FIVE CROP RESEARCHERS WHO COULD CHANGE THE WORLD

The current crisis in worldwide food prices reinforces the need for more productive agriculture. **Emma Marris** meets five ambitious scientists determined to stop the world from going hungry.

The rust hunter

Peter Dodds

Molecular biologist at the Commonwealth Scientific & Industrial Research Organization Plant Industry in Canberra, Australia

Timescale for change: 10 years

It was only when his supervisor showed him a picture of a tractor crossing a rust-infected field of wheat that Peter Dodds really understood what he was up against. Behind the tractor bloomed an orange plume of spores several times higher than the vehicle itself. "It is just amazing the amount of spores that get released in an infected wheat field," says Dodds. "It is like looking at Mount Everest."

The cloud of fungal spores revealed a terrifying strength in numbers. You might think that if a mutation that will overcome wheat's resistance to a strain of rust is a one in a million fluke it would not be worth worrying about. But there in that one picture were thousands of billions of spores, obscuring the sky. And there are millions of fields.

Since the early days of its domestication, wheat has been plagued with various strains of rust. The fungus's spores infiltrate the stomata through which the plant takes in carbon dioxide from the atmosphere, and poke tentacle-like haustoria into the wheat's cells, extracting their nutrients. If the conditions are to its liking, stem rust (*Puccinia graminis*) can kill 50–70% of the wheat in an area.

ILLUSTRATIONS BY JAY TAYLOR

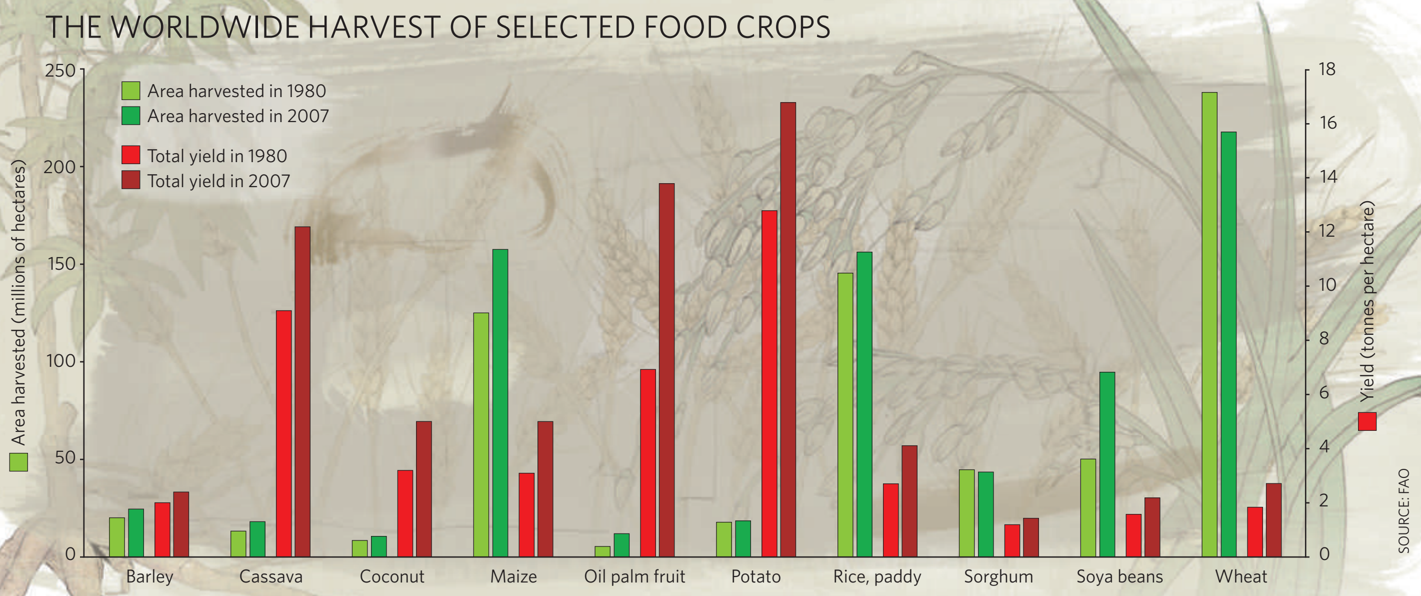
These losses can be prevented if the wheat is resistant to the rust. Resistant plants can identify an invasion early and sacrifice the invaded cell, stopping the rust in its tracks. But domesticated wheat, which is bred for yield, has a limited gene pool from which to draw the genetic variations that might offer resistance. So whenever a strain of fungus overcomes the resistance genes, researchers need to scour wild relatives of wheat for new ones that can be introduced to the crop by cross breeding.

