHESIS

The rate of assimilation of CO_2 per unit projected area of a leaf of a C_3 species is given by

$$A = V_c - 0.5V_O - R_d \, , \qquad (1)$$

where A (μmol CO_2 m^{-2} s^{-1}) is the rate of assimilation, V_c (μmol CO_2 m^{-2} s^{-1}) is the rate of carboxylation of ribulose-1,5-bisphosphate (RuP_2), V_O (μmol O_2 m^{-2} s^{-1}) is the rate of a competitive reaction, oxygenation of RuP_2, and R_d (μmol CO_2 m^{-2} s^{-1}) is the rate of respiration. The rate of photorespiration, $0.5V_O$, is half the rate of oxygenation since only one CO_2 molecule is lost for every two molecules of RuP_2 being oxygenated.

In turn, the rate of photorespiration, $0.5V_O$, is given by

$$0.5V_O = V_c\Gamma_*/C \, , \qquad (2)$$

where Γ_* is the CO_2 photocompensation point and C is the partial pressure of CO_2. Equations (1) and (2) may be combined to yield

$$A = V_c\,(1 - \Gamma_*/C) - R_d \, . \qquad (3)$$

At a physiological level, particularly in ambient O_2 concentrations, most data are accounted for by considering that rate of carboxylation occurs at the greatest rate consistent with the constraints imposed by (a) the amount of Rubisco (RuP_2 saturated rate - W_c), (b) the rate, W_r, allowed for the regeneration of the CO_2 acceptor, RuP_2, often limited to the rate, W_j, allowed by electron transport or (c) W_p, the rate of carboxylation allowed by availability of inorganic phosphate.

The RuP_2-saturated rate of carboxylation is given by

$$W_c = \frac{V_{c\max}\, C}{C + K_c\,(1 + O/K_O)} \, , \qquad (4)$$

where V_{cmax} is the maximum rate of carboxylation, C and O are the partial pressures of CO_2 and O_2 at the RuP_2 carboxylase-oxygenase (Rubisco) sites in the chloroplast, and K_c and K_o are the respective Michaelis constants of Rubisco for CO_2 and O_2.

The resulting expression for the RuP_2-saturated rate of assimilation (Farquhar and von Caemmerer, 1982) is found by assuming $V_c = W_c$. Thus

$$A = \frac{V_{c\max}\;(C - \Gamma_*)}{C + K_c\,(1 + O/K_O)} - R_d \, . \qquad (5)$$

The maximum rate, V_{cmax}, depends on the number of sites of Rubisco, E_t (μmol m^{-2}), per unit area of leaf, and k_c(s^{-1}), the catalytic turnover number.

$$V_{c\max} = k_c E_t \, . \qquad (6)$$

Each Rubisco molecule is an octamer, with eight sites of catalysis. The above equations only apply to activated Rubisco sites. As well as being involved in catalysis, CO_2 also binds, together with Mg^{2+}, elsewhere on each monomer to activate it. The dependence on partial pressure of CO_2 for this partial process is loosely described by $C/(C+K_a)$ where K_a is the effective Michaelis constant for activation. Von Caemmerer and Edmondson (1986) estimated K_a at saturating light intensities from *in vivo* measurements of radish leaves (*Raphinus sativa*) as 10 μbar. However K_a is inversely proportional to the concentration of free Mg^{2+} in the chloroplast stroma. CO_2 affects the rates of carboxylation and oxygenation, and thereby affects the concentrations of the CO_2 acceptor, RuP_2, and of other phosphorylated compounds, such as phosphoglyceric acid, PGA, the product of RuP_2 carboxylation. These compounds chelate Mg^{2+}, making it less available for activation (see theoretical treatment in von Caemmerer and Farquhar, 1986). The activation is also profoundly affected by pH (Mott and Berry, 1986), which is in turn affected by CO_2 concentration, both directly via conversion to bicarbonate, and indirectly via its effects on the concentration of compounds like PGA.

Other parameters in the earlier equations, such as k_c, and hence V_{cmax} (but not Γ_* [Jordan and Ogren, 1984]) are also affected by pH. This dependence may explain why increased partial pressure of CO_2 sometimes causes a decline in the rate of photosynthesis (Woo and Wong, 1983), particularly at nonphysiological, low partial pressures of O_2. The last topics--chelation, pH effects, control of activation (Salvucci *et al.*, 1986)--are active areas of biochemical research.

The capacity for regeneration of RuP_2, W_r, is most frequently at the rate W_j limited by the potential rate of electron transport, J (μmol e^- m^{-2} s^{-1}), at a particular light intensity. Since about four electrons are required for each carboxylation and each oxygenation (see discussion by Farquhar and Kirschbaum, 1985), the capacity for RuP_2 regeneration is

$$W_r \leq W_j = \frac{J}{4 + 8\Gamma_*/C} \; . \tag{7}$$

Substituting $V_c = W_j$ in Equation 3, we obtain the electron transport limited rate of assimilation

$$A = \frac{J\,(C - \Gamma_*)}{4C + \Gamma_*} - R_d \; . \tag{8}$$

In turn the potential rate of electron transport at a particular light intensity is given approximately (Farquhar *et al.*, 1986) by the solution of

$$\Theta J^2 + (J_{\max} + I/2)\,J + J_{\max}\,I/2 = 0 \;, \tag{9}$$

where I (μmol quanta m^{-2} s^{-1}) is the irradiance (400-700 μm) effectively absorbed for photosynthesis, and J_{max} is the temperature-dependent maximum rate (see Kirschbaum and Farquhar [1984] for temperature dependence). Although a leaf typically absorbs about 0.8 of the incident photosynthetically active quanta, only about 0.7 absorbed "white" quanta appear to be effective (Farquhar and Kirschbaum, 1985). The irradiance is halved in the equation because one photon must be absorbed by each of the two photosystems for the passage of an electron. The parameter θ depends on the balance of limitations imposed by the components of the chain, and its value affects the curvature of the relationship between J and I, making it small as θ approaches zero. Recent unpublished experiments suggest magnitude of about 0.7.

If the photosynthetical machinery is used optimally then J_{max} is distributed within the leaf according to the proportion of quanta absorbed at a particular layer (Farquhar *et al.*, 1986). The same arguments can be made for a whole canopy and the result is that Eq. 9 can be used for the whole canopy with I being the total absorbed irradiance, and J_{max} the sum of the capacities at the various layers. From the results of Terashima and Inoue (1985) it appears that chloroplasts within leaves tend to have the above properties. The capacities (J_{max} and V_{cmax}) of leaves lower in a canopy are also usually lower than those higher up. However, changing solar angle, and wind movement of leaves mean that real, closed canopies have internal distributions of light intensity which are continually changing. Nevertheless, it appears to me that these uncertainties are often less than those associated with the biochemical capacities, and that the solution of Eq. 9 will be useful for modeling closed canopies as well as leaves and thylakoids. Modification is obviously necessary for isolated plants.

The third limitation on rate of carboxylation is that associated with the supply of inorganic phosphate. This supply is controlled in part by starch synthesis which releases phosphate and in part by extra-chloroplastic metabolism (typically to sucrose) of triose phosphate exported from the chloroplast. This releases inorganic phosphate for reentry into the chloroplast. If the rate of supply of phosphate, S, say, is limiting, the rate of CO_2 assimilation should be independent of CO_2 and O_2 concentrations (Farquhar and von Caemmerer, 1982) and given by

$$A = 3S - R_d \; . \tag{10}$$

Sharkey (1985) noted a correlation between CO_2 and O_2 insensitivities in *Xanthium strumarium.* The latter occurred after water stress, and were also observed after large amounts of carbohydrate were accumulated (Azcon-Bieto, 1983).

We see then that, theoretically, the sensitivity (d nA/d nC = β) of assimilation rate to CO_2 partial pressure depends on the conditions imposed and can be positive (Equations 5, 8) or zero (Equation 10). In practice, as noted earlier, it can also be negative (Woo and Wong, 1983).

Thus, even short-term effects of changes in partial pressure of CO_2 are not well understood. Carbohydrate accumulation is obviously a potential feature of vegetation grown at increased CO_2 concentration, and over the short-term (one day) can change the pattern of response.

However, the limiting capacities V_{cmax}, J_{max} and S also change (and adjust?) with time. For example, von Caemmerer and Farquhar (1984) found that V_{cmax} (and possibly J_{max}) was less in *Phaseolus vulgaris* plants grown at 660 μbar than in plants grown at 330 μbar. The net result was that the assimilation rate per unit area at 660 μbar CO_2 in leaves from plants grown at 660 μbar was actually slightly less than that at 330 μbar from plants grown at 330 μbar.

Effects of CO_2 at longer time scales are diverse, and the reader is referred to the recent review by Warrick and Gifford (1986) for details. The following are broad generalizations.

Decrease in photosynthetic capacity (V_{cmax}, J_{max}, etc.) is a common but not universal feature in plants grown at high $p(CO_2)$ (Kriedeman and Wong, 1984). This decrease probably depends on the extent to which growth interferes with the supply of light, water, and nutrients. It probably also depends on the extent to which 'sinks' for photoassimilate become filled, thereby affecting capacity via hormones (?), or less frequently, it appears, via a reduction in S. The latter was reported as an unpublished observation in Sharkey (1985). Thus, while the early rates of photosynthesis at 660 μbar in young plants are usually greater than those in 330 μbar, sometimes giving a substantial increase (almost doubling) of initial growth rate, the advantage generally decreases, at a rate which is variable among species and conditions.

The net effect is that the increase of growth following a doubling of the CO_2 concentration is 40 ± 7% for immature shoot dry weight and 26 ± 9% for marketable yield of C_3 species grown under good environmental conditions (Warrick and Gifford, 1986, based on a survey of Kimball, 1983).

LIMITING FACTORS

A common misconception about effects of CO_2 on yield is that higher concentrations will have little or no effect when other environmental factors also limit yield. Warrick and Gifford (1986) review challenges to this notion. Based on their findings, my guess is that CO_2 will have an impact when the limitation is fundamentally one that limits CO_2 fixation. Light is probably such a case, if one takes the view that the major role of light is to provide energy, and that most of the energy is used for carbon fixation. Water is another, if one assumes that transpiration is largely currency for the "purchase" of CO_2 via stomata. Nutritional limitations are probably not always of this kind, since the minerals are often essential in their own right. For example, nitrogen is needed for proteins found in cell walls.

STOMATA

The mechanism of stomatal action is very little understood--least of all the response to CO_2 concentration. Double normal CO_2 concentration typically reduces stomatal conductance to diffusion by about 40% (Morison, 1986). The nature of the CO_2 sensor is unknown. While I have emphasized the reactions of Rubisco with CO_2, and while this enzyme may be present in some guard cells (Zemel and Gepstein, 1985) it is unlikely to be the sensor. The only other two proteins which I know to catalyze a reaction with CO_2 are carbonic anhydrase (CO_2 HCO_3) and phospho-enolpyruvate (PEP) carboxylase (PEP + $HCO_3^- \rightarrow$ oxaloacetate) [N.B. HCO_3^- rather than CO_2]. However there are probably many other proteins containing amino groups which react with CO_2 to form carbamates; such a reaction occurs in Rubisco activation (Lorimer, 1983). It is our experience that stomatal conductance is more sensitive to CO_2 when the leaves are stressed--lack of water, nutrients, chilling, etc. (Farquhar and Sharkey, 1982), and involvement of the hormone abscisic acid has been suggested (Raschke, 1975). Nevertheless, the mechanism remains elusive. Wong *et al.* (1979) showed stomata usually function such that the ratio of assimilation rate (μmol CO_2 m^{-2} s^{-1}) to stomatal conductance (μmol m^{-2} s^{-1}) is often about 100×10^{-6} = 100 ml CO_2/ℓ air, when the ambient concentration of CO_2 is 330 $\mu\ell/\ell$ and the vapor pressure difference between leaf and air is 20 μb. This ratio appears to double when the ambient concentration doubles.

SUMMARY

The short-term (one hour) responses of photosynthesis to increased concentration of CO_2 are partly understood, while those of stomatal conductance, although perhaps equally well characterized, are not at all understood.

The amounts of various enzymes and electron transport carriers, etc., which together determine photosynthetic capacity change with time, and with growth conditions. The long-term effects of increased CO_2 are partially characterized, but not mechanistically, since the control of gene expression is not even established in plants growing at present day levels.

Where growth and reproduction are clearly limited by factors unaffected by, and not linked with, carbon fixation, then predictions of response to increased concentration of CO_2 may be made with some confidence. This is rare. Predictions of vegetation cover and succession are at present largely based on the physiology and vital attributes of a 300 ppm world, which may, or may not, resemble those of the next century.

REFERENCES

Azcon-Bieto, J., 1983: Inhibition of photosynthesis by carbohydrates in wheat leaves. *Plant Physiol., 73*, 681-686.

Farquhar, G.D. and S. von Caemmerer, 1982: Modelling of photosynthetic response to environmental conditions. In *Physiological Plant Ecology II*, O.L. Lange, P.S. Nobel, C.B. Osmond and H. Ziegler (eds.), *Encyclopedia of Plant Physiology*, New Series, Vol. 12B, Springer-Verlag, Heidelberg, pp. 549-587.

Farquhar, G.D. and T.D. Sharkey, 1982: Stomatal conductance and photosynthesis. *Ann. Rev. Plant Physiol., 33*, 317-345.

Farquhar, G.D., M.H. O'Leary and J.A. Berry, 1982: On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves. *Aust. J. Plant Physiol., 9*, 121-137.

Farquhar, G.D. and M.U.F. Kirschbaum, 1985: Environmental constraints on carbon assimilation. In *Regulation of Sources and Sinks in Crop*

Plants, B.F. Jeffcoat, A.F. Hawkins and A.D. Stead (eds.), British Plant Growth Regulator Group Monograph No. 12, 87-97.

Farquhar, G.D. and M.U.F. Kirschbaum, 1985: Environmental constraints on carbon assimilation. In *Regulation of Sources and Sinks in Crop Plants*, B.F. Jeffcoat, A.F. Hawkins and A.D. Stead (eds.), British Plant Growth Regulator Group Monograph No. 12, 87-97.

Farquhar, G.D., J.R. Evans, J.A. Berry and O. Björkman, 1986: A model of whole-chain electron transport/photophosphorylation for application to studies of leaf photosynthesis (in preparation).

Hubick, K.T., G.D. Farquhar and S.C. Wong, 1986: Effects of plants on the isotope abundances of oxygen in atmospheric carbon dioxide (in preparation).

Jordan, D.B. and W.L. Ogren, 1984: The CO_2/O_2 specificity of ribulose-1, 5-bisphosphate carboxylase/oxygenase. Dependence on ribulose-bisphosphate concentration, pH and temperature. *Planta, 161*, 308-313.

Kimball, B.A., 1983: Carbon dioxide and agricultural yield; an assemblage of 430 prior observations. *Agron. J., 75*, 779-788.

Kirschbaum, M.V.F. and G.D. Farquhar, 1984: Temperature dependence of whole leaf photosynthesis in *Eucalyptus pauciflora*. *Aust. J. Plant Physiol., 11*, 519-538.

Kriedemann, P.E. and S.C. Wong, 1984: Growth response and photosynthetic acclimation to CO_2: Comparative behavior in two C_3 crop species. *Acta Horticulturae, 162*.

Lorimer, G.H., 1983: Carbon dioxide and carbamate formation: the makings of a biochemical control system. TIBS - Feb, 1983, pp. 65-68.

Morison, J.I.L., 1987: Intercellular CO_2 concentration and stomatal response to CO_2. In *Stomatal Function*, E. Zeiger, G.D. Farquhar and I.R. Cowan (eds.), Stanford University Press, Stanford, California (in press).

Mott, K.A. and J.A. Berry, 1986: Effect of pH on activity and activation of RuBP carboxylase at air level CO_2. *Pl. Physiol.* (in press).

Pearman, G.I. and P. Hyson, 1985: Global transport and inter-reservoir exchange of carbon dioxide with particular reference to effects on concentration and stable isotope distributions. *J. Atmos. Chem.* (in press).

Raschke, K., 1975: Simultaneous requirement of carbon dioxide and abscisic acid for stomatal closing in *Xanthium strumarium* . L. *Planta, 125*, 243-259.

Salvucci, M.E., A.R. Portis and W.L. Ogren, 1986: A soluble chloroplast protein catalyzes ribulosebisphosphate carboxylase/oxygenase activation *in vivo*. *Photosynthesis Research* (in press).

Sellers, P.J., 1985: Canopy reflectance, photosynthesis and transpiration. *Int. J. Remote Sensing, 6(8)*, 1335-1372.

Sharkey, T.D., 1985: O_2-insensitive photosynthesis in C_3 plants. Its occurrence and a possible explanation. *Pl. Physiol., 78*, 71-75.

Tans, P.P., R.J. Francey and G.I. Pearman. Large scale variations in the $\delta^{18}O$ of Tropospheric CO_2. In *Baseline 1983-1984*, R.J. Francey (ed.), Dept. of Science and Technology, Australia.

