The Race to Find Plants for a HOT PLANET

In the coming years, the food you get at the grocery store—from rice to beans to greens—could be very different. As climate change threatens many of our current crops, researchers and geneticists are looking for both "lost" and novel varieties that can replace them.

By MARISSA CONRAD

Illustrations by KATE DEHLER

In 1999, as the United States experienced its then-third-warmest year in recorded history, a plant breeder stumbled upon a wild white carrot that might just change the future of how crops are grown. Philipp Simon, Ph.D., a professor of horticulture at the University of Wisconsin-Madison, had just arrived in Izmir, Turkey, a city on the coast of the Aegean Sea. He was there on the hunt for diverse varieties of carrots, including purple ones favored by Turkish farmers. "They grow them for a local drink called şalgam," says Simon. But first, he had to drive to the farms where these violet vegetables grew, "a big circle from Izmir to the east and back," he says.

As Simon and another plant scientist made the journey by Jeep, he noticed wild carrots growing on the side of the road, "just like along the roadside in Wisconsin," he says. These carrots were white and acerbic. They had forked roots, an undesirable trait. Yet, they were surviving, without farmer intervention, in close to triple-digit weather—temperatures that would wreak havoc on the crisp orange carrots grown back home. Simon stopped every 30 miles or so to collect a few.

Today, the seeds from those carrots, and other wild crops like them, are helping horticulturists answer an urgent question: How do we breed fruits and vegetables that will adapt to the world's rapidly changing climate? Historically, the temperature in Kern County, the area in California's Central Valley where more than 80% of U.S. carrots are grown, rarely broke 100 degrees; in 2017, temperatures climbed over 100 on 57 days. Farmers were complaining to Simon about poor crops: bland, knobby, low-yielding. "Things were off," he says.

Farms across America are in the same kind of trouble. In South Dakota, flooding throughout 2019 prevented 40% of farmland from being planted in the first place. In Wisconsin, record rainfall and changing weather patterns have ravaged crops, with the increased humidity affecting last year's broccoli at Plowshares & Prairie Farm, an organic farm in Argyle. "A lot of it got black mold," says Chelsea Chandler, who runs the farm with her husband, Scott. And the future looks worse. By 2050, up to 66% of California's tomato fields may be unfit to grow the fruit, due to extreme heat. Across the country, each time the mean temperature ticks up another 1° Celsius (1.8°F), yields of corn, wheat and soybeans (much of which feed the livestock and poultry raised in the U.S.) are projected to decline by an average of 10%, 6% and 7%, respectively. Globally, in the next 30 years, climate change could shrink total crop yields by up to 12%.

By crossing that tough roadside carrot with today's grocery-store variety, Simon may be able to breed a new type that is orange and sweet but also more tolerant of high temperatures. Across the world, other scientists are working on similar climate-adapted crops: a drought-tolerant bean, salt-tolerant rice, a tomato relative that can grow in swampy soil. "It's a lot of work," Simon says. But there's also a lot at stake, from the micro to the macro. The selection at your store depends on thriving crops. Far more consequentially, so does food security around the globe. Of the tens of thousands of edible plants on the planet, we count on fewer than 20 types—including corn, wheat, beans, rice—to feed the world, and many of them are at risk.

BREEDING CLIMATE-HARDY CROPS

To understand climate-adapted crops, it helps to understand the origins of the produce we eat today. Not one of the plump, pretty fruits and vegetables at the market was born that way, so to speak. Thousands of years ago, farmers began domesticating wild plants, choosing the ones they considered best—the biggest, the fastest-growing, the most delicious—and crossing them to get new generations that combined these desirable traits. An ear of corn, for example, gradually morphed from a scraggly specimen with maybe two rows of kernels to a hefty cob with 20.

But for every wild crop selected for desirable traits that made it good to eat and easy to farm, many others were ignored. Wild plants, despite being hardy, often grow slowly, bruise easily or don't taste very good, among other flaws. "You need to remember that a pretty small gene pool actually went into each domesticated crop," says Stephanie Greene, Ph.D., a plant physiologist with the USDA who researches and conserves wild crop cousins. On the other hand, plants left in the wild got more resilient over time. "They adapted to grow in crazy environments," says Greene. "And so we're reaching out into the wild gene pool to look for those useful genes that might not have been captured when we domesticated the species."

In fields about 12 miles west of his Madison labs, Simon grows thousands of carrots—that Turkish one and many varieties—in screened-in enclosures about 6 feet tall and 3 feet across. Flies and bees buzz about, transferring pollen between the different cultivars of plants. Cross-pollination is a classic breeding technique; in the biz, they call it conventional breeding. "Basically, what we're doing is mixing up the genes from the wild carrot with those of the cultivated carrots, and hoping for, just by chance, the best combinations of those genes," Simon explains. The carrots from a first cross were pale and scrawny. "You'd think, 'What the heck is going on? This isn't a carrot,'" Simon says. He chooses the best of the bunch and crosses them with another batch of cultivated carrots, and does that again and again for every seed generation, until he has carrots that are mostly pulling from the elite gene pool with a dash of wild. Looking at the ones he's working with now, you'd never know they were different from what's at the grocery store.