In 1999, the stem-rust-resistance gene *Sr31* — hitherto an unbeaten champion and relied on by wheat farmers throughout the developing world — succumbed to a new strain of rust from Uganda. The Ug99 rust has since spread through Kenya and Ethiopia, crossed the Red Sea and reached Iran (see map, overleaf). Experts estimate that 19% of global wheat production grows in the potential migration path of the rust. If it covers the entire zone at risk, losses are estimated to be tens of millions of tonnes, and thus billions of dollars, per year.

Dodds might be the man to stop it in its tracks. A laconic Australian, originally from Melbourne, Dodds wants to understand how rust invades cells so that he can engineer resistance proteins from scratch. That would remove the need to find hardy relatives in their wild redoubts. Making the leap from crossbreeding to genetic engineering would also remove the problem of incorporating large chromosome segments that reduce yield along with the resistance genes. Wheat with *Sr31*, for example, is unfit for making yeast-based bread thanks to some undesirable genes that come along with its top-of-the-range resistance.

Dodds and his team in Canberra use flax and flax rust as a model; they rarely see a commercial wheat field, and never an infected one — hence Dodds's amazement at the ominous orange wake in that photo. His team's work centres on substances that the rust secretes to gain entrance to plant cells, or perhaps to manipulate their metabolism — substances the plant can use to recognize that is it being invaded, and thus get its countermeasures up and running. These compounds, says Dodds, "make [the rust] vulnerable to recognition by the plant, but the rust can't do without them".

The hope is that once the interaction between these substances and the wheat immune system is worked out, all a bioengineer will need to do is to look at how the rust strain has evolved to identify effective resistance genes. Such an advance would change the arms race between man and rust. "Initially it will make the catch-up several times faster," says Dodds. Eventually, he adds, varieties engineered to express several new resistance genes might be too complex for rust to adapt to for years and years. After that it will just require

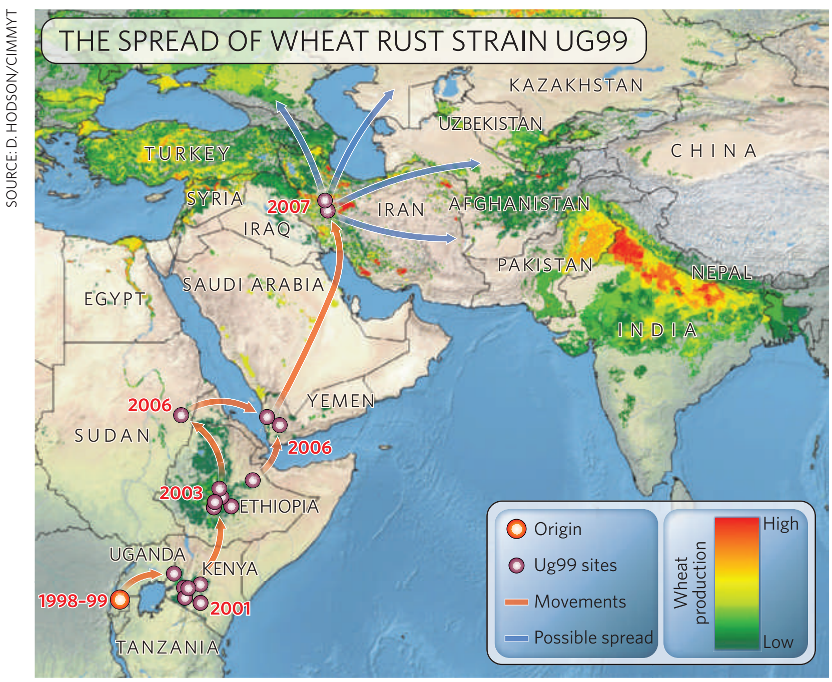


occasional tweaking to keep ahead of the pathogen.

But will countries in East Africa, where rust often takes hold, open their arms to genetically modified wheat when it is ready for use? "That is a question that I have difficulty answering," says Dodds. "When any part of the world is going to be ready to accept that is hard to know, but having the things available puts forth a strong argument."

"Dodds took the analysis of the flax–rust interaction to another level," says Jonathan Jones, a specialist in disease resistance at the John Innes Centre in Norwich, UK. Jones says that Dodds is "the best young guy coming through. He's an outstanding young scientist, but also the work that he is doing is of profound importance". Many molecular biologists, says Jones, wouldn't be interested in such a difficult problem. "The pay off is too long term," he says.

