FEATURES

THE NEW POTATO

Breeders seek a breakthrough to help farmers facing an uncertain future

By **Erik Stokstad**, *in the Sacred Valley of the Incas in Peru*

On a bleak, brown hill here, David Ellis examines a test plot of potato plants and shakes his head. "They're dead, dead, dead," he says. Pests and lack of rain have laid waste to all 17 varieties that researchers had planted.

It is a worrying sign for Ellis, the now-retired director of the gene bank at the International Potato Center (CIP) in Lima. People have grown potatoes in this rugged stretch of the Andes for thousands of years. In recent years, that task has gotten tougher, in part because of climate change. Drought and frost are striking more often. The rains come later, shortening the growing season. And warmer temperatures have allowed moths and weevils to encroach from lower elevations.

To find potatoes that can cope with those challenges, researchers and Peruvian farmers are testing dozens of the 4350 locally cultivated varieties, or landraces, kept in CIP's refrigerated storage. The plants in this plot fell short. "Native landraces evolved over time," Ellis says. But, he says, climate change is happening "too fast for these varieties to adapt."

In Peru and around the world, enhancing the potato has become a high priority. It is the most important food crop after wheat and rice. Potatoes are already a staple for 1.3 billion people, and the nutritious tubers are becoming increasingly popular in the developing world. Keeping up with the demand means adapting the potato to various soils and climates. It must also resist new threats from pests, disease, heat, and drought.

Unlike other major crops, however, the potato has not had a breeding breakthrough of the kind that helped dramatically boost yields during the Green Revolution of the 1950s and 1960s. The reason is that creating a new potato variety is slow and difficult, even by the patient standards of plant breeders. Commercial varieties carry four copies of each chromosome, which forces breeders to create and test hundreds of thousands of seedlings to find just one with the desired combination of traits.

Diverse potatoes, such as these from Peru, will help breeders create resilient new varieties.

PHOTO: JIM RICHARDSON/NATIONAL GEOGRAPHIC

Readying a new variety for farm fields can take a decade or more.

Many countries continue to plant popular potato varieties that have remained essentially unchanged for decades. But new approaches, including genetic engineering, promise to add more options. Potato breeders are particularly excited about a radical new way of creating better varieties. This system, called hybrid diploid breeding, could cut the time required by more than half, make it easier to combine traits in one variety, and allow farmers to plant seeds instead of bulky chunks of tuber. "It will change the world tremendously," says Paul Struik, an agronomist at Wageningen University in the Netherlands.

To breed a better potato, it helps to have plenty of genetic raw material on hand. But the world's gene banks aren't fully stocked with the richest source of valuable genes: the 107 potato species that grow in the wild. Habitat loss threatens many populations of those plants. In a bid to preserve that wild diversity before it vanishes, collectors have made their biggest push ever, part of a $50 million program coordinated by the Crop Trust, an intergovernmental organization based in Bonn, Germany.

The collectors and breeders are racing against warming, drying, and the proliferation of pests. "Because of climate change," says Nigel Maxted, a conservation biologist at the University of Birmingham in the United Kingdom, "we require higher levels of diversity than ever before."

THE CLOSEST ANCESTORS of cultivated potatoes evolved in the Andes, where people domesticated the plant at least 7000 years ago. After the Spanish brought the tuber to Europe in the 16th century, it remained a botanical curiosity and was mostly fed to livestock. Europeans began to eat potatoes in earnest only in the 1800s, during the famines of the Napoleonic Wars.

Once the potato caught on, there was no turning back. The plant can grow in cold climates and poor soil, and in some places yields several crops per season. Once harvested, the energy-rich tubers, packed with vitamin C, can be stored for months and cooked in many ways. A hectare of potatoes can provide up to four times the calories of a grain crop.

Like rice and wheat, the potato was a target for improvement during the Green Revolution. Yields increased thanks to fertilizer and improved farming techniques, but they didn't skyrocket. Potato breeders achieved no genetic gains such as the one that produced wheat with short, sturdy stalks that can bear more grain.

Still, global potato production has steadily grown (see graph, p. 576). China has doubled its harvests over the past 20 years. It now grows more than twice as many potatoes as India, the next-biggest producer. Uzbekistan and Bangladesh, among other nations, have come to depend on the potato for food security. In 2005, developing countries for the first time grew more potatoes than the developed world. Many African countries are aiming to boost production.

To reap bigger harvests, farmers will have to manage many risks, including disease. The potato's greatest scourge is the funguslike pathogen *Phytophthora infestans*, which causes a disease called late blight. The pathogen unleashed the Irish potato famine in the mid–19th century, and plant breeders have struggled ever since to rein it in. "*Phytophthora* is always evolving and overcoming resistance," says Jadwiga Śliwka of the Plant Breeding and Acclimatization Institute in Młochów, Poland. Rich countries use fungicides to minimize the devastating losses from late blight. But in developing countries, 15% to 30% of the crop is ruined.

