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FRUGAL FARMING

Old-fashioned breeding techniques are bearing more fruit than genetic engineering in developing self-sufficient super plants.

BY NATASHA GILBERT

Jonathan Lynch likes to look beneath the surface. In his quest to breed better crops, the plant physiologist spends a lot of time digging up roots to work out what makes some varieties extremely good at extracting nutrients from the ground. Lynch wants to use this knowledge to develop plants with extra-efficient roots — crops that grow well in the nutrient-starved soils of the developing world. These plants could also reduce the use of fertilizers in richer nations.

Last year, Lynch's forays into the dirt paid off. He and his team at Pennsylvania State University in University Park reported[1] that they had produced a variety of common bean, or string bean (*Phaseolus vulgaris*), with a combination of root traits that allows it to take up phosphorus from the soil with improved efficiency. In experimental plots, the plants produced three times the bean yield of typical varieties.

That result has raised hopes in Africa, where common beans are one of the most important sources of protein for poor people. Researchers in Mozambique are testing how Lynch's beans perform in the country's ecological zones, and they expect to win regulatory approval to bring the crop to market by next year.

Lynch's beans are among the first successful attempts in a global race to develop crops that grow well in soils depleted of nutrients. "Low availability of nitrogen, phosphorus and water are the main limitations of plant growth on Earth. We desperately need this technology," says Lynch.

His work stands out because he has taken an old-school approach. He is leading a renaissance in some conventional crop-breeding techniques that rely on laboriously examining plants' physical characteristics and then selecting for desirable traits, such as growth or the length of fine roots.

And surprisingly, this approach seems to

Farmers in the developing world would benefit from nutrient-efficient crops.

be outpacing the high-tech route.

Big corporations such as DuPont Pioneer in Johnston, Iowa, have spent more than a decade developing improved crops through genetic engineering, and some companies say that their transgenic varieties look promising in field trials. But there are still no fertilizer-frugal transgenic crops on the market, and several agricultural organizations around the globe are reviewing their biotechnology initiatives in this area.

Plant biologist Allen Good of the University of Alberta in Edmonton, Canada, spent years working with companies to develop genetically modified (GM) crops that require little fertilizer, but he says that this approach has not been as fruitful as conventional techniques. The problem is that there are so many genes involved in nutrient uptake and use — and environmental variations alter how they are expressed.

"Nutrient efficiency was supposed to be one of those traits with broad applicability that could make companies lots of money. But they haven't developed the way we thought," says Good.

Despite the scientific and breeding challenges, some researchers say that all strategies must be explored to develop crops that are less nutrient needy. With the global population heading towards 10 billion people by 2050, frugal crops could be essential to feed the planet. "There is a huge worldwide potential for these traits to help increase food production and sustainable development," says Matin Qaim, an agricultural economist at the University of Göttingen in Germany.

MAGIC BEANS

Lynch says that he spent years "groping around in the dark" before he worked out which root characteristics help *P. vulgaris* to grow in low-phosphorus soils. Screening for root traits is a messy and difficult business, so it is unpopular among researchers, he says. That's why most previous research had focused on crop shoots rather than their roots. His team dug up plants to decipher which characteristics were beneficial, taking great care to avoid damaging the fragile root structures. The researchers didn't even know what traits they were looking for in the tangled masses, which could contain thousands of roots per plant.

The key to success is having an open mind and just seeing what the root looks like, says Lynch. "I tell my students they should drop acid before they go to the field, and just look at the plants and let them tell you what they are doing," he jokes.

One feature that interested Lynch and his team was root depth, because they knew that phosphorus tends to stick to the upper layers of soil. The researchers reported[1] last year that beans with basal roots — those close to the base of a plant — that grow at a shallow angle produced 58% more above-ground biomass than beans with steeper basal roots. The team also discovered that plants with long root hairs took up phosphorus better and improved the bean yield by 89%, relative to the variety with shorter root hairs. When the researchers knitted both the root traits together, they saw much bigger gains. In field trials in Mozambique, beans with shallow roots and long root hairs gave yields of 1,500 kilograms per hectare in soils depleted in phosphorus, compared with local varieties that give just 500 kilograms per hectare.