Dodds seems to have the long-term gene. He has been working on rust for 10 years and says he still finds it as interesting as ever. Ug99 has sharpened his focus. "There is certainly a higher level of urgency when you see that there is a problem that needs a solution rapidly. Every now and then you get a really bad epidemic like this and it requires a response." ■



The perennial optimist

Jerry Glover

Agroecologist at the Land Institute in Salina, Kansas

Timescale for change: 30 years

He didn't want to stay on the Colorado farm he grew up on; he wanted to become a philosopher. But a summer job in landscaping led Jerry Glover to a community-college course in soil science. He had always loved the loamy smell of the freshly turned land at ploughing time, and the soil drew him back. He got a PhD at Washington State University in Pullman and took a job at the Land Institute, which focuses on sustainable agriculture. There he works on a soil-improvement project that he acknowledges might not be finished in his lifetime.

Glover and his collaborators around the world are in the midst of a decades-long attempt to breed wheat into a perennial plant. About 85% of Earth's cultivated land is planted with annual crops (see world map, page 566). That means that every year they must be planted anew from seed. On most farms that means ploughs, and ploughs mean carbon loss — those rich loamy smells — and erosion. One way round this is 'no-till' farming, in which seeds are inserted into unploughed land. But although this technique has its advantages, when the crops involved are annuals, they never manage to get their roots as deep into the soil as they might if they had longer to grow.

If crops such as wheat could instead be made to persist from year to year — to become perennial — they would require less fertilizer and fewer passes of heavy machinery,

and would have more growing seasons. The world's arable lands would revert to something more like the prairies and savannahs that agriculture has replaced, and that would bring many benefits. Some perennial grasslands can be harvested time and again with few or no human inputs of fertilizer without depleting the soil of nutrients[1]. With roots like the beards of grand old men, perennials control erosion in ways that the spindly whippersnapper whiskers of annuals simply cannot. They also improve the quality of the soil and pump more organic matter into it.

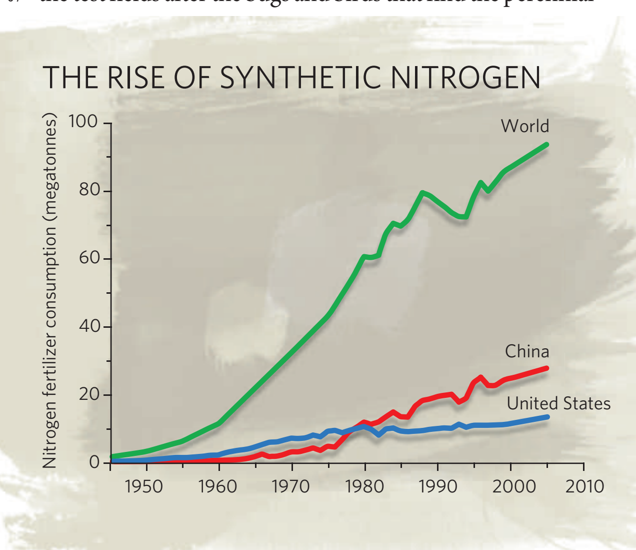
Glover's particular concern is nitrogen. "We need a lot for good plant yield," he says, "and we often need to remove a lot for our needs." All the nitrogen removed from a farm in the form of protein in crops must somehow be returned to the soil if long-term fertility is to be assured. Most farmers who can afford to do so use synthetic nitrogen fertilizers for the job (see graph, below). But these fertilizers are expensive to make, and are often applied in such a way that a fair amount flows unused into rivers, disrupting the ecosystems downstream.

As the roots of perennials can tap into naturally occurring nitrogen resources that annual crops can't reach, they could make more harvestable protein with less added nitrogen. Also, perennial plants have more opportunities and more root space to interact with the mycorrhizal fungi and bacterial populations that fix nitrogen for them. According to Glover's experiments, perennials, as represented by tall-grass prairie meadows, require just 8% of the energy that a typical high-input annual wheat field needs to make the same amount of harvestable nitrogen.

Glover lives across the road from some of his experimental plots, a few kilometres out of town, with his wife and triplet sons, who are still too young too start running through the test fields after the bugs and birds that find the perennial plots more congenial than normal fields. Cats and dogs lounge around the property. Comparing his spread to the working farm he grew up on, he says, with a laugh, "I feel more like a gentleman farmer on five acres in the country."

Glover's graduate adviser, John Reganold, says that Glover is motivated by thoughts of the future. "I don't think he would take on a project that would not feed the planet and also be good for the environment," he says. Glover was "the best graduate student I've ever had, and one of the best that I've ever seen", he adds.

