



# Breeding beans for better roots

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- Past and present researchers from Penn State's Roots Lab published papers in *Crop Science* describing root architecture in a diverse swath of grain legumes.
- 'Shovelomics'—digging up mature plants to examine their roots—is a low-tech method for selecting plants with root phenotypes that will optimize their growth in low-input environments.
- Celestina Jochua, a researcher and bean breeder in Mozambique, implemented shovelomics to breed three varieties of phosphorus-efficient common bean with almost double the yield for subsistence farmers in southern Africa.

Shovelomics? It's not that hard. I teach all my technicians in Mozambique. The hardest part is the digging," Celestina Jochua says. "We take some pictures, show them how to

score. It just needs some practice. Three, four tries then you'll get it."

Jochua makes the process of phenotyping roots—affectionately dubbed "shovelomics"—sound simple. And it is.

It's a low-tech, hands-on method for characterizing physical aspects of the roots of mature plants, and it can have big impacts on low-input cropping systems.

Jochua is a researcher and common bean breeder at the Chokwe Research Station, working for the Agricultural Research Institute of Mozambique. Using root phenotyping to select for low-phosphorus adaptability, Jochua and her team have already bred and released three commercially available varieties of common bean with yields 90% greater than local varieties. For farmers who can't afford irrigation or fertilizer, more resilient, higher-yielding beans are life changing.

Jochua and other members of the Roots Lab, headed by Jonathan Lynch and Kathleen Brown at Penn State University, published a pair of articles in *Crop Science* describing the great diversity of root architecture phenotypes in a variety of grain legumes. Lynch is a 36-year member and Fellow of CSSA.

The papers describe methods for examining roots in the field—'shovelomics'—and propose idealized root types that breeders can select for and test to take advantage of nutrients and water in the soil, without additional inputs.

## **Why Dig?**

Most beans are grown and consumed in the tropics, where soil fertility is often degraded and seasonal drought plagues farmers. Amendments and irrigation are unaffordable solutions for farmers with no income to spare.

“The average yield for beans in Africa is 400 or 500 kilograms per hectare, which is just about 10% of its yield potential,” Lynch says. “We can make huge strides there—we can double their yields.”

These low yields in subsistence-farming countries are not a new issue. Lynch’s first post-doctoral position was at the International Center for Tropical Agriculture (CIAT) in Colombia. When he joined, the organization had just terminated an unsuccessful 20-year bean breeding project.

“They were using brute-force screening, putting as many genotypes as they could of common bean out in low-fertility soil and seeing which ones grew better. And they just failed,” Lynch says.

Lynch tried a new tactic: screening the roots.

“I thought that we could take a more trait-focused approach and see if there was something we could use,” Lynch says. “If we knew what traits could help us, then we could target those for an ideotype breeding program.”

Ideotypes are biological models. They’re the ideal plant type. As Jimmy Burrridge puts it, “You can have as many ideotypes as environments.”

A former Ph.D. student in the Roots Lab, Burrridge is currently a post-doctoral researcher at the Institut de Recherche pour le Développement (IRD) in Southern France. There, he’s using his knowledge from Penn State and applying it to the roots of sorghum and pearl millet.

In Burrridge’s recent *Crop Science* article, co-authored by Lynch and modeler Harini Rangarajan, the team lays out a diversity panel of root architecture in a huge variety of grain legumes (<https://doi.org/10.1002/csc2.20241>).

From chickpea to groundnut, soybean to tepary bean, the diversity panel encompasses what's possible for roots across species. Armed with knowledge of the sheer possibility of root strategies, breeders can select for phenotypes, in line with their ideals, to take advantage of naturally available resources.

## **Strategic Roots**

Beans depend on adequate water and phosphorus; without them, yield falls dramatically. These two key resources are stratified in the soil: phosphorus remains in the topsoil, bound to clay particles, while water tends to be deeper, as the upper layers of soil dry.

Bean roots have a spectrum of strategies, ranging from shallow to deep root growth. Plants that grow deep roots are in search of water while plants with shallow roots are scavenging the topsoil for phosphorus.