The beans could be a boon for African farmers who struggle with depleted soils. According to the Food and Agriculture Organization of the United Nations, soils in sub-Saharan Africa lose around 26 kilograms of nitrogen and 3 kilograms of phosphorus per hectare each year through farming and erosion. Because many farmers cannot afford to replenish these nutrients with fertilizers, this stunts yields to about one-tenth of those in developed countries.

The next big research challenge is to improve the beans' tolerance to drought while maintaining their ability to thrive in low-phosphorus soils. This could be tricky because crops under water stress need deep roots — the opposite of what they need to absorb phosphorus, says Magalhaes Miguel, a plant physiologist at the Agricultural Research Institute of Mozambique in Chimoio who collaborates with Lynch. Miguel is testing the beans in different locations around Mozambique to win approval for seed companies to produce and sell the crops.

Lynch's phosphorus discoveries have already made the jump into farmers' fields in China. His colleagues there have shown[2] that some of the same root traits that boost common beans also improve growth in soya beans (*Glycine max*). The regulatory system in China is faster at approving new crop varieties than that in Mozambique, so the improved soya beans are already in use and have been planted on 67,000 hectares so far.

Lynch has also had some success in improving crops' uptake of nitrogen, which tends to accumulate deeper in the soil. The ability to grow deep roots is influenced by several factors, including the characteristics of a plant's lateral roots — those that grow out of the main framework of roots. Working in maize, or corn (*Zea mays*), Lynch found that plants perform better under low-nitrogen conditions[3] and water stress[4] when they have just a few long lateral roots rather than many short ones. This arrangement requires less energy to grow, so plants can invest more resources in above-ground vegetation and developing deep roots that can suck up water and nitrogen.

Tests in US fields starved of nitrogen showed[3] that maize with few long lateral roots produced yields more than 30% higher than maize with many short lateral roots. The long-lateral-root variety performed even better in a test of drought-like conditions, where it showed a 144% increase in yield[4].

Other research teams are taking different approaches to breeding fertilizer-frugal crops. Over the past six years, a group at the International Maize and Wheat Improvement Centre (CIMMYT), headquartered in Texcoco, Mexico, has had success using conventional breeding to create maize that grows well in the nitrogen-starved soils of Africa.

Field trials show that CIMMYT's maize produces up to 20% higher yields than existing commercial maize varieties in low-nitrogen soils. By the end of 2015, the centre had won regulatory approval for 14 nitrogen-efficient maize varieties across 6 countries, including Malawi and Kenya. The organization has more than 50 other varieties in the works. Biswanath Das, a maize breeder who leads CIMMYT's project in Nairobi, says that the team is still investigating why some varieties are better than others at finding and using nitrogen. "We hope to have some answers in the next two years," says Das.

"THERE IS A HUGE WORLDWIDE POTENTIAL FOR THESE TRAITS TO HELP INCREASE FOOD PRODUCTION."

BOOM AND BUST

As Lynch and CIMMYT make big leaps forward, they are overtaking agricultural-biotechnology companies that have invested years of work in tests with GM crops.

Good, who was involved in some of the early experiments, remembers those heady times. In 2001, he walked up and down rows of transgenic and conventional oilseed rape (*Brassica napus*, also known as canola) growing side by side in Californian test fields starved of nitrogen. He marvelled at the contrast between the bigger, greener GM plants, flourishing in the stressful conditions, and their unmodified relatives that were struggling to survive. The GM plants' advantage was a transgene: alanine aminotransferase (*AlaAT*), which came from barley.