Terashima, I. and Y. Inoue, 1985: Vertical gradient in photosynthetic properties of spinach chloroplasts dependent on intra-leaf light environment. *Plant Cell Physiol., 26*, 781-785.

von Caemmerer, S. and G.D. Farquhar, 1984: Effects of partial defoliation, changes of irradiance during growth, short-term-water-stress, and growth and enhanced $p(CO_2)$ on the photosynthetic capacity of leaves of *Phaseolus vulgaris* . L. *Planta, 160*, 320-329.

von Caemmerer, S. and D.L. Edmondson, 1986: The relationship between steady state gas exchange, *in vivo* RuP_2 carboxylase activity and some carbon reduction cycle intermediates in *Raphanus sativus*. *Aust. J. Plant Physiol.* (in press).

von Caemmerer, S. and G.D. Farquhar, 1986: A model describing the effects of phosphorylated compounds, and their chelation by magnesium, on the kinetics of Rubisco. Submitted to *Aust. J. of Plant Physiol.*

Warrick, R.A. and R.M. Gifford, 1986: CO_2, climatic change and agriculture: assessing the response of food crops to the direct effect of increased CO_2 and climatic change. In *International Assessment of CO_2 and Other Radiatively Active Gases in the Atmosphere*. WMO/UNEP/ICSU (in press).

Wong, S.C., I.R. Cowan and G.D. Farquhar, 1979: Stomatal conductance correlates with photosynthetic capacity. *Nature, 282*, 424-426.

Woo, K.C. and S.C. Wong, 1983: Inhibition of CO_2 assimilation by supraoptimal CO_2: effect of light and temperature. *Aust. J. Plant Physiol., 10*, 75-85.

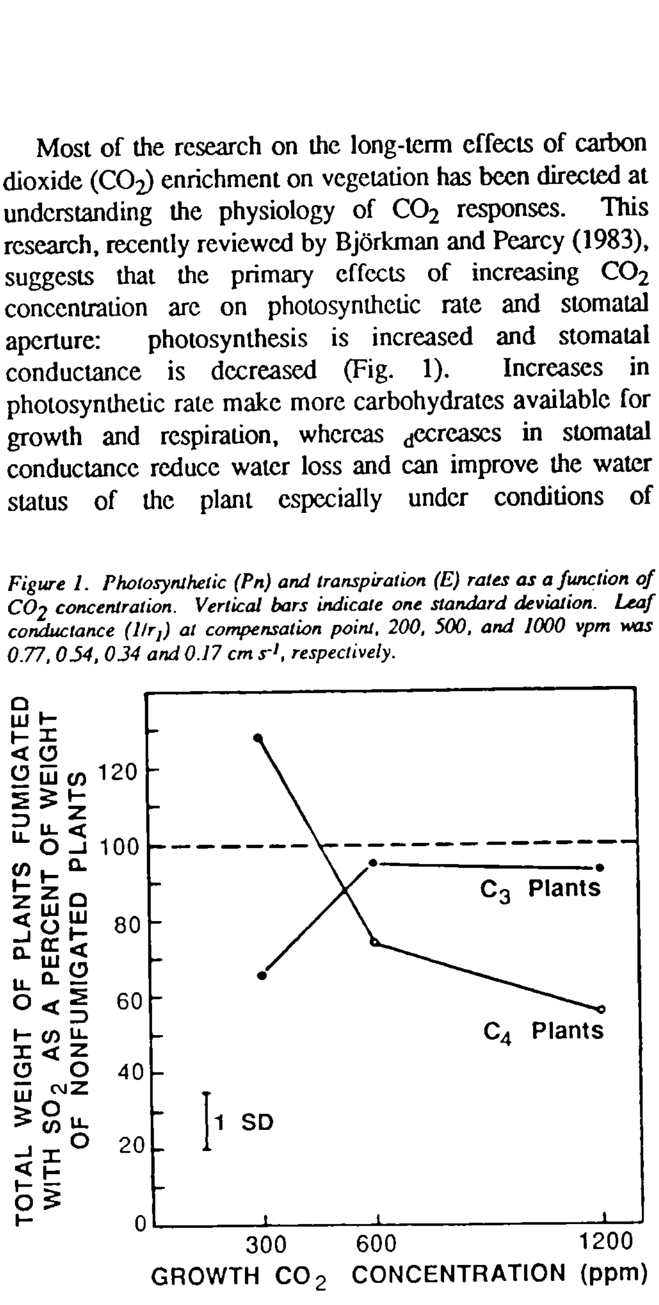
Zemel, E. and S. Gepstein, 1985: Immunological evidence for the presence of ribulose bisphosphate carboxylase in guard cell chloroplasts. *Plant Physiology, 78*, 586-590.

Global CO_2 Levels and the Response of Plants at the Population and Community Levels

Fakhri A. Bazzaz

Most of the research on the long-term effects of carbon dioxide (CO_2) enrichment on vegetation has been directed at understanding the physiology of CO_2 responses. This research, recently reviewed by Björkman and Pearcy (1983), suggests that the primary effects of increasing CO_2 concentration are on photosynthetic rate and stomatal aperture: photosynthesis is increased and stomatal conductance is decreased (Fig. 1). Increases in photosynthetic rate make more carbohydrates available for growth and respiration, whereas decreases in stomatal conductance reduce water loss and can improve the water status of the plant especially under conditions of

Figure 1. Photosynthetic (Pn) and transpiration (E) rates as a function of CO_2 concentration. Vertical bars indicate one standard deviation. Leaf conductance ($1/r_l$) at compensation point, 200, 500, and 1000 vpm was 0.77, 0.54, 0.34 and 0.17 cm s^{-1}, respectively.



water stress. Significant differences in response to elevated CO2 occur among species even of the same community.

Extensive studies have been made of the growth of agricultural crops under elevated CO_2 concentrations (reviewed by Wittwer, 1983; Kimball, 1983). Results of this research indicate that productivity and yield almost always increase with elevated CO_2 levels, but variability is large among species in the amount of response. Crop plants with the three-carbon (C_3) pathway, for example, always show greater photosynthetic enhancement than do the four-carbon (C_4) plants. This effect has a clearly understood physiological basis. There also are many differences among C_3 species and even among genotypes of the same species, but the physiology of these differences has not yet been investigated.

Differences in response to elevated CO_2 levels among the members of an ecological community are likely to result in changes to the species composition of the community. The composition of the communities depends on the interactions of the community members with their physical and biotic environments. The result is a very complex set of interactions that will affect communities in complex ways as CO_2 levels increase.

The effects of elevated CO_2 levels on plant communities have been studied in two ways. Most studies involve several species of plants grown individually and focus on the differences observed in final biomass, growth rates, seed or fruit weight, or some other measure of potential competitive success. There have been relatively few examples of the other type of study, in which natural or artificial communities of plants are exposed to different levels of CO_2 and competitive outcomes directly observed. Efforts are being made to bring these two approaches together by mathematical modeling techniques.

Carlson and Bazzaz (1980) studied 14 plant species, finding a wide variety of changes in plant weight and photosynthetic rate for two CO_2 concentrations (Table 1).

Species	Percent Increase*			
	Photosynthesis		Biomass	
	600 ppm	1200 ppm	600 ppm	1200 ppm
C_3 Plants				
Datura stramonium (1)	74	96	74	115
(2)	67	83	60	107
Chenopodium album	57	79	76	140
Polygonum pennsylvanicum	51	64	48	100
Abutilon theophrasti	44	75	38	65
Ambrosia artemisiifolia	10	24	68	112
Acer saccharinum	61	89	32	63
Populus deltoides	65	74	29	20
Platanus occidentalis	13	30	33	33
Glycine max	58	75	47	100
Helanthus annuus	20	38	40	55
C_4 Plants				
Setaria faberii	13	37	42	106
Setaria lutescens	40	20	70	45
Amaranthus retroflexus (1)	41	21	36	59
(2)	27	33	29	48
Zea mays	24	-7	21	10

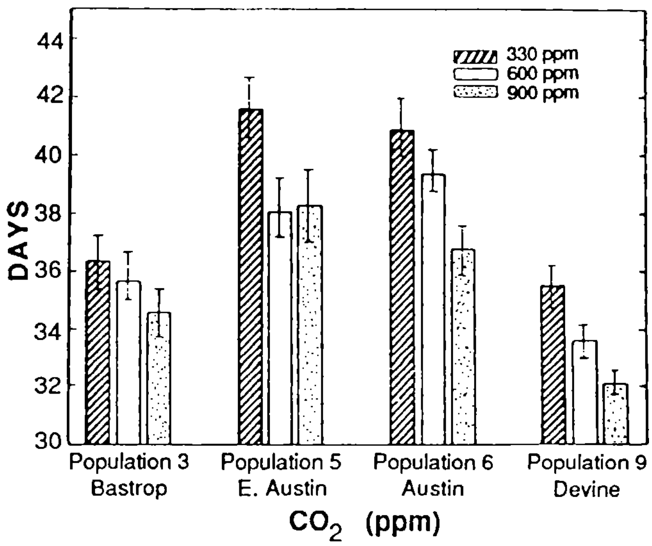
*Percent increase over values at 300 ppm.
Source: Carlson and Bazzaz

Table 1. Percent increase in total biomass and in mean single-leaf photosynthesis for growth 28 days after planting at different CO_2 concentrations relative to the values at 300 ppm.

Total biomass changes were significantly different among species.

Experiments were performed by Garbutt and Bazzaz (1984), on the effects of CO_2 concentration on flowering and fruiting with particular attention given to the timing of flowering. An alteration of the flowering time could disrupt pollination relationships in insect-pollinated flowers. Figure 2 shows that increased levels of CO_2 advance the flowering time for several populations of *Phlox drummondii* Hook., but that the differences in timing among the populations were preserved. Increased CO_2 levels enhanced all floral characters measured, that is, maximum display, flower production rate, longevity, and the total number of flowers produced. Figure 3 shows the results of a study of CO_2 effects on the reproductive biomass of *Datura stramonium* and *Abutilon theophrasti*. As CO_2 concentration increased, seed number did not significantly increase in *D. stramonium* and actually decreased in *A. theophrasti*, but this decrease was offset by increases in individual seed weight. Fruit weight increased

Figure 2. The flowering responses (days to flowering) of four populations of Phlox drummondii *to three levels of CO_2. Bars indicate two standard errors. Source: Garbutt and Bazzaz (1984).*



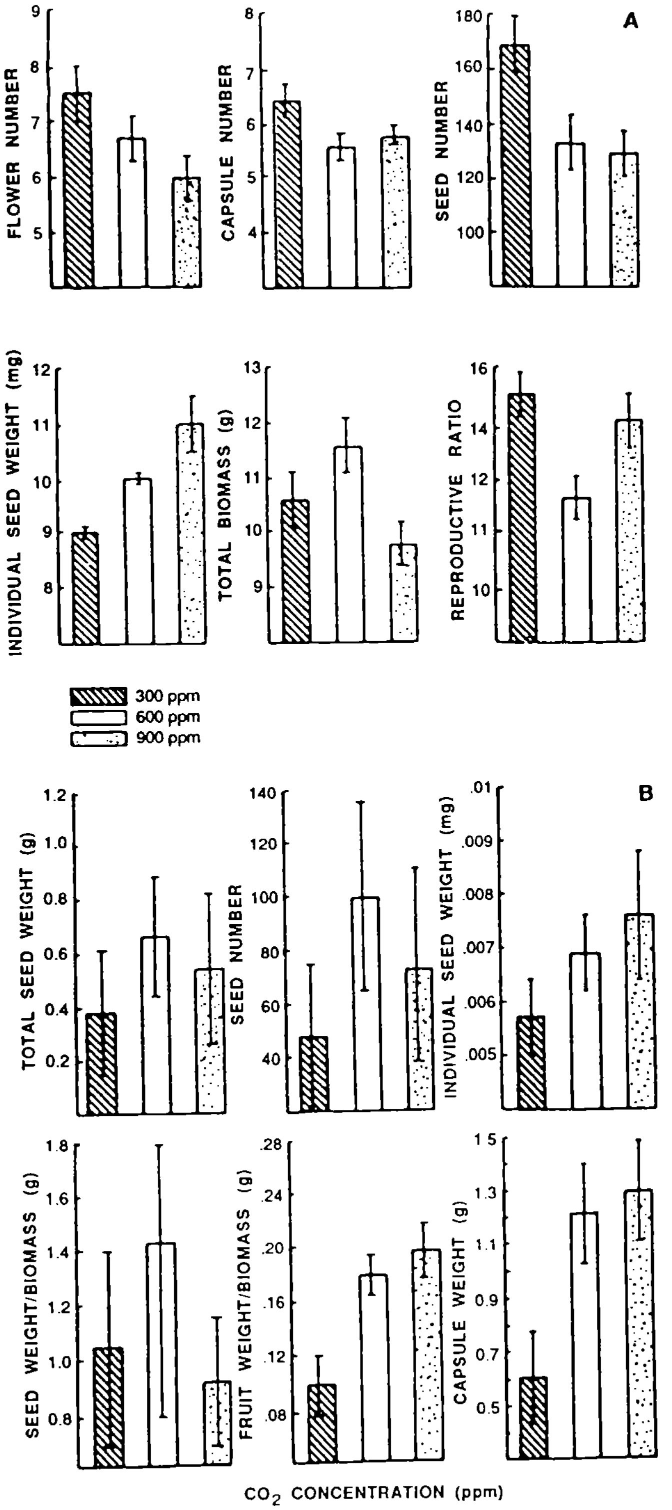


Figure 3. The reproductive response of two old-field annuals to concentrations of CO_2. (A) Abutilon theophrasti. *(B)* Datura stramonium. *All data are on a per-plant basis, all weights are grams. Source: Garbutt and Bazzaz (1984).*

significantly in *D. stramonium*. *A. theophrasti* grew more quickly, but final biomass was not significantly affected by the CO_2 concentrations. Taken together, these studies illustrate the danger of assuming that increased biomass translates into increased seed output, especially if increased biomass is measured at any time before reproductive maturity.

Direct competition experiments have communities consisting of old field annuals, deciduous tree seedlings, and herbs of a California serpentine grassland.

A recurrent theme in competition research is the pairing of C_3 and C_4 species, presumably because prediction of the outcome based on physiology is so clear: as the CO_2 concentration increased, the C_3 plant should do progressively better with respect to the C_4 plant, unless there is water stress. If there is water stress, the competititive relationship probably would not change significantly with the level of CO_2 (Björkman and Pearcy, 1983).

Bazzaz and Carlson (1984) have studied the competition among four species, three C_3 and one C_4, at two levels of moisture (Fig. 4). The effects of moisture and CO_2 amplified each other, so that *Polygonum pennsylvanicum*, a wet-soil C_3 species, gradually displaced *Amaranthus retroflexus*, a C_4 species, as the CO_2 and moisture levels increased. The total biomass of the community increased with an increase in the CO_2 concentration, but the interactions of the other two species, *Abutilon theophrasti* and *Ambrosia artemisiifolia*, did not change with a change in the CO_2 concentration.

Zangerl and Bazzaz (1984) exposed six members of an annual community to combinations of CO_2 and nutrient concentrations, and of CO_2 concentrations and light intensities. In the CO_2-nutrient study, plants were collected at reproductive maturity, and seeds were sorted out and weighed separately from the rest of the plant (Fig. 5).