After phenotyping thousands of plant samples in three different experimental locations over several years, Burrige cites two species as extreme examples of each strategy.

"The tepary has a 'live-fast-die-young' strategy while the chickpea takes a 'slow-and-steady' approach," Burrige says. "That's really it, in a nutshell."

Those strategies can tell us a lot about where the species was domesticated.



*Example of common bean displaying shallow (left), deep*

For the tepary, traditionally grown in short-season environments like the Southwest United States and Northwest Mexico, water is scarce, and the growing season limited by rainfall. The tepary uses water aggressively, growing very deep roots very quickly, tapping into stored water. Typically grown in floodplains with rich, fertile soil—finding nutrients was not an issue. The plant could afford to grow deep, and only grow deep.

*(middle), and dimorphic root architecture, with characteristics of both shallow and deep exploration (right). Photos by Jimmy Burrige.*

On the other hand, the team found that chickpea grown in the same conditions for the same amount of time takes a very different tack.

Domesticated in the Mediterranean, the chickpea was not limited by water availability, but by soil fertility. Instead of growing deep, it grows low and slow, with branching shallow roots scavenging clay-bound phosphorus particles in the topsoil.

The rest of the species Burrige categorized ranged the gamut between shallow and deep growth. The team documented root diversity across legume species, including common bean, cowpea, soybean, and groundnut, too.

From this diversity, the team proposed an ideotype—an example of roots that could maximize its use of limited resources by growing shallow roots for phosphorus while still growing deep enough to get water during the driest parts of the season. It's a kind of "Goldilocks" of root systems; a hypothetical top contender for areas short on both phosphorus and water.

But the team still needs breeders to select for the phenotypes represented by this idealized root system, testing plants in field trials to see if they do increase plant resilience, thereby indirectly increasing yield.

“There’s a huge focus on genes, but that’s not the bottleneck,” Lynch says. “If you knew the function of every gene in common bean...now what? How do we improve beans for Africa? For North Dakota? We have to think: what do I want? I want disease resistance, or this or that bean color, or to cook like this—I want the roots to get water and nutrients out of the soil effectively. But how do I do that? You have to have an ideotype. You need to understand the phenome.”

Burridge’s work outlines the diversity of root phenomes in a number of bean species, but Jochua’s recent article looks at the diversity within a single species: the common bean (*Phaseolus vulgaris* L.) (<https://doi.org/10.1002/csc2.20312>).

### **Common Bean Roots**

Just as the location in which tepary bean and chickpea were domesticated impacted their heritable root architecture, the common bean has two gene pools, each from a distinct area of domestication.

Common bean is divided into Andean and Mesoamerican gene pools, with more subdivisions of races within these pools. These classes were determined by genetics, geographical origin, seed, and shoot characteristics. Here, for the first time, the Roots Lab team including Jochua, Christopher Strock, and Lynch phenotyped roots to see if race differences extend underground.

The team ran lab and field trials with subsets of 196 accessions of common bean from the core collection at CIAT.



*Celestina Jochua with her low-phosphorus-adapted common bean lines in a low-phosphorus field in Central Mozambique. Photo courtesy of Jimmy Burrige.*

In the lab, the team documented root hair length and density on germinated seedlings. They then completed field trials in Pennsylvania, USA, and the Chokwe Research Station in Mozambique. The team grew a subset of 155 accessions of common bean for 45 days—long enough for the plants to fully develop their root phenotype, but not so long that they started flowering.

In bucket-brigade fashion, two technicians dug up plants and roots, two washed and tagged them, and Jochua phenotyped roots.

“If you have five people, you can score around 250 research plots a day,” Lynch says. “That’s pretty high throughput.”

The team found great diversity in root strategies. And they found differences in those strategies based on gene pools, race, and country of origin—potentially reflecting the way those accessions adapted to their original growing locations.

