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Plague of plenty

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A rising tide of carbon dioxide could spark an epidemic of malnutrition in a world overflowing with food, says Graham Lawton

PLANTS have never had it so good. Ever since the Industrial Revolution we've been pumping billions of tonnes of their favourite food into the atmosphere, and they're lapping it up. Of course, filling the atmosphere with carbon dioxide has had some serious effects on the climate. But look on the bright side; at least we'll have more food.

Not so fast. According to Princeton biologist Irakli Loladze, we may have overlooked a potentially devastating consequence of rising CO_2 levels. It might be a boon to plants, but higher levels of the gas could trigger a pandemic of human malnutrition.

At first, this sounds nonsensical. Surely faster-growing plants can only make food more plentiful? Indeed it will, but quantity isn't the issue here. Loladze reckons we should be deeply worried about the quality of food from these plants. According to his analysis, crops that grow in high CO_2 are nutritionally barren, denuded of vital micronutrients such as iron, zinc, selenium and chromium. If he's right, we're heading for a world where there's food, food everywhere, yet not a thing to eat.

We'll all be affected, but the impact will hit some people harder than others. Much of the developing world is already burdened by "hidden hunger" - chronic mineral and vitamin deficiencies caused by eating "green revolution" crops. Bred in the 1960s and 70s, these high-yield crops staved off starvation, but turned out to be low in essential nutrients, particularly iron, zinc and vitamin A (*New Scientist*, 30 March 1996, p 32). Now those people face a second dietary whammy, while millions more will be pushed over the edge into malnutrition.

The problem arises because we ultimately rely on plants to create the raw materials that make our bodies. Photosynthesis captures CO_2 and transforms it into carbohydrates such as starch and sugar. These compounds are the starting point for other biomolecules such as DNA bases and amino acids. In fact, plants make the carbon backbones of almost every biomolecule on Earth.

But biomolecules aren't the whole story. Organisms also need tiny amounts of trace elements such as iron and zinc. Although they make up less than 0.01 per cent of your body mass, these micronutrients are absolutely essential to keep your systems ticking over (see "You gotta have them"). Plants draw most of these elements from the soil and hoard them along with spare carbohydrates in cellular stores called vacuoles. Anything that disrupts this intricate physiology will spell trouble for plant-eaters that depend on these stores. In other words, what happens to plants also happens to us.

In the mid-1980s, it dawned on ecologists that elevated CO_2 was probably having a profound effect on plants. We've known for some time that the amount of available CO_2 is what puts the brakes on photosynthesis. Raise CO_2 levels, and you increase photosynthesis, and hence plant growth can run riot.

Though its effect on climate remains controversial, levels of CO_2 in the atmosphere are unquestionably climbing. Today, plants the world over are exposed to 30 per cent more CO_2 than in pre-industrial times (see Graph). By 2100, levels will have doubled to approximately 550 parts per million.

Over the past 15 years, nearly 3000 published studies have looked at what elevated CO_2 can do to plants. These experiments, known as free-air CO_2 enrichment (FACE) experiments, have probed almost every conceivable effect of elevated CO_2, from growth rates to the decomposition dynamics of leaves. One outcome is a general consensus that rising CO_2 promotes plant growth: if CO_2 doubles, agricultural yields will increase by around 40 per cent.

Until recently, however, attempts to assess the nutritional quality of such plants have only created confusion. Take protein levels in maize, for example. Some experiments show a rise, some a fall, and still others no effect at all. The pattern is repeated across myriad combinations of nutrients and crop species, from lipid concentrations in wheat to vitamin C in tomatoes.

The reason behind this chaos is the kaleidoscopic complexity of plant biochemistry. Each plant cell can assemble and disassemble thousands upon thousands of complex carbon-based biomolecules. Against this background of ceaseless flux and endless variety, it is small wonder that suddenly injecting vast amounts of carbon perturbs the system in unpredictable and seemingly random ways.

Loladze, though, says he's found a way of cutting through the noise. Sure, the plant cells contain an ever-shifting cast of thousands of biomolecules. But these are all constructed from a finite pool of immutable building blocks - just 32 different chemical elements. And that, Loladze argues, gives you a powerful tool for analysing the nutritional value of crops grown under high CO_2 levels. Of those 32 elements, at least 24 are essential for the human body, and must continuously be replenished from food. And food equals plant material: plants directly provide 84 per cent of our calorie intake, and almost all the rest comes indirectly through animal fodder.

When Loladze started combing the FACE literature for studies that looked at single elements instead of complex compounds, patterns began to emerge. Take nitrogen, for example. Five years ago, a team of researchers in Italy and Britain - led by Francesca Cotrufo of the University of Naples and Phil Ineson of the University of York - compiled 75 FACE studies and concluded that, in leaves and stems, nitrogen content consistently dropped, on average by 14 per cent (*Global Change Biology*, vol 6, p 43). A more recent analysis by Peter Curtis of Ohio State University in Columbus found a similar downward trend. Curtis looked at 159 studies published between 1993 and 2000 and found an average 14 per cent decline in the nitrogen content of seeds compared with plants grown in ambient air (*New Phytologist*, vol 156, p 9).

