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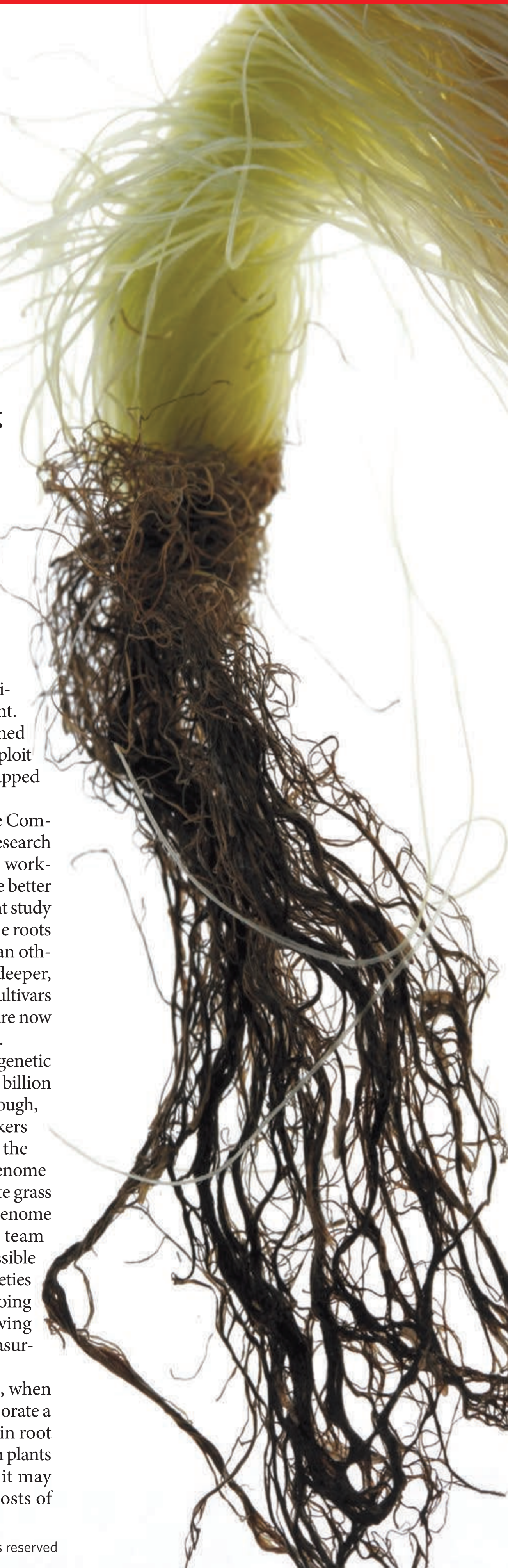

AN UNDERGROUND REVOLUTION

Plant breeders are turning their attention to roots to increase yields without causing environmental damage. **Virginia Gewin** unearths some promising subterranean strategies.

Tangled, dirty and buried underfoot, roots are a mess to study. Digging them up is a time-consuming and sometimes back-breaking process. The shovel must be wielded with care to preserve the roots' delicate branching patterns, the root hairs and the microbes that cling to them. All of this explains why roots have been largely out of mind, as well as out of sight, for agricultural researchers — until now.

Many scientists are starting to see roots as central to their efforts to produce crops with a better yield — efforts that go beyond the Green Revolution. That intensive period of research and development, starting in the 1940s, dramatically boosted food production through the breeding of high-yield crop varieties and the use of pesticides, fertilizers and more water. But the increases were accompanied by a depletion of groundwater and, by 1998, an eightfold increase in nitrogen-based fertilizer usage[1], bringing environmental problems such as polluted waterways. The leaps in yield have still left many hungry. And the revolution missed many developing nations, some of which have poor soils and limited access to irrigation and expensive fertilizers. "Those strategies of the past aren't working now to meet growing food needs," says Jonathan Lynch, a plant nutritionist at Pennsylvania State University in University Park.

"Roots are the key to a second green revolution — one that doesn't rely on expensive inputs," says Lynch. Roots deliver water and nutrients, two of the most essential, often-limiting, factors that a plant needs. Why keep putting in more water and fertilizers, he and others reason, when they might instead improve roots' ability to use what's already there and, in the process, help to convert 'marginal' lands into productive ones.

