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The other greenhouse effect

Rising carbon dioxide levels should increase crop yields. But what if their effect on the nutritional value of our food is less benign, asks **Ned Stafford**.

When you step into a commercial greenhouse, the chances are you are stepping into the future. To plants, carbon dioxide is food, and greenhouse operators, knowing this, use it to fatten them up. While today's atmosphere contains about 380 parts per million of carbon dioxide, commercial greenhouses often contain carbon dioxide concentrations of twice that or more — the sort of concentration that we might expect in the open air at the end of the century.

The fact that plants thrive in environments with high levels of CO_2 — all other things being equal — seems to offer a silver lining to the otherwise dark clouds of climate change. Many crop scientists believe that this carbon dioxide fertilization effect will go at least some way towards offsetting the losses in yield to be expected as a result of the higher temperatures, flooding, drought and rising sea levels that the CO_2 greenhouse effect will bring. The fact that many horticulturalists already choose higher CO_2 environments for their work underlines this assumption.

But some are not so sure. They are sounding alarm bells about potential negative impacts; bigger yields, they say, are not always better. Their worry is that the nutritional value of crops could suffer regardless of overall abundance. These researchers point to the known negative effects that increased carbon dioxide concentrations have on the protein content of crops. They also worry about subtler effects that might be felt in everything from the micronutrient properties of soya beans to the ability of wheat to be baked into bread. They do not all share the same level of concern, but they do all agree on one thing. Compared to the amount that is being spent on climate research, the amount being spent on understanding the agricultural effects of higher CO_2 levels is woefully inadequate.

Steven Adams, head of strategic and applied research on the physiology of protected crops at the University of Warwick's Horticulture Research International in the UK, reflects the relatively relaxed attitude of most crop scientists. He acknowledges that hardly any research has been done on the effect of high–CO_2 in greenhouses on food quality and concedes that a drop in nutritional value is possible. "If it affects photosynthesis and yields, it could do," he says. "But I would have thought the impact is relatively small."

A more complex view comes from Bruce Kimball, a soil physicist with the United States Department of Agricultural in Maricopa, Arizona — a pioneer in high-CO_2 plant research. When he started out in the 1970s, available technology for high-CO_2 research was limited mainly to greenhouses and open-top chambers, both of which offer questionable results. Plants grown in such systems are not exposed to environmental variables such as wind and normal variations in temperature and humidity.

In the mid 1980s, Kimball was a driving force in development of a system dubbed FACE (free air carbon dioxide enrichment), which simulates natural field conditions. A FACE system includes a ring of equipment up to 30 meters in diameter encircling the plants that are the subject of the research. The vertical pipes in this ring emit CO_2; sensors measure wind speed, wind direction and carbon dioxide levels. A computer uses this data to keep the CO_2 within the ring at the target level by releasing it from specific upwind pipes as required. It's not a perfect simulacrum of a high-CO_2 world—for one thing, the gas is pumped in only while there's daylight for the plants to photosynthesize in. But it's the best so far.

After his decades of work Kimball agrees that higher CO_2 concentrations can lead to lower nutritional quality of crops. But he sees nothing in his FACE studies — or those of others — to cause alarm. Based on current knowledge, he says, the net effect of increasing CO_2 is a good one: "As far as crops go, I think higher CO_2 is a definite benefit. Yes, a little less nutrition than before, but we get more food."

The plants almost always deliver higher yields than controls, with more sugar and starch in their leaves. They also take up less nitrogen from the soil, because they are making less protein. A lot of the protein in leaves is involved in assimilating CO_2 into sugars. At higher CO_2 levels that becomes easier; less protein is needed, and so less protein is made. The major exception is in the 'C4 plants', which are better at photosynthesis in less favourable conditions and so are less susceptible to the effects of changing CO_2 levels. C4 crops include maize, sorghum and sugar cane.

But while Kimball thinks that, in general, the gains in yield are the most important thing, he is not blind to the drop in protein levels. Talking of data from a cotton-leaf experiment, he finds himself struck by the size of the effect: "That is a big change," he says, wondering aloud what that might mean for lettuce, other plant leaves and grasslands. "Think of all the livestock that only eat leaves." Grass-grazing livestock in the 550 parts per million CO_2 world that is likely, though not inevitable, by 2050 might be getting significantly less protein from their forage.