Climate change threatens yields in Potato Park, a farming association near Cuzco, Peru.

Then there is heat and drought, which climate change is exacerbating. In some parts of the world, farmers are planting their crop earlier so that it matures before the nights get too hot, which prevents tubers from forming. But eventually farmers will need hardier plants. "We focus on developing a robust potato that will perform better in a stressful environment," says Thiago Mendes, a potato breeder with CIP's regional office in Nairobi. "Our target is food security."

The key to that robust potato may be waiting in the wild species that grow from southwestern North America through Central and South America. Wild potatoes from Mexico, for example, evolved in the presence of *P. infestans* and can resist many strains. Many other wild species have yet to be thoroughly collected or studied.

IN JUNE 2018, beside a cattle pasture in southern Brazil, botanist Gustavo Heiden strode along an embankment, his eyes fixed on the long grass. Then, he dropped to his knees and jabbed a trowel into the soil. "Aha! Look at this," said Heiden, who works with the Brazilian Agricultural Research Corporation (EMBRAPA) in Pelotas. He pulled up a short plant with small tubers dangling from its roots. It was *Solanum commersonii*, one of three wild relatives of the potato known in Brazil.

Brazil is far from the potato's center of origin in the Andes. But the ranges of wild relatives extend into the state of Rio Grande do Sul, where the climate shifts from temperate to tropical. Plants in this transition zone have evolved to survive occasionally harsh winters and hot, dry summers. "The wild potatoes here are probably pretty adapted to the extreme weather that will be happening more frequently with climate change," Heiden says.

Heiden's collecting trip was just one element of the Crop Trust's effort to collect, conserve, and breed the wild relatives of 29 crops, which began in 2011. Plant collectors used to travel the world on such expeditions. But they became much less frequent after governments began to adopt the Convention on Biological Diversity in the 1990s. Intended to prevent unfair exploitation of biodiversity, the convention made it harder to get collecting permits and to exchange plant material. An international seed treaty established in 2004 eased swaps for crops and wild relatives, but collecting remained stagnant because of lack of funding and expertise. "We didn't have any experience on how to collect wild potatoes or how to conserve them," says Cinthya Zorrilla, subdirector of genetic resources at the National Institute of Agricultural Innovation in Lima.

The Crop Trust has provided grants and training to collectors around the world. The effort on wild potatoes, which wraps up this month, has yielded a collection representing 39 species from six nations: Peru, Brazil, Ecuador, Guatemala, Costa Rica, and Chile. Zorrilla's team alone found 31 species in Peru, including one for which no seeds had ever been collected. They plan to continue to search for four other species still missing from gene banks. "We will not stop," she says. The plants are being stored in each nation's gene bank, CIP, and the Millennium Seed Bank at the Royal Botanic Gardens, Kew, in

PHOTO: JIM RICHARDSON/NATIONAL GEOGRAPHIC the United Kingdom. The stored seeds will be available to potato breeders worldwide.

THE HARDEST PART comes next: getting desirable genes from wild species into cultivated potatoes. In the past, breeders acquired traits such as disease resistance from a dozen wild species. Those victories were hard-won, some taking decades to achieve. That's largely because wild relatives also carry many unwanted traits, which combine with those of cultivated potatoes and vastly lower a breeder's chances of finding a good variety.

Even without wild species, potato breeding is a crapshoot. Because breeding lines have four copies of their 12 chromosomes, the traits of the two parents show up in the next generation in largely unpredictable combinations. As experts say, the current varieties don't breed true, which is why farmers plant bits of "seed tuber," which yield genetically identical plants, rather than seeds. Compounding the headache, breeders select for many traits at once, further lowering the probability of finding a winner. "The numbers get really hard, really fast," says Laura Shannon, a potato breeder at the University of Minnesota in St. Paul.

Genetic markers linked to specific genes have sped up the process. To find out whether seedlings have inherited a trait such as disease resistance, breeders can quickly test for the marker rather than wait for the plants to mature and then expose them to the disease. Even with this tool, a potato breeder must screen up to 100,000 offspring per year. It can take 15 years or longer to find one with the right traits, fully test it, and generate enough seed tubers to distribute to farmers.

Another frustration is that potato breeders can't easily improve existing varieties. Once a potato variety is established, introducing new traits while retaining all of its favored characteristics is practically impossible. That's why classic, widely grown varieties, such as the russet burbank, still dominate the market many decades after their debuts.