There is room for improvement. Although plant breeders have already made huge gains by manipulating 'above ground' traits — for example, by breeding dwarf plant varieties, which put more energy into producing grain rather than the stalk — the same is not true for root traits. "One reason we now have any potential to increase yields is because the tremendous genetic variation trapped in roots has been neglected," says Lynch. Here, *Nature* reports on four of the most promising leads for boosting food production through roots.

Designer roots

Roots are most efficient when their architecture is tailored to their environment. Deep roots can tap water beneath parched soils, whereas fine, shallow roots can exploit soils in which limiting nutrients are trapped at the surface.

Michelle Watt, a plant biologist at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Canberra, is working to produce varieties of wheat that are better suited to drought-prone areas. In a recent study of wheat lines, Watt's team found that the roots of some lines penetrate 25% deeper than others[2]. The team crossed lines that had deeper, faster-growing roots with widely used cultivars to develop 400 new wheat lines, which are now being field-tested in India and Australia.

Watt is also taking advantage of new genetic tools. Rather than wade through the 17 billion base pairs of the bread wheat genome, though, her group is searching for genetic markers that are associated with deep roots in the much smaller (271 million base pair) genome of *Brachypodium distachyon,* a temperate grass in the same subfamily as wheat whose genome was sequenced earlier this year. The team hopes that the markers will make it possible to identify, from seeds, which wheat varieties are likely to have deep roots, without going through the laborious process of growing the seedlings, digging them up and measuring their roots.

At Penn State, Lynch has found that, when water is limited, maize lines that incorporate a large amount of intercellular air space in root tissue have an eightfold higher yield than plants without this ability[3]. When stressed, it may be that plants reduce the metabolic costs of

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growing new root tissue by incorporating more air into them, leaving extra energy to invest in grain, says Lynch. He is not yet sure to what extent this trait could be beneficial in future breeding efforts. Root architecture research is in its infancy, he says. "Right now, it is like going from analysing the shape of a font to predicting the content of a Shakespeare play — there are emergent properties of root architecture that cannot yet be predicted."

Stealth scavengers

Roots seek nutrients. And some researchers are finding ways to help them, often by enhancing the ability to liberate nutrients from the soil or to neutralize toxins.

In the savannah of central Brazil, known as the cerrado, the high acidity of most soils solubilizes the aluminium present, making it toxic to plant roots. Some crop varieties can protect themselves: their root tips release organic acids that render the aluminium ions chemically inert. In 2007, Leon Kochian, a plant geneticist at Cornell University in Ithaca, New York, and his team reported that they had identified a gene responsible for aluminium tolerance by comparing aluminium-tolerant and aluminium-sensitive sorghum varieties from the cerrado[4]. They are now working to find genetic markers that will allow breeders to screen regional varieties of sorghum and other crops for superior variants of these and other aluminium-tolerance genes. In initial fieldwork in Brazil, lines identified to have genetic variants that provide aluminium tolerance had about one-third higher yield than other varieties when grown on acidic soils, says Kochian.

"Roots are the key to a second green revolution."

Trevor Garnett, a plant biologist at the University of Adelaide in Australia, is working with Arcadia Biosciences, an agricultural biotechnology company headquartered in Davis, California, to commercialize a method that tricks roots into taking up nitrogen from the soil more efficiently. It does this through the overexpression of genes involved in synthesizing the amino acid alanine, which contains nitrogen. "Currently only 40–50% of the nitrogen applied as fertilizer gets into the plant — which is dreadful," says Garnett. The unused nitrogen not only goes to waste but also pollutes lakes and streams. "We want a greedier plant that takes up nitrogen early in the season before it is lost to the environment, so that it will be stored and remobilized as needed later in the season," says Garnett.

Microbial manipulations

Another group of root aficionados wants to improve crop yields by harnessing microbes that grow on and around the rhizosphere — the narrow band of soil that surrounds the roots. The concept is in its early stages. It's not clear whether, for example, introducing a new fungus-fighting gene into a microbe or a new microbe into a poorly understood microbial community will be feasible approaches.