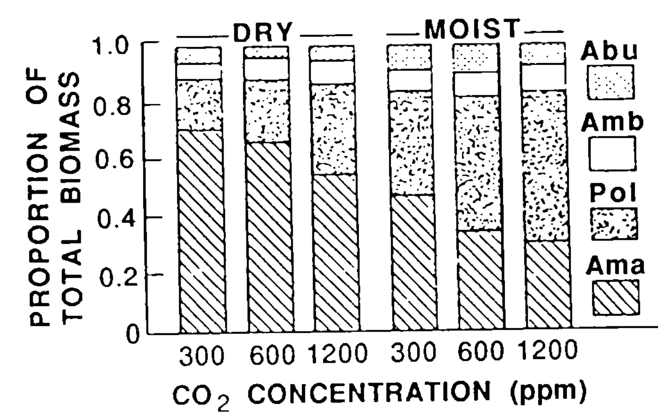


Figure 4. Proportion of total above-ground biomass for assemblages of Abutilon theophrasti *(Abu),* Ambrosia artemisiifolia *(Amb),* Polygonum pennsylvanicum *(Pol) and* Amaranthus retroflexus *(Ama) grown at 300, 600, and 1200 μL CO_2 and 15% (dry) or 30% (moist) soil moisture. Source: Bazzaz and Carlson (1984).*

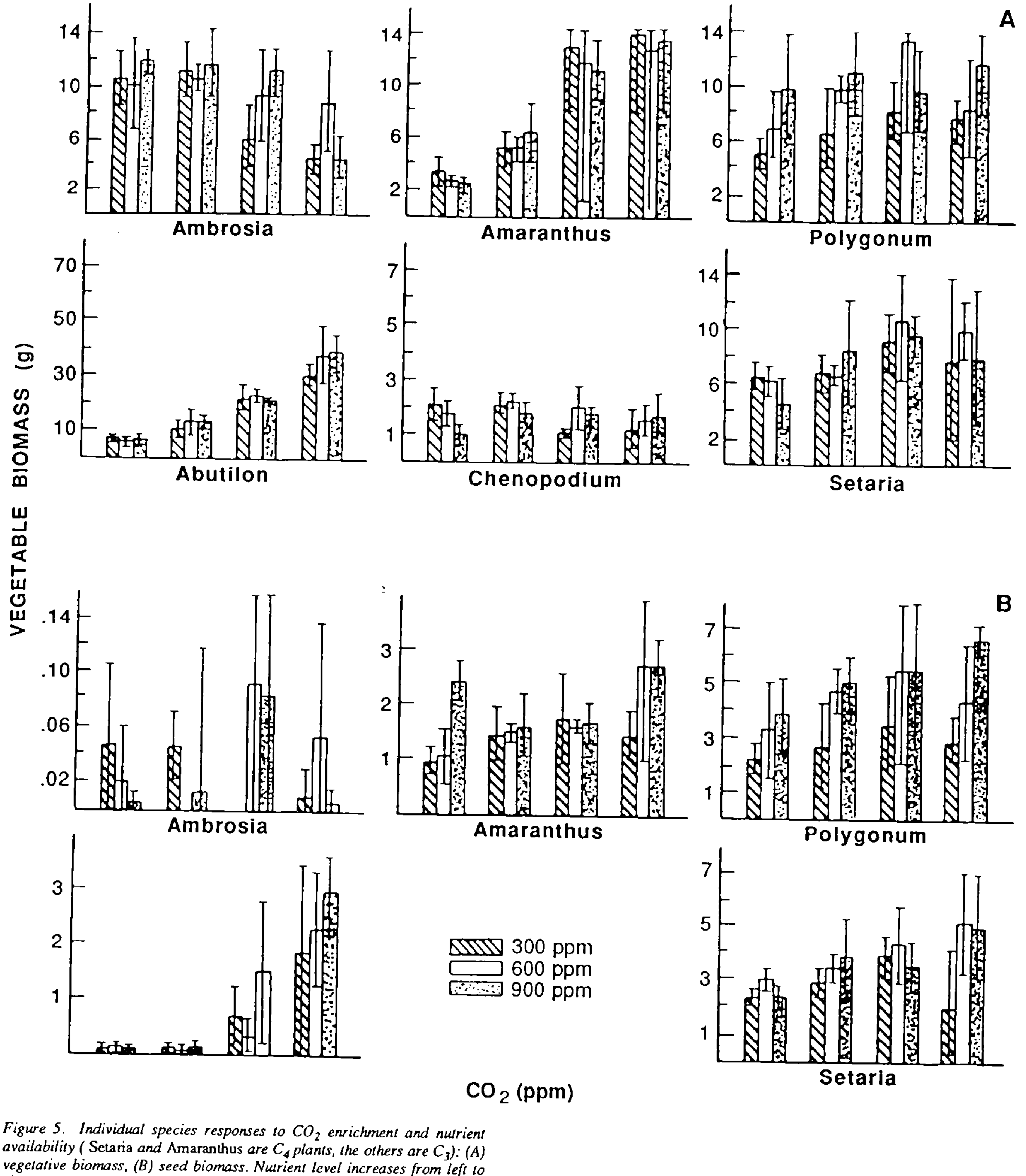
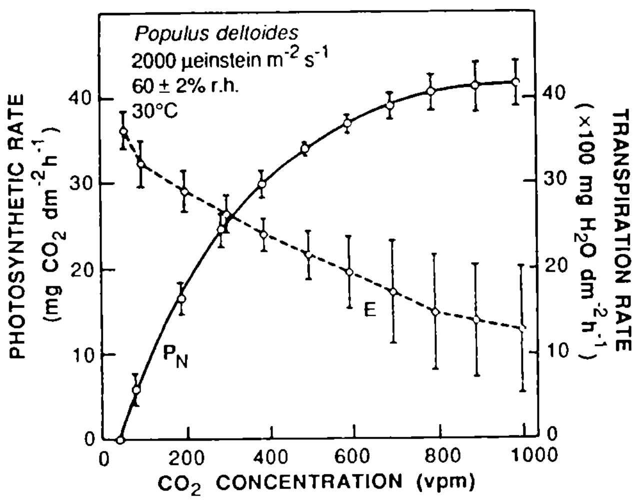


Figure 5. Individual species responses to CO_2 enrichment and nutrient availability (Setaria *and* Amaranthus *are C_4 plants, the others are C_3): (A) vegetative biomass, (B) seed biomass. Nutrient level increases from left to right: 95% confidence limit is indicated for each mean. Source: Zangerl and Bazzaz (1984).*

Under low light levels, total community production was not highest at the highest CO_2 concentration, suggesting that some environmental conditions may cause the production of at least some members of the community to decrease with elevated CO_2 concentrations.

The results of these experiments suggest strong interactions with other environmental factors. Furthermore, the response of a species in the community may not be predictable from the response of an isolated species. There were also differences between vegetative response and reproductive response of the species. Carlson and Bazzaz (1984) examined the effects of SO_2 on plant growth with or without CO_2 and found that the reduction in photosynthesis and growth by SO_2 is greatly diminished by increased CO_2. Apparently, reduction in stomatal conductance caused by high CO_2 reduced the rate of entry of SO_2 into leaves and lowered its damage. Again C_3 and C_4 species differed in their response (Fig. 6). Thus, factor interactions are important in plant response to increased CO_2. Environmental factors could be antagonistic, additive, or synergistic and correct assessment of the response of biota to their environment must consider their joint action.

Figure 6. Average total growth of C_3 and C_4 plants fumigated with 0.25 ppm SO_2 expressed as a percent of the growth of nonfumigated plants at 300, 600, and 1200 ppm CO_2.



REFERENCES

Bazzaz, F.A. and R.W. Carlson, 1984: The response of plants to elevated CO_2. I. Competition among an assemblage of annuals at different levels of soil moisture. *Oecologia, 62*, 196-198.

Björkman, O. and R.W. Pearcy, 1983: Physiological effects. In *CO_2 and Plants: The Response of Plants to Rising Levels of Atmospheric Carbon Dioxide*, E.R. Lemon (ed.), Westview Press, Boulder, Colorado, pp. 65-106.

Carlson, R.W. and F.A. Bazzaz, 1980: The effect of elevated CO_2 concentration on growth, photosynthesis, transpiration, and water-use efficiency of plants. In *Environmental and Climatic Impact of Coal Utilization*, J.J. Singh and A. Deepak (eds.), Academic Press, New York, pp. 609-623.

Garbutt, K. and F.A. Bazzaz, 1984: The effects of elevated CO_2 on plants. III. Flower, fruit and seed production and abortion. *New Phytologist, 97*, 433-446.

Kimball, B.A., 1983: Carbon dioxide and agricultural yield: an assemblage of 430 prior observations. *Agron. J., 75*, 779-788.

Wittwer, S.M., 1983: Rising atmospheric CO_2 and crop productivity. *Hortscience, 18*, 667-673.

Zangerl, A.R. and F.A. Bazzaz, 1984: The response of plants to elevated CO_2. II. Competitive interactions between annual plants under varying light and nutrients. *Oecologia, 62*, 412-417.

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Not A Catastrophe, A Boon: The Good News About Carbon Dioxide

BY KENNEDY MAIZE

Sherwood Idso adores carbon dioxide. Doubling the atmospheric content of carbon dioxide, says the agricultural scientist from Arizona, would be a wonderful boon to the world, rather than the catastrophe described by the scientists who believe that the world is headed for global warming because of CO_2.

"The rapidly rising carbon dioxide content of earth's atmosphere bodes well for biology," Idso told *The Energy Daily* last week. "A great greening of the Earth is in progress in a world-wide biological system starved for carbon dioxide."

With more carbon dioxide in the atmosphere, said Idso, deserts will green, forests will advance, and soil erosion will decline. "Greater agricultural productivity will mean a greater return of organic matter to the soil." Idso is a researcher at the U.S. Department of Agriculture's conservation laboratory in Tempe and a botany professor at Arizona State University. He has published his views on carbon dioxide in a new book, *Carbon Dioxide and Global Change: Earth in Transition.*

According to Idso: "If we add another 300 parts per million of carbon dioxide, we will increase the productivity of all plants by about one-third." That is because the pores in leaves where water escapes close up in the presence of CO_2. That means the plants lose less water and increase productivity as a result. "That's really amazing when you think about it," he said. "It's a free by-product to atmospheric CO_2 enrichment. But you don't hear that side often because of the unbelievable warnings we hear about warming."

Idso is one of many scientists who reject the warming hypothesis advanced by, among others, James Hansen of NASA's Goddard Institute of Space Science in New York. "The global circulation models," upon which Hansen's work is based, "include only physical and chemical things," Idso said. But they don't include the effects of biological systems. "It is very likely that the biology of plants is playing a rather significant role" in the global climate, he said. "But that area has not really been dealt with."

Biology may provide a large negative feedback mechanism to counter global warming, said Idso. "If the surface of the oceans warms, the productivity of the phytoplankton is increased. They produce more dimethylsulfaniopropinate. This gets released as dimethylsulfide, which is oxydized to form particles that serve as cloud condensation nuclei. You get new clouds, and more cooling. You also get increased cloud reflectivity, a powerful negative feedback to warming."

Most of the actions proposed by environmental groups to counter global warming, such as increased energy efficiency and saving the tropical rain forests, are worth doing in their own right, said Idso. "The only argument I have with them is with CO_2. It is the prime byproduct of combustion and we could never do anything about it, even if we wanted to. But we shouldn't want to. Carbon dioxide is a basic building block of nature. We need it. We need more of it."

Labor Groups Battle Morales

While the environmental group Greenpeace has been grabbing the headlines, the U.S. labor movement has been quietly working in the trenches to undermine the nomination of Diane Morales to be assistant energy secretary for environment, safety and health. Opposition to the nomination by the Industrial Union Department and the Metal Trades Department of the AFL-CIO is a far more formidable threat to the tottering Morales nomination than the fuss raised by the gadfly Greenpeace.

"The Senate Energy Committee isn't going to fall all over themselves to placate Greenpeace," said a labor movement source close to the Morales fight. "But organized labor means something to many of the members of the committee." Also, labor's opposition gains significance because many of the DOE-owned, contractor-operated weapons facilities that require clean-up are unionized.

Last month, the heads of the two powerful departments in the AFL-CIO wrote to Sen. Bennett Johnston (D-La.), chairman of the Senate committee. Howard Samuel and David Mallino of the IUD told Johnston that Morales "is simply not qualified to make the critical decisions and take the kinds of policy actions necessary to protect the lives and health of 80,000 workers currently employed at DOE's nuclear facilities. She has neither the educational background, training or practical experience to assume the responsibility of this office."

The labor leaders noted that "many of the workers at the DOE nuclear facilities, most of whom are represented by unions affiliated with the Industrial Union Department, have lost all confidence in DOE's ability and commitment to protect their safety and health. The Morales nomination will do nothing to restore this confidence."

In the letter from the Metal Trade Department, president Paul Burnsky wrote: "To bring the DOE facilities into compliance with environmental, safety and health laws the assistant secretary of energy for environment, safety and health must be an individual who enjoys the confidence of DOE workers, DOE contractors and the public at large....nothing in the background of Diane Morales indicates an ability to begin immediate oversight of environmental clean-up and the creation of safe workplaces at the DOE facilities."

The Political Science of Global Warming

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University of Virginia

Paper prepared for the Cato Institute conference on "Global Environmental Crises: Science or Politics?"

Washington, D.C.
June 5-6, 1991

Concern about the issue of anthropogenerated climatic change is not new. Thomas Jefferson, in *Notes on the State of Virginia* --the first respectable ecology text written about the United States--speculated that deforestation was altering sea breeze dynamics and that its continuation would bring those winds all the way to the Blue Ridge Mountains. His concern over this issue in general was such that he suggested that individuals be appointed in each state, and that they should meet every thirty years or so to see if the climate was indeed changing.

Nonetheless, Jefferson never wrote that human beings should adjust their economic activity as a result of its propensity to change the climate. What he did say was "study it".

If he were alive today, Jefferson would probably call for extensive scientific investigation of the problem of global warming, and how it might effect ecological change. That belief, which says no more than our policy should be commensurate with our science, would be wholly unpopular.

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Virtually all scientists directly involved in research on climatic change believe that the earth will undergo some warming as a result of the increase in anthropogenerated emissions that enhance the "greenhouse effect". Nonetheless, there are now several compelling lines of evidence that indicate the chance of an ecologically or economically disastrous global warming is becoming more remote, either as a result of a substantial delay in onset, or because the warming may express itself in ways that are primarily benign.

Moreover, within certain broad limits, how *much* the world warms can be irrelevant. Rather more important is *how* the world warms, because the ecological effects will be determined by the regionality, seasonality, and distribution of warming within the day-night cycle. Given these considerations, both observed and projected climate changes now suggest a future that is at considerable variance with what might be referred to as the "Popular Vision": global temperature change of approximately 4°C, pronounced sea level rise because of the melting of major areas of land ice and thermal expansion of water, and starvation and civil strife resulting from ecological chaos. An additional aspect of this Vision is that any meaningful attempt to prevent warming will entail major economic dislocation.

The Popular Vision became prominent because of two synergistic events. The first was the publication of a generation of general circulation model (GCM) climate simulations in the mid to late 1980's: These predicted a mean global warming of 4.2°C with winter warming of as much as 18°C for the north polar regions; a typical example of one of these is given by Washington and Meehl (1983), and shown in Figure 1. The second event was the Congressional testimony of June 23, 1988 that there was a "high degree of cause and effect" between current temperatures and human greenhouse alterations.

Nowhere in that testimony, and nowhere else did NASA's James Hansen ever state that the anomalously warm summer of 1988 in the United States was caused by human enhancement of the greenhouse effect. Nonetheless, the press and the public concluded otherwise: 70% of the respondents to a subsequent Cable News Network poll agreed with the statement that the 1988 drought was in fact caused by "the greenhouse effect". There is little doubt that such unanimity in fact does reflect a very Popular Vision.

Does that Vision remain warranted, or is it dramatically distorted? In order to determine this, we examine here six important aspects of global warming.

1. Greenhouse Gas Concentrations and Temperature Histories

While several greenhouse gases that have increased, almost all of the potential temperature change is from (in descending order), Carbon Dioxide, Methane, Nitrous Oxide, and Chlorofluorocarbons.

Continuous instrumental records of CO_2 concentration date from the late 1950's at Mauna Loa Observatory, where the 1958 annual average was 315 parts per million (ppm). The concentration now is near 354ppm. "Pre-industrial" (circa 1800) concentrations were in the range of 270ppm , giving a rise of 31% to date. Based on the mid-1980's climate models, this should have increased global mean temperature approximately 1.5°C, if other factors were not either delaying or mitigating the warming, and the atmosphere and oceans were in equilibrium.

Other greenhouse gases have also increased considerably. The current climate forcing of methane is nearly 40% of the effect of increased CO_2. In fact, the combined effect of all of the non-CO_2 anthropogenerated greenhouse enhancers is approximately an additional 80% of that caused by a change in CO_2 alone. Thus the current *effective* CO_2 concentration is approximately 420ppm, or 151-161% of the background range of 260-279ppm. *We have already gone at least half-way to an effective doubling of the background CO_2 concentration.*

While the citation is often made that the history of global temperature as "at least not contradictory to" the mid-1980's climate model projections, those models produce an expected equilibrium global warming for this change of approximately 2.5°C , while a least-squares fit of the surface (and primarily land based) global data gives a rise of 0.45±.10°C in the last 100 years. Further, Figure 2 demonstrates that virtually *all* of the warming of the northern hemisphere was prior to the major postwar emissions of the trace gases. This discrepancy is further compounded by the fact that the "water" (southern) hemisphere, which should warm up least and slowest, in fact shows the more "greenhouse-like" signal.

Objective statistical analyses of this record doemonstrate that fully 90% of the warming of the global record took was realized prior to 1945, with very little net change since then. In 1945 the actual CO_2 concentration was in the range of 307ppm and the effective concentration was approximately 322ppm. This is only one-third of the total forcing to date, and implies that there has been very little warming during the period in which the majority of the greenhouse enhancement has taken place.

Are the oceans holding it back? According to climatologist Tom Wigley (1987), even liberal estimates of what is called "oceanic thermal lag" still imply that that the globe should still have warmed over a degree celsius (primarily after 1950), while the net global warming since then is in fact approximately 0.30°C. Sea surface temperature analyses from Massachusettes Institute of Technology (Bottomley, et al, 1990) demonstrate very little lag between that record and land readings. Thus if an ocean-atmosphere interaction is the major reason for the relatively small warming to date, then some unknown deep ocean process is required. Alternatively, the very small amount of observed warming suggests that the time delay may be very long, or that there simply will not be that much change, unless there are other mechanisms that are inhibiting it.

Idso (1990) recently compared northern and southern hemisphere temperature histories and found a striking difference between them that appears with the onset of world industrialization after world war II. As shown in Figure 3, beginning at that time, northern hemisphere temperatures stopped rising at the rate that characterizes the 20th century, while those in the southern hemisphere--which should warm less and slower--continued to rise.

2. Urban Heat Islands and Long-Term Site Bias

Localized warming related to urban buildup has long been recognized as a confounding factor in regional and global temperature analyses. While causes include changes in the surface energy balance, local wind flow, and amount of open sky, precise calculations on the various components of the "urban effect" are not available. However, the effect is statistically detectable at population levels of 2,500 and up. The temperature record is further confounded by the fact that exponential population increases suggest the urban warming bias should be of the same functional form as enhanced greenhouse forcing, and that it will therefore contaminate the latest years of temperature measurement. In other words, it would be striking if the last years in the record *weren't* the warmest.