"Agriculture is one, if not the largest, single threat to biodiversity in terms of human behaviour," says Glover. "People have to eat — but what can they eat without destroying the environment?" Perhaps they will someday do that by eating food from farms that run more like the natural landscapes they replaced, acting like a healthy ecosystem and a farm all at once. ■



The thriving peasant

Zhang Jianhua

Plant physiologist at Hong Kong Baptist University

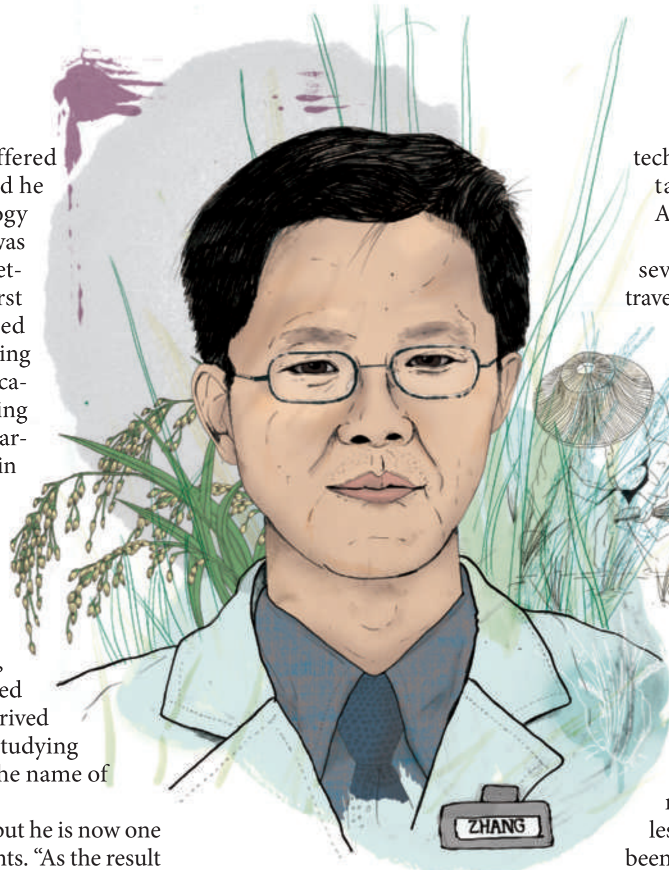
Timescale for change: now

Unlike most successful agricultural scientists, Zhang Jianhua knows what it is to be hungry. And it was an observation sharpened by hunger that provided the motivation for much of his research.

Zhang, 52, grew up on a farm in the Chinese countryside where every day was hard work in the fields, just as it is for the best part of a billion of his compatriots today. His father, a schoolteacher, was imprisoned in a re-education camp for three years starting in 1957, one of tens of thousands branded as 'rightists' after responding to the call for constructive criticism in Chairman Mao Zedong's 'Hundred Flowers Campaign'. Later, Zhang's father was assigned to teach far from his family, and rarely saw them.

Zhang, his siblings and his mother worked on a collective farm, living in a hut with an earth wall and a rice thatched roof. Each household in the collective also had a small plot for its personal use. Zhang vividly remembers the year "when I was supposed to be in high school" when he noticed his family plot, which sat a little higher than the others the irrigation channels served, was drying out a bit just as the rice crop was producing its grains in mid-autumn. "I worried a lot that my rice's yield would suffer," he says. "But at harvesting time, I found that the kernel weight was actually heavier than average. I always remembered that."

Zhang's abilities as a farmer saw him promoted to a post as a technical expert in his collective. He went on to a local agricultural college, where he studied crop production and breeding, and taught himself English in part by reading works by Charles Dickens with a dictionary in his left hand. "I spoke with a very strange accent," he says, laughing.



In 1985, the Chinese government offered him an opportunity to work abroad and he wound up in Bill Davies's plant-physiology lab at Lancaster University, UK. "There was something pretty compelling about his letter," remembers Davies. "He was the first Chinese person to join the lab." Worried about his English, Zhang avoided answering the phone, but started pumping out publications. "He did the definitive work[2] showing that roots can signal to shoots using a particular plant hormone — abscisic acid — in response to drought stress," says Davies.

One idea Zhang worked on, as remembered from his rice patch back at home, was that drought stress can, at times, convince a plant to throw all its resources into reproduction, as death by drought might be imminent. As a result, nutrients throughout the plant are rushed to the grains. Management techniques derived from this insight, which Zhang is now studying in molecular and genetic detail, go by the name of 'deficit irrigation'.

Zhang didn't invent deficit irrigation, but he is now one of its most influential scientific proponents. "As the result of his work," says Davies, "it became a much more focused effort." These days, Zhang's team is looking at the gene functions that are induced by water stress. The team has found, for example, that when deprived of water, plants protect themselves by producing more enzymes that scavenge reactive oxygen species. The group is now busy untangling the details of that regulation.