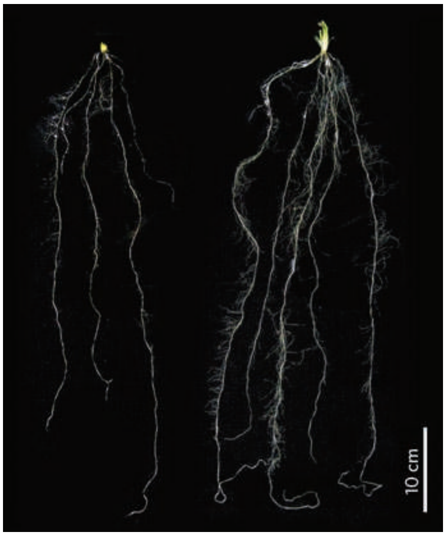
Ian Sanders, an ecologist at the University of Lausanne in Switzerland, recently stumbled on one potential technique. He studies *Glomus intraradices*, a mutualistic fungus that typically benefits plants by supplying inorganic nutrients, such as phosphate, in exchange for carbon. Last month, he showed how crossing *G. intraradices* individuals results in progeny with novel combinations of nuclei, and when he applied some of these to greenhouse-grown rice, they boosted plant growth fivefold[5]. He's now working to find out why. Sanders thinks that this technology might help to maintain yields in soils that are low in phosphorus.

Some microbes need to be discouraged. Seeking plants that are resistant to root rot caused by the fungus *Rhizoctonia*, plant breeder Kim Kidwell, at Washington State University in Pullman, used the chemical ethylmethane sulphonate to create wheat mutants. After screening 500,000 of them, her group found one with a higher level of tolerance than they'd ever seen. "We were sky-high optimistic," she says. But the team has struggled to identify the gene responsible — and without genetic markers with which to follow its inheritance, it is difficult to select plants with the trait on a large scale. In addition, Kidwell is not sure whether the root-rot resistance gene, if found, will produce similar results in field conditions. "For one thing, the environment plays such a big role; the trait doesn't always manifest in the field," she says.

A healthy fixation

The notion of engineering cereal plants such as wheat, maize and rice to supply their own nitrogen will not go away, despite decades of failed attempts. If the crops could 'fix' nitrogen from the atmosphere instead of absorbing it from the soil, this would reduce, or eliminate, the need for costly and environmentally damaging fertilizers. But to mimic legumes, such as lentils and soya beans, which can already do this, plants need to forge a complex symbiotic interaction with a nitrogen-fixing microbe such as *Rhizobium*. Most efforts have focused on getting plants to form nodules — the oxygen-free bumps on the roots where *Rhizobium* resides.

In the early 1990s, researchers hailed the identification of nodulation, or Nod, factors — the signalling molecules that the microbes use to initiate nodule formation on legume roots. But efforts to introduce receptors for



M. WATT, CSIRO

A wheat line with increased root growth (right) is being tested for higher yield.

these Nod factors into other crops have failed so far. More recent findings — for example, that certain species of the symbiotic bacterium *Bradyrhizobium* can fix nitrogen but lack Nod-factor genes — indicate that other nitrogen-fixation genes exist. "It's not so much about nodulation any more, but about simply establishing nitrogen-fixing bacteria intracellularly," says Edward Cocking, a plant physiologist and director of the Centre for Crop Nitrogen Fixation at the University of Nottingham, UK.

Many researchers believe that putting nitrogen-fixation genes of some kind into non-leguminous plants is a vital goal for agricultural science. Eric Triplett, chair of the Department of Microbiology and Cell Science at the University of Florida in Gainesville, says that it will require a team "with the courage and resources to take on what will be at least a ten-year effort".

"We've gone quite a long way over the past 40 years without worrying about roots at all, but the economic and environmental consequences of inefficient nutrient applications are now apparent," says Peter Gregory, chief executive of the Scottish Crop Research Institute in Dundee, UK. "The only way we can avoid these costs is to get smarter about roots." ■

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