Tom Karl, of the U.S. National Climatic Data Center, and his coworkers have created a deurbanized "Historical Climate Network" (HCN) of 492 stations that have been checked for instrumental and location changes, and adjusted for population. While this record only applies to the coterminous United States and is therefore not necessarily representative of global trends (i.e. it shows a slow but unsteady cooling for much of the last fifty years), it serves as an important check on other global records because they can be compared to it over this limited region of high accuracy.

That comparion reveals an artifical warming of 0.10-.15°C in the global temperature records of Jones (1988 and updated) presented in figure 2. Because of the urban effect, it therfore appears that the true global warming in figure one during the last 100 years is 0.35-0.40°C.

An additional, and more insidious problem may be introduced into long-term land based climate records by a *general* site bias. Over what was the "developing world" of the late 19th century, the longest-standing climate records have tended to originate at points of commerce. Because of the predominance of water power during that era, it is likely that the longest records are in fact at sites that are preferential for cold air drainage. Such locations may be bufferered from some true warming.

3. High Latitude and Daily Temperature Regimes

All general circulation climate models suggest that the polar warming will be magnified in winter, and that these regions should already have warmed several degrees. Nonetheless, there has been a substantial secular decline in winter temperatures over the Atlantic Arctic since 1920, and there has been no change in polar night temperatures at the south pole --a station that surely has no urban warming. Interestingly, Laurence Kalkstein and his colleagues at the University of Delaware (1990) recently documented that, while there has been no *net* warming of the North American arctic, the coldest airmasses, whose mean surface temperatures are approximately -40°, have warmed some two degrees. Thus the most severe airmass in North America may be undergoing some mitigation that is consistent with an enhanced greenhouse. The only animals that live under these airmasses are either in water, sleeping, or dressed like the Michelin Tire Man. If this is the expression of the enhanced greenhouse, it is hardly supportive of the Popular Vision.

The Popular Vision is not supported by recent studies on daily temperature regimes.

Karl and coworkers examined maximum and minimum values from the U.S. HCN and found that the daily range (difference between the two) has declined precipitously since 1950, and is now two standard deviations below the mean for the century. In that record, maximum values have actually declined while minimum values have risen (Figure 4).

This behavior of the HCN is consistent with an enhanced greenhouse combined with observed increases in cloudiness of 3.5% and reduced sunshine (Angell, 1990) that have been documented across the coterminous United States. In spite of a slight (1.5% since 1970) ozone depletion in our latitudes, ultraviolet radiation reaching low elevations is *declining,* while it is increasing at high elevation. This is also consistent with an increase in low level cloudiness.

If enhanced greenhouse warming takes place primarily at night, the Popular Vision of future climate is wrong. Evaporation rate increases, which are a primary cause of projected increases in drought frequency are minimzed. The growing season is longer, because that period is primarily determined by night low temperatures. Finally, many plants, including some agriculturally important species, will show enhanced growth with increased moisture efficiency because of the well-known "fertilizer" effect of CO_2. Night warming also minimizes polar melting because mean tempeatures are so far below freezing during winter that the enhanced greenhouse is insufficient to induce melting.

I recently aggregated the monthly mean maximum and minimum records from the U.S. HCN, rural Soviet data, and rural data from mainland China. Together, these sets comprise almost one-half of the land area of the northern hemisphere. In them, the ratio of night to day warming, since concurrent records began in 1950, was 10 to 1. On a 100-year trended basis, it was 16 to 1. As would be expected, if clouds were cancelling daytime warming and warming the nights, the winter (longest) nights showed the most warming, and the summer (longest) days showed an actual cooling. The summer (shortest) nights showed the least relative warming, and the winter (shortest) days showed the least cooling.

Thus "how" the world has warmed already appears to be beneficial. If this is indeed the expression of the altered greenhouse, the earth will have to reverse a course it has already embarked upon to get to an enhanced-greenhouse disaster. The consistency of climate behavior with the benign greenhouse hypothesis is profound and compelling.

4. More Recent Climate Models

The earlier generation of GCM's calculated a mean equilibrium warming for a doubling of atmospheric CO_2 of 4.2°C, with maximum warming of as much as 18°C during north polar winter, and less significant warming (approximately two degrees) over tropical oceans.

These models have now been improved with more realistic ocean-atmosphere and cloud dynamics, and they have cooled their projections. By changing the cloud calculations, warming in the United Kingdom Meteorological Office (UKMO) model for a doubling of CO_2 dropped from 5.2°C to 1.9°. With a coupled ocean and atmosphere general circulation model, the net warming in the National Center for Atmospheric Research (NCAR) model dropped to 1.6°C for thirty years after a shock doubling, compared to 3.7° in an earlier equilibrium calculation (Washington and Meehl, 1990). The net equilibrium warming for a doubling of CO_2 in the with a new atmosphere-ocean model of the Geophysical Fluid Dynmics Laboratory dropped to 1.8°C, compared to 4.3° in the more primitive version. Warming projected for the southern hemisphere is approximately 1.0°C, with 2.5° projected for the Northern Hemisphere.

The mean of these three runs is 2.0°C, down over two degrees from the previous mean. This sustantially reduced warming is calculated *either* with altered cloud or ocean parameters. It therefore sems logical that a combination of the two will produce even less net warming.

Because maximum warming in all GCM's tends to concentrate at high latitude winter, *virtually all of the strong warming is now projected either for twilight or night,* which is consistent with what has been observed in the U.S. HCN.

It is tempting to view the unanimity of these newer models as a sign of reliability, but that is not the case. In a version of the NCAR model that increases greenhouse gases by a realistic 1% per year (as opposed to the "shock doubling" used in the model cited above), calculations imply that the current land temperature should be 1.4°C above the 1950 mean ; in fact the rise has been on the order of 0.3°. Thus, even the most conservative (least warm) climate model appears to have grossly overestimated global land warming to date. This version also predicts very unrealistic regional temperatures for the current greenhouse enhancement.

5. The Response of Vegetation to an Increase in CO_2

It has long been known that many plants show increased growth rates when subjected to increasing concentrations of CO_2. In fact, this response may be an expression of plant evolution, inasmuch as virtually all terrestrial plant species evolved when the atmospheric CO_2 concentration was higher than it is today. Many plants continue to show this enhanced growth at concentrations higher than 3000ppm, some ten times greater than late 19th century values.

In the last ice maximum, only 18,000 years ago,the earth's atmosphere was within 100ppm of being *unable* to support plant life because of a lack of carbon dioxide. In fact, during the last 100million years, the earth has undergone a general cooling associated with a reduction in atmospheric CO_2 that has only been reversed by human industrial activity.

Enhanced atmospheric CO_2 appears to stimulate plant growth both by increasing the rate at which carbon is fixed and by increasing plant water use efficiency. Thus we can expect that plants of the 21st century, on the average, will grow more rapidly per unit of moisture consumed. If the climate of that era is going to be dominated by night warming--which will lengthen the growing season without substantially increasing the natural evaporation rate--we may therefore expect a profound "greening" of the planet.

Atmospheric CO_2 has increased some 31% over background concentrations; is there any evidence that this greening has begun? Yes: plant specimens from the British Museum collected in the mid 19th century (prior to the major CO_2 input) have more stomata than members of the same species collected today. These are the pores through which gases exchange and are the major pathway for loss of moisture. This verifies laboratory experiments that demonstrate that plants grown under enhanced CO_2 have fewer stomata than those grown under ambient concentrations.

Several "real world" surveys also indicate that vegetative growth is accelerating as a result of the increase in carbon dioxide. The effect has been noted in montane species in the western United States, in a virgin forest plot being carefully monitored by the Oak Ridge National Laboratory, and in the northern forests of Scandinavia. In all these studies the growth responses have been dramatic and appear to be unexplainable by any conventional weather variable . Further, they have occurred at time when forest growth is ostensibly being retarded by acid precipitation. .

There is some other evidence for large scale vegetation expansion. Brush surveys in the state of Texas indicate a change in the area infested by woody plants from 88 million acres in 1963 to 106 million in 1983. In fact, these and other changes have prompted two rangeland specialists to comment recently that "an experiment assessing the consequences of increased CO_2 levels has already been conducted on a global scale, and we should consider the possibility that the recent increases in abundance of woody plants on rangelands are its most visible result" .

I recently published some computer models for corn yields in eastern North America that changed the daily temperature range by warming the nights, and the yield response was much greater than if growing season rainfall had increased. In other words, we are *already* increasing crop yields because of climatic changes that are consistent with an enhanced greenhouse.

6. Compensatory Cooling from other Industrial Products.

It is clear that human activity, besides enhancing the greenhouse effect, also produces substances that can serve to counter that effect. These include particulates, which serve to scatter radiation, and sulfur dioxide, which when oxidized to sulfate can nucleate clouds.

The human sulfate load in the Northern Hemisphere atmosphere now is equivalent to the maximum loading from the 1815 Tambora volcano, which was been associated with a 2.0° cooling of short duration. Because anthropogenerated sulfates are primarily produced and reside in the northen hemisphere, we may therefore be equalling or overcompensating for current greenhouse forcing with actual negative forcing in the hemisphere that contains most of the world's population.

In fact, if anthropogenerated particulates such as sulfates are in fact mitigating the Popular Vision, we would expect to see the following:

1) Night warming from an increase in both clouds and greenhouse forcing,

2) A counteraction of daytime warming by the greenhouse forcing because of an increase in clouds, and

3) A decrease in daily temperature range.

4) The smallest warming should be during the short summer nights,

5) The maximum cooling should be on long summer days,

6) The greatest warming should be on long winter nights, and

7) The minimum cooling should be on short winter days.

8) The effects should be concentrated in the industrial (Northern) hemisphere, and we should see

9) Enhanced brightening of low-level clouds near sulfate souce regions.

All of these have been observed.

7. Summary

There are now several mutually consistent observations indicating that the Popular Vision of apocalyptic climatic change is dramatically distorted. The Northern Hemisphere, which should warm first and most, shows little net change in the last half-century. Repeated measurements now show relative warming at night, which may in fact be beneficial. The amount of global warming is clearly less than it should be according to the earlier GCM's, given the fact that we are already half way to an effective doubling of CO_2.

The only high-latitude signal that seems consistent with a greenhouse alteration is a 2.0° warming of airmasses whose average surface temperature is approximately -40°, which is a slight modification of the airmass type that is most inhospitable in North America. Other anthropogenerated compounds may be mitigating the warming. New climate models partition almost all of the warming of more than 4°C to polar twilight or night, which will have a minimal effect on ice melting. Observed data compellingly state that Northern Hemisphere warming is occurring in a benign, if not beneficial, fashion.

If this is the couse the earth has embarked upon in response to human insults of the atmosphere, the Popular Vision cannot be realized unless that course were diametrically reversed. Further, have we inadvertantly discovered a very effective control technology against greenhouse warming, or at least have fortuitously bought time to develop a solution that is less disruptive than the 60-80% carbon emission reductions that are generally considered required to stabilize concentrations?

In conclusion, the Popular Vision is now barely defensible. The earth's temperature history suggests that warming for a doubling of CO_2 will be less than the four degrees associated with the Vision, and that warming will take longer than previously thought. Concentration of that delayed warming into winter and night will minimize ecological disruption, and growth enhancement by CO_2 itself may produce a beneficial net change. Finally, we may be able to control warming, via aerosols, without the massive economic disruption inherent in the Popular Vision. The data have dealt the Popular Vision a serious, and perhaps fatal blow.

References

Angell, J. K., 1990. *J. Climate* 3, 296.

Bottomley, M., Folland, C.K., Hsuing, J., Newell, R.E., and D. E. Parker, 1990.

Global Ocean Surface Temperature Atlas, U.K. Meteorological Office, Bracknell, UK. 20pp. + 313 Plates.

Jones, P.D., 1988 and updates. *J. Climate* **1**, 654.

Kalkstein, L.S., Dunne, P.C., and R. S.Vose, 1990. *J. Climate* **3**, 1154.

Karl, T.R., Baldwin, R. G., and M. G. Burgin, 1988. *Historical Climatology Series 4-5*, National Climatic Data Center, Asheville NC 28801. 107pp.

Washington, W.M, and G.A. Meehl, 1983. *J. Geophys. Res.* **88**, 6600.

Washington, W.M., and G. A. Meehl, 1989. *Cli. Dynamics* **2**, 1.

Wigley, T.M.L., 1987. *Cli. Monitor* **16**, 14.

LIST OF FIGURES

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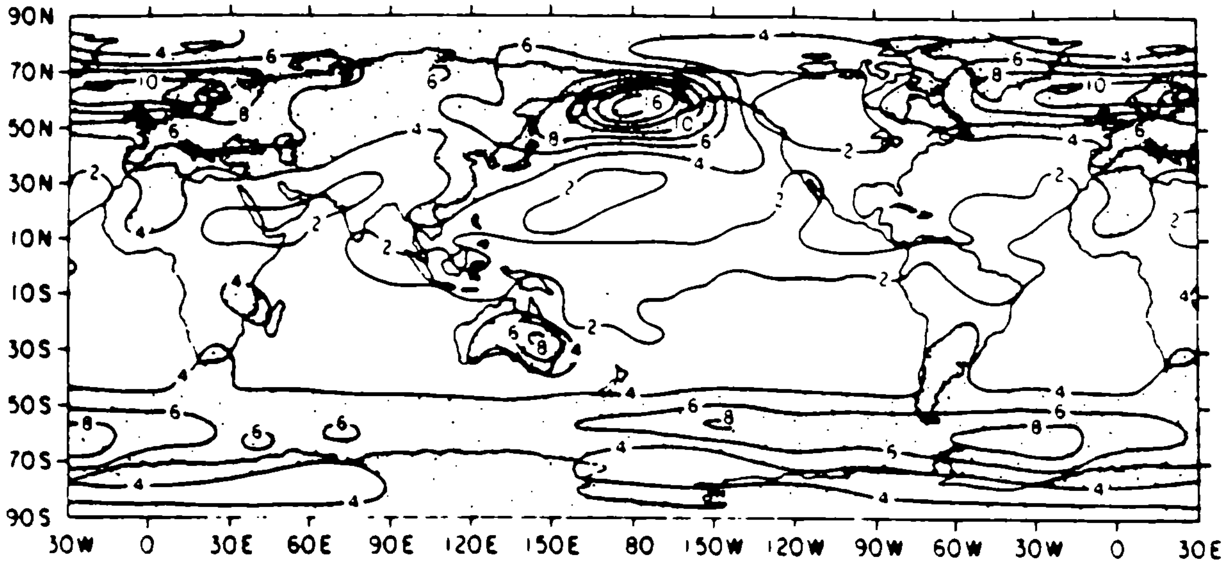
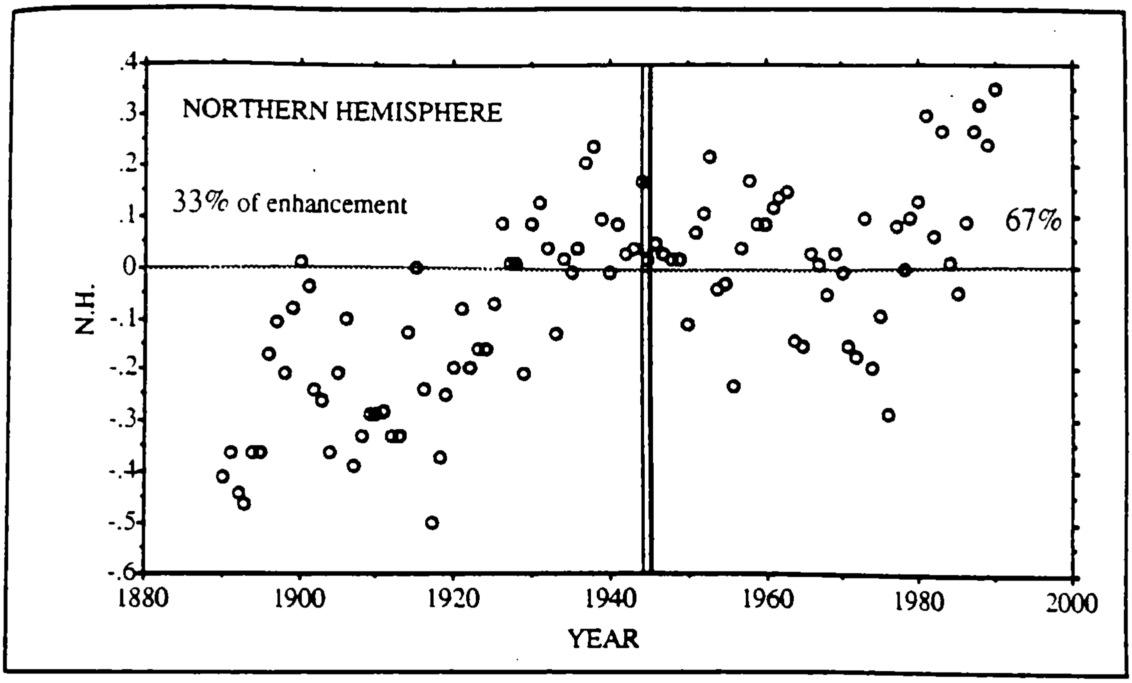


