AGROBIODIVERSITY

The living library

Wild and heirloom plants are giving major crop varieties, and the global food system, a genetic makeover.

BY KARL GRUBER

Tomatoes come in all colours and sizes; some wild species have traits that may benefit commercial varieties.

SONJALAZUKIC/GETTY

The world has more than 50,000 edible plants. But 90% of the world's energy demands are fulfilled by just 15 crops, according to estimates by the Food and Agriculture Organization (FAO) of the United Nations. About two-thirds of our calorie intake is provided by three: rice, maize (corn) and wheat.

Dependency on a handful of crops is problematic. In cultivating countless generations of a few staples, we have inadvertently lost some of their most valuable properties. Modern crops are susceptible to changing climatic conditions, for example, and are heavily affected by pests, which can claim 30–40% of global production of staple crops such as maize, rice and potatoes[1] and call for ever-stronger pesticides.

The nutritional content of what we grow is also declining. "Breeding and intensified cultivation for high yield tend to reduce the concentration of nutrients," says Donald Davis, now retired, but who in 2004 documented, with colleagues at the Bio-Communications Research Institute in Wichita, Kansas, the nutritional decline of dozens of fruits and vegetables over a 50-year period[2]. Modern staples may produce more grain or fruit than their ancestors, but the edible product is not able to absorb or synthesize a corresponding amount of nutrients, Davis explains. In broccoli, for instance, iron has fallen by 32% and zinc by 37% since 1950. "Bigger heads mean lower mineral concentrations," says Davis. "I always buy the smallest heads I can find."

Demand for food is set to increase over the next few decades (see page S6). To address issues of nutritional quality, scientists are looking to nature for help. Millions of years of adaptation to varied and often extreme environments has created a rich genetic diversity of wild relatives of modern staples. These plants represent an immense library of valuable traits with the potential to improve the quality and resilience of modern crops. Across the globe, researchers are trying to endow domesticated crops with these traits through interbreeding. "Plant-breeding programmes benefit from such genetic diversity by creating new crop varieties that are nutritious, use natural resources more efficiently, and are able to respond to stringent environmental conditions and destructive pests and diseases," says Nora Castañeda-Álvarez, a plant biologist at the Crop Trust, a non-profit organization in Bonn, Germany. But if the full potential of plant-breeding programmes is to be realized, scientists need to conserve the many wild varieties that are threatened with extinction, before these plants disappear and take their secrets with them.

BUILDING RESILIENCE

The humble tomato is a staple crop in a large part of the world. It is the third most cultivated vegetable crop, according to the FAO, after potatoes and cassava; in 2014, around 170-million tonnes were produced, belonging to about 7,500 varieties of the species *Solanum lycopersicum*. But there is room for improvement. Wild tomatoes grow in a wide range of habitats, in defiance of pests and soil quality, and researchers are exploring whether these traits could be transferred to commercial varieties to improve resilience.

A commercial tomato that could naturally fight off pests would be a major asset. Peter Hanson and Mohamed Rakha, plant geneticists at the World Vegetable Centre in Tainan, Taiwan, are using the wild tomato species *Solanum pimpinellifolium*, *Solanum galapagense* and *Solanum cheesmaniae*, all of which are found on the Galapagos Islands, to create new tomato varieties that are resistant to multiple diseases and insect pests.

These wild tomatoes can fight off insects thanks to small hair-like structures called glandular trichomes that cover the leaves and stems. "These trichomes produce acyl sugars and other compounds that repel or are toxic to a wide range of insects," says Hanson.

Endowing a commercial tomato with these insect-repelling hairs involves 'backcrossing' with one of the wild species. Hanson is using a tomato elite line (a stock of pure seeds with certain traits) called CLN3682C, which is already resistant to bacterial wilt, tomato yellow leaf curl virus, root-knot nematodes and fusarium wilt.

The plants that result from a cross are screened to identify those that carry the wild trait of interest as well as those already held by the elite variety, explains Hanson. If the wild insect-resistance traits have been genetically sequenced, selection can be accelerated — rather than monitoring expression, researchers can simply look for the presence of the gene or allele, known as marker-assisted selection.

The selected plants are then crossed with the elite variety to increase the odds of a plant carrying every possible desirable trait. "Insect-resistant varieties must also produce high yields of high-quality fruit," says Hanson.

This whole process is repeated for each wild species, so it takes time. "Each cross and selection takes most of a year to complete," says Hanson. He estimates it will take about five years before a commercial tomato variety bearing the wild traits of insect resistance is available.

In 2016, Mark Tester, a plant biologist at King Abdullah University of Science and Technology in Thuwal, Saudi Arabia, and PhD student Yveline Pailles found that *S. galapagense* and *S. cheesmaniae* are also able to thrive in highly salty soils[3]. The aim now is to breed this trait into commercial lines.