Patient breeders using traditional methods can nevertheless achieve impressive results. In 2017, for example, CIP released four new varieties in Kenya, the result of crosses from established breeding lines. In field trials, the new potato plants maintained yields with 20% less rainfall and temperatures higher by 3°C.

Such success shows there is still genetic diversity to be tapped in existing breeding lines. But researchers fear that gene pool may not be deep enough to adapt the potato to future climates or enable other improvements. Wild potatoes, however, hold valuable, untapped genetic diversity. One trait from those wild plants, Mendes says, "could save our life."

THE SEARCH for vital traits is already underway. Last year, at an EMBRAPA research station near Pelotas, technicians in lab coats leaned over the wild species Heiden had collected. They gently daubed their faintly purple flowers with yellow powder from a plastic tube, fertilizing them with pollen from domesticated potatoes.

In a nearby greenhouse, tables were lined with the offspring of previous crosses. Researchers have evaluated thousands of those seedlings for health and yield, among other traits. They screened older plants for drought resistance by limiting the water in plastic-lined troughs. In a temperature-controlled walk-in chamber, researchers tested the ability of other plants to withstand heat; the yellowed plants appeared to be sweltering.

Such expansive testing is aimed at moving wild genes into traditional breeding programs as quickly as possible. It's part of EMBRAPA's larger effort to help Brazil expand production of potato, the country's most important vegetable crop.

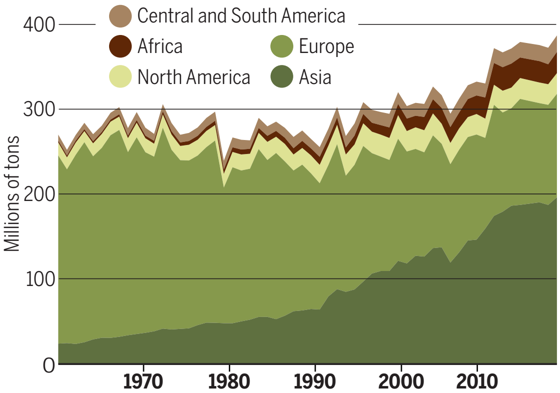
In Lima, the Crop Trust has funded CIP to test wild varieties for promising traits even before any breeding begins. In 2013, center researchers started to characterize 12 wild species collected 30 years ago. Records suggested those species might tolerate drought and resist diseases such as bacterial wilt, a serious problem for developing countries. Merideth Bonierbale and colleagues planted seeds and have tested the plants in greenhouses at CIP's main facility. Mendes is now expanding the work to Kenya.

Other researchers are skirting the limitations of traditional breeding by using genetic engineering. CIP's Marc Ghislain and colleagues, for example, have directly added genes to already successful potato varieties without altering the plants in any other way—an approach not possible with traditional breeding. They took three genes for resistance to late blight from wild relatives and added them to varieties of potato popular in East Africa. The engineered varieties have proved successful in 3 years of field tests in Uganda and are undergoing final studies for regulators. Transgenic potatoes that resist late blight have already been commercialized in the United States and Canada.

Biotech approaches have their own limits. They have succeeded with traits controlled by single genes, such as disease resistance and tolerance of bruising. But improving complex physiological traits governed by many genes, such as water-use efficiency, requires traditional breeding, however cumbersome.

Growing appetite

Potato production has grown in Asia, particularly in China and India, while falling in Europe.



IN WAGENINGEN, Pim Lindhout has been plotting a revolution that would do away with much of that tedium and complexity. As head of R&D for Solynta, a startup company founded in 2006, he and his colleagues have been developing a new way to breed potatoes: creating hybrid offspring from true-breeding parent lines. "Everyone was convinced it's impossible," he says. "Many people thought I was crazy."

Hybrid breeding revolutionized maize production in the 20th century. It enabled breeders to quickly create high-yielding varieties that have what's known as hybrid vigor. The first step is to make inbred parent lines, which have identical alleles on all chromosome copies; the offspring of those true-breeding parents then inherit a predictable set of traits. Making the inbred lines requires repeated self-pollination over many generations. That process tends to impair the health of the plants, but when breeders cross two inbred lines, the first-generation offspring are healthy and have beneficial traits from both parents.

Potato breeders doubted the approach was possible for tubers. "I was trained to believe that potatoes can't be inbred," says Shelley Jansky, a potato breeder with the U.S. Department of Agriculture in Madison. One big obstacle is that many potato species cannot fertilize themselves. In 1998, researchers discovered a gene that somehow allows one wild species of potato to self-fertilize. When that gene is bred into other species, it lets them self-fertilize as well. But the resulting plants are frail and produce puny tubers.

