Redesigning roots to help crop plants survive hard times

May 10 2016, by Cherie Winner

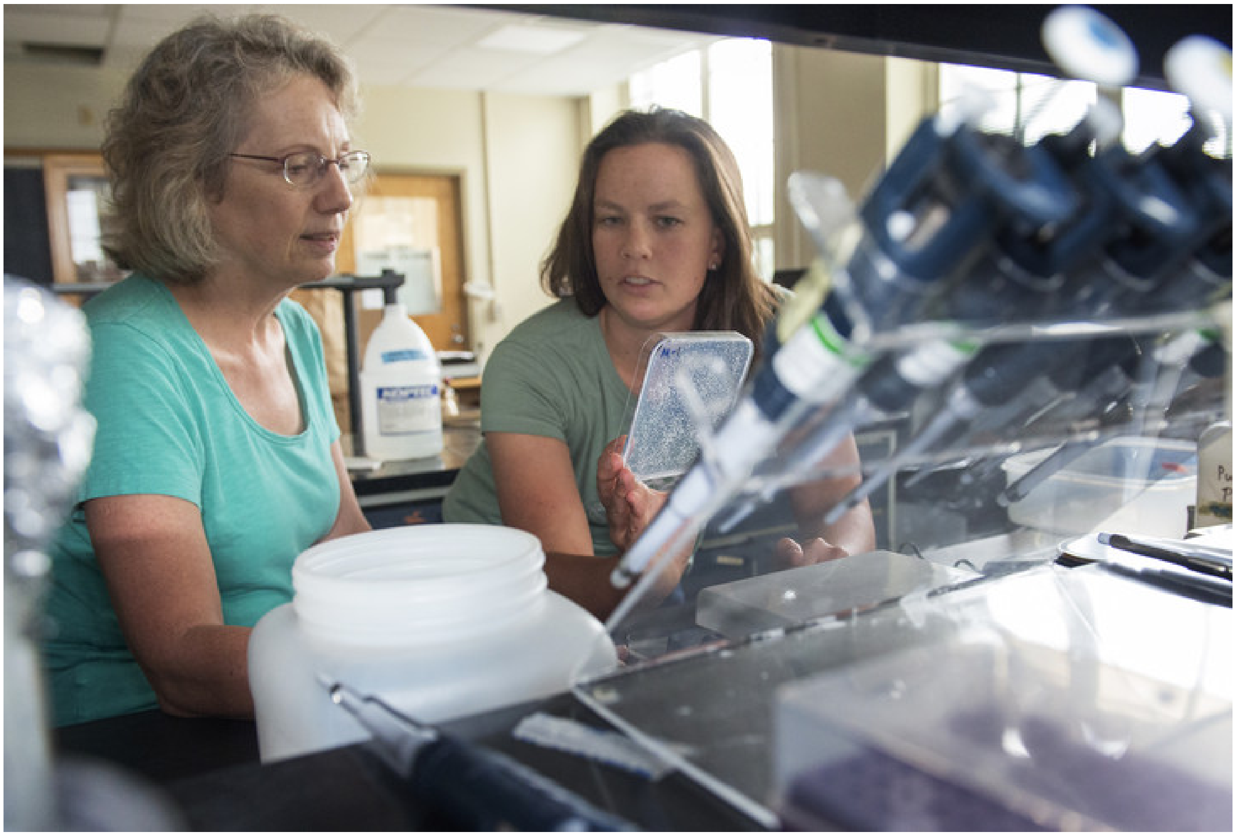
The root balls of two maize plants, cleaned of soil. A plant's ability to access water and nutrients depends in large part on the length and direction of growth of its roots. Credit: Patrick Mansell

Among the likely effects of climate change, perhaps the one with the most potential to devastate human and natural communities is drought—not just a dry season or two, but a prolonged lack of rainfall over vast areas, lasting years or even decades.