The effect of elevated CO_2 on other elements has not been studied as extensively as nitrogen, but Loladze says what evidence there is points to a general downward trend. In a recent paper in *Trends in Ecology and Evolution* (vol 17, p 457), he pulled together all the relevant data he could find from experiments with doubled CO_2. The results make depressing reading. There was an overall decline in almost every element he looked at. Admittedly, most of the studies are on non-food plants or marginal crops such as radish and mango. But the handful that look at staples offer few crumbs of comfort. In one study on rice, for example, nitrogen declined 14 per cent, phosphorus 5 per cent, iron 17 per cent and zinc 17 per cent. In three studies of spring wheat, nitrogen, phosphorus, sulphur, magnesium, iron, zinc and manganese consistently dropped.

So how does rising CO_2 strip plants of micronutrients? According to Curtis, the effect is largely down to "biomass dilution". When more abundant CO_2 ramps up photosynthesis, plants make more carbohydrate than they can use to grow and fuel their metabolism. They respond by stuffing this spare starch and sugar into their vacuoles, huge cellular storage depots for water and nutrients. So the plant ends up with higher-than-normal levels of carbohydrate, which means the relative levels of other components fall. A mouthful of rice, say, has a lower concentration of micronutrients today than it did just a few generations ago.

To make matters worse, Loladze says there's another effect dragging element ratios down. Excess CO_2 stifles a plant's ability to absorb these nutrients in the first place. Normally, plants absorb chemicals through their roots in two ways. Compounds can be sucked in along with the water absorbed by the plant, or they can just diffuse into the root down a concentration gradient.

Loladze says increased CO_2 disrupts both mechanisms. For starters, higher levels of CO_2 put a squeeze on the rate at which plants absorb water - by making them "breathe" less deeply. Normally, gases diffuse into plants through tiny pores in their leaves. But these open pores mean the plant loses water by evaporation. When the air contains more CO_2, plants can get away with narrowing the pores a little. That way, they get enough CO_2 while reducing their risk of drying out. But this has a profound effect on the water flowing through their tissues. Roots suck in water using the pull of water evaporating through leaf pores. Close the pores, even a little, and the flow of water slows down.

With less water flowing through their system, plants suck in less of the micronutrients. And it gets worse - reduced water flow makes the soil wetter, which dilutes its nutrient content so diffusion rates drop. Overall, the effect drastically reduces the availability of nutrients. Loladze is now busy building a formal mathematical model of this effect, taking into account the absorption dynamics of each element. He has yet to publish his model but says it shows a general, though inconsistent, decline in the micronutrient composition of plants.

Strangely enough, the plants seem none the worse for this nutrient depletion, says Loladze. Plants do need micronutrients, such as manganese which gets their photosynthetic enzymes working. Yet all the experiments show that plants grow like the clappers in elevated CO_2, so they're hardly suffering from malnutrition. Thanks to their vacuoles, plants squirrel away huge surpluses of everything they can extract out of the soil, even biologically useless elements such as uranium. And they can call on these supplies to utilise all the carbon nature throws at them.

The biggest obstacle now facing Loladze is a dearth of information. "He's working in a data vacuum," says Curtis. "For many micronutrients there are only one or two studies." Even so, Curtis, a veteran of experiments with elevated CO_2, says Loladze's ideas have already made an important contribution in the field. "He's picked it up and put a very interesting spin on it. It's a defensible theoretical position. But additional work is needed."

Loladze acknowledges the problem. For example, no one has yet looked at maize or rye. And, despite the fact that hundreds of millions of people rely on plants as a source of iodine, Loladze says he couldn't find any data for iodine. But he says one reason for compiling and publishing the data is to draw attention to the problem and stimulate research.

Curtis has a idea where Loladze might get more information. Most FACE researchers put tissue samples from their old experiments into long-term storage. All Loladze has to do is check the elemental composition of these tissue banks. "There's got to be tonnes of stuff out there," Curtis says.

Meanwhile, fresh results are starting to come in, and it doesn't look good. In a forthcoming issue of the *European Journal of Agronomy*, plant ecologist Andreas Fangmeier of the University of Hohenheim in Germany reveals that concentrations of several elements including iron, zinc, manganese and sulphur decline in potatoes grown under high CO_2 - by amounts in line with the previous studies. And John Kanowski of Griffith University in Nathan, Queensland, has sent Loladze unpublished data from experiments on the Queensland maple (*Flindersia brayleyana*). His results show a drop in 13 different elements under raised CO_2 - aluminium, boron, calcium, copper, iron, potassium, magnesium, sodium, manganese, nitrogen, phosphorus, sulphur, and zinc - the most comprehensive list yet.