And it's not only livestock that eat plants — there's the rest of the ecosystem too. Kimball conducted side experiments in the 1990s when growing crops in his FACE systems. He describes the effects of a diet of high–CO_2 cotton leaves on beet armyworms. "What we found is that their growth and reproductive capability was reduced," he says.

But Kimball believes that the protein levels can be lifted by increasing the amount of nitrogen supplied to the plants. "The farmer in the future would have to be sure and apply ample fertilizers to keep protein quality up," he says. And he thinks crop scientists and plant breeders will be able to rectify most other potential problems arising from high-CO_2 levels. But he believes more money is needed to fund high–CO_2 food research. Operating FACE systems is expensive — according to Keith Lewin of Brookhaven National Laboratory, US, a forest-based FACE system costs about $1.5 million a year to run even before you include the costs of research — and Kimball's last major field experiments were in 1999. "After that, funding dried up," he says. "I think we need to do more experiments at much higher CO_2 concentrations," he goes on, noting that nearly all CO_2 plant research up to the present has been done at 550 parts per million, not at any of the higher levels that are conceivable in the second half of the century.

Feedback from wind sensors helped Bruce Kimball control the release of CO_2 in a FACE study on wheat.

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"If we see this change in just five years, what will happen in 50 years?" - Stephen Long

But while Kimball is confident that increasing nitrogen levels could help retain higher protein levels in plants, others are not so sure. Arnold Bloom, a plant biologist at the University of California, Davis, believes the reduction in nitrogen content seen in plants in a high CO_2 environment is not just due to a lowered need for protein in leaves. He thinks it is because of a decreased ability to take-up nitrates from the soil. If this is the case, then adding nitrogen fertilizer would be less effective in future, which could have implications both for protein content and for overall yields (see 'Diminishing returns').

The question of whether adding nitrogen can offset the effects of increased carbon dioxide remains open, according to Hans-Joachim Weigel, director of the Institute of Agroecology, part of the Federal Agricultural Research Centre in Braunschweig, Germany. For some crops you have to add "enormous amounts of nitrogen", amounts that would be unfeasible in terms of cost and unacceptable in terms of environmental damage.

Weigel's FACE research on barley, wheat and sugar beet in the past six years leaves no doubt in his mind that higher CO_2 levels in coming decades will have a significant impact on crop quality. "We should be concerned about it, but not in a panic about it," he says. Herbert Wieser, head of cereal proteins at the German Research Centre for Food Chemistry in Garching, has provided some of the grounds for that concern by milling Weigel's winter wheat into white bread flour and analyzing the flour for protein content.

Wieser found that high-CO_2 wheat, grown with a normal amount of nitrogen fertilizer, produced white bread flour with 7.8 grams of total protein per 100 grams of flour, 14% less than the 9.1 grams of protein in flour from wheat grown at normal CO_2 levels. When the wheat was grown with half the usual fertilizer, the protein level was 6.7 grams in the control, and 6.1 grams in the high-CO_2 group.

The total protein content is not the only thing that changes — so does the type of protein. Gluten proteins are used as a nitrogen store in wheat, and in high-CO_2 conditions this store was lowered more than the overall protein level, dropping by 18%. The high-molecular-weight subunits which are particularly important for dough and bread quality fell by 23%. Wieser concludes that high-CO_2 growing conditions cause "a serious impairment of wheat baking quality".

This goes some way towards vindicating Andreas Fangmeier, professor of plant ecology and ecotoxicology at the University of Hohenheim in Germany, who was quoted in a university-issued press release earlier this

Diminishing returns

Higher levels of carbon dioxide stimulate overall crop yields if other conditions remain suitable. But increases in crop yields may not be as great as once thought.

Studies from the 1970s and 1980s offered the optimistic possibility that CO_2 fertilization could offset weather-related losses due to climate change. But newer data offer less hope, says Stephen Long of the University of Illinois. In soya bean studies that he has compared, those in closed systems show yields up an average of 28–30% in an atmosphere with 550 parts per million CO_2, compared with an increase of only 13–15% in studies done in open-field conditions using FACE (free air carbon dioxide enrichment) technology.

In general, he says, FACE studies indicate yields increasing only half as much as they did in studies done in closed chambers. Overall, too little has been done to assess the impact of climate change on crops and the lack of data makes it hard to be precise. "We are not in a good position right now to predict our future," Long says. "We need to start preparing or we are going to have problems."