Figure 1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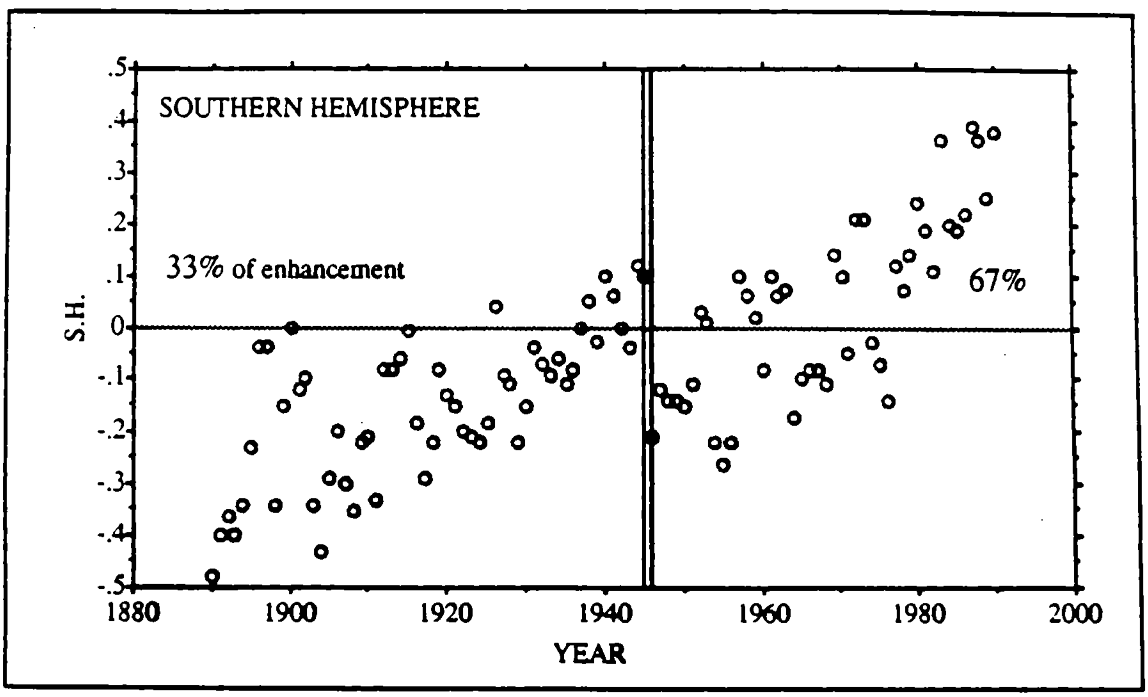
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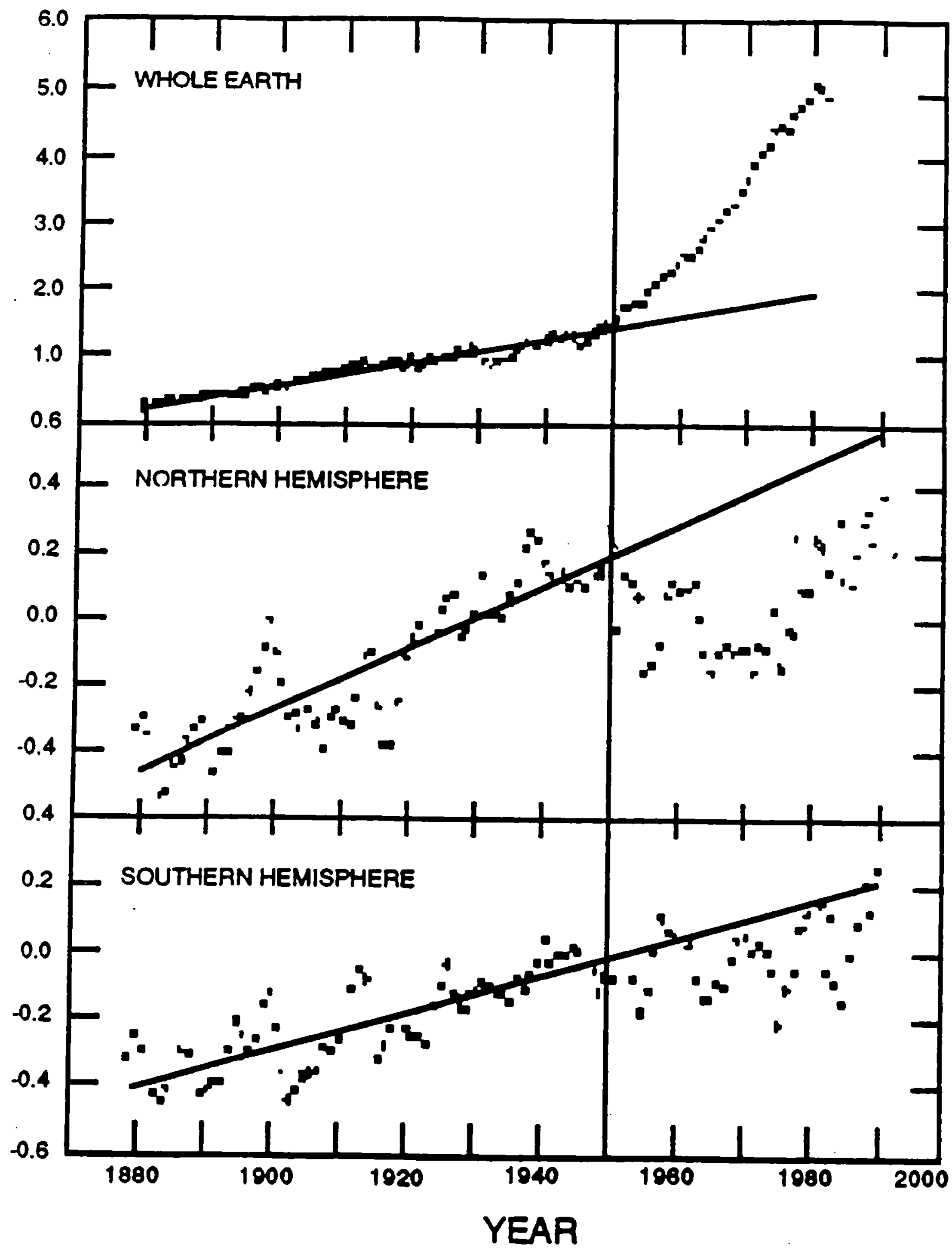
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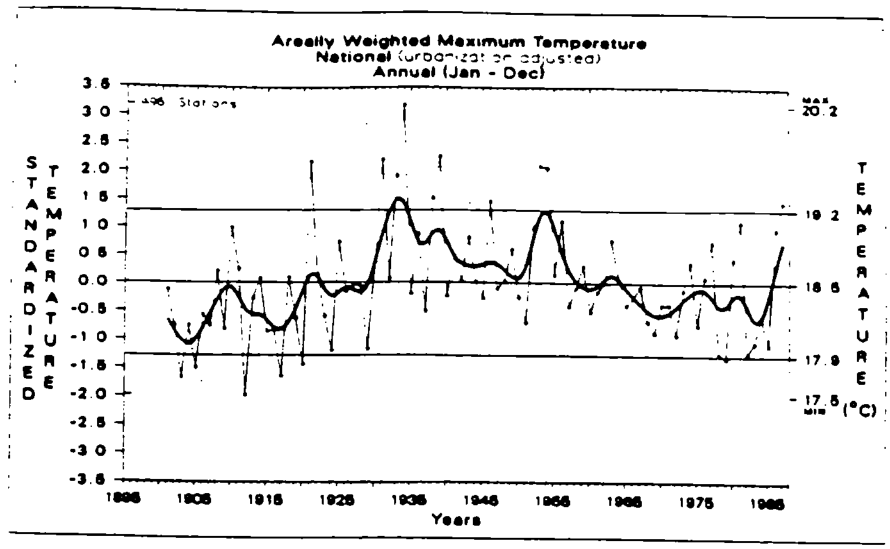
Figure 3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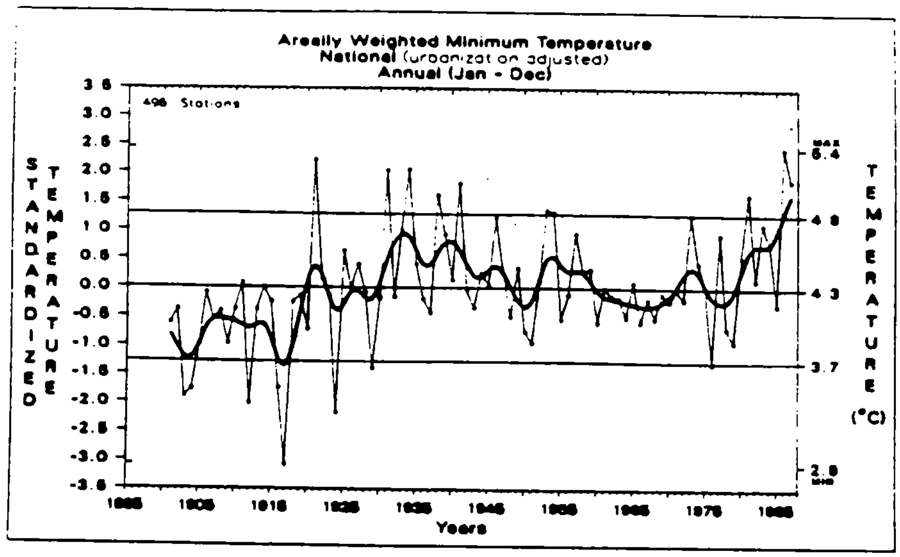
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Annual (Jan - Dec)
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STANDARDIZED
TEMPERATURE
TEMPERATURE (°C)
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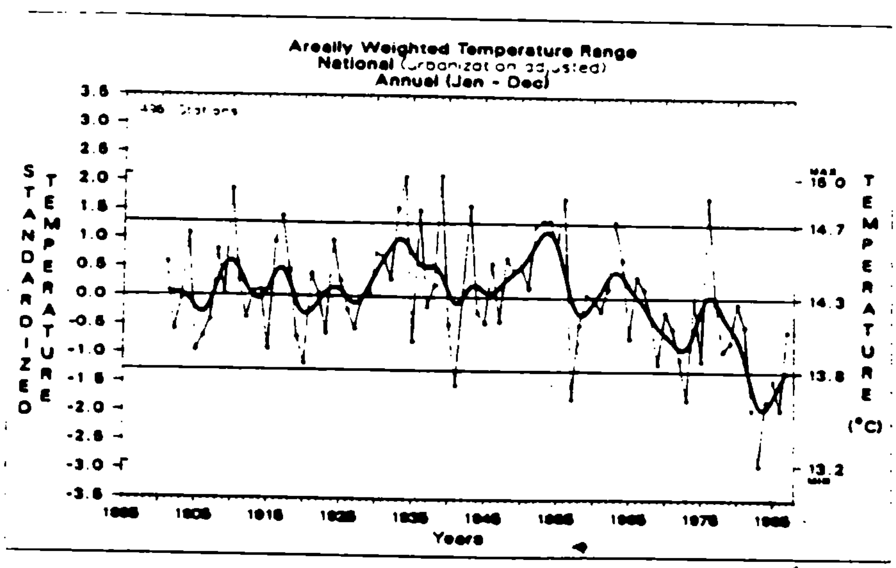
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Figure 4

ɔarbon Dioxide Rise May Alter Plant Life, Researchers Say

Studies suggest the ʒas could feed a burst ɔf vegetation.

By WILLIAM K. STEVENS

EVEN if rising concentrations of carbon dioxide in the atmosphere do not cause the earth's climate to warm, ıey will probably work dramatic hanges in natural and agricultural cosystems, plant physiologists and cologists say.

In a research effort that has been ccelerating over the last five years, cientists are uncovering intricate ɔatterns of plant responses to higher evels of carbon dioxide. But they are ı considerable distance from understanding the full range of responses ɔr achieving a consensus on how the ɔositive and negative effects add up ɔn balance.

Carbon dioxide is accumulating in the atmosphere so rapidly, largely because of the burning of fossil fuels, that the global concentration will double by the end of the next century if the present rate of buildup continues, experts say. While scientists are still uncertain about the ultimate impact of the gas's heat-trapping properties on global climate, some believe that they can already detect the early stage of a worldwide explosion of vegetation stimulated by carbon dioxide, and their latest experiments suggest that astonishing developments may lie ahead.

In a controlled experiment at a Federal laboratory in Phoenix, for instance, orange trees raised from seedlings have been exposed to nearly doubled levels of carbon dioxide for the last three years. The combined volume of their trunks and branches is almost triple that of orange trees grown in normal air.

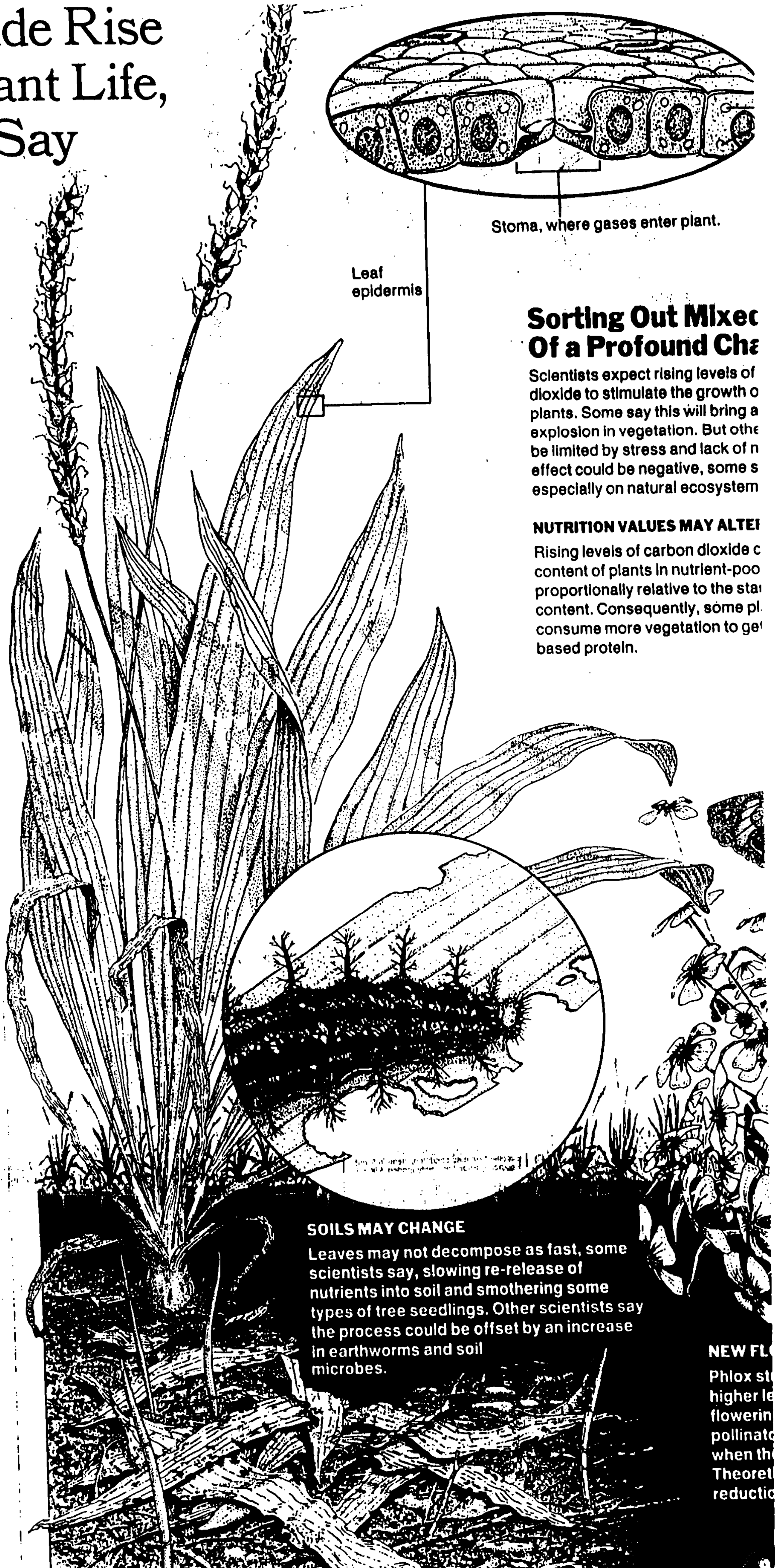
For some experts, this eye-opening growth portends major improvements in agricultural productivity, promises a lusher and more robust natural world, and suggests that burgeoning trees and other vegetation might remove enough carbon dioxide from the air to stablize atmospheric concentrations, although at higher levels than now.

Scientists have found that plants growing amid higher carbon dioxide levels also are hardier in some respects. They use water more efficiently and because of their greater mass, they can better resist stress in general.

"I'm really sold on carbon dioxide; I think it's very beneficial," said Dr. Sherwood B. Idso of the Agriculture Department's water conservation laboratory in Phoenix, where the orange-tree experiment is under way.