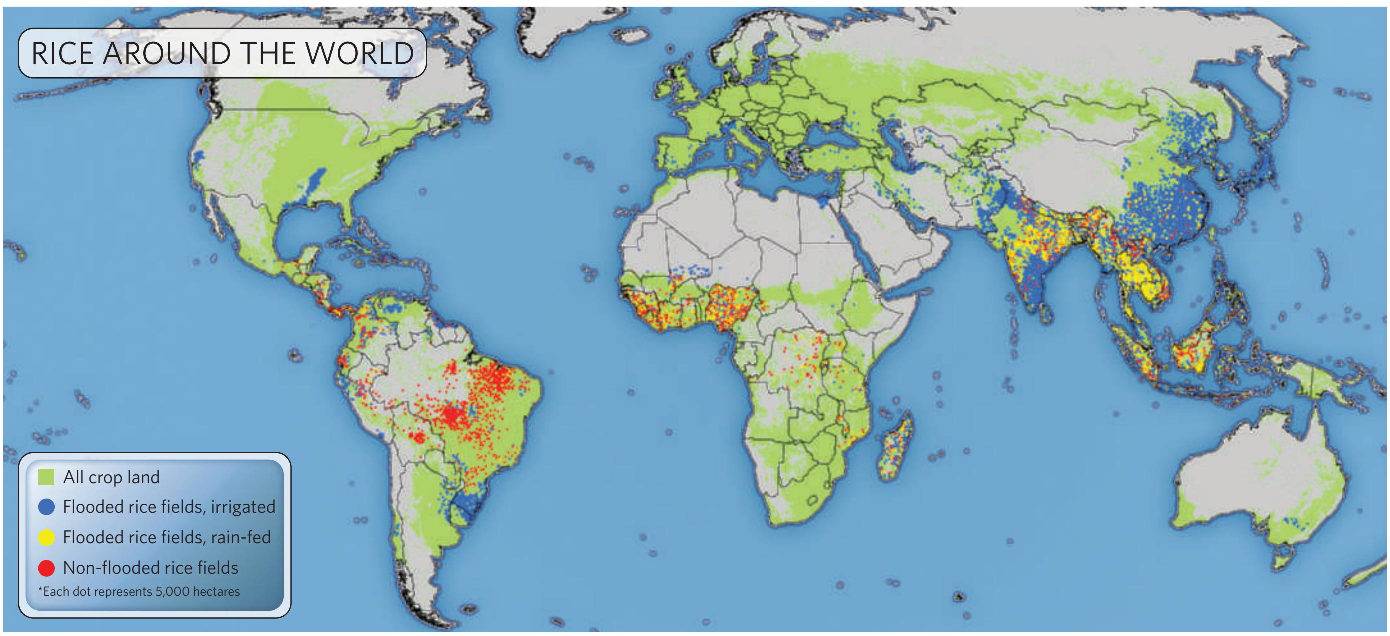
On the management side, one of Zhang's specialities is a technique called 'partial root zone drying', in which some roots are watered and others are not. The idea is that the plant gets both the water it needs and the focus-your-efforts, put-it-all-into-seeds-for-tomorrow-we-die hormone signals. This technique has been enthusiastically taken up by wine growers in Australia, among others.

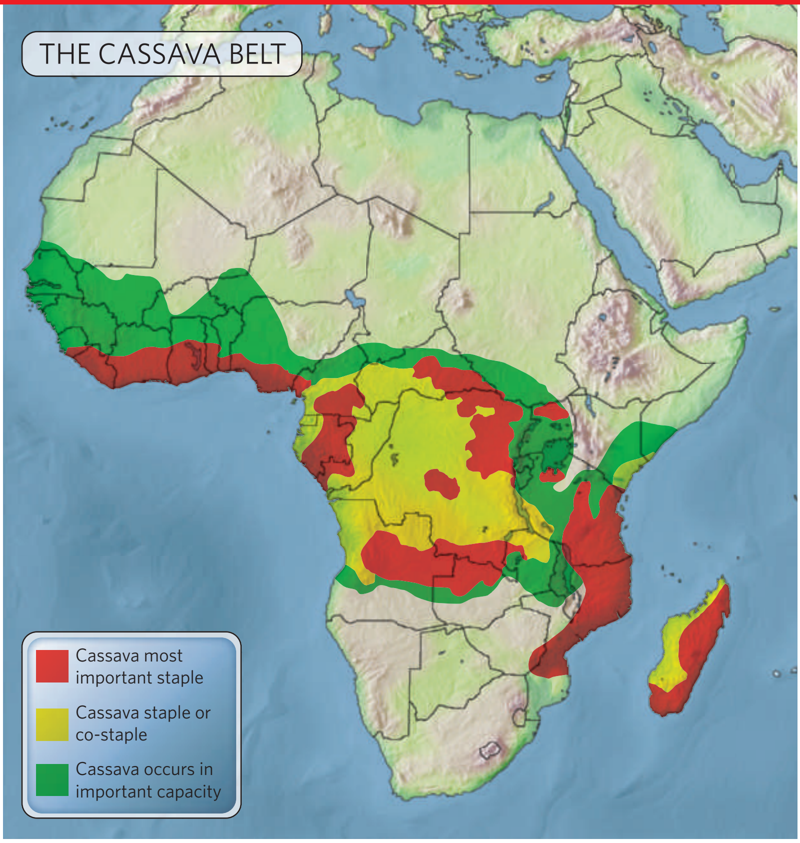
Zhang moved to Hong Kong after several years at Lancaster and now travels throughout China talking about research on deficit irrigation as a way to improve agricultural efficiency. He had always intended to bring his skills home. "It is very, very unusual to find someone who is so unselfish," says Davies of his former protégé.