Pramod Aggarwal, head of environmental sciences at the Indian Agricultural Research Institute in New Delhi and a co-author of the food, fibre and forest-products section of the Intergovernmental Panel on Climate Change's latest report, says the idea that CO_2 fertilization will offset weather-related losses "is a Western point of view" that ignores much of the developing and underdeveloped world. He argues that high CO_2 levels are beneficial only when crops are adequately fertilized, irrigated and protected from pests, so food crops in tropical climates will derive less, if any, yield benefit from increased CO_2 concentrations.

Take rice for example. According to Reiner Wassmann, coordinator of the Rice and Climate Change Consortium established by the Philippines-based International Rice Research Institute in 2006, whereas rice yields increase under higher CO_2 levels, the probable higher temperatures could depress yields. But the research infrastructure to study future conditions is inadequate. Only two large FACE systems are dedicated to rice, one in Japan and the other in China: there is no research being done in tropical nations. Wassmann thinks improved temperature tolerance might be achievable, but it requires more research. "Adaptation of rice production to climate change will require substantial funds to support vigorous and concerted efforts by national and international research institutions," he says.

Aggarwal is more concerned about the global quantity of food in coming decades than about quality. "The food supply must be maintained," he says. "That is the primary goal. We need to have something to eat, even if it is low quality. To have nothing is a big problem." **N.S.**

year warning that by 2050, CO_2 concentrations could make French fries poisonous, beer foamless and wheat flour unbakeable. Unfortunately, Fangmeier did not actually bake bread, brew beer or fry chips from crops harvested from his high-CO_2 test fields. Chemical analysis of his crops merely indicates "the potential" for the problems foreseen — the press release, he admits, was "an exaggeration".

Despite his lapse into hype, though, Fangmeier refuses to back down from the underlying sentiment that higher atmospheric CO_2 levels will damage crop quality in a number of ways. For example, he notes that in one of his high-CO_2 field tests, Vitamin C in potato tubers dropped by 50–60%. He can't explain the drop, but says it is just one of many indications that high-CO_2 levels will have a much larger impact on food quality than many currently believe. Weigel says the database for speculating about such things is currently too small.

Another researcher convinced that protein levels are not the whole story is Irakli Loladze, now a mathematician at the University of Nebraska in Lincoln. In 2002, while doing postdoctoral work in mathematical biology at Princeton University in New Jersey, Loladze published an opinion article (I. Loladze *Trends Ecol. Evol.* **17,** 457–461; 2002) highlighting the risks of changed plant composition in a high-CO_2 world and focusing on micronutrients such as iron, iodine, copper and manganese. Scouring the "surprisingly scant" literature he found that, on average, the concentrations of all the micronutrients he looked at decreased. The plants put more effort into storing up carbohydrates, and the resultant "carbohydrate dilution" reduced the proportion of metabolically important trace elements such as chromium, selenium and zinc.

Loladze believes that with current atmospheric CO_2 levels a third higher than pre-industrial levels, plants have already changed in this way, and that they will inevitably change more. He's concerned that this could put hundreds of millions at risk of the "hidden hunger" of micronutrient malnutrition. However, he has been unable to attract significant funding for further research into the area.

Soil cores measure how much water plants in a elevated CO_2 environment take from the soil.

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Peter Curtis, professor of ecology at Ohio State University in Columbus, Ohio, says Loladze's 2002 paper identified "a clear gap in our understanding of plant responses to elevated CO_2: how this global change in plant nutrition will affect plant tissue micronutrient status". Even subtle changes in micronutrient status could affect both human health and the wider ecosystem.

Some research has bolstered Loladze's argument, at least in part. Stephen Long, a crop scientist at the University of Illinois at Urbana-Champaign, says that soya beans grown in his FACE fields have shown drops in calcium and zinc levels of 10–20%, sugars and starches have been up 50%. The drop in calcium might be particularly noteworthy, as soya beans are used to make substitute dairy products.

His team also found effects passing up the food chain. For example, western corn rootworms feeding on high-CO_2 soya bean leaves live longer and produce twice as many young as those feeding on normal soya bean leaves. "They lay eggs in the soya bean fields in late summer so that they are ready to infect the corn crop that will be planted in the next year," Long says, referring to the standard practice in the region of rotating corn and soya beans annually. They have also measured changes in the microbial community within the FACE rings. "We don't know whether this is good or bad," he admits. "But if we see this change in just five years, what will happen in 50 years?" ■

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