But other scientists, urging caution, are not so sure, and some say it is possible that greater carbon dioxide levels may be harmful on balance. They say the growth can be limited or even canceled out by a number of offsetting factors, particularly shortages of soil nutrients. They also say a growing body of research leaves no

Continued on Page C9



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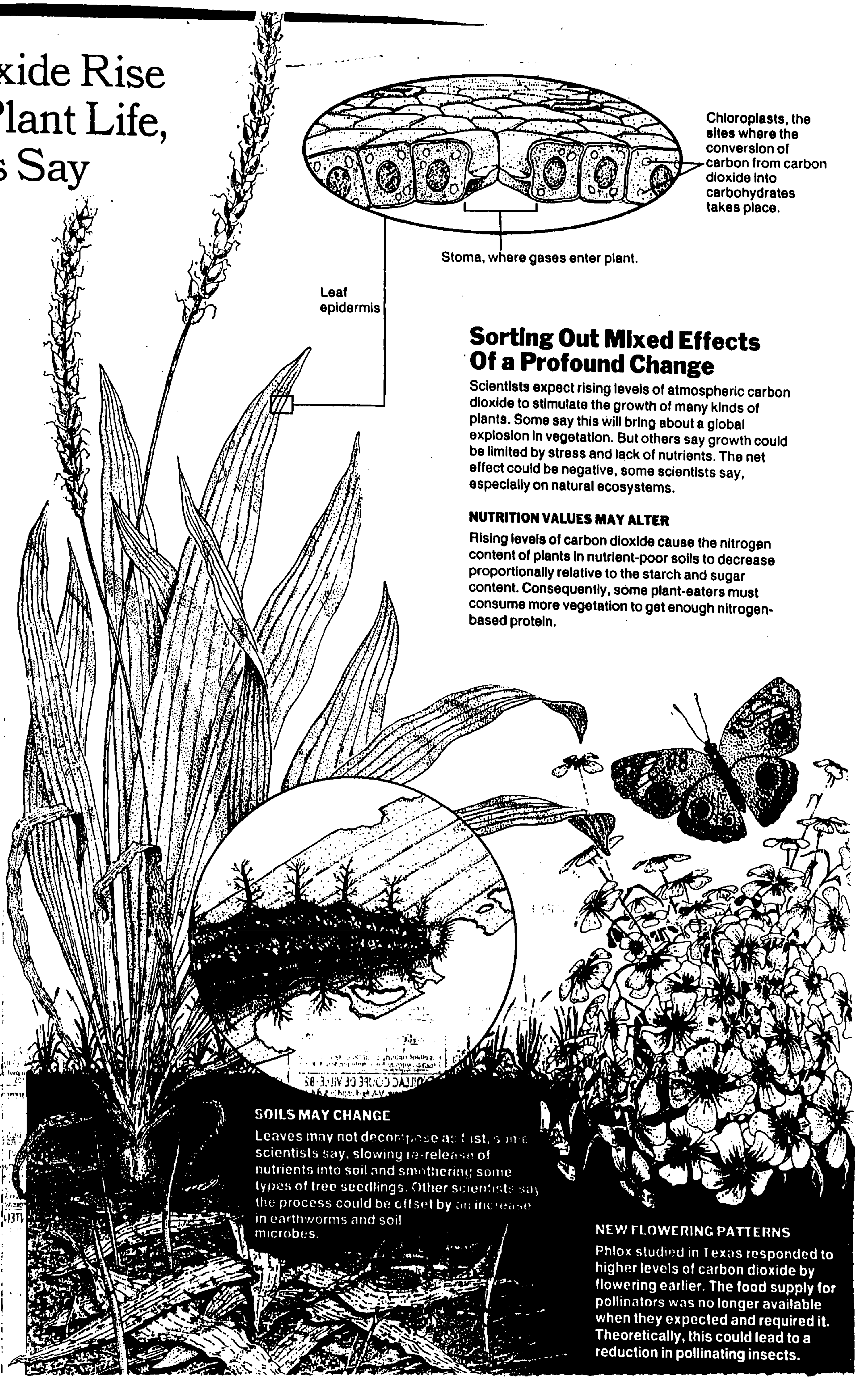

Rise in Carbon Dioxide May Alter Plant Life

Continued From Page C1

›ubt that the growth spurt induced / carbon dioxide affects some plant ›ecies much more than others, and ›me very little if at all. Some trees, :asses and other plants will flourish : the expense of others, they say, srupting the ecological makeup of ·oplands, forests, marshes and ·asslands with consequences that ill reverberate through entire eco- 'stems.

And because the nitrogen content unfertilized plants is diluted as ırbon dioxide stimulates their ·owth, they say, many will be less ıtritious. Experiments suggest that ›me insects that eat such plants do ›t develop properly and display gher mortality rates even if they ıt much more plant material to ›mpensate for the lower quality. ıis, scientists fear, could reduce in- :ct populations and affect entire od chains.

Scientists are also turning up evi- :nce that increased carbon dioxide ay alter the timing of plants' flow- ·ing, disrupting the interaction be- veen some plants and their pollina- ·rs to the detriment of both.

"The consequences are unbeliev- ›ly complicated and there are so many of them," says Dr. Fakhri A. Bazzaz, a plant ecologist at Harvard University who is in the forefront of research on the question. Experimental work suggests there is "no reason to be sanguine" about the responses of both natural and human-made ecosystems to higher levels of carbon dioxide, he said.

The Dynamics

Carbon Dioxide And Plant Growth

Carbon dioxide is the primary raw material used by plants in manufacturing carbohydrates from which they build their tissues and enzymes. Using energy acquired from visible light in photosynthesis, plants "fix" or capture carbon dioxide molecules from the air.

In the last century, roughly the industrial age, atmospheric carbon dioxide has increased to about 350 parts per million from about 280 parts per million. In the latter half of the next century, many scientists say, it will reach 600 to 700 parts per million if the current rate of increase continues.

Scientists have established that doubled concentrations of the gas would have startling effects on the growth of many types of plants, greatly increasing rates of photosynthesis and agricultural yields. One survey of 700 agronomic studies by Dr. Bruce Kimball at the Phoenix laboratory found that crop yields improved by 34 percent where carbon dioxide was doubled.

Trees and plants usually grow taller, produce more and bigger branches, flowers and fruit, display more and thicker leaves with more chlorophyll and send out more extensive root systems to search out more nutrients in the soil. Scientists have also established that increased carbon dioxide causes small pores on the outside of leaves, called stomata, to close slightly. This reduces the amount of moisture lost from the leaf to the atmosphere, enabling the plants to withstand drought better.

A number of studies have suggested that the carbon dioxide increases of the last few years are stimulating a worldwide surge of plant growth. Some scientists say this is reflected in increased widths of tree rings and in changes in the number of stomata on plant leaves.

But the chief evidence comes from studies by a number of independent researchers in the late 1980's showing that terrestrial vegetation in the Northern Hemisphere is absorbing more and more carbon dioxide in the spring and early summer and releasing more to the atmosphere as plants die in the fall.

"This tells me the biosphere as a whole is being stimulated," said Dr. Idso. "More carbon dioxide is being taken out of the atmosphere and more is being put back in; the biosphere breathes once a year and is breathing deeper."

Although plants emit oxygen as part of photosynthesis, he said, the amount added to the atmosphere because of increased growth would not be enough to have a significant effect on the vast pool of oxygen that animals breathe.

The Caveats

Not All Plants Respond Alike

Not all plants are taking in carbon dioxide at the same rate. The difference shows up most broadly between two main classes of plants, C3 and C4, so named because of differences in the way they absorb carbon dioxide. In the first stage of absorption, C3 plants manufacture a molecule with three carbon atoms, while C4 plants manufacture a four-atom molecule. The C4 molecule is part of a chemical mechanism, or "pump," that enables the plant to assimilate carbon dioxide more efficiently.

Lacking the more efficient mechanism of the C4 plants, the C3's de on simple diffusion of carbon dic through their tissues. Higher coı trations of the gas in the air aic diffusion, but make less differen a C4 plant. The result is that benefit more than C4's from the er concentrations.

In the salt marshes of Chesap Bay south of Annapolis, scientist by Dr. Bert Drake of the Smithsc Environmental Research Cente Edgewater, Md., have studied the fects of increased carbon dioxic naturally growing C3 and C4 m grasses for the last four years. rounded by special chambers allow the plants to be saturatec carbon dioxide, the C3 gr: showed increases in photosynt rates and mass of 60 to 80 per The C4 grasses showed no incr Both species demonstrated grc efficiency in water use.

Other species of C4 plants : some increase in growth amic creased carbon dioxide, but gene the C3's outperform them. Aı C3's are many important field c including wheat, rice and soybc although a few field crops, like s cane and corn, are C4's. Virtuall trees and most broadleaf plants C3's, while grasses may be eithe.

Some scientists say that with creased carbon dioxide, C4 crops find it more difficult to compete C3 weeds and vice versa.

Even within each of these b classes, species respond differe In a study led by Dr. Boyd Stra plant ecologist and physiologis Duke University, two common Sc ern species of C3 trees, sweet and loblolly pine, were subjecte higher carbon dioxide levels. Lob is the South's most important tir crop, and sweet gum is a major c petitor for resources in the ecc tem they share. The study found sweet gum seedlings, largely bec of their broad leaves, respoı more dramatically than the pine

Many scientists believe differe: in species' response to enhanced bon dioxide, and other problems sc attribute to the enhancement, ca: satisfactorily managed and n mized in agricultural settings wi one crop predominates, and that h er carbon dioxide levels will be agricultural boon.

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But the price of this might be l says Dr. Bazzaz, since crops dc benefit from higher carbon dio levels unless more fertilizer is plied and more pesticides are usc kill insects and, in the case o crops, competitive C3 weeds. would increase costs, and farmer some development countries m not be able to afford it, he said.

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In the salt marshes of Chesapeake Bay south of Annapolis, scientists led by Dr. Bert Drake of the Smithsonian Environmental Research Center at Edgewater, Md., have studied the effects of increased carbon dioxide on naturally growing C3 and C4 marsh grasses for the last four years. Surrounded by special chambers that allow the plants to be saturated with carbon dioxide, the C3 grasses showed increases in photosynthetic rates and mass of 60 to 80 percent. The C4 grasses showed no increase. Both species demonstrated greater efficiency in water use.

Other species of C4 plants show some increase in growth amid increased carbon dioxide, but generally the C3's outperform them. Among C3's are many important field crops, including wheat, rice and soybeans, although a few field crops, like sugar cane and corn, are C4's. Virtually all trees and most broadleaf plants are C3's, while grasses may be either.

Some scientists say that with increased carbon dioxide, C4 crops will find it more difficult to compete with C3 weeds and vice versa.

Even within each of these broad classes, species respond differently. In a study led by Dr. Boyd Strain, a plant ecologist and physiologist at Duke University, two common Southern species of C3 trees, sweet gum and loblolly pine, were subjected to higher carbon dioxide levels. Loblolly is the South's most important timber crop, and sweet gum is a major competitor for resources in the ecosystem they share. The study found that sweet gum seedlings, largely because of their broad leaves, responded more dramatically than the pines.

Many scientists believe differences in species' response to enhanced carbon dioxide, and other problems some attribute to the enhancement, can be satisfactorily managed and minimized in agricultural settings where one crop predominates, and that higher carbon dioxide levels will be an agricultural boon.

"Agriculture has survived so many catastrophic events," said Dr. David T. Patterson, a plant physiologist for the Department of Agriculture associated with Dr. Strain's laboratory. "It's likely that this change will also be weathered."

But the price of this might be high, says Dr. Bazzaz, since crops do not benefit from higher carbon dioxide levels unless more fertilizer is applied and more pesticides are used to kill insects and, in the case of C4 crops, competitive C3 weeds. This would increase costs, and farmers in some development countries might not be able to afford it, he said.

Tim Koors for The New York Times

Dr. Sherwood B. Idso with a three-year-old orange tree grown in high carbon dioxide levels at Agriculture Department laboratory, Phoenix. Such trees were found to be hardier in some respects.

Natural Ecosystems

The Impact On the Wild

Natural ecosystems cannot be managed like agricultural fields, Dr. Bazzaz said. Both Dr. Strain and Dr. Bazzaz, whose work deals mainly with natural ecosystems, say shifts in competitive advantage among plant species could produce far-reaching changes in the wild and even reduce the number of species.

In his laboratory at Harvard, Dr. Bazzaz has found that some annual plants do not do as well as others amid increased carbon dioxide. This, he said, suggests that annuals will leave fewer seeds when they die and that other species that do better in elevated carbon dioxide will become dominant the following year. Other experiments at Harvard have found that increased carbon dioxide altered the relative strength of five species of tropical trees.

While there is cause for concern on this score, Dr. Idso wrote in a 1989 review of research on the subject, it is possible that ecosystems could adjust much as forests did in the remote past, when carbon dioxide levels were higher than now.

Humans also have little or no control over what Dr. Bazzaz and Dr. Strain say is a drop in the nutritional quality of natural vegetation that accompanies its jump in quantity at higher levels of carbon dioxide.

"Without fertilizing the soil," said Dr. Strain, "you pump more carbon into the plant and the ratio of carbon to nitrogen or phosphorus goes way up." He said this means insects and other plant-eaters have to eat more plant material to get enough protein.

In an experiment at Dr. Bazzaz's laboratory, Dr. Eric D. Fajer found that larvae of the buckeye butterfly ate 20 to 30 percent more vegetation from plants when they were grown in an atmosphere of doubled carbon dioxide, but that even so they developed more slowly and had higher mortality rates. Dr. Bazzaz suggests such effects could "cascade down the food chain" as fewer insects survive to provide food for predators. Dr. Idso, in his recent review, wrote that while some studies have found harmful repercussions for a number of insect species, they have not done so for others.

Reduced nitrogen in plants could slow the decay of leaves and other plant litter, said Dr. Bazzaz, reducing soil fertility and producing a thick carpet of undecayed leaves and twigs that could hinder seed germination and, ultimately, the regeneration of forests. Dr. Idso says this could be offset by higher populations of litter-eating microorganisms that would be attracted to the larger root networks, and by an increase in earthworms.

While scientists struggle to learn how all these factors play out in nature, another question looms: If the global climate does warm substantially, how will this change the picture? Dr. Idso says the stress of high temperatures can be mitigated by carbon-dioxide enrichment. But studies at the University of Florida found that at both present and higher levels of carbon dioxide, grain yields decrease as temperature rises. A world 5 to 6 degrees warmer than now, as climatologists now predict by the end of the next century, "may not overpower the carbon dioxide effect, but we haven't run the numbers," said Dr. Hartwell Allen, a plant physiologist with the university and the Agriculture Department.

Global climate change and US agriculture

Richard M. Adams*, Cynthia Rosenzweig†, Robert M. Peart‡, Joe T. Ritchie§, Bruce A. McCarl‖, J. David Glyer¶, R. Bruce Curry‡, James W. Jones‡, Kenneth J. Boote & L. Hartwell Allen, Jr††**

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Agricultural productivity is expected to be sensitive to global climate change. Models from atmospheric science, plant science and agricultural economics are linked to explore this sensitivity. Although the results depend on the severity of climate change and the compensating effects of carbon dioxide on crop yields, the simulation suggests that irrigated acreage will expand and regional patterns of US agriculture will shift. The impact on the US economy strongly depends on which climate model is used.

CARBON dioxide concentration of the atmosphere has increased from ~280 p.p.m. before the industrial revolution to ~350 p.p.m. today[1]. According to most climate models, a continued build-up of CO_2 and other infrared-absorbing 'greenhouse' trace gases is likely to lead to surface air temperature rises of 1.5–5.5 °C and changes in precipitation patterns over the next 50–75 years[2-7]. Climate changes of the magnitude suggested by climate models will have agricultural consequences. Many authors have presented qualitative discussions on these agricultural implications[8-10], but quantitative estimates of changes in crop yields and irrigation water use and the resulting effects on producers and consumers have not appeared.

Here we report the results of a multidisciplinary study using global climate models, crop-growth models and an economic model to estimate effects of possible CO_2-induced climate change on US agriculture. Although this research provides quantitative estimates of potential effects on the agricultural economy, perhaps the main contribution is highlighting uncertainties in current knowledge. For example, differences in average seasonal temperature and precipitation between two climate model forecasts result in substantial differences in crop yields and irrigation water requirements in some regions of the US. The effect of these and other uncertainties on the economic assessment is one means of finding priorities for future research.

Another contribution is recognition of the value of integrating models from various disciplines, here atmospheric science, agronomy and economics. Although interdisciplinary efforts of this kind are encouraged[11-13], it is stressed that the results of such an integrated approach do not predict the future; rather, evaluation of results offers insights into effects of the hypothesized conditions (here, CO_2-induced climate change) on a system (here, the US agricultural economy) as it is currently understood. These insights may then contribute to the larger societal policy discussion of both potential control strategies to reduce CO_2 and other trace-gas emissions and on appropriate strategies to prepare for change.

TABLE 1 Summary of climate change in GCMs for doubled CO_2: average of US grid points

Model	Temperature change (°C) Annual	Winter	Summer	Precipitation change (mm day^{-1}) Annual	Winter	Summer
GISS	+4.32	+5.46	+3.50	+0.20	+0.13	+0.24
GFDL	+5.09	+5.25	+4.95	+0.09	+0.19	−0.08

Source: ref. 30.