Thanks to Zhang and others, farmers in northern China have learned to use less water. In northwest China, for example, the amount of water used for irrigation has almost halved from what it was a decade ago, according to Zhang. "This is a huge and significant achievement and means that we are using less underground water, which has been depleted rapidly in recent years," he says. "In north China where most of the country's wheat is produced, irrigation times have been reduced from traditionally 4–5 times per crop to today's 1–2 times per crop."

"Life for peasants in the countryside is so hard," Zhang says. "We suffered a lot." He and his parents are happier now, but many of his childhood friends are still in poverty. "If you ask how much has changed in the farmers' lives, it is very little," he says. "My dream is to see the farmers have a better life and to have equal rights as city people. I always want to do something for the village people, for the peasants. I am one of them." ■

R. HIJMANS/IRRI





The biotech humanitarian

Richard Sayre

Director of the Enterprise Rent-A-Car Institute for Renewable Fuels at the Donald Danforth Plant Science Center in St Louis, Missouri

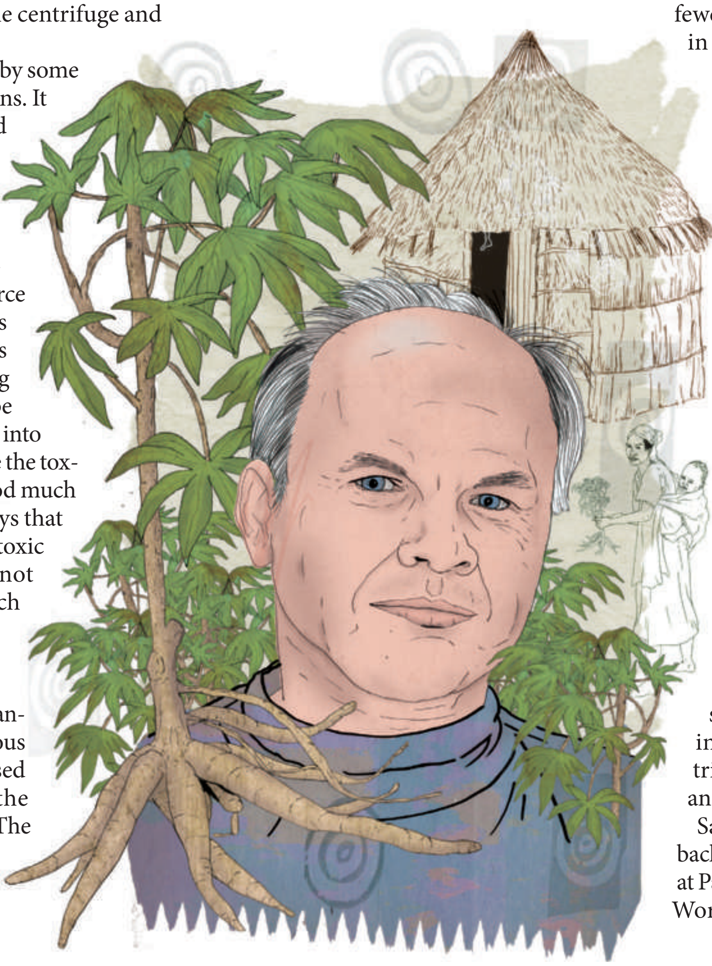
Timescale for change: 6 years

"I like being challenged," says Richard Sayre. "I couldn't do one project; I would get bored."

Sayre recently left Ohio State University in Columbus with a caravan of lab members and their families to direct the Enterprise Rent-A-Car Institute for Renewable Fuels at the Donald Danforth Plant Science Center in Missouri. In that position he will be working on turning algae into biofuel. He has also got a hand in a start-up firm called Phycal, based in Cleveland, Ohio, that works on renewable energy. And he is the head of the BioCassava Plus collaboration. Funded by the Bill & Melinda Gates Foundation, BioCassava Plus is a US$12-million, five-year effort to turn cassava, a South American plant widely cultivated in Africa (see map, right), into a super-food that provides extra protein and a wide range of micronutrients. In his cassava role, Sayre coordinates 19 investigators from five continents and works on getting the intellectual rights to use the relevant genes as well as the tools needed to get the modified root into the public domain. He's still active in the lab, too, mostly as a troubleshooter. "Instruments break down and protocols go wrong and I'll go in and fix them," he says. "I'll go under the centrifuge and fix the brushes."

