Researchers are trying to develop varieties of crops such as rice that can thrive even in the most severe droughts.

PLANT BREEDING

Discovery in a dry spell

Improved crops have helped farmers maintain yields in times of drought. But as climate change looms, will the gains keep coming?

BY MICHAEL EISENSTEIN

Rice growers in the northeastern Indian state of Jharkhand have known for some time how to maximize crop yields during droughts: they cultivate their seed beds during the hot, dry summer months and transplant the seedlings at the start of the rainy season in July. Unfortunately, these strategies are increasingly ineffective in the face of highly erratic rainfall and drought patterns, and the results have been devastating. “For three years in a row, farmers have had their rice seedlings ready in the nursery but they were not able to transplant because there was not enough water,” says Arvind Kumar, a breeder specializing in drought-tolerant rice at the International Rice Research Institute (IRRI) in Los Baños, the Philippines.

A landmark 1982 study¹ of staple crops such as wheat and corn by John Boyer, a plant physiologist at the US Department of Agriculture

(USDA) in Urbana, Illinois, revealed the scale of the damage done by droughts. He estimated that up to 69% of yield losses in North America were potentially attributable to abiotic stresses — those arising from environmental conditions such as heat and water deprivation. Bolstering crop defences against such stresses has been a priority for decades. Today’s grain plants are dramatically more bountiful than their ancestors, and maintain higher yields in hostile conditions. Since the middle of the twentieth century, annual yields of maize, for example, have increased by 60 to 100 kilograms per hectare under both water-scarce and normal conditions, according to François Tardieu, a plant physiologist at the French National Institute for Agricultural Research (INRA) in Montpellier.

Mark Lawson, who leads research into yield and stress at the agricultural company Monsanto in St Louis, Missouri, points out that this steady improvement prevented the recent

North American drought from becoming a full-blown catastrophe. At the start of 2012, “the USDA predicted corn yields of around 160 bushels per acre, and the final yields ended up being 123,” he says. “But in 1988, which was the last year we had a somewhat similar drought, yields were around 85 bushels per acre, and I think that’s a testament to improvements in our ability to manage plant stress.”

But such a rate of gains might not be sustainable. “A lot of wheat and corn are growing at the limits of where they like to be, temperature-wise,” says David Lobell, associate director of the Center on Food Security and the Environment at Stanford University, California. Any further rise in temperature would threaten productivity and raise costs for staple crops in many regions. This environment of heightened risk and uncertainty has injected more urgency

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Recently developed rice varieties are providing greatly improved yields.

into the hunt for drought-tolerant plants. But it remains unclear whether agricultural researchers can continue to deliver the yield gains of recent decades, or whether such gains are even adequate for the changes ahead.

BEST OF BREED

Heat and drought are deadliest during a plant's flowering phase, when reproduction is occurring. Many crops have evolved mechanisms to accelerate flowering before the dry season arrives. Breeders have exploited this feature to generate early varieties of crops through traditional cross-breeding. "In Australia, adjustment in flowering time has been the biggest factor in improving wheat yield," explains Richard Richards, who leads research to breed high-performance crops at Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO).

Breeders at IRRI have also used conventional breeding strategies to generate Sahbhagi Dhan, a rice variety that flowers weeks earlier than other types. This variety, which is now cultivated throughout South Asia, "can provide farmers with a yield advantage of one tonne per hectare under drought," says Kumar.

Conventional breeding is slow, however, and makes it difficult to amplify specific traits. Many researchers are instead using 'molecular breeding' to target the genetic determinants of drought tolerance. Molecular breeding uses marker-assisted selection (MAS), a process of controlled plant crossing that allows researchers to find genomic regions associated with improved productivity, which may contain genes that enable the plant to produce more grain from a limited amount of water. These quantitative trait loci (QTLs) can then be bred into existing varieties to improve their robustness.

Rajeev Varshney, a geneticist at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in Andhra Pradesh, India, is using MAS on crops such as chickpea and groundnut. These crops are important sources of nutrition in many drought-prone regions, but they have been largely ignored by the agricultural industry. "We identified a genomic region in the chickpea that contains QTLs for several drought tolerance-related traits," says Varshney. "When we did molecular breeding with this QTL, we found a gain of 10–20% higher yield in an already drought-tolerant chickpea variety."