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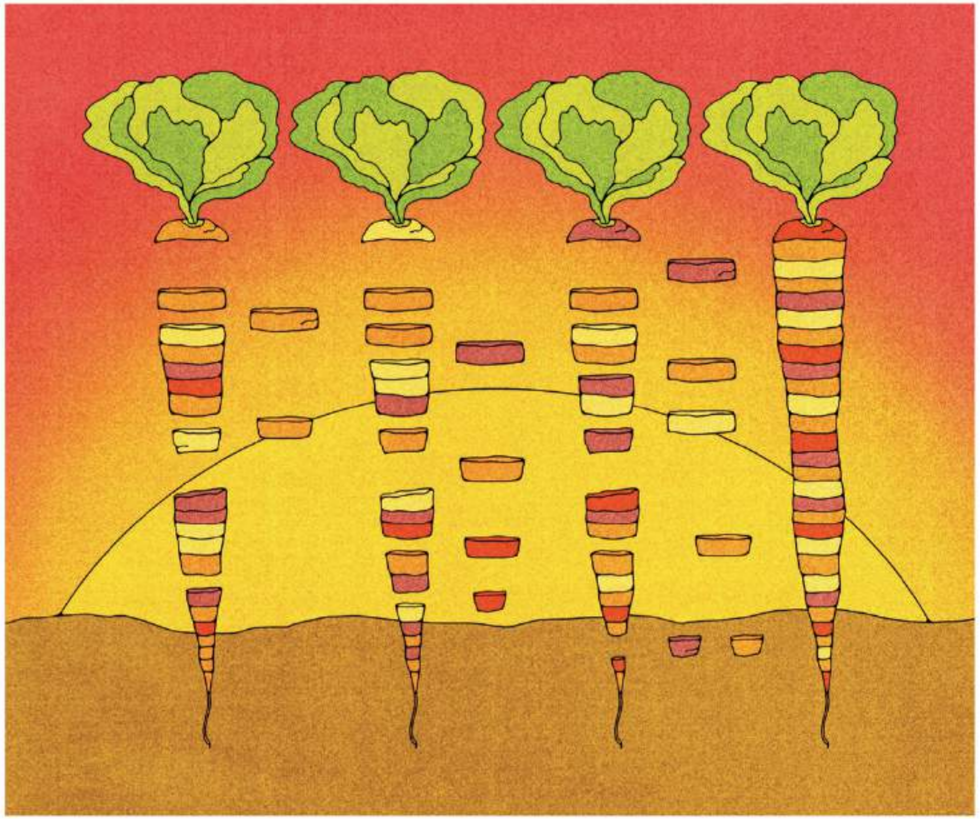
Breeders call this introgression; put another way, the wild trait of interest is bred into the elite line. When a devastating fungal disease (late blight of tomato) threatened tomatoes around a decade ago, breeders discovered that a tomato wild relative from Peru wasn't susceptible and introgressed that resistance into tomatoes. Over the years, many crops have borrowed genes from wild ancestors to fight diseases. Climatic events—temperature swings, rain, drought—are a newer focus. An early victory happened in 2006, when Pamela Ronald, Ph.D., a plant pathologist and geneticist at the University of California, Davis, and her colleagues isolated a gene in an ancient rice species that allowed the crop to survive underwater for 14 days, leading to the development of a flood-resistant rice.

Breeding for climate tolerance is harder than breeding for color, flavor, size or yield. Simon can see if his cross-pollinated carrots are orange or taste if they're sweet. "I eat a lot of carrots over the course of a year," he says. But to know if a carrot offspring has inherited the ability to survive scorching temperatures isn't obvious. Currently, he has 3,000 plots of carrots growing in the California desert, about 8 miles from the Mexican border. The plants that can take the heat will make the cut for the next round of backcrossing with the elite pool. "It's a good 10 to 15 years to move the genes from a wild carrot," Simon says. "If we push hard."

A HIGH-TECH SOLUTION

Introgression is slow because it opens the door to many genetic changes, some that may be less desirable. "To take a step forward, you also need to kind of take steps back," explains Nicholas Karavolias, a plant biology Ph.D. candidate at the University of California, Berkeley. "Let's say this wild crop ancestor has really good disease tolerance. But it also has terrible yields. You're inviting both traits in, only to have to breed one out again."