Effect of CO_2 increases on US climate

A number of global-climate research projects have calculated likely climate changes under alternative CO_2 levels using numerical models of the atmospheric general circulation known as GCMs[7]. The forecasts used here are from the NASA/Goddard Institute of Space Studies (GISS) model[14] and the Princeton Geophysical Fluid Dynamics Laboratory (GFDL) model[5]. Ratios of mean monthly temperature, precipitation, and incident solar radiation for doubled CO_2 (to 630 and 600 p.p.m. respectively) simulations to current climate simulations were applied to observed (1951–1980) daily station climate variables. Observed variables at individual locations were multiplied by ratios of climate change from the appropriate GCM gridbox (8° lat. × 10° long. for GISS; 4.5° lat. × 5° long. for GFDL). No interpolations were made between or within grid boxes because GCM calculations do not account for this variation. The calculation of the GISS and GFDL climate-change models does not

TABLE 2 Derived climate parameters of selected agricultural regions as predicted by GISS and GFDL

Region*	Evaporation ratio† GISS	GFDL	Precipitation ratio‡ GISS	GFDL	Average annual temperature increase (°C) GISS	GFDL
Southeast	1.08	0.93	1.11	0.92	3.5	4.9
Delta	1.02	1.02	1.02	1.00	5.3	4.4
Northern Plains	1.09	0.99	1.07	0.97	4.7	5.9
Southern Plains	0.99	1.02	0.92	1.00	4.4	4.5
Mountain	1.10	1.06	1.11	0.99	4.9	5.3
Pacific	1.11	1.03	1.15	1.02	4.7	4.7

Source: ref. 30.
* The southeast region includes Florida, Georgia, South Carolina and Alabama; Delta region includes Arkansas, Louisiana and Mississippi; Northern Plains are Kansas, Nebraska, North Dakota and South Dakota; Southern Plains are Oklahoma and Texas; Mountain region includes Arizona, Colorado, Idaho, Montana, New Mexico, Nevada, Utah and Wyoming; Pacific region includes California, Oregon and Washington.
† Evaporation ratio is the doubled-CO_2 forecast for evaporation relative to the current-CO_2 forecast.
‡ Precipitation ratio is the doubled-CO_2 forecast for precipitation relative to the current-CO_2 forecast.

include changes in the space and time distribution of climate events. Therefore many significant climate and biophysical features are ignored. Forecasts of annual as well as seasonal temperature and precipitation changes are summarized in Tables 1 and 2. The use of two GCM models reflects some of the variation in climate estimates. For example, both models forecast increases in regional temperature but differ on changes in precipitation and evaporation. Table 2 points out the lack of consensus for some important agricultural regions, an issue that has implications for assessing climate-change effects[7,15].

It should be stressed that the doubled-CO_2 model represents an equilibrium climate, rather than one responding transiently to the gradually increasing trace-gas forcing. Because other trace greenhouse gases (for example, CH_4, N_2O, chlorofluorocarbons) are increasing, the climate-change models may be considered to be an 'effective' doubling of CO_2, meaning that the radiative forcing of all greenhouse gases has the same radiative forcing as doubled CO_2. The effective doubling of CO_2 concentrations will occur around the year 2030, if present emission trends continue[4]. The climate change caused by this effective doubling may be delayed, owing to slow uptake of heat by the oceans and other factors. A more detailed discussion of these and other uncertainties is presented by Schneider[7].

TABLE 3 Predicted percentage change in irrigated-crop water use requirements and water supply for irrigated regions*

Region	Irrigated-crop water use GISS	Irrigated-crop water use GFDL	Supply†‡ GISS	Supply†‡ GFDL
Southeast	15	147	16.0	−9.0
Delta	16	60	2.0	−3.0
Northern Plains	−13	14	1.0	−3.0
Southern Plains	−4	−10	−3.0	−2.0
Mountain	−8	2	2.0	−7.0
Pacific	−9	3	7.0	−2.0

* Regions are defined in Table 2.

† Water availability in areas that currently do not rely on irrigation is not addressed in these analyses. These excluded areas contain <3% of current (1985) irrigated acreage.

‡ Changes in water supply are calculated using base weather, precipitation (ratios) and evapotranspiration (ratios). Specifically, the percentage change in water supply is calculated as $\%\Delta(WS) = [(BP \times PR) - (BE \times ER) - BWS]/BWS \times 100$ where WS, water supply; BP, base precipitation; PR, precipitation ratio (forecast precipitation/base precipitation); BE, base evaporation; ER, evapotranspiration ratio (forecast evaporation/base evaporation); and BWS, base water supply (BP − BE).

Physical effects on the agricultural system

Crop yield effects. The climate changes described in Tables 1 and 2 are expected to lead to changes in crop yields, but substantial resources and time would be needed to perform experiments to explore even part of the range of these variations. In this study, the SOYGRO (version 5.41)[16], CERES-Maize[17] and CERES-Wheat[18] dynamic-growth crop-simulation models are used to project the effects of climate changes on the yields of irrigated and rainfed winter wheat, maize (corn) and soybeans[19-21]. The choice of these widely validated models is based on several criteria. First, the models simulate crop response to the major climate variables of temperature, precipitation and solar radiation, and include the effects of soil characteristics on water availability for crop growth. They are also physiologically oriented, with functions that calculate the rates of photosynthesis, translocation, respiration and other crop processes. Growing-degree days and photoperiod effects are modelled for the three crops. Second, they are validated for a range of soil and climate conditions. Third, these models are developed with compatible data structures so that the same soil and climate data bases could be used with all crops. An important issue in assessing agricultural effects of climate change is the role of elevated CO_2 on plant growth[22,23]. Increased CO_2 has been found to increase photosynthesis and decrease stomatal conductance in most crop plants in experimental settings, resulting in reduced transpiration rate per unit leaf area and overall increase in water-use efficiency (seed yield divided by total evapotranspiration during the growing season (kg ha^{-1} mm^{-1}))[23,24]. Modifications to the crop models were made to calculate photosynthesis and evapotranspiration rates under increased CO_2[19-21]. Photosynthetic rates were increased by 35, 25 and 10% for soybeans, wheat and maize, respectively, under doubled-CO_2 conditions.

Limitations of the crop models. Although the crop-simulation models were developed and tested over a range of climate conditions, they have not been tested under the temperature conditions suggested by the GCMs. The crop models also assume that soil nutrients are not limiting, there are no other major soil problems, and that pests (insects, diseases, weeds) pose no limitation to crop growth and yield. Further, the beneficial effects of CO_2 on crop yields will be overestimated if the equivalent warming of the doubled-CO_2 climate occurs before an actual doubling of atmospheric CO_2 (due to increases of other greenhouse gases) and if the experimental results are not reproduced under warmer, more variable and pest-infected field conditions. Finally, changes in climate variability, which were not simulated, could significantly alter the results. If frequency of droughts or mesoscale convective complex (MCC) rainfall and hail damage increases, climate-change effects on crop yields could be more severe[25].

Crop yield results. Rainfed-crop yield estimates shown in Fig. 1 differ markedly for the two GCMs, even though the annual average changes shown in Table 1 are not very different. Crops are sensitive to weather over relatively short periods of time, and annual averages do not convey important shorter-term differences. For example, consider the average monthly growing season precipitation for one location, Columbia, South Carolina. The historical average for June is 113 mm. For the doubled-CO_2 analysis, the models differ sharply in monthly precipitation forecasts, with GISS forecasting 148 mm and GFDL 50 mm. The lower summer growing-season precipitation for the GFDL model accounts for its much lower yields under rainfed conditions.

The simulated changes in crop yields are driven by two effects, changes in climate and CO_2 enrichment. The interaction of these forces leads to predictions that vary by region. In more northern latitudes a longer frost-free growing season and increased temperatures had a beneficial effect on simulated yields. In other regions, high temperatures shortened the duration of crop growth stages, especially grain-fill, resulting in moderate to severe yield decreases[19-21]. The beneficial effects of elevated CO_2 on crop yields, however, offsets some or all of the adverse climate effects. As a result, average yields in most regions actually increase in the milder GISS climate-change model, whereas a pattern of yield decreases persists in the hotter and drier GFDL model. Irrigated yields tend to be higher and less variable than rainfed yields, in both the base-period and climate-change scenarios[19-21].

In regions where present crop yields are relatively low, high percentage increases in yields do not indicate large absolute increases in crop yields. For instance, the Lake States and Northern Plains regions currently have low relative average yields based on 1951–1980 climate, so these increases may not be as significant as the smaller percentage increases in the higher-yielding Corn Belt. Similarly, for the Southern Plains, Mountain, and Pacific regions, changes in maize yields for rainfed production are not as important as changes under irrigation, because the majority of the production from these regions is from irrigated land.

Irrigation water use and availability. Rising temperatures in Tables 1 and 2 suggest increased evapotranspiration, crop water use and irrigation demand. The CERES and SOYGRO models calculate the irrigation water applied by irrigating the soil profile up to field capacity whenever the crop becomes water-stressed. Changes in irrigated-crop water-use requirements are presented in Table 3. The irrigation water use values reported in Table 3 for the GISS and GFDL models are used to adjust irrigation water requirements in the economic model of the agricultural sector. Changes in water use vary with GCM models, with modest increases or slight decreases under GISS but substantial increases projected under GFDL in the southern United States.

Changes in ground- and surface-water availability are estimated using a simple hydrologic mass-balance approach that reflects the interactions of evaporation, rainfall and temperature forecasts from the GCMs (Table 3). If a region currently has greater annual precipitation than annual potential evaporation, the same percentage increase in evaporation and precipitation could increase the differential, suggesting an increase in runoff. Predicted changes in regional water supply that reflect these estimates are reported in Table 3. Note that GFDL projections are much more severe than GISS, showing water-supply reductions in all irrigated regions, caused by increased evaporation driven by high temperatures. The procedure used to calculate regional changes are described in Table 3. Assumptions underlying forecast changes in agricultural water availability are discussed by Adams, Glyer and McCarl[26].

Economic consequences. The final step in the assessment involves adjustments in the parameters of an economic model of the US agricultural sector to reflect the crop yield, water use and water-supply effects of climate change. A correct translation of these effects into their implications for societal well-being requires a model that reflects the adjustments that producers, consumers and other affected parties are likely to take to soften the impacts of adverse climate[12]. Thus, human behavioural responses to adverse climate must be modelled.

The economic model is one previously used in a number of appraisals[27-29] and is designed to simulate the effects of changes in agricultural demand, resource usage or resource availability on agricultural prices, quantities produced, consumers' and producers' welfare, exports, imports and food processing. The model considers production, processing, domestic consumption, imports, exports and input procurement for most crop and livestock commodities. Included are both primary commodities (those produced directly by farms) and secondary commodities (activities such as soybean crushing and livestock feeding and processing).

A total of 1,683 production possibilities are specified to represent major field crop and livestock production in the United States. For some regions, field crops are divided into irrigated and non-irrigated production. Each crop and livestock

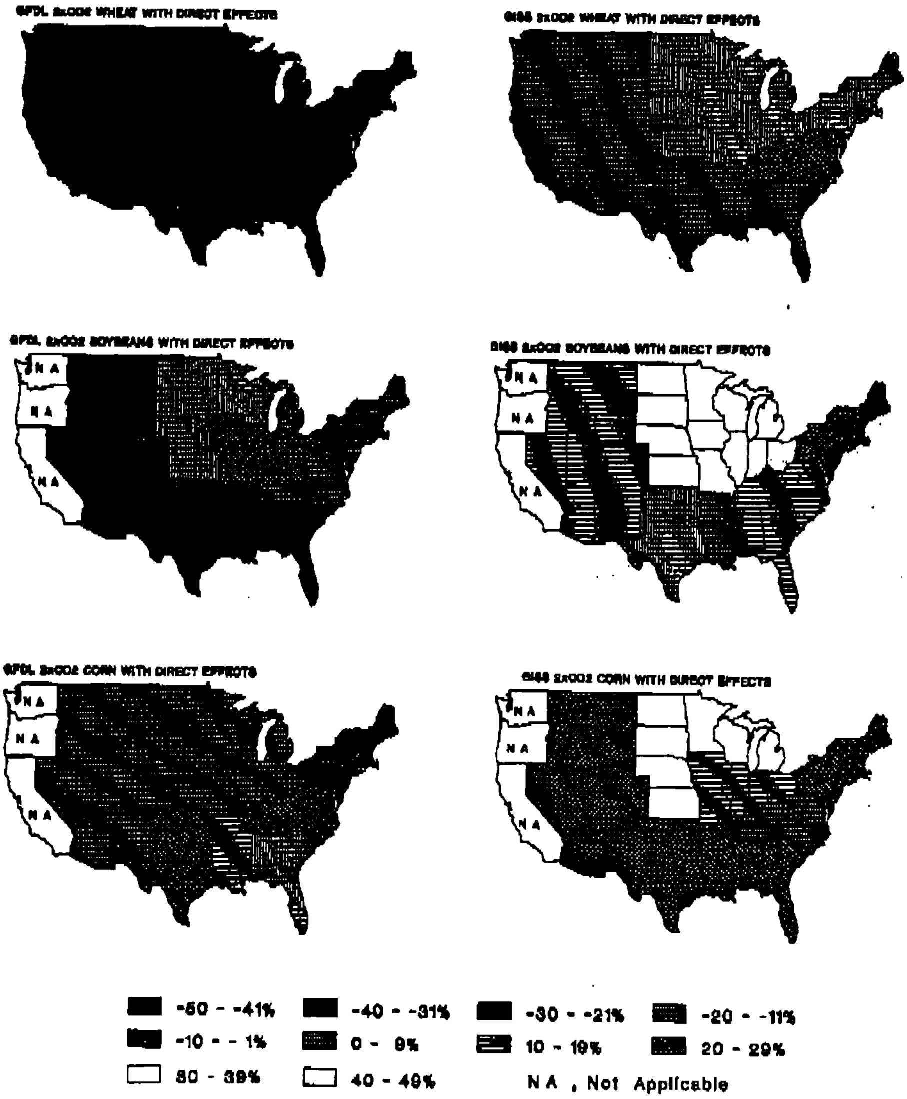

FIG. 1 Percentage change in rain-fed crop yields simulated by the SOYGRO, CERES-Maize, and CERES-Wheat models modified for the direct effects of CO_2 on photosynthesis and transpiration using GISS and GFDL doubled-CO_2 climate-change models. Soybeans and corn were modelled at sites in the following states: Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Indiana, Michigan, Ohio, New York, Pennsylvania: winter wheat and corn were modelled in Nebraska, Kansas, Oklahoma and Texas. Results were extrapolated to other sites on the basis of similarity of current-climate growing conditions.

TABLE 4 Estimated economic consequences of climate change on US agriculture

Model/analysis	Effect: Consumers	Effect: Producers	Effect: Total	Change from base: Consumers	Change from base: Producers	Change from base: Total
	(thousand million 1982 $)					
Base (1981–83 climate, demand and technology)	77.32	17.80	95.12	—	—	—
GISS with doubled CO_2	86.62	19.39	106.01	+9.30	+1.59	+10.89
GFDL with doubled CO_2	63.44	21.35	84.78	−13.89	+3.55	−10.33

production activity requires information on yields and usages of inputs or other commodities. This information is from the 1982 United States Department of Agriculture (USDA) Farm Enterprise Data System (FEDS) budgets, the USDA survey of irrigated acreage, Extension budgets, and Soil Conservation Service (SCS) budget sets.

Production is simulated in 64 geographical subregions distinguished by resource endowments. These areas are then grouped into ten larger regions for purposes of land, labour and water supply. The water resource is of particular interest here and is disaggregated into surface and pumped ground water sources. Surface water is available for a constant price within each region, but pumped ground water is provided according to a supply schedule where increasing amounts of water are available for higher prices.

The production and consumption sectors are assumed to be made up of a large number of individuals operating under competitive market conditions. This leads to a model that maximizes the difference between the areas under the demand and supply curves. This area can be interpreted as a measure of economic welfare (ordinary consumers' plus producers' surplus) equivalent to the annual net income (in 1982 dollars) lost or gained by agricultural producers and consumers (both domestic and foreign) as a consequence of climate change. The model is solved as a quadratic programming problem. A more detailed description of the model is found in Cheng and McCarl[27].

Economic model simulations

Adjustments in crop yields, irrigated-crop water requirements and irrigation water availability were made in the economic model according to each GCM forecast (Fig. 1 and Table 3). In addition to the modelled crops (maize, wheat, soybeans), the yields for cotton, barley, grain sorghum, rice and alfalfa were adjusted (by the average yield changes of the modelled crops) based on similarity of current-climate growing conditions. Inclusion of these other major crops is needed to account for potential substitution of crops within and across regions and to reflect the role of such crops in livestock production. A model solution is then generated to see how climate change and elevated CO_2 might alter the economics of the agricultural sector relative to a hypothetical 'no climate change' case.

Three solutions were generated with the economic model. These include the yield and water manifestations of each climate-model forecast and a base solution of the 1981–83 economic model. The direction and magnitude of the changes in income, crop acreage and other modelled characteristics between the base and the climate-change solutions indicate potential economic and resource implications (in quantitative terms) of each climate scenario.

Results from the economic model

The economic consequences of climate change are dependent on the GCM projections. This can be seen in Table 4 where annual aggregate effects on consumers and producers range from a net gain of over $10,000 million (GISS) to a loss of over $10,000 million (in 1982 dollars) for GFDL. These estimates are ~8% of the 1982 market value of US crop and livestock production. The GFDL losses are driven by the yield losses shown in Fig. 1 and the substantial increases in irrigation water requirements associated with adverse climate change. (Without the mitigating effect of CO_2 on crop yields, economic losses under GFDL would increase threefold[26].) Note that the change in producers' income is positive under GFDL because of prices rising by more than the climate-induced reduction in total production (that is, inelastic demand). Producers in some regions do lose, however, as regional production declines by more than the increase in prices.