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The newer approach of creating genetically modified organisms (GMOs) has so far delivered little in the way of improved drought resistance. Several companies are exploring GMOs, including the Canadian company Performance Plants, based in Kingston, Ontario, which has developed genetically modified 'heat and drought tolerance' (HDT) varieties of various crops. "We've done field tests with HDT canola in hot regions of Chile, and saw a range of 28–50% improvement, depending on the severity of the stress," claims Yafan Huang, the company's president and chief scientific officer.

Even with a promising transgene, however, the process of developing GM plants is daunting. Huang estimates that it could be 5 years before Performance Plants seeks regulatory approval for any HDT crop, partly because of the laborious process of ensuring that the inserted gene is active only at the right time and in the right amount.

The first — and so far only — USDA market approval for a drought-tolerant GMO was in December 2011 for Monsanto's DroughtGard maize, which expresses *CspB*, a stress-response gene originally identified in bacteria². This gene enables plants to decrease the rate at which they absorb water from the soil in dry conditions. Mark Edge, who led Monsanto's drought-tolerance project, makes it clear that DroughtGard does not guarantee productivity in a drought, but says that it can provide some insurance. During Monsanto's field trials, "a number of growers lost their plots," says Edge. "But we had several growers whose DroughtGard crops lasted another ten days, and then rain came through, and all of a sudden you have got a huge difference because of those extra days."

Not all scientists are convinced that GMOs are worth the time and money invested, however. "There is clear proof that breeding and molecular breeding have given a 1% gain in yield per year," says Tardieu. "If Monsanto has improved yield under drought by around 6%, this is great, but it's nothing more than five or six years of conventional breeding." Progress on GMOs is also limited by the sometimes daunting regulatory and cultural hurdles they face. For example, although Monsanto received US approval for DroughtGard in 2011, this was of little value to the many US farmers who produce for the export market until China approved the import of DroughtGard maize in June 2013. More recently, the company announced that it will abandon its efforts to seek European Union approval for its GM crops in the face of multiple stalled approvals and both political and cultural hostility towards GMOs in general.

THE YIELD IN THE FIELD

Although geneticists have made steady progress in manipulating the way plants in the lab manage their water use, these improvements have rarely translated into benefits in the field. "Many papers look at seedlings in a Petri dish, where you can get a lot of fast results," says Huang. "Nobody wants to look at yield — but for agronomists, yield is everything."

Many plant physiologists are therefore taking a top-down approach to dissect the secrets of successful plants. As well as the strategies described above, plants also survive dry conditions by using avoidance and tolerance processes, modulating their ability to harvest more water from the environment and maintaining healthy function when water is limited. Some of these strategies are more effective than others. "It could involve a deeper root system," says Richards — but that's ineffective if there is no deep water. "Another way might be to reduce evaporative water loss from soil by developing leaves that better shade the soil."

There are trade-offs to be made as well. Shutting down production in drought conditions will render a crop worthless, whereas

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focusing on producing fruit or grain at the expense of maintenance may lead to premature death. The ideal plant should therefore maintain a careful balance. “There are plants that cleverly change their mechanism to continue transpiration,” says Kumar, referring to the process by which plants control water loss through stomata — the openings that also draw in carbon dioxide. “These plants open their stomata only to the extent that is required to continue their productivity, yet grow grain only to the extent that is possible — these are plants that breeders want.”

Several researchers have devised platforms for the automated analysis of hundreds of plant specimens in parallel. As coordinator of the European Union’s Drought-Tolerant Yielding Plants (DROPS) project, Tardieu uses two such platforms, Phenoarch and Phenodyn, to monitor the growth and physiology of plants under different conditions. “We have one panel of 250 maize plants and one panel of 200 durum wheat plants that we have genotyped, and we are trying to characterize them thoroughly,” he says. Tardieu makes it clear that these platforms cannot quantify yield improvement — instead, his team couples these platforms with an extensive network of field experiments to identify plant phenotypes that correlate meaningfully with drought performance in the real world.

Reality checks such as these are vital but are surprisingly rare. “There is an excess of people with expertise in biotech but without experience in the field,” says José Luis Araus Ortega, a plant physiologist at the University of Barcelona in Spain. To close this gap, Araus and his team are exploring high-tech methods of gathering in-depth phenotype information from entire fields of experimental crops under different environmental conditions. By using near-infrared and multispectral images, for instance, his team can collect information about vegetation, water status and photosynthetic efficiency.