"Tomatoes are the world's biggest horticultural crop, by far, and they use a lot of water," says Tester. Commercial tomatoes need fresh water — an increasingly limited resource. "A major water source that is currently unused is brackish water," he says. "This is the driver of my research."

The Svalbard Global Seed Vault.

CROP TRUST

He estimates that new lines of salt-tolerant tomatoes could reach breeders in a couple of years.

PACKED WITH GOODNESS

Researchers are also improving the nutritional properties of tomatoes. In 2003, Hanson and colleagues released two tomato varieties in Taiwan that were bred to pack up to six times more vitamin A than the average tomato. The source of this, as well as their characteristic orange colour, is a gene called *Beta*, discovered in the wild tomato *Solanum habrochaites* in 1950, Hanson explains.

"We hope our high-beta carotene cherry tomato varieties can become popular in home gardens in countries like Bangladesh where vitamin A deficiency is a problem, especially among children," Hanson says. But demand in the first ten years has been poor. Hanson attributes this to difficulties in convincing people that orange-fleshed tomatoes are as good and tasty as the familiar red varieties. "The key factor is creating consumer demand," he says, but a lack of resources has hampered the promotion of his tomatoes.

At Oregon State University in Corvallis, vegetable breeder and geneticist Jim Myers is also creating more-nutritious tomatoes. He has bred purple tomatoes that are rich in antioxidants called anthocyanins. Tomato breeders have been trying to generate an anthocyanin-rich variety from various wild species, including *Solanum lycopersicoides*, *Solanum peruvianum*, *Solanum chilense* and *S. cheesmaniae*, for half a century, with little success. The one variety produced from these efforts, the Purple Smudge, was created in the 1950s and only weakly expresses anthocyanin-producing genes.

Myers and his team crossed *S. chilense* and *S. cheesmaniae*. "If we combine the genes from the two wild species, then we obtain a dramatic increase in pigment expression — tomatoes as black as an eggplant," Myers says. The result is the Indigo Rose, which contains between 10 and 30 milligrams of anthocyanin per 100 g of fresh fruit; the average tomato contains none.

There are more than 20 Indigo Rose cultivars commercially available in the United States, most of which have been bred from the original lines that Myers created.

Breeding wild traits into commercial crops is a lengthy process. To speed things up, neglected crops can be used in their entirety (see 'Investment in indigenous crops') or commercial plants can be genetically modified (GM). Indigo Rose tomatoes are not classed as GM — Myers used only conventional breeding techniques. Genetic modification techniques allow researchers to insert genes of wild varieties directly into plants, greatly increasing the speed at which new cultivars can be created. Genes can also be sourced from different organisms, such as bacteria. "At that point, the possibilities of introducing new characteristics into our crops will be, in principle, unlimited," says Francesca Quattrocchio, a plant geneticist at the University of Amsterdam.

"Insect-resistant varieties must also produce high yields of high-quality fruit."

But although GM crops are accepted in Australia, the United States and most of South America, there is significant opposition elsewhere. GM crops are either banned or have to go through an intensive authorization process in many European and African countries. Any time saved in the creation of a new variety through genetic modification is lost by hold ups further down the line, and restrictions on who can use it.

SAFE BET

The valuable genetic diversity held in wild-crop relatives could be at risk, however. More than 70% of wild relatives have been identified as being in urgent need of conservation[4]. As a whole, around 20% of the world's plants are threatened with extinction[5].

The expansion of agriculture into natural ecosystems is one of the leading causes of this decline, Castañeda-Álvarez says. And plant

RURAL FARMING

Investment in indigenous crops

In 2016, researchers at the World Vegetable Center released a report[6] outlining some of the most important but underused African crops. One of these is a genus of leafy plant called *Amaranthus*, which is found widely across African and Asian countries. “The amaranth grain can be consumed in various forms, turned into flour or even popped as popcorn,” says Fekadu Fufa Dinssa, a vegetable breeder at the World Vegetable Center’s regional programme for Eastern and Southern Africa in Arusha, Tanzania. The grain is richer in protein, iron and vitamin C than wheat, maize and brown rice. Amaranth flour can be blended with maize flour to make ugali — a staple dish in many African countries — to improve the ugali’s nutrient content.

Amaranth is one of a host of plants used by indigenous communities around the world that researchers are turning their attention to. The appeal of these traditional crops lies in their pre-adapted condition. Unlike a new line of rice or wheat that requires careful testing before it can be used commercially, and may not be suited to every environment, these underused crops have been growing locally for centuries. They are well adapted to their environment, and often resistant to a region’s pests and diseases.

At the centre of the effort to bring back traditional crops is the not-for-profit organization Slow Food International in Bra, Italy. The group is collating valuable information on crops used by indigenous communities, including how they are cultivated and used.