The next step is to inbreed those weaklings by self-fertilizing them, generation after generation. Don't bother trying it at home: Success with cultivated potatoes would likely

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Wild species have traits that could improve cultivated potatoes. Alberto Salas of the International Potato Center in Lima prepares a sample of *Solanum contumazaense* (above); its hairs defend against insects.

take decades because of the small odds of getting the same allele on all four copies of their chromosomes. Breeders reduce the complexity either by using species with only two sets of chromosomes (known as diploids) or by manipulating domesticated potatoes to cut the number of chromosomes in half. With persistence, diploid potatoes can be inbred. In 2011, Lindhout published the first report of inbred diploid lines that are vigorous and productive. More recently, Jansky and colleagues also created inbred diploid lines.

Such diploid inbred plants are at the heart of Solynta's strategy to revolutionize potato breeding. They will make it possible to combine traits in commercial varieties with unprecedented certainty, ease, and speed. And the plants will simplify efforts to add desirable traits directly from wild relatives while eliminating their many drawbacks, such as small tubers or poor flavor. Undesirable traits can be bred out of the descendants of a diploid cross through a standard technique called backcrossing.

In 2016, Solynta conducted its first field trials of hybrid seedlings in the Democratic Republic of the Congo and in 17 locations across Europe. The plants did well, yielding large tubers over a typical growing season. The company has not yet commercialized a variety. Within a few years, it hopes to create customized potatoes for European and African markets. Other firms, including large seed companies, are also working to develop hybrid potatoes. HZPC in Joure, the Netherlands, has begun field trials in Tanzania and in several countries in Asia.

Hybrid breeding "could be a real game changer," says geneticist Glenn Bryan, head of the Potato Genetics and Breeding group at the James Hutton Institute in Dundee, U.K. "It will definitely make breeding more agile."

Basic research could benefit from the work. "Having diploid potatoes will drastically increase our understanding of the potato genome," Shannon says. Although firms typically keep their inbred plants secret, Solynta plans to release a line, dubbed Solynthus, so that scientists can study its genetics. Jansky, for one, hopes further research could reveal genes that control yield, which might then be tapped to boost harvests.

Hybrids could also change how potatoes are planted, giving farmers the option of sowing fields with true seeds, because these are genetically identical in hybrids. Another benefit is logistical; planting 10 hectares, for instance, takes just 200 grams of easily transported seeds, compared with 25 tons of bulky tubers. In the developing world, where quality seed tubers are rare, seeds could also make obtaining superior plants easier for farmers. And in perhaps the biggest advantage over tubers for poor farmers, seeds transmit no major diseases.

Hybrid potato seeds aren't a panacea. Young plants grow more quickly and vigorously from tubers than from seeds, putting seeds at a disadvantage in some climates. And depending on how complete the inbreeding, hybrid potatoes could have less uniformly shaped tubers than those of traditional plants, a problem for farmers who supply food-processing companies. Such complexities have prompted the Dutch government to commission a study of the potential socioeconomic impacts of hybrid potatoes.

With collectors amassing genetic diversity and new techniques promising to overcome the complexities of the potato genome, researchers are optimistic that they can make significant improvements. "That's what gets me up in the morning," Jansky says. "There's no better time to be a breeder—and especially a potato breeder."

UNTIL HYBRID BREEDING and other strategies produce more resilient potatoes, farmers will have to work with the resources at hand. Here in Peru's Sacred Valley, Ellis and others from CIP have teamed with small-scale farmers who belong to an association known as Potato Park, which is dedicated to preserving hundreds of local potato varieties. The group has been planting those colorful potatoes in test plots.

Some succumb to pests or drought, like those that Ellis found dead, whereas others survive. In May 2018, as part of their search for more resilient tubers, Potato Park farmers neatly piled red, yellow, and brown tubers harvested from some of Ellis's experimental plots on rows of sacks, scoring each variety for yield and health. Local farmers had abandoned many of those landraces generations ago, as villages faded and exchange fewer plants.

Bringing some of that ancient diversity back into cultivation could hedge against environmental change. In Potato Park, farmers have already tried to escape the pests and disease that thrive in warmer temperatures by moving their cultivation 200 meters higher over the past 30 years. But René Gomez, CIP's curator of cultivated potatoes, warns that arable land is scarcer at higher elevations.

Pedro Condori Quispe, one of the park's growers, is optimistic that the communities will find a way to keep growing potatoes here. Potato farmers, he says with a smile, "are used to challenges." ■

PHOTO: SARA FAJARDO/CIP

Science

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Science **363** (6427), 574-577.
DOI: 10.1126/science.363.6427.574

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