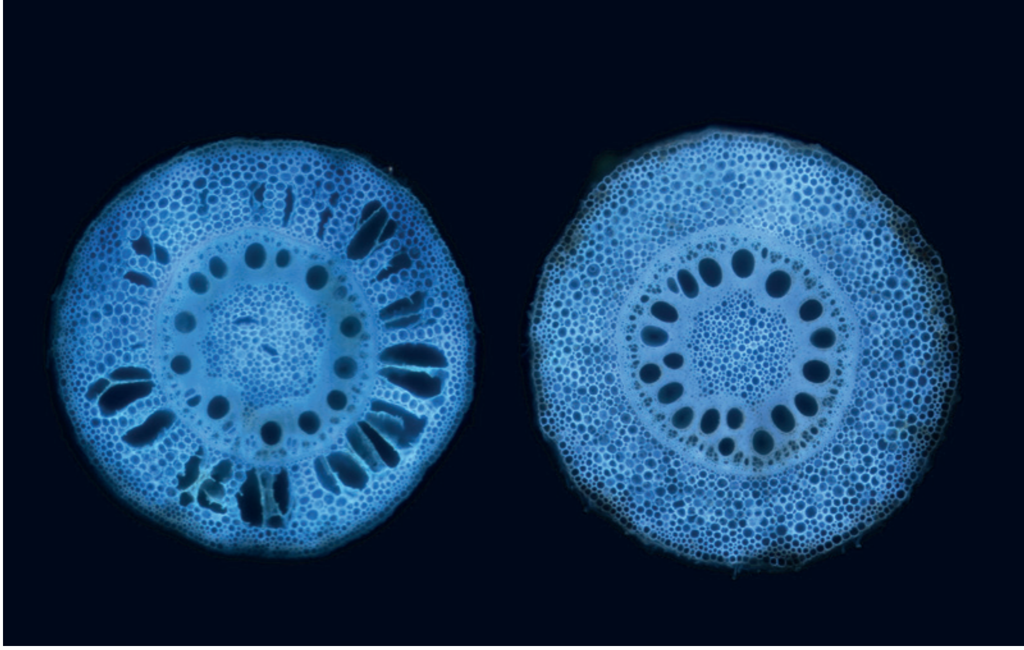
"I thought, 'Oh my god, you can see the gene working in the field,'" says Good. A few years earlier, he had discovered that *AlaAT* — which has an important role in how plants metabolize nitrogen and incorporate the nutrient into grain — could help crops to thrive in low-nitrogen soils. The gene is still one of the more advanced targets for transgenic approaches to farmers' over-dependence on fertilizer.

The 2001 trials were run by Arcadia Biosciences, an agricultural-biotechnology company in Davis, California, for which Good was working at the time as a consultant, and to which he had licensed the *AlaAT* discovery. In a collaboration with biotechnology company Monsanto in St Louis, Missouri, separate field studies[5] showed that the transgenic oilseed rape produced 42% more seeds under low-nitrogen conditions than did conventional controls. They also found that the GM crop needed 40% less nitrogen fertilizer to achieve yields equivalent to those of unmodified crops.

Arcadia says that it has successfully put the gene into other crops, including wheat and rice. The company has one of the industry's most robust nitrogen-efficiency programmes, says Roger Salameh, Arcadia's chief operating officer. "We have significant evidence from multiple years of field trials in the two largest food crops in the world — wheat and rice — that we are driving double-digit yield gains," he says.

Despite the positive results, Arcadia has not yet commercialized these or related crops. The company has worked on the nitrogen-efficient wheat with several other companies and governmental agencies, including the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia's national science agency, but the CSIRO pulled out of that project. A spokeswoman for the organization says that it "did not see results that met its objectives so is no longer actively researching this area".

Arcadia was hoping to have a transgenic variety of nitrogen-efficient wheat on the market this year, but it will miss that target. Salameh says that it is uncertain when the plant will be ready, but the company is now working with Vilmorin and Cie, a seed company in Saint-Beauzire, France, to commercialize the wheat.