Drought is already making itself felt in Europe, Australia, and the United States. Much of the American West and Southwest is several years into a deep drought, and by 2060 the Midwest is expected to experience conditions that rival the Dust Bowl. But it is developing countries that are suffering the most, with drought so severe that it has disrupted societies, spawned or worsened civil strife, and led to the forced migration of millions of people no longer able to find water or grow food in their homelands.

Penn State crop scientist Jonathan Lynch has spent his career exploring how to make crop plants better able to grow in dry, low-nutrient soils, as a way to fight the chronic food shortages that plague much of the world. He has never considered himself a climate-change scientist, but in recent years his work has taken on new urgency due to the global changes we're seeing.

"If you're a small farmer in Rwanda and you only have half an acre of land to feed your family, and your crops are only yielding ten percent of what they should because of drought and poor soil, that's a serious problem," says Lynch. "Right now there are about 850 million chronically hungry people on Earth. 850 million! Chronic malnutrition is the leading cause of childhood deaths in the Third World. It's already a massive problem, and climate change has barely begun to sink its teeth into these agricultural systems yet.



Plant biologist Kathleen Brown and graduate student Molly Hanlon examine a plate of seedlings in the Roots Lab. Planting a combination of crop varieties that thrive under different conditions could shield farmers in poor areas from total disaster. "That can mean the difference between starvation and eating," Brown says. Credit: Patrick Mansell

"An important way to address this challenge is to develop plants that can tolerate these stresses."

Where the good things are

Plant breeders worldwide have been trying to do that by improving the efficiency of physiological processes such as photosynthesis.

Those are good improvements for plants that are well-watered and in nutrient-rich soil, says plant biologist Kathleen Brown, but in poor soils or drought conditions, having souped-up physiology won't help. What will help is enabling the roots to reach more sources of water and nutrients in soils that have little of either.

So Brown, Lynch, and their students at the Roots Lab at Penn State study how [root](#) structure can improve the ability of key crop plants—primarily corn (Zea mays) and the common bean (Phaseolus vulgaris)— to produce good yields under stressful conditions.

Roots that don't spread as widely but go deeper allow the plant to reach more nitrogen and water. Credit: Jonathan Lynch