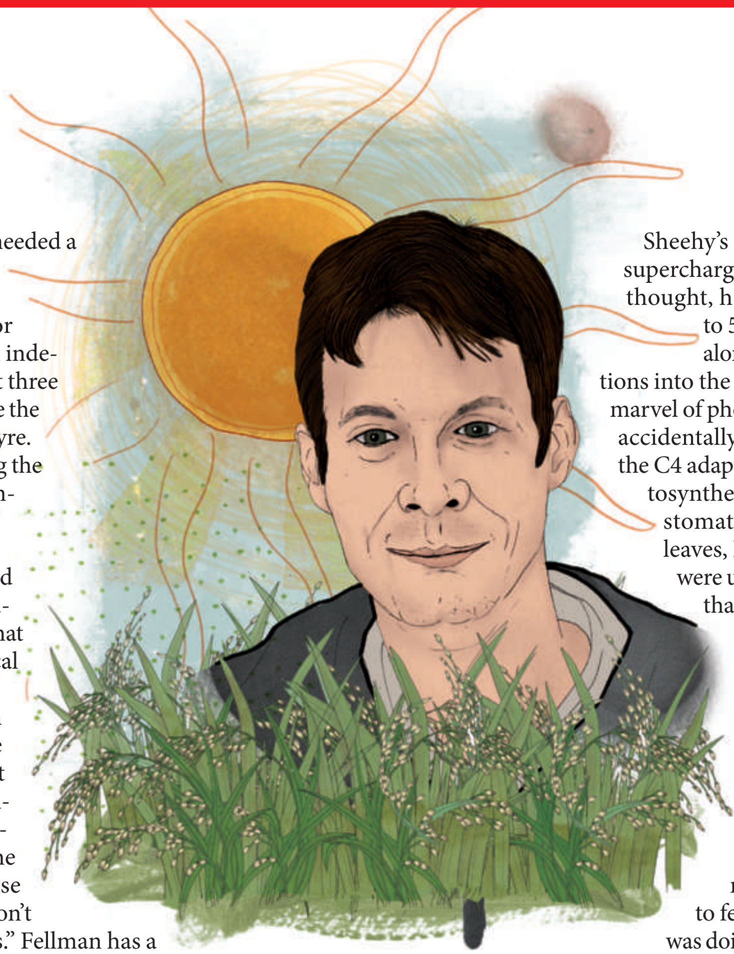
Cassava is a staple food eaten by some 250 million sub-Saharan Africans. It grows well in very poor soils and requires very little labour, so even people sick with AIDS can grow it. It also tolerates drought better than maize (corn) and other crops do. Unfortunately, it is not a very rich source of nutrients, and many varieties are tainted with bitter compounds that turn to toxic cyanide during digestion. These varieties must be soaked for a long time or ground into flour and then cooked to remove the toxins. Although this makes the food much more labour intensive, Sayre says that many farmers prefer the more-toxic varieties because thieves will not bother with roots that need such laborious preparation.

BioCassava Plus aims to improve Cassava both as a crop and as a foodstuff; so far it has managed to hit almost all the ambitious targets the collaboration promised the Gates Foundation when the programme was set up in 2005. The consortium has developed a number of genetic modifications aimed at getting the levels of specific nutrients high enough that 500 grams of cassava would contain the minimum daily allowance. These target nutrients include protein, vitamin A, vitamin E, bioavailable zinc and iron. Another engineered strain now resists some viral infections, and yet another has many fewer cyanogens. Many of these lines are in field trials in Puerto Rico. Next, the group will try to squeeze several or all of these traits into one, farmer-preferred variety of cassava. Sayre says they can physically deliver four genes at a time to the cassava genome, but he is not yet sure if they will all be properly expressed. Eventually, they may have to smuggle 15 genes into one line, a complex undertaking.



"All the collaborators in the cassava project are committed to changing the world, and we think we can," says Sayre. He insists that genetic manipulation is essential, despite the resistance of many African countries. "We cannot get to target levels of iron or zinc without transgenics," he says. Sayre is working to manage the resistance in his target markets by building local involvement into the scheme. "Our strategy is to have gene introgression happen in Africa by Africans," he says. "We think it is a critical element in adoption of the programme." Field trials are scheduled for Nigeria for 2009 and are being developed for Kenya.