Notably, Andean and Mesoamerican gene pools *do* have distinctive integrated root phenotypes. Beans from the Andean gene pool tended to show roots with very shallow growth angles and more basal root whorls while the Mesoamerican beans had more adventitious roots and deeper basal roots.

All of this to say: even within common bean, there is a massive diversity of root architecture. Like chickpea and tepary bean, there are roots that invest in shallow soil, and roots that go deep.

With an understanding of diversity *within* a species, bean breeders like Jochua can now take advantage of different root phenotypes and select the best strategy for the soil resources available.

## **Breeding Beans for Mozambique**

Jochua has already put root phenotyping to good use in Mozambique. Located on the southeastern coast of Africa, the country has three distinct regions: north, central, and south.

Each of these regions vary in soil nutrient availability and rainfall—plus, farmers and consumers prefer their common bean to have distinct colors and cooking qualities.

Jochua and her team at the Agricultural Research Institute of Mozambique received material from CIAT and then screened lines to select parent plants with roots adapted to low-

phosphorus availability.

“We were looking for good root traits we can easily screen for, here, in Mozambique: Basal root number, root angle, root hairs,” Jochua says.

The best parent plants from CIAT were bred with locally adapted lines. Farmers were involved every step of the way.

“We don’t just give them bean varieties—we test them, in the field, with them,” Jochua



*Jimmy Burrige inspects freshly excavated common bean plants in a low-phosphorus field at the Sussundenga Research Station in Central Mozambique. Photo by Magalhaes Miguel.*

says. "Before we even pick a variety, we ask them to come with us, look at the color, test the cooking. If they like how the plant is growing, they look at the grain to see if it's what they want."

In Mozambique, consumers prefer large-seeded beans, about the size of kidney beans. Farmers and consumers prefer mottled red-and-cream colored beans, or dark red kidney beans. Consumer and farmer preferences vary by region and sex, too.

"Men want beans they can sell at market," Jochua says. "But women want both: they want to sell them and use them at home, too."

Once Jochua's team selected suitable varieties, they embarked on a promotional campaign, distributing seed from three lines to 2,400 farmers in eight different villages. Those farmers will grow the crop and distribute seed to their neighbors.

For Jochua, hands-on selection makes a huge difference. Not only do farmers receive bean varieties with higher average yield without additional inputs, but the beans are more nutritious, too.

"Here in Mozambique, we have a big problem with malnutrition," Jochua says. "These beans have a high concentration of iron and zinc; they're high in protein. They're good for children, for pregnant women. This is such a big problem that it's part of our program to promote them, to get people to eat them."



*Examples of major market classes of bean in Central Mozambique. From top to bottom: cream mottled, red kidney, and red mottled. Photo by Jimmy Burrige.*

And with higher yields, farmers have better incomes, and bean prices in the city are lower, making food more affordable.

According to the World Food Programme, an income-adjusted plate of food that costs only \$1.26 in New York state would set you back \$46.19 in Mozambique (<https://bit.ly/3nANIOj>). The Roots Lab's work in doubling the yield of a bean crop is a big stride in bringing the cost of food down for people in developing countries.

Jochua and her team have already sent the bean lines they bred out to test in other locations in southern Africa. She reports that early trials in Malawi and Zambia show promising results. The next big hurdles are testing varieties in more locations and selecting plants for greater heat stress tolerance and disease resistance.

In the end, the success of Jochua's bean varieties in Mozambique is a testament to the power of selecting for specific root phenotypes.

"We can do such big things if we get yields up in these subsistence crops," Lynch says. "For the local people, they can feed their kids; maybe they save some money to send their kids to school. We can improve this."

## **Dig Deeper**

Check out the following two open access articles in *Crop Science* on this topic: “Comparative Phenomics of Annual Grain Legume Root Architecture” available at <https://doi.org/10.1002/csc2.20241> and “Root Phenotypic Diversity in Common Bean Reveals Contrasting Strategies for Soil Resource Acquisition Among Gene Pools and Races” available at <https://doi.org/10.1002/csc2.20312>.

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