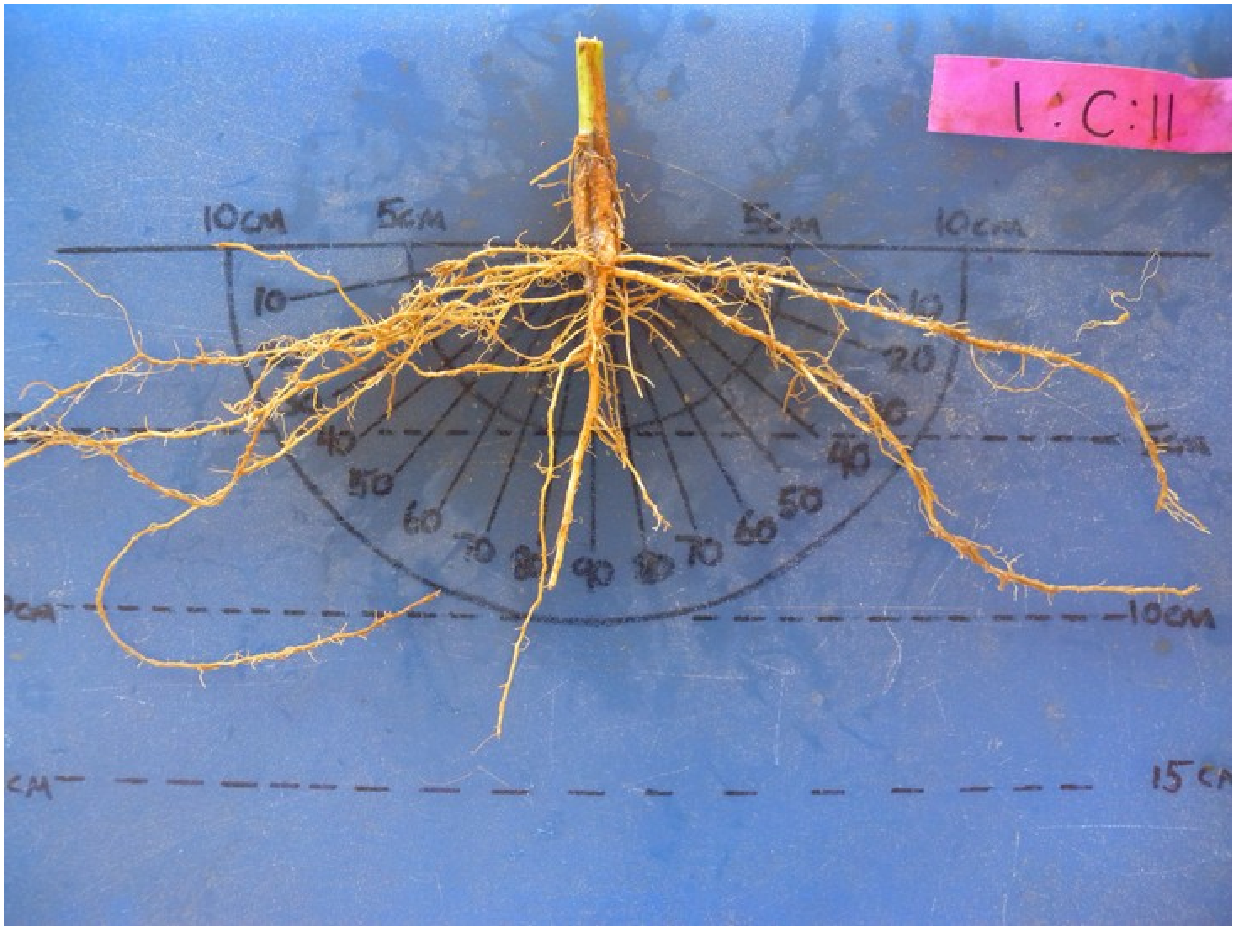
That may sound simple, but it gets complicated in a hurry. For one thing, most of the root features known to enhance resilience to poor conditions are not controlled by a single gene and therefore are hard to select for. A plant may have to have a whole suite of genetic variations to produce the kinds of roots that will enable it to grow deep enough to access water deep below the surface.

"If Nature could improve drought tolerance in plants by changing one gene, that would have been figured out, like, 300 million years ago," says Lynch. "It's more complex than that."

Another challenge is that not everything the plant needs can be found with the same root characteristics. Fertilizers and natural decomposition of the previous year's crop residue deliver nitrogen and phosphorus to the soil surface. Nitrogen almost immediately moves down, riding along with water as it seeps deep into the soil. Phosphorus, though, stays near the surface.

"It stays stuck to the soil particles, so it can't move freely," says Brown. "If the root isn't extremely close, microscopically close, to phosphorus, it doesn't get it. If the plant has used up all the phosphorus around it, it has to keep growing and exploring new soil to keep getting phosphorus."

So for the plant, the architecture of its roots is a tradeoff—make lots of branches that stay near the surface, to find phosphorus, or send roots deep enough to reach water and nitrogen. Individual plants tend to do one or the other, but not both. That makes it unlikely that any single variety of a crop plant will solve all of the problems that might arise in a given location, but a combination of varieties could shield farmers from total disaster.