As an undergrad, Karavolias worked in a conventional breeding program, but at Berkeley he now focuses on a potentially faster route to climate-adapted crops: CRISPR-Cas9, the gene-editing technology that made headlines last year for restoring vision in patients with a rare genetic eye disorder. (Using this molecular tool, sometimes called genetic scissors, doctors sent an enzyme into the eye's nerve tissue to "snip" and correct the mutated gene.) Jennifer Doudna, Ph.D., the co-developer of CRISPR who co-won the 2020 Nobel Prize in chemistry, is excited about what the tool can do with plants, "especially as we deal with the challenges of climate change," she said at a lecture in September.



Genes are depicted by lines of code—a bunch of As and Ts and Cs and Gs (representing the chemicals adenine, thymine, cytosine and guanine) that tell us, for example, how large a plant will grow or what color fruit it will bear. One way to use CRISPR is to decipher the genetics of a beneficial trait from a crop wild relative, then edit the genetic code of the domesticated crop so it has the same characteristics—a procedure known as a knock-in. This is a more precise version of what Simon's bees are doing to his carrots, though it's not a simple copy-and-paste. Traits like heat- and drought-tolerance are usually polygenic, which means there could be thousands of genes, working together in complex ways, that account for why a plant is able to survive in a harsh climate.

Karavolias is more focused on the potential of using CRISPR to perform knock*outs*. Similar to what doctors did with the vision-impaired patients, this involves identifying genes that, if deleted, could improve a plant's climate tolerance, and then using the Cas9 tool to cleave those genes. This can be less difficult than inserting genetic code, and in some countries, subject to fewer regulations. "It's kind of sociopolitical, why we're pursuing knockouts," he says.

In the U.S., edited crops are not considered to be genetically modified organisms by the USDA. That's because GMOs contain DNA from a different species, like inserting apple genes into a kiwi, or even enlisting bacteria from a foreign organism as the vessel that carries kiwi DNA into another kiwi, an older way of using the CRISPR technology. The way breeders use CRISPR today is to insert DNA from the same species (apple to apple, kiwi to kiwi) sans foreign bacteria, or to cleave a gene, making fruits and vegetables that could have been created by nature. Per a new rule abbreviated as SECURE, the USDA does not subject CRISPRed crops to biotech regulations if the same change to the plant could be achieved through conventional breeding. In an editorial for *The CRISPR Journal*, geneticist Rodolphe Barrangou, Ph.D., called SECURE "arguably the most significant, and perhaps overdue, new regulatory framework for plant breeding since 1987." That said, the rule, at nearly 49 pages, details how many insertions and deletions of genetic code, under what circumstances, are and aren't allowed—making a relatively simple single-gene knockout all the more appealing.

In September, Karavolias and colleagues published a review of work researchers around the world have done in the field of climate-adapted agriculture.

"More or less, every example is based on a knockout," he says. For example, knocking out a gene in rice plants known as OsRR22, which was associated with salt susceptibility, helped the plants grow in sodium-rich conditions, potentially of use in areas where rising sea levels have led to saltwater-contaminated fields.

Karavolias has worried about climate change since 2005, the day that his third-grade teacher warned his Long Island class about global warming, as it was then commonly called. "It just really clicked for me," he says. "I decided that it was terrifying." Often, in the car with his family on hot days, he would scream the words "global warming" over and over until a sibling talked him down. As he got older, he began to think about how he could be part of the solution. It was personal too. His parents, who emigrated from Cyprus, both came from farm families. "I've seen the ways that my uncle, raising olive or citrus crops in Cyprus, could benefit from technology, varieties, developments that occur," he says.

Karavolias recently shipped off his latest project, a drought-tolerant rice variety, for field testing. It took him three years to get this far. There are no guarantees, but he hopes that the seed will be ready for distribution in another few years. It has the potential to help rice farmers all over the world, from Colombia to Arkansas.

REDISCOVERING "LOST" CROPS

Plant physiologist Stephanie Greene sometimes compares wild species to wolves and elite crops to poodles. In the middle of that spectrum is a wealth of genetic diversity. Landraces are crops that have been domesticated to some extent but not intensively bred, grown by small-hold farmers for generations (many heirlooms fall under this category). Landraces may not be as productive as elite cultivars, but because they've persevered without much coddling, they're resilient. Then there are orphan crops, which are similarly grown on a small scale, have often adapted to extreme conditions and haven't received much attention from researchers. These crops, such as the lablab, a drought-tolerant bean grown in some parts of Africa, offer an interesting opportunity for breeders. Instead of retrofitting elite crops to handle extreme weather, could they take a crop that's already hardy—one with potential for large-scale growth—and edit out some of its flaws? "Can we elevate an entire family of orphan crops?" asks plant geneticist Zachary Lippman, Ph.D., a Howard Hughes Medical Institute investigator and professor at Cold Spring Harbor Laboratory, a leading research center in New York. "This is where I think genome editing gets really exciting."