Sayre's interest in cassava can be traced back to Offiong Mkpong, who now teaches at Palm Beach Community College in Lake Worth, Florida. In the late 1980s, Sayre



heard about a Nigerian student who needed a job. "I hired this guy as a dishwasher," he says. Sayre had a policy at the time that he would support any student or technician who wanted to work on an independent research project. "After about three months he said he would like to remove the cyanide from cassava," remembers Sayre. "He grew up in the Niger Delta; during the Biafran civil war, cassava kept his family alive." Mkpong and Sayre worked together on the project, starting with enzyme kinetics. When Mkpong moved on, Sayre kept plugging away, eventually engineering strains[3] of the plant that produce 99% less cyanogen than typical cultivars.

With so much on his plate and an avowed love of stress, Sayre sounds like he just might be the uptight type. Not at all, according to Washington State University's John Fellman, one of the investigators at BioCassava Plus. "That's the paradox," says Fellman. "Most of these people who are such hard-chargers don't have time for you, but he always does." Fellman has a story that illustrates Sayre's generosity and what Fellman calls his "California laid-back" personality.

"When we were coming back from a meeting in Kampala, Uganda, we had to do some time in Amsterdam waiting for flights," says Fellman. "One of the marketing guys for the Danforth Plant Center had a world club membership for KLM. So we were sitting around drinking Heinekens at 7:30 in the morning. I was complaining I didn't have a lecture ready for my class. He said, 'here, just take this summary lecture I gave at the meeting, and this could be your lecture for Monday'. He gave me his whole presentation — I put it on my thumb drive — and every one of the slides had a specific credit on it. He wasn't saying this is my work. He was saying this is our work." ■

The rice transformer
Julian Hibberd

Molecular biologist at the University of Cambridge, UK
Timescale for change: 15–20 years

If there was a moment when Julian Hibberd's pure science got a mission, it was halfway through a lap of the guest-house pool of the International Rice Research Institute (IRRI) in Laguna in the Philippines.

It was 2006. Hibberd was attending a meeting of a dozen scientists who study photosynthesis in rice. They had been gathered there by IRRI scientist John Sheehy, who had a very ambitious plan and wanted them on board.

Some plants, especially various grasses growing in hot climates, have evolved a way to supercharge photosynthesis. They do this by fixing CO_2 into a four-carbon sugar before feeding it into the cells doing the photosynthesizing, thus increasing the concentration of CO_2 and the efficiency of the photosynthesis. The process is known as C4 photosynthesis because of the four carbons in that sugar.

Sheehy's idea was to engineer the C4 supercharger into rice. In one stroke, he thought, he could increase yield by up to 50%. Hibberd had been asked along because his basic investigations into the still-imperfectly understood marvel of photosynthesis had more or less accidentally taken him near the heart of the C4 adaptation. While looking at photosynthesis in cells far away from the stomata that let CO_2 into a plant's leaves, Hibberd had found that they were using a number of the proteins that C4 plants use.

And so he found himself, before dinner one night, in the pool with "all the big names of C4". He remembers "swimming up and down thinking about C4 rice", with the vast experimental rice fields of the institute in the distance. "I think the most exciting thing was just to feel that the pure science that I was doing might have a route out into agriculture and make a difference to people."

Hibberd returned to Cambridge with a mission. After a lean couple of years, the Bill & Melinda Gates Foundation has recently given Sheehy's project $11 million over three years, according to the IRRI. Meanwhile, Hibberd has been moving forward, examining which genes change as C4 metabolism evolves — as it has done on many independent occasions. "C4 leaves have modifications in biochemistry, anatomy and organelle structure," says Hibberd. "That is why it is really complicated." On just the gross anatomy level, many more veins must be made to grow in the leaves.

But there is hope. The fact that the C4 process evolved independently dozens of times means that "there is a biological precedent to say there is some relatively easy or tractable route to get these changes", says Hibberd. In particular, Hibberd's lab is looking at integrating genes from maize — which benefits naturally from the C4 pathway — into rice. Luckily, they often seem to express themselves in the right cells. "We almost certainly need to use genes from other plants," say Hibberd. "To our knowledge, there just isn't enough variation in rice to get there through conventional breeding."

Hibberd, whom fellow Cambridge plant-man David Baulcombe calls "a very modest guy", seems undaunted by the scale of the project. "When people say to me, 'don't you think that's ridiculous, to make C4 rice?' I say that I've got 30 years before I retire. It would be defeatist of me to think I can't understand the pathway pretty well. The projected benefits of having C4 rice are huge. If C4 can have 50% more yield, it would impact billions of people." ■

Emma Marris writes for *Nature* from Columbia, Missouri.

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2. Zhang, J. & Davies, W. J. *Plant Cell Environ.* **12,** 73–81 (1989).
3. Siritunga, D. & Sayre, R. *Plant Mol. Biol.* **56,** 661–669 (2004).