Shallow roots that spread more widely near the soil surface aid uptake of phosphorus. Credit: courtesy Jonathan Lynch

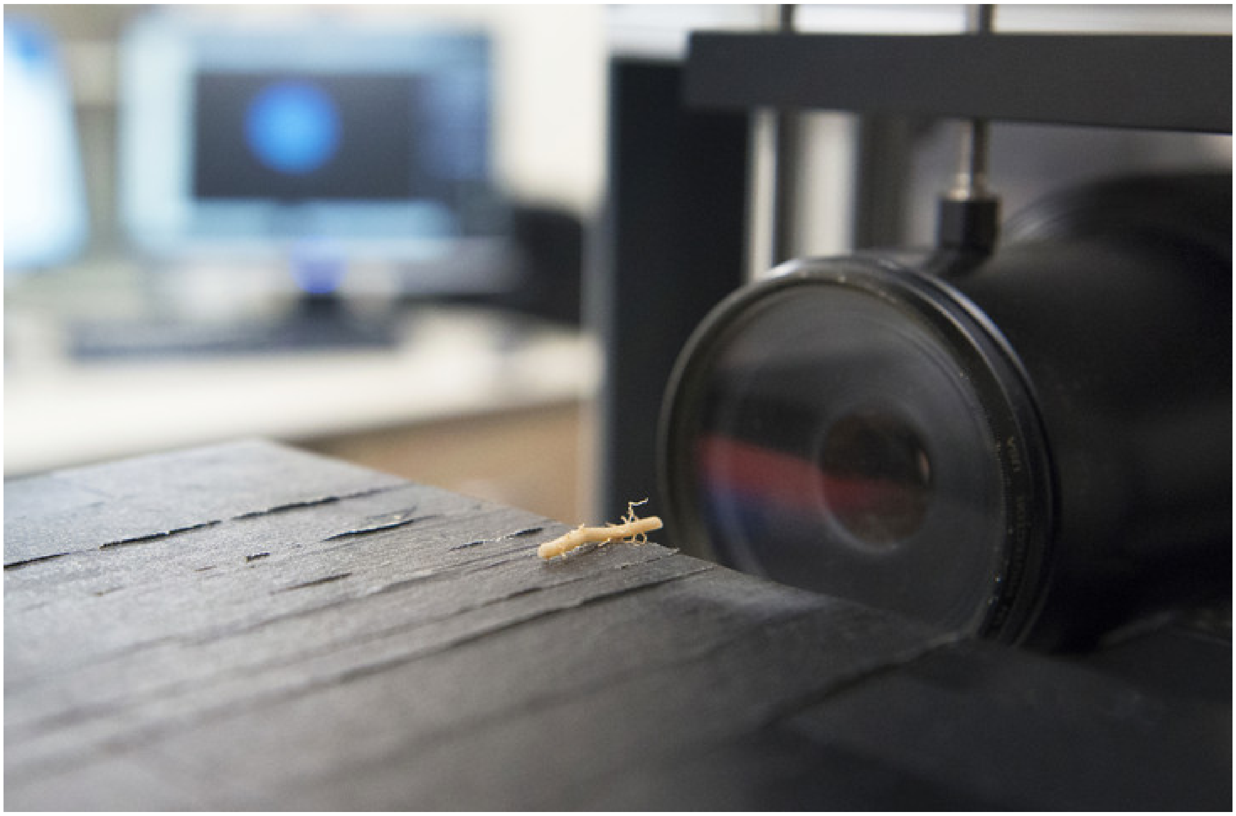
"If you can be guaranteed of always having some yield, especially if the people are really poor, that can mean the difference between starvation and eating," says Brown. "It's important that they have some resilience, that a weather event isn't going to totally wipe them out."

Good roots, cheap

Whether a plant goes deeper or reaches more soil near the surface, it is growing more root tissue—and roots have a cost, says Brown.

Every cell in the plant, including in the roots, requires water and nutrients. A cell that photosynthesizes, transports water, or brings in resources from the soil earns its keep. But in a root, most of the uptake of water and nutrients occurs at the growing tip. Some occurs in a short zone just behind the tip where tiny root hairs develop. Farther up the root, where lateral branches form, there's almost no uptake. If the growing tip is two feet underground, that means that a foot to a foot and a half of that root is not actively bringing in water and nutrients. The cells in that part of the root still use water and nutrients, though—and the metabolic cost of maintaining those cells limits how much root the plant can grow.