Under the GFDL climate-change model, crop prices increase from reduced production of some crops. These price increases work against consumers, whose losses are greater than the gains to producers reported in Table 4. Aggregate price and quantity adjustments for crops and livestock commodities, expressed as indices (weighted by the quantities of each crop), are reported in Table 5. Price changes are slight to moderate across the climate-change projections. GISS yield (increases) and water forecasts result in price declines of 17 and 16% for eight field crops and four livestock commodities, respectively. These price declines are the result of 9 and 6% increases in agricultural output for each group. For GFDL yield and water changes, prices increase by 34 and 8% for the same set of commodities, due to production reductions of 20 and 2% for crops and livestock.

For perspective, we compare these aggregate economic consequences of climate change and elevated CO_2 to the economic effects of other environmental stresses. The economic consequences of anthropogenic tropospheric ozone on US agriculture have been estimated to be $2,000–$3,000 million per year in 1982 dollars[28] whereas the estimates of a 15% depletion in the stratospheric ozone column amount to ~$2,500 million[29]. Thus, the agricultural consequences of climate change under GFDL imply potential economic costs four times greater than these other environmental stresses.

A major policy concern is whether climate change is a food security issue for the United States. The results of these analyses suggest that it is not. For GFDL, the capacity of the US agricultural system to produce food and fibre is reduced, but under GISS production actually increases. US consumers face moderately higher prices under a GFDL climate-change model and the movement of US production into export markets is reduced. Indeed, almost half of the consumers' losses arising under the GFDL climate change accrues to foreign consumers. The analysis here, however, does not consider changes in agricultural production due to climate change in other countries.

These simulations were derived from an economic model based on 1981–83 economic and agronomic conditions. As the full extent of the climate changes projected here will not occur for decades, the sensitivity of the economic estimates were tested

TABLE 5 Agricultural commodity price and quantity indices* for climate-change models (base = 1.00)

Climate model	Field crops† Price	Field crops† Quantity	Livestock commodities‡ Price	Livestock commodities‡ Quantity
GISS with doubled CO_2	0.83	1.09	0.84	1.06
GFDL with doubled CO_2	1.34	0.80	1.08	0.98

* Indices reported here are Fisher indices, where $P = [(p^1 \cdot q^1/p^0 \cdot q^1)(p^1 \cdot q^0/p^0 \cdot q^0)]^{1/2}$, $Q = [(p^1 \cdot q^1/p^1 \cdot q^0)(p^0 \cdot q^1/p^0 \cdot q^0)]^{1/2}$, and where $p^0(q^0)$ and $p^1(q^1)$ are vectors of prices (quantities) in the original and final equilibria, respectively[3].

† Field crops include maize, wheat, soybean, sorghum, cotton, oats, hay (alfalfa and grass hays) and silage.

‡ Livestock commodities include poultry, pork, beef and milk products.

TABLE 6 Effects of climate change on irrigated and rain-fed crop acreage

Region*	Base acreage Irrigated	Base acreage Rain-fed	Base acreage Total	GISS, change from base Irrigated	GISS, change from base Rain-fed	GISS, change from base Total	GFDL, change from base Irrigated	GFDL, change from base Rain-fed	GFDL, change from base Total
Corn Belt	NA	95.46	95.46	NA	+1.53	+1.53	NA	−4.93	−4.93
Lake States	NA	33.79	33.79	NA	+0.14	+0.14	NA	+3.40	+3.40
Southeast	1.72	10.79	12.51	−0.06	−3.78	−3.84	−0.16	−4.52	−4.68
Delta	3.11	16.77	19.88	+1.08	−11.68	−10.60	+5.91	−9.09	−3.18
Northern Plains	10.28	91.40	101.68	+3.94	−1.12	+2.82	+4.03	−2.14	+1.89
Southern Plains	5.31	49.4	54.70	+1.50	−12.40	−10.90	−0.60	−1.90	−2.50
Mountain	16.14	5.54	21.68	−2.69	+1.46	−1.23	+0.02	−0.27	−0.25
Pacific	7.73	1.94	9.67	−0.21	+1.03	+0.82	+0.26	+0.95	+1.21
Other (Northeast and Appalachian)	NA	19.54	19.54	NA	−5.68	−15.68	NA	−8.76	−8.76
	44.29	324.63	368.92	+3.56	−40.50	−35.94	+9.46	−27.26	−17.80

* Corn Belt region includes the states Illinois, Indiana, Iowa, Ohio and Missouri; Lake States include Michigan, Minnesota and Wisconsin; other regions defined in Table 2. NA, not applicable.

by changing demand and technology parameters in the economic model. Specifically, US domestic and export demands were increased to reflect increases in US and world population, and yields were increased based on historical per annum yield changes, projected until 2050. Increases in domestic and foreign demand increased economic losses for the GFDL climate model. Conversely, technology (through increased yields) offsets the climate-induced losses reported in Table 4 for GFDL if yields increase at rates comparable to the last three decades. Although such yield increases offset the effects of adverse climate, climate change still imposes economic costs (in the form of foregone higher yields in the absence of climate change).

Effects on regional production, irrigated acreage and the environment. Climate change leads to a slight reduction in total US cropped acreage. Aggregate (and regional) acreage adjustments are presented in Table 6. Under GISS, aggregate acreage is reduced due to increased yields. For GFDL, acreage is reduced owing to shifts in production between regions and associated changes in resource availability. Both analyses show reductions in aggregate rainfed acreages. Included are some potentially large regional adjustments, driven by the regional variations in climate change. For example, north or northwest shifts in acreage and production occur for some commodities (Table 6). This implies increased input demands in areas of expanded crop acreage, such as the Pacific and Lake State regions, and corresponding reductions in regions experiencing acreage declines, such as the southeast and Southern Plains. Shifts in regional production patterns imply changes in the status of natural resources. For example, expansion of agricultural production in some areas increases the potential for soil erosion, ground- and surface-water pollution, and loss of wildlife habitats.

Changes in precipitation and temperatures under doubled-CO_2 conditions favour irrigated crop production. Also, rising commodity prices from reductions in total output under the GFDL climate-change model enhance the feasibility of irrigation activities, particularly those associated with groundwater use. As a result, modelled irrigated crop acreage increases in most regions, as seen in Table 6. In the aggregate, the increases vary from 3.5 (GISS) to ~10.0 (GFDL) million acres. Regionally, major increases in irrigated acreage occur in the Northern Plains and in the Delta. The southeast is the only region that shows declines in irrigated acreage, due to the large increase in crop water-use forecast by the crop simulation models. The sustainability of any increase in irrigated acreage was not included in the analysis.

Discussion

Our results show a range of possible outcomes for US agriculture, depending on the severity of climate change and the compensating effects of CO_2 on crop yields. Changes in temperature and precipitation as forecast by the GCMs lead to reductions in yield and increases in crop water demands. As modelled here, increased atmospheric CO_2 enhances crop yields, mitigating some or all of the climate-induced yield changes. Under the most adverse case of climate change (GFDL), domestic and foreign consumers face moderate increases in real prices. These same price increases benefit US producers.

Some general implications for the US agricultural sector can be drawn. First, because of possible changes in domestic and foreign production under a GFDL climate, the role of the United States in agricultural export markets may change. Second, patterns of agriculture in the United States are likely to shift as a result of changes in regional crop yields and in crop irrigation requirements. Third, concern for future agricultural impacts on important natural resources, especially land and water, seems to be justified. Simulated irrigated acreage increases in most major irrigated regions under the models of climate change examined. In addition, irrigation may increase in more humid regions, a trend that is already occurring.

These results are a preliminary assessment of the potential effects of climate change on agriculture. Critical uncertainties remain, as does the question of appropriate action in light of uncertain but potentially important economic effects. We suggest three sets of considerations to pursue. First, policy makers need to assess whether the probability of the projected agricultural outcomes, coupled with the non-agricultural effects of climate change (for example, sea level rise, damage to natural ecosystems, and increased energy demand) warrant action now to plan for and to reduce the magnitude of climate change. Second, further research must be stimulated to understand likely crop yield, crop water demand and water supply as well as economic adjustments to climate change, thereby reducing the uncertainty of yield projections and other critical inputs to policy analyses. Better projections of changes in regional climate variables, particularly those affecting hydrological balances, are essential. Knowledge of potential change in global agricultural supply and demand is also crucial. Finally, it seems desirable that, for those regions (or countries) that may be adversely affected by climate change, research priorities be set on adapting varieties, species and production techniques to increased temperature and drought stress. □

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1. Keeling, C., Bacastow, R. & Whorf, T. in *Carbon Dioxide Review: 1982* (ed. Clark, W.) 377–384 (Oxford University Press, 1982).
2. Ramanathan, V., Cicerone, R. J., Singh, H. B. & Kiehl, J. T. *J. geophys. Res.* 90, 5547–5566 (1985).
3. Washington, W. M. & Meehl, G. A. *J. geophys. Res.* 89, 9475–9503 (1984).
4. Hansen, J. et al. *J. geophys. Res.* 93, 9341–9364 (1988).
5. Manabe, S. & Wetherald, R. T. *Science* 232, 626–628 (1986).
6. National Research Council *Current Issues in Atmospheric Change* (National Academy Press, Washington, DC, 1987).
7. Schneider, S. H. *Science* 243, 771–781 (1989).
8. Decker, W. L., Jones, V. & Achutuni, R. in *Characterization of Information Requirements for Studies of CO_2 Effects: Water Resources, Agriculture, Fisheries, Forests and Human Health, Report DOW-ER-0236* (ed. White, M. R.) 69–93 (U.S. Department of Energy, 1985).
9. Schelling, T. C. in *Carbon Dioxide Assessment Committee, Changing Climate* 449–4985 (National Academy of Sciences, Washington, DC, 1983).

10. Smit, B., Ludlow, L. & Brklacich, M. *J. envir. Qual.* 17, 519-527 (1988).
11. Rind, D., Rosenzweig, A. & Rosenzweig, C. *Nature* 334, 483-486 (1988).
12. Sonka, S. T. & Lamb, P. J. *Clim. Change* 11, 291-311 (1987).
13. Parry, M. L., Carter, T. R. & Konijn, N. T. *The Impact of Climate Variation on Agriculture*, Vols 1 & 2 (Kluwer Academic, Norwell, 1988).
14. Hansen, J. *et al. Mon. Weath. Rev.* 3/4, 609-622 (1983).
15. Kellogg, W. W. & Zhao, Z. *J. Clim.* 1, 348-366 (1988).
16. Jones, J. W., Boote, K. J., Jagtap, S. S., Hoogenboom, G. & Wilkerson, G. G. *Florida Agricultural Experiment Station Journal* No. 8304, FAS (University of Florida, Gainesville) 1988).
17. Ritchie, J. T. & Otter, S. AGRISTARS publication No. YM-US-04442OJSC-18892 (Michigan State University, 1984).
18. Jones, C. A. & Kiniry, J. R. (eds) *CERES-Maize: A Simulation Model of Maize Growth and Development* (Texas A&M University Press, College Station, 1986).
19. Peart, B., Jones, J. W., Curry, R. B., Boote, K. J. & Allen, L. H. Jr in *The Potential Effects of Global Climate Change on the United States*, Appendix C (eds. Smith, J. B. & Tirpak, D. A.) (US Environmental Protection Agency, 1989).
20. Ritchie, J. T., Baer, D. B. & Chou, T. W. *The Potential Effects of Global Climate Change on the U.S.* Appendix C (eds. Smith, J. B. & Tirpak, D. A.) (US Environmental Protection Agency, 1989).
21. Rosenzweig, C. *The Potential Effects of Global Climate Change on the U.S.* Appendix C (eds. Smith, J. B. & Tirpak, D. A.) (US Environmental Protection Agency, 1989).
22. Kimball, B. A. in *Carbon Dioxide Enrichment of Greenhouse Crops* (eds. Enoch, H. Z. & Kimball, B. A.) (CRC, 1986).
23. Rosenberg, N. J. *Clim. Change* 3, 265-279 (1981).
24. Baker, J. T., Allen, L. H. Jr, Boote, K. J., Jones, P. & Jones, J. W. *Crop Sci.* 29, 98-105 (1989).
25. Ramanathan, V. *Science* 240, 293-299 (1988).
26. Adams, R. M., Glyer, J. D. & McCarl, B. A. in *The Potential Effects of Global Climate Change on the U.S.* Appendix C (eds. Smith, J. B. & Tirpak, D. A.) (US Environmental Protection Agency, 1989).
27. Cheng, C. C. & McCarl, B. A. *The Agricultural Sector Model* Texas Agricultural Experiment Station Misc. Report, College Station (in the press).
28. Adams, R. M., Hamilton, S. A. & McCarl, B. A. *Am. J. agric. Econ.* 68, 886-894 (1986).
29. Adams, R. M. & Rowe, R. D. *J. envir. Manage.* (in the press).
30. Smith, J. B. & Tirpak, D. A. (eds) *The Potential Effects of Global Climate Change on the United States. Executive Summary* (US Environmental Protection Agency, Washington, DC, 1989).
31. Diewert, W. E. *J. Economet.* 4, 115-145 (1976).

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Nuclear receptor that identifies a novel retinoic acid response pathway

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Molecular cloning and transcriptional activation studies have revealed a new protein similar to the steroid hormone receptors and which responds specifically to vitamin A metabolites. This protein is substantially different in primary structure and ligand specificity from the products of the previously described retinoic acid receptor gene family. By indicating the existence of an additional pathway through which retinoic acid may exert its effects, these data lead to a re-evaluation of retinoid physiology.

THE retinoids comprise a group of compounds including retinoic acid, retinol (vitamin A), and a series of natural and synthetic derivatives that exert profound effects on development and differentiation in a wide variety of systems[1-8]. Retinoic acid has also been shown to induce the transcription of several genes[9], supporting the hypothesis that it functions in a fashion analogous to steroid and thyroid hormones (reviewed in refs 10, 11). Recently, a new member of the nuclear receptor superfamily was identified as a retinoic-acid dependent transcription factor, referred to as RARα (refs 12, 13). Subsequently, additional RAR-related genes have been isolated and at least three different RAR subtypes (α, β and γ) are now known in mice and humans[12-17]. These retinoic acid receptors (RARs) share homology with the superfamily of steroid hormone and thyroid hormone receptors and have been shown to regulate specific gene expression by a similar ligand-dependent mechanism[18]. The ligand-binding domains of these receptors are highly conserved (>75% amino acid identity), suggesting that they all arose from a common ancestral retinoic acid receptor. Nonetheless, these RAR subtypes are expressed in distinct patterns throughout development[19-21] and in the mature organism[13,15-17,22], indicating that they may mediate different functions. One important question is whether all the actions of retinoic acid are mediated through these proteins or whether additional retinoic acid substrates and regulatory networks exist.

Here we describe the molecular cloning and characterization of a gene for a novel or 'orphan' receptor and report that it encodes a 462-amino-acid polypeptide that functions as a transcription factor responsive to retinoic acid. Surprisingly, this retinoic acid receptor-like protein is not part of the previously described RAR-subfamily of receptors. These data demonstrate the existence of an evolutionarily parallel regulatory system through which retinoids may exert their control of transcription.

Orphan receptor

Sequential low-stringency screening of a human liver and kidney complementary DNA library with a cDNA fragment encoding the human (h)RARα DNA-binding domain led to the isolation of several cDNA clones encoding a novel nuclear receptor (referred to as hRXRα). The restriction map and nucleotide sequence of one of these clones, λXR3-1, are shown in Fig. 1. The λXR3-1 sequence contains a long open reading frame of at least 462 amino acids ending at the termination codon at nucleotide position 1,462-1,464. The presumptive initiation methionine is placed at the first in-frame ATG at nucleotide position 76-78, although an upstream termination codon is not present. A second potential initiator methionine occurs 27 amino acids downstream. The sequence surrounding both ATG sites conforms well with the consensus described by Kozak[23] for a translation initiation site. *In vitro* translation of RNA derived from the insert (data not shown) shows that λXR3-1 produces a protein of relative molecular mass 54,000 (M_r, 54 K), close to the predicted M_r of 50,811.

The amino-acid sequence of hRXRα has been compared with that of other members of the steroid hormone receptor superfamily (Fig. 2*a*). The highest degree of similarity between hRXRα and the other receptors is found in a cysteine-rich sequence of 66 amino acids beginning at hRXRα residue 135 (Fig. 1*b*). We have shown previously that this region of the human glucocorticoid receptor (hGR), thyroid hormone receptor (hTR) and retinoic acid receptor (hRAR) is the DNA-binding domain[11,18,24,25]. hRXRα shares striking similarity with the *Drosophila* receptor dXR2C8 (A. Oro, M. McKeown and R.E., manuscript in preparation), both in its DNA-binding (86%) and putative ligand binding (44%) domains. Although the RXRα DNA-binding domain is similar to that of other receptors such as RARα (61%) and TRβ (53%), the putative ligand-binding domain is much less similar (<27% identity) and provides no hint of the nature of the RXRα ligand. A comparison between