JONATHAN LYNCH/PENN STATE

Specially bred maize (left) has roots that transport nutrients better than a conventional plant.

FROM THEORY TO PRACTICE

Qaim and some other agricultural analysts are impressed with the results of several transgenic efforts. For example, Arcadia and its research partners say that they have developed a transgenic variety of rice that produced, on average, 30% higher yields than conventional controls during four years of field trials in Colombia under low-nitrogen conditions. However, Qaim says that the crops' performance has yet to be demonstrated in realistic field conditions.

Good has heard that the GM oilseed rape is 'tweaky', meaning that it performs well in some environments but not others. He has lost his initial rapture with it, and says that if he had his time again, he would put the lion's share of his efforts into conventional breeding approaches like those of Lynch and CIMMYT.

Good and the CSIRO are not the only ones worried that the transgenic crops are not yet delivering as hoped. The CIMMYT effort to improve maize yields in low-nitrogen soils kicked off in 2012 with a project to develop a transgenic variety as well as the conventional maize. The transgenic plants are based on technology donated by DuPont Pioneer. They have produced some increases in yields, but not yet enough to warrant the huge effort required to gain regulatory approval, says Das. The transgenic programme is now under review. "The yield benefits are just not that exciting for commercialization yet," he says.

DuPont Pioneer has also seen some delays in its transgenic products targeted to US markets. The company told *Nature* in 2010 that it would have a product available by 2022 (see *Nature* **466,** 548–551; 2010). It now says that the products are still in the proof-of-concept stage, and will not be ready until the middle or late 2020s.

David Spielman, an economist at the International Food Policy Research Institute in Washington DC, says that the delays don't necessarily signal disaster: companies forecast precise timelines to satisfy investors, but the science doesn't always deliver according to corporate plans. The pushed-back timelines do not mean that the scientific advances won't come at some point in the future, he says.

"It is more important to consider if the traits are showing improvement and if public and private sectors are investing in the research with a longer-term view of the path to commercialization," says Spielman.

A key challenge for transgenic efforts is that traits such as nutrient-use efficiency are influenced by a complex web of genes that interact with each other and the environment. "It's very difficult to take one transgene and stick it into a maize variety and expect a big effect," says Das.

DuPont Pioneer and Arcadia are still confident that a single gene will one day deliver the nutrient-efficient goods. "People question if we could find a single gene with a big enough effect, but we are having real success," says Tom Greene, research director at DuPont Pioneer. And Salameh also remains confident about this approach.

Meanwhile, researchers are trying to combine old-fashioned breeding with a variety of high-tech methods. Lynch is now using a computer model that simulates natural selection to work out what combination of root characteristics will boost crops' performance under nutrient stress. He is also identifying genetic markers for useful root traits, which should help to indicate whether plants' offspring have the desired genes and should speed up the breeding processes, he says.

Government regulation could perhaps be the biggest hurdle to both conventional and transgenic frugal crops. Regulatory hurdles in Europe and Africa keep many transgenic technologies from reaching large-scale field testing and commercialization, says Qaim. These hurdles bear part of the blame for the slower-than-expected progress in transgenic frugal crops, he says.

And in some African countries, it can take up to ten years to get new conventional varieties to market because of stringent testing requirements, says Das. Farmers and breeders are also hesitant to take a risk on new varieties.

But if CIMMYT can get the seeds into farmers' fields, the impact on food security and the environment in developing countries could be massive, says Das. "The beauty of it is that the solution is packaged in the seed," he says, so there is no need for extra fertilizer. "Once the farmers have the seed, they have the solution." ■

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CORRECTION

The figure given for the planting of super soya bean in the News Feature 'Frugal farming' (*Nature* **533,** 308–310; 2016) should have been 67,000 hectares, not 1 million. In addition, the feature failed to make it clear that Jonathan Lynch was joking when he suggested that students should "take acid".