One possible side effect of any experiments that flow from Loladze's analysis is to pull the rug out from under those fringe scientists who argue that rising CO_2 is a free lunch. One leading advocate of this view is Sherwood Idso, a former US Agricultural Research Service researcher who now runs the Center for the Study of Carbon Dioxide and Global Change in Arizona, a not-for-profit organisation that promotes the idea that elevated CO_2 benefits humanity. Idso is predictably dismissive of Loladze's work, calling him "the latest fatality in a long line of Cassandras". But he can't produce a compelling argument to prove Loladze wrong.

Meanwhile, mainstream researchers are taking Loladze's proposals very seriously. Peter Curtis says: "Let's do the experiments, let's take the time to test the hypothesis. I can't see why people would oppose that."

And experiments are certainly needed, as there are confounding factors that might yet prove Loladze wrong. Rising CO_2 isn't the only atmospheric change induced by human activity. Ozone levels are also on the up, and experiments on wheat show that increased ozone can cancel out the yield-boosting effects of elevated CO_2. What's more, ultraviolet light levels and temperature are also rising and both can be expected to affect plant growth.

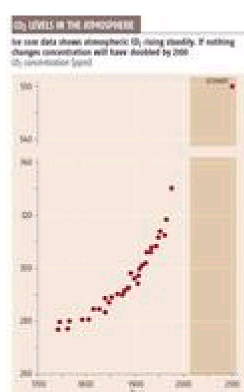
But if Loladze is right, the world has a serious problem on its hands. Micronutrient malnutrition is already rife and we can ill afford for it to get any worse. UN figures say iron deficiency alone is the world's biggest health problem, with 3.5 billion people - over half the world's population - suffering mental and physical impairment as a result. Zinc deficiency, which causes pregnancy complications and poor growth and health in childhood, may be just as widespread.

What to do? Fortunately there are several options, but all mean levels of investment and political will that far exceed today's efforts to eliminate hidden hunger. Distributing food supplements is the obvious solution, but hard to implement effectively. Already, dozens of public and private groups hand out vitamin and mineral supplements and fortify food in the developing world, yet billions of people are still deficient in micronutrients. As Loladze points out, iodising salt is easy and cheap, costing just 10 cents per person per year, yet 700 million people have thyroid problems.

What about fertilising soil to keep plant composition optimal for human nutrition? Idso has shown that simply adding nitrogen fertilisers all but eliminates the decline in nutrients such as proteins and vitamin A. Loladze admits that's true, but says it's hopelessly impractical. "Farmers are primarily driven by yield. There's no incentive to add fertilisers to keep plant composition optimal for humans."

Perhaps the most promising option is "biofortification", boosting micronutrient levels through plant breeding and genetic engineering. Moves are afoot to tackle hidden hunger this way. Earlier this year the Consultative Group on International Agricultural Research (CGIAR), an international collaboration of agricultural research organisations, set up an $80 million project to develop iron and zinc-rich varieties of six staple crops: rice, wheat, maize, cassava, sweet potato and common bean. Similar efforts are under way elsewhere. For example, the team at the Swiss Federal Institute of Technology in Zurich that developed vitamin-A enriched "golden rice" are now working on inserting genes to boost iron and zinc levels. The snag is that all these projects take time. CGIAR says it will be 7 to 10 years before its new crops are widely available. And none have taken into account the extra burden of malnutrition caused by biomass dilution. What's more, even brilliant humanitarian projects can be held back by fears over the safety of GM crops, as the golden rice team found to their frustration.

Perhaps the fact that elevated CO_2 levels threaten to bring the hidden-hunger problem to Europe and North America will concentrate minds. Loladze for one says intervention can't come soon enough. "I think it's already a factor. It's like sprinkling every bite you take with starch and sugar." And that leaves us with an unpalatable dilemma. To avoid malnutrition you have to consume more calories. To keep the same calorie intake, says Loladze, you have to accept a diet low in essential elements. "In either case, not a healthy choice."



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Chemical elements are a vital part of a healthy diet. If levels decline in food, malnutrition surely follows

Mineral	Function
Iron	Oxygen carrier
Iodine	Contained in the hormone thyroxine which aids metabolic regulation
Zinc	Transport of vitamin A, wound healing, sperm production, fetal development. Component of many enzymes, hormones, DNA and proteins
Copper	Absorption of iron, component of many enzymes
Selenium	Antioxidant
Chromium	Energy release, sugar and fat metabolism
Molybdenum	Component of many enzymes
Manganese	Component of many enzymes
Cobalt	Component of vitamin B12

Graham Lawton