making RNA. But the convergence of the biochemical and cellular results is finally making sense of the cellular train station.

–**Elizabeth Pennisi**

Additional Reading

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PLANT SCIENCE

Making Plants Aluminum Tolerant

Among all the high-profile pests and blights that plague the world's agriculture, there is a culprit less well known: aluminum. The most common metal in soils, aluminum is a problem on 30% to 40% of the world's arable lands, where acid soil releases aluminum ions into the ground water. Indeed, for some important crops, such as corn, it is second only to drought as an impediment to crop yields, reducing production by up to 80%. Now, Mexican researchers have come up with a possible genetic-engineering fix.

On page 1566, molecular biologist Luis Herrera-Estrella and his team at the Center for Research and Advanced Studies of the National Polytechnic Institute in Irapuato, Mexico, report that they were able to make tobacco and papaya plants aluminum tolerant. They did so by genetically engineering them to pump out citric acid from their roots. This organic acid ties up aluminum ions in the soil, preventing them from entering and damaging the plants' roots.

Crop researchers using traditional plant-breeding methods have boosted the aluminum tolerance of some food crops, notably wheat. But they would like to have a gene for aluminum tolerance that they could introduce into a wide variety of crop strains already bred for high yield and pest resistance. Herrera-Estrella's work is "a powerful first step" toward that goal, says Leon Kochian, who studies aluminum tolerance in crop plants at the U.S. Department of Agriculture's (USDA's) Agricultural Research Service laboratory in Ithaca, New York.

Farmers around the world would reap the benefits of such a gene, but the payoff would be especially high in developing countries. Although aluminum is present virtually everywhere, in nonacid soils it is locked up in insoluble compounds. But in acidic soils, which are most common in the tropics (where heavy rains leach alkaline materials from the land), the aluminum becomes soluble. It can slip into the cells of plant roots, where it poisons cell metabolism and prevents healthy root growth.

One solution is to plow lime into the soil, but lime must be added every few years, can treat only the top layer of soil, and is too expensive for many farmers in developing countries, says plant geneticist Shivaji Pandey, who directs the aluminum-tolerance breeding program for corn at the International Research Institute for Breeding of Maize and Wheat in Mexico City. As a result, farmers in much of the world settle for poor crop yields on acidic soils. The toll is huge: Strains of corn that would yield 10 tons per hectare in neutral soil may produce only 2 tons in acidic soils, says Pandey.

In their effort to create aluminum-tolerant crops that could boost these yields without extra cost, Herrera-Estrella and his colleagues built on prior work by Emmanuel Delhaize and his colleagues at the Commonwealth Scientific and Industrial Research Organization in Canberra, Australia. Delhaize's team found that some naturally aluminum-resistant plant strains have roots that secrete citric or malic acid, which binds to aluminum and prevents it from entering the roots. Several labs are chasing down the mutant gene responsible for the acid secretion, but Herrera-Estrella decided to take a different approach. "It occurred to us that because organic acid biosynthesis is a general phenomenon," he says, "we could use genes from other organisms to produce organic acids in plants."

LUIS HERRERA-ESTRELLA

Invisible shield. In an aluminum concentration that causes malformed roots in wild-type tobacco plants *(bottom)*, the root of a genetically engineered plant *(middle)* grows as normally as one not exposed to aluminum *(top)*.

The organism the researchers turned to was the bacterium *Pseudomonas aeruginosa*. They introduced the bacterial gene for citrate synthase, the enzyme that makes citric acid, into two plant species: tobacco, a popular plant for laboratory work because it is easy to transform with foreign DNA, and papaya, an important crop in tropical Mexico that is highly sensitive to aluminum.

The gene transfers had the desired effect. The plants carrying the citrate synthase gene secreted five to six times more citrate from their roots than control plants did. And that extra citrate translated into aluminum tolerance: The citrate-producing plants could grow well in aluminum concentrations 10-fold higher than those tolerated by control plants. "That is a significant increase," says Kochian.

This degree of tolerance could well allow some crop plants to be planted where they couldn't grow before. For example, Mexico's papaya crop, estimated at $97 million a year, comes from 20,000 hectares of land in the tropics, says Jose Garzon of the National Institute of Forestry, Livestock, and Agricultural Research in Celaya, Mexico. That crop could be expanded, he adds, if the new aluminum-tolerant plants could be grown on some of the 3 million hectares of tropical Mexican land where aluminum toxicity has prevented papaya cultivation.

With tobacco and papaya as a first step, Herrera-Estrella's team has recently moved on to put the citrate synthase gene into two major food crops: rice and corn. They found that the engineered plants make extra citrate, although the results aren't in yet on whether they are aluminum tolerant.

Still, all the work so far has been in the lab, and Kochian and plant physiologist Michael Grusak of the USDA laboratory in Houston caution that the transferred gene may impose physiological costs on the recipient plants; those could show up in the field and offset some of the benefit. All that extra citrate the plants are churning out means that "fixed carbon … is lost from the plant," Kochian says. And that, he says, will impose an extra energy demand that could reduce the plants' productivity. "It is a trade-off," says Grusak, but one that might prove well worthwhile in areas where aluminum takes a serious toll.

–**Marcia Barinaga**