In the late 1800s, biologists recognized that many aquatic plants have a lot of what looks like empty space in their roots. They figured out that this aerenchyma ("air tissue") enables the plants to live in standing water by allowing transport of oxygen into the submerged roots. The roots start out packed with cells, but as they mature most of the cells die, leaving only channels for transport of fluid and the structural parts that support the lower end of the root.



A short piece of maize root is ready for its closeup during laser ablation tomography. A laser beam (not visible here) vaporizes very thin slices of the root. After each pass of the laser, the camera records the appearance of the fresh surface. Thousands of such images can be combined to create a detailed picture of the root's internal structure. Credit: Patrick Mansell

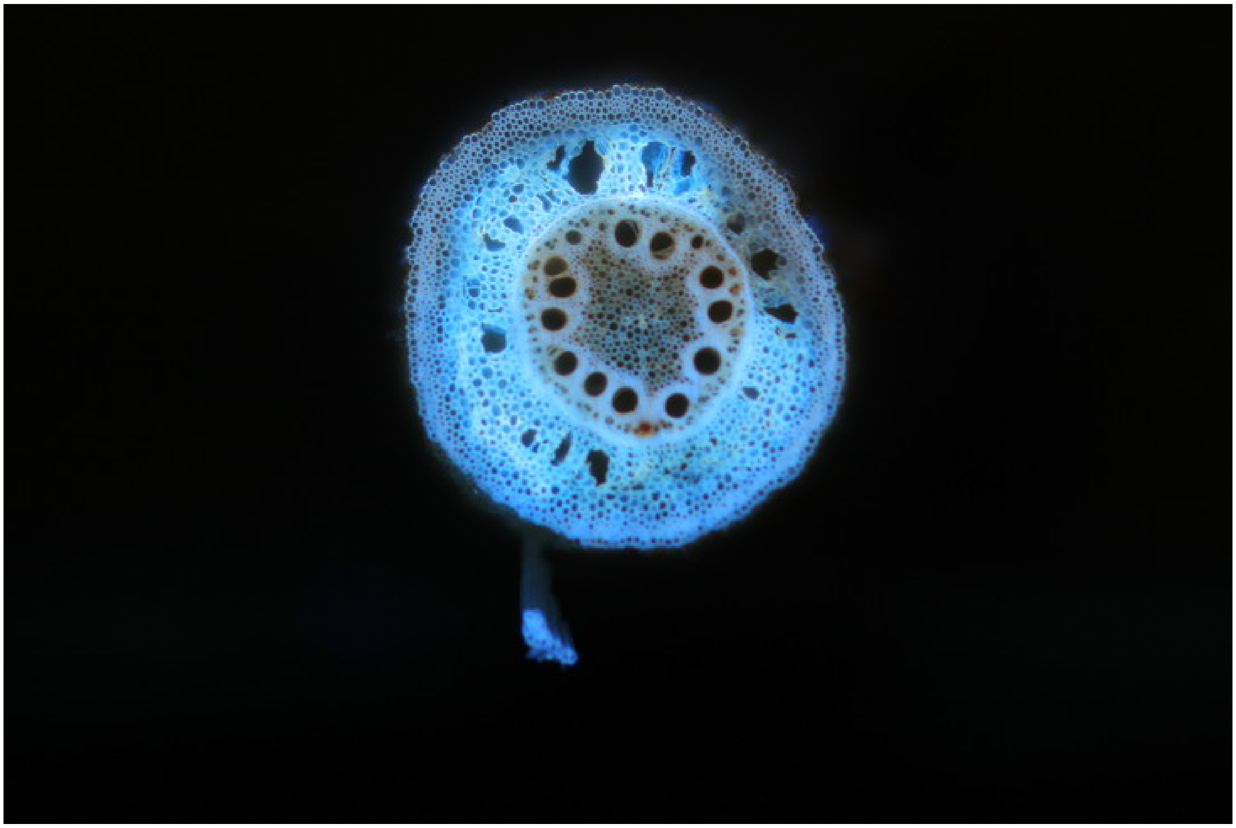
Several years ago Brown and Lynch realized that roots of plants adapted to other kinds of stresses—high temperatures, nutrient shortage—also tend to contain a lot of aerenchyma. They hypothesized that the ability to make lots of aerenchyma could enable a plant to grow more or longer roots and thereby handle a variety of stressful conditions.