But drought conditions vary dramatically from region to region, so no single trait will confer ideal drought resistance for farmers everywhere. For example, there is little irrigation in Australia, rendering the country dependent on rainfall to sustain its extensive wheat fields and making it highly vulnerable to drought. Accordingly, CSIRO scientists have put considerable effort into breeding wheat with improved ‘water-use efficiency’ — maximizing the grain production a plant can maintain with a given amount of water. This tactic helped to mitigate the effects of Australia’s ‘millennium drought’ (whose worst years were 2001–09) but these plants tend to be small and underproductive in milder conditions. “In most drought scenarios in Europe, this material would not be helpful, because we have more water than Australia,” says Tardieu.

Crops in many regions face both water shortage and high temperatures — stresses that

Last year’s drought in the United States highlighted the need for maize that can withstand heat stress.

trigger different physiological responses that can compound each other’s effects. Lobell and colleagues have shown that an increased number of extremely hot days during the summer can make plants ‘thirstier’, so they use more of the limited water, and this can stimulate water stress even if rainfall remains unchanged³. Tackling both stresses simultaneously could bring great benefits for some regions. Indeed, this could be a critical consideration in developing future-proofed, drought-tolerant crops. Various climate models from the Intergovernmental Panel on Climate Change (IPCC) suggest that the average global surface temperatures in 2100 will be 1.1–6.4 °C higher than they were in 2000, potentially resulting in more extreme environmental conditions than we find in today’s droughts. “You might want a very different type of plant in that situation,” says Lobell.

SPREADING THE WORD

These advances in crop technology are slow to reach the developing world, however. “It takes six or seven years for a variety to reach the poorest farmers in drought-prone areas,” says Kumar. Even when new varieties arrive, they may not be adopted. Many smallholders are not only supporting their own livelihood but also feeding their families. Accordingly, new seed varieties can be seen as too risky unless farmers can see the improvements for themselves. “We do something called ‘farmers’ participatory varietal selection’, where we go to those smallholders and take an area of around 0.5 hectares and demonstrate the crops,” says Varshney. “We then ask: ‘We gave you these six varieties and you grew your traditional variety — which one was best?’”

Building local capacity for research and development (R&D) can also help accelerate progress. But this is heavily dependent on local governments and private-sector investment, so progress varies from crop to crop, and region to region. The Bill & Melinda Gates Foundation has been a powerful force in this regard, expanding local access to drought-tolerant crop varieties and building regional expertise.

Two such projects are the Generation Challenge Programme, an initiative from CGIAR (the Consultative Group on International Agricultural Research) that aims to strengthen agricultural R&D in the developing world, and the Water-Efficient Maize for Africa (WEMA) project, a public–private partnership that unites agricultural researchers in Uganda, Kenya, Mozambique, Tanzania and South Africa with international experts in the public and private sectors.

“The focus is on developing drought-tolerant and pest-resistant hybrids for sub-Saharan Africa, and increasing the local capacity for scientific research,” says Edge, who now serves as the WEMA project lead at Monsanto. “WEMA is the biggest corn [maize] breeding programme in East Africa, covering around 8–10 million hectares.” As a partner in WEMA, Monsanto has provided genetic material for breeding as well as the drought-tolerant transgene used in DroughtGard royalty free. The first WEMA hybrids, derived using both conventional and molecular breeding, are expected to be available in Kenya this autumn.

Various organizations including WEMA are also teaching better land management and agricultural practices. “There’s a tendency to focus on genetics, because there’s lots of appealing things about creating a new ‘superseed,’” says Lobell. “But the evidence is that agronomy is really important — for example, the trend towards less tilling, which helps preserve soil moisture.” Richards points out that careful land and water management have done far more to preserve agricultural productivity in Australia’s arid soils than any particular improvement to the crops themselves. And Edge explains: “We’re talking about a very complex system, requiring a systems-based approach that combines agronomics, breeding and biotechnology.”

But progress is slow. “Unfortunately, there’s not a lot of good news,” says Richards. “If you look at the rate of progress we have to achieve in order to feed our population in 2050, it’s going to be an incredible job.” Unless governments in the developed world can overcome political inertia and mobilize their resources to confront the realities of climate change, we may find ourselves poorly positioned to face future agricultural crises (see ‘Legislating change’, page S12). “My concern,” says Lobell, “is that people may be spending a lot of time preparing for the droughts we used to have, and not so much for the droughts we’re going to have.” ■

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