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Lippman's lab works with orphan crops, such as the African eggplant, a distant relative of the tomato. One edible and attractive cultivar, grown in sub-Saharan Africa, is small and red and looks like a cross between a tomato and a miniature pumpkin. Other varieties are white or orange. Some can grow in swampy, inhospitable soil or in upward of 110°F heat. Many are prickly and impractically large. Lippman is using CRISPR to try to eliminate the prickles, shorten stems and kick up the yield. "Farmers facing crop loss should have the ability to say, 'OK, I want to try the African eggplant. It's going to be able to grow in soils that are more challenging,'" he says.

In 2018, Lippman achieved a similar transformation in the groundcherry, a South American orphan crop with sweet berries. He got a lot of attention for it, but notes that working with orphan crops is not a slam dunk—it's more complicated than that. "The reality is that a lot of this is still a black box," he says. Yet: "The other side of the coin is that it's working."

Ultimately, he sees potential in a combination of gene editing and conventional breeding. With CRISPR he can make a few leaps, called step changes—using what he knows about, say, the tomato's DNA to target the gene that might increase yield or accelerate growth in the African eggplant, its orphan-crop relative. From there, conventional breeding could step in to try for adaptations where it's not so obvious which genes to target, ones that might take a few generations of selection to achieve.

There are many orphan crops to explore, Lippman notes, adding that "teff is a great example." The grain is nutritious and drought-tolerant. On the flip side, rain can wipe it out pretty easily, and the plant's tiny seeds—the smallest of all grains in the world—often blow away in the wind. "It's a horrible plant," Lippman says. "Is it worthwhile to make it into a genome-edited less-horrible plant or not-at-all horrible plant? I don't know. But those questions can and should be asked across the board."

COMING TO A GROCERY NEAR YOU

In 2020, SCOPE, a plant-breeding project at UC Davis, unveiled six varieties of heat- and disease-tolerant dried beans, bred conventionally by crossing common varieties with more resilient relatives. Farmers around the country are growing the new varieties now, and a California-based company called Primary Beans, founded by sisters Lesley and Renee Sykes, will be among the first to sell them.

Globally, organizations such as the International Rice Research Institute and the International Crops Research Institute for the Semi-Arid Tropics are helping to distribute climate-adapted seeds to farmers struggling with the effects of climate change. The crops are already making a difference. In the semi-arid tropics of India, farmers who planted drought-tolerant groundnut increased their yield by 23%. More than 6 million farmers around the world are now growing flood-resistant rice, making it the fastest-adopted rice variety in the history of modern farming. And in 2019, the Crop Trust, an international nonprofit based in Germany, wrapped a seed collection project of unprecedented size. After six years of scouring deserts, grasslands and mountains in 25 countries for crops that naturally grow in harsh conditions, collectors returned with more than 4,600 different samples. Ahmed Amri, Ph.D., a plant geneticist in Morocco, searched more than 400 miles of Mauritania, in northwestern Africa, during one of his collection missions. He was successful, bringing back samples of heat-tolerant wheat, barley and sorghum.

Seeds like this will live in vaults around the world, where breeders can request to work with them, almost like a library. Greene is the seed curator for the U.S.'s largest seed vault, a high-security building in Fort Collins, Colorado, designed to withstand tornadoes and floods. "It's pretty amazing," she says. She recently oversaw research to collect and conserve U.S. native wild relatives of blueberries, raspberries, pecans, plums, sunflower, potatoes, barley and other crops—all "valuable genetic resources," she says. Maybe one of these wild crop cousins will, one day, help save blueberries in Maine, suffering through hotter springs, or barley in North Dakota, drowned by wetter summers.

Moving CRISPR-edited crops from lab to grocery store is more of a challenge. The Broad Institute, a genomic research center in Cambridge, Massachusetts, holds the commercial patent to use CRISPR-Cas9 on plants. To bring edited produce to market, a breeder would need to license the seeds through the institute, likely for a steep fee. Some fear this will give a leg up to companies using CRISPR not just for climate work, but to develop food that can be sold at a premium. Pairwise, a startup backed by $125 million in funding from ag-tech conglomerate Monsanto (now Bayer) entered a CRISPR-Cas9 licensing agreement with the Broad Institute in 2019 for an undisclosed sum. Among their big projects? Seedless berries and less-bitter salad greens.

Back on Long Island, Lippman let his thoughts move from what's possible now to what might happen in 10 or 15 years. Eventually, he says, breeders might be able to use CRISPR to rewrite a plant's entire genome, editing dozens of traits in one sweep. "We can be realistic now, but we should also be optimistic, open-minded and embracing of the technology and all that's coming with it," he says. "Let's roll, let's run—you know, let's just do this."

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