"Having aerenchyma means the root doesn't cost as much," says Brown. "If you can make roots cheaper, then you can grow more roots, and if that root growth goes in the right direction to get the resource you're missing, you can benefit."

In computer simulations developed by the lab, plants with more root aerenchyma obtained more nutrients and grew better in low phosphorus and low nitrogen environments. Then the team confirmed this in real life: In field tests with maize grown in drought conditions, natural variation in the amount of root aerenchyma resulted in an eight-fold difference in yield.

Low tech and high

Studying roots can be tricky. You can't just look at the visible part of the plant and know what's going on below ground. To evaluate the overall architecture of a plant's roots, the Roots Lab team uses a low-tech but highly effective technique they call "shovelomics": When test plants have grown big enough to have well-developed roots, the researchers dig up the whole root system, carefully clean off the dirt, and assess the number and length of the roots and their angle of growth.



Roots with little or no aerenchyma, or open space, require more energy and nutrients to maintain, which limits how long they can grow. Credit: Jonathan Lynch

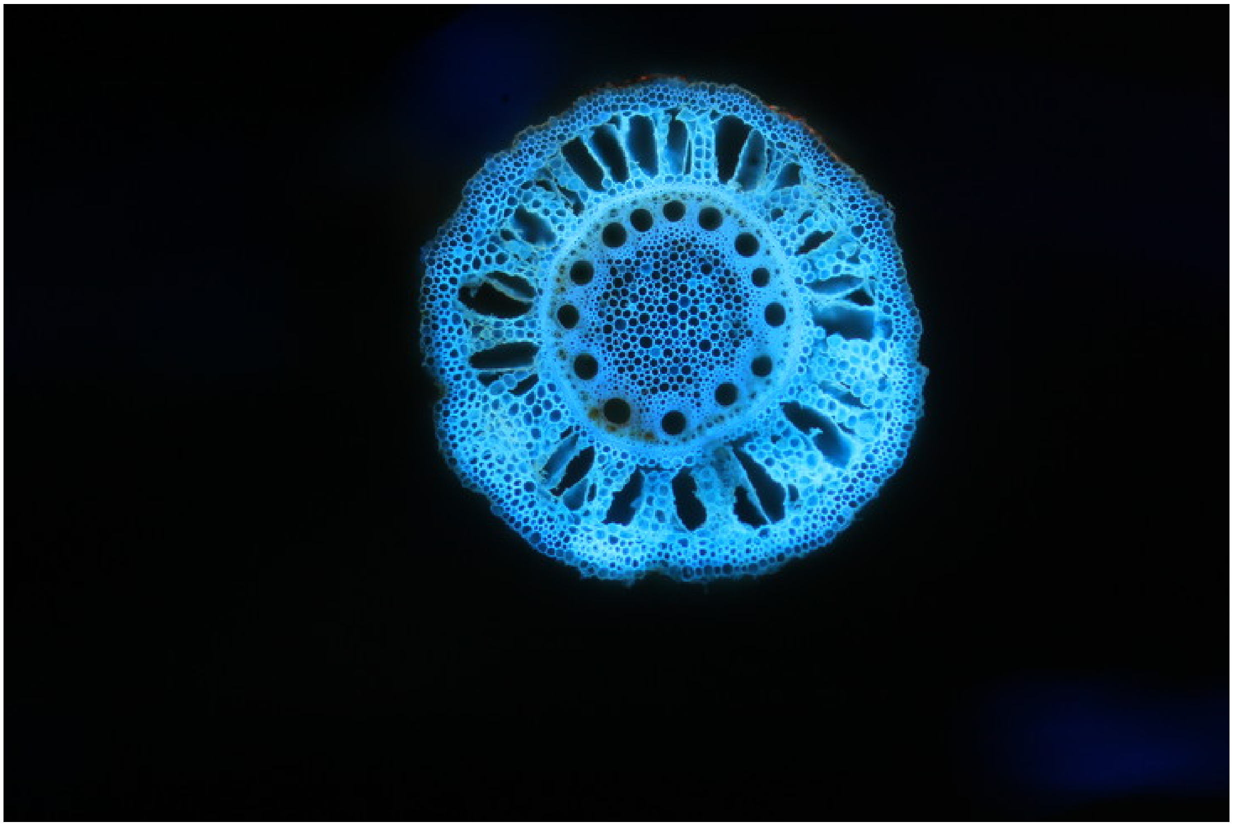
The Roots Lab has also developed computer modeling software that lets them compare how root architecture and anatomy affect a plant's ability to explore the soil and take up water and nutrients.