Once registered in Slow Food’s Ark of Taste database, the organization nurtures these traditional crops, and the agricultural and processing methods associated with them, by building local groups of small-scale farmers that it calls Presidia.

“Through our Presidia and other projects we aim to help local communities secure a sustainable source of food,” says Edie Mukiibi, vice president of Slow Food International. “Rather than trying to get rice or wheat to a far-away location where these crops are not traditionally found, we believe in promoting the use of local products that are already adapted and ready to be used as crops,” he says.

The project provides farmers in more than 500 Presidia in 60 countries, including many that have pressing food-security problems, with technical assistance and advice on how to improve production and promote their produce. One Presidium is in the lowlands of the Gran Chaco, a bioregion encompassing parts of Argentina, Bolivia, Brazil and Paraguay. Around 1,600 women of the Wichí and Comle’ec ethnic groups work together in the region to preserve knowledge about local fruits such as those of the white carob tree (*Prosopis alba* and *Prosopis chilensis*). These oblong fruits with a fleshy, sugary pulp have seeds that can be ground into flour and used in pastries. The Presidium has written a guide (see go.nature.com/2ohgqr2; in Spanish) highlighting the fruits of the region and their uses, and its work has led to the enrichment of native woodland with around 300,000 carob trees. K.G.

species in the tropics are twice as likely to be threatened as those in temperate regions[5]. “These plants and animal breeds have developed and survived because they were best adapted to a given territory,” says Edie Mukiibi, vice president of Slow Food International, an organization in Bra, Italy, that works to prevent the disappearance of local food cultures. “We must take care of this biodiversity because it represents the best of several millennia of agriculture.”

The International Potato Center in Lima is seeking to protect potato varieties *in situ* through their *Chirapaq Ñan* network. The idea, says Severin Polreich, a plant geneticist at the centre, is to record locations across Peru, Bolivia and Chile with a rich diversity of potato varieties. “This network will help enable and support *in situ* conservation monitoring of the world’s largest potato gene pool, right at its centre of diversity,” he says.

Other projects focus on conserving wild varieties outside their natural habitats. Around the world, about 1,750 gene banks, as well as botanical gardens, hold more than 7.4 million seeds or plant tissues from thousands of crop species. Nearly 90% of these samples are held in national gene banks — the Centre for Genetic Resources (CGN), part of Wageningen University in the Netherlands, for instance, currently holds one of world’s largest and most diverse collection of lettuces.

> *“We must take care of biodiversity, it represents the best of several millennia of agriculture.”*

To protect against the loss of seeds in collections such as these, the Svalbard Global Seed Vault acts as a backup. Located deep in a mountain on the Norwegian archipelago of Svalbard, the bank has capacity for 2.5 billion seeds; currently, it holds more than 880,000 samples, representing the world’s major food crops. The seeds are meant to be used only in an emergency — be it a major catastrophe or incremental loss of diversity over time. “Each gene bank prepares a duplicate of their collection and sends this to Svalbard,” explains Castañeda-Álvarez. “External users, like you and me, can’t make seed requests directly to Svalbard — this can only be made through the corresponding gene bank in case of emergency,” she says. The only withdrawal so far was made by the International Centre for Agricultural Research in the Dry Areas (ICARDA) in 2015, to re-establish its collection after it relocated its gene bank to Lebanon and Morocco from Aleppo, Syria. In February, ICARDA returned more than 15,000 seeds to Svalbard.

The Crop Trust, which is responsible for the vault, sees the preservation of crop diversity as a crucial means of attaining global food security. The trust also heads a US$50-million research initiative on crop wild relatives, in collaboration with the UK’s Royal Botanic Gardens, Kew, and a number of breeders and researchers around the world. The ten-year initiative launched in 2011 and is funded by the Norwegian government. The aim of the project is to collect and preserve more than 450 wild relatives of 29 priority crops, says Hannes Dempewolf, Head of Global Initiatives at the Crop Trust. In the long term, the plan is to breed a new generation of superior crops that carry one or more of the desirable traits of their wild relatives. Pre-breeding programmes — in which genetic traits are isolated and introduced into breeding lines that are easier to cross with commercial varieties than wild plants — have been established for 19 wild relatives, including aubergines and rice.

Wild-crop relatives look set to be a part of the answer to the food-insecurity problem, whether they are used to form new crops or growers simply make better use of the neglected crops already available to them. “The genetic diversity available in wild varieties is, at the moment, the best solution,” says Quattrocchio, at least until GM crops gain wider acceptance. Castañeda-Álvarez agrees, “Crop wild relatives can help us to continue producing more sustainable food, in the amount and quality the world needs.” But first, she says, “we need to conserve them to secure their availability”. ■

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