With SimRoot, a researcher defines the extent and direction of root growth. Then the program shows a 3D simulation of what the root architecture will look like and calculates how nutrient uptake will change over time. With RootSlice, a researcher can find out how features of the root's internal anatomy, such as amount of aerenchyma, will affect the root's function and how efficiently it can explore the soil.

In 2011, the team came up with a new way of getting a detailed look at the internal anatomy of roots. The conventional method involved using a fine blade to take very thin cross-sectional slices from a root, mounting the slices on a glass slide, and examining them under a microscope. Since each root might be several inches long and each section was just a tenth of a millimeter thick, this technique was not nearly efficient enough to handle the huge numbers of samples they generated each year.

At the suggestion of Lynch's son Galen, who was then an undergraduate at Penn State, the team began working with Ben Hall, a graduate student in the Applied Research Lab, and Hall's adviser Ted Reutzel on a method using a laser instead of a blade. The laser cut beautiful sections, says Brown, but the big breakthrough came when they realized they didn't have to collect and examine sections at all. They could just have the laser ablate, or vaporize, thin sections from the root, and have a camera take a picture of the fresh surface after each pass of the laser. The digital images are then manipulated with computer software to create a 3D image of the root that allows scientists to tally the number and size of cells, volume of aerenchyma, and other traits.

This process, called laser ablation tomography (LAT), was patented by Hall, Reutzel, and Jonathan and Galen Lynch. In 2014, Hall launched Lasers for Innovative Solutions, a startup venture based on LAT technology, with support from the Ben Franklin TechCelerator program at Penn State's Innovation Park.



Roots with more aerenchyma have lower metabolic costs and can therefore grow longer to reach water and nutrients. Credit: Jonathan Lynch

Taking it global

Over the past several years, Lynch, Brown, and their colleagues have identified the genetic basis for aerenchyma in maize, shallow (phosphorus-seeking) root architecture in common bean, and other valuable traits. They are helping plant breeders develop strains of both crops that combine a desired root architecture with the ability to make aerenchyma, and testing them on farms and agricultural stations in Africa, Asia, Latin America, Arizona, and Pennsylvania.

With their focus on the structure of roots beginning to pay off, Lynch is more convinced than ever that the Roots Lab team can help relieve the persistent lack of food in so much of the Third World—and reduce the suffering that will ensue if predictions of severe drought later this century are borne out.

"We can solve this problem," says Lynch. "We can develop plants that need less water and less nutrients and that grow better in these stressful environments. And such plants are going to be really useful even in America and other rich nations in the future, because of climate change.

"We shouldn't feel helpless. This is something we can tackle."

Provided by Pennsylvania State University

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