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Reinventing Rice to Feed the World

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High and dry.

An IRRI researcher examines submergence-tolerant rice that survived being underwater for 2 weeks; a nontolerant variety, to the left, perished.

CREDIT: ARIEL JAVELLANA/CPS/IRRI

outh Asia's monsoon is a mixed blessing for rice farmers. The rains fill paddies. Light flooding brings ediment that replenishes soil nutrients. But almost every year, somewhere, flooding is so severe it wipes ut the crop.

n 2007, disaster struck the floodplains of the Tista and Jamuna rivers in north-central Bangladesh. Over a illion hectares of farm fields were flooded, some inundated for as long as 3 weeks. Agricultural losses topped $600 million. A few pioneering farmers, however, were testing an experimental rice variety that tolerates submergence, and their plants recovered even after 12 days underwater—three times longer than normal varieties can endure. Yields suffered: They got about 4 tons per hectare, about 1 ton less than they would have without flooding, according to M. A. Salam, research director at the Bangladesh Rice Research Institute (BRRI) in Gazipur. “The farmers were very happy to get this yield under these circumstances,” he says, because many of their neighbors were left with nothing.

Submergence-tolerant rice and other new yield-boosting varieties are arriving at a critical time. In recent weeks, the collision of rising demand and tightening supplies has driven a phenomenal spike in rice prices that sparked riots in Haiti, Bangladesh, and Egypt. A dozen countries, including India and China, have restricted rice exports, deepening the crisis. Exacerbating a bad situation, rice production in Myanmar this year will likely drop 6%, to 9.4 million tons, according to a U.S. Department of Agriculture (USDA) forecast, after extensive damage from Cyclone Nargis in early May. A storm surge flooded about 1.75 million hectares of the Irrawaddy River delta with saltwater and destroyed embankments and irrigation systems.

The global food crisis grabbed the attention of G8 leaders meeting in Japan last week. They pledged to reverse the decline of aid and investment in agriculture and accelerate research and development (R&D) to boost food production. Nevertheless, the looming food shortage “is a story that's going to be here for a while,” says Philip Pardey, an agricultural economist at the University of Minnesota, St. Paul. Demand will continue to rise, he says, as the world's population grows and more grain is diverted to produce biofuels and to feed livestock as meat consumption rises. At the same time, Pardey says, funding constraints have slowed R&D on improving grain yields and have crippled developing country extension systems, which get the latest seeds and techniques into farmers' hands.

All grains are affected by the trend. But a rice shortfall could be disastrous. In 2005, rice supplied 20% of total calories consumed worldwide, including 30% in Asia, according to the International Rice Research Institute (IRRI) in Los Baños, Philippines. IRRI claims that two-thirds of the world's poor—those living on less than $1 per day—subsist primarily on rice. And production is stagnant. Over the past several years, more rice has been consumed than grown—the difference made up by dipping into world rice stockpiles, which peaked at 146.7 million tons in 2001 but declined to 73.2 million tons in 2006, according to USDA. Prices were already rising, then lackluster harvests, export restrictions, and speculative buying sent prices soaring. For example, a popular export variety of Thai rice jumped from $362 per ton last December to $1000 per ton in April. Prices have retreated to $720 per ton.

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To balance production and consumption, IRRI forecasts that by 2015 the world must grow 50 million tons more rice per year than the 631.5 million tons grown in 2005. This will require boosting global average yields by more than 1.2% per year, or about 12% over the decade, says IRRI's research director, Achim Dobermann. In the near term, he says, farmers could wring an extra 1 to 2 tons of grain per hectare by growing the latest varieties and improving farm management—everything from optimizing fertilizer use to building rat-proof granaries that stem postharvest losses. A long-term trial plot at IRRI produces 18 to 20 tons of grain per year per hectare, but the average field in Asia yields half of that. Existing technologies “haven't been moved out sufficiently to farmers,” Dobermann says, because many extension systems are poorly funded and staffed. IRRI runs a training program that helps address this issue (see sidebar, p. 332).

In the long term, superior rice varieties are key to averting widespread food scarcity, says Pardey: “The yield levels we're seeing are historically high, and to even maintain them let alone increase them, you have to run pretty hard to keep ahead of evolving pests and diseases and other stresses.” Given how long it takes to develop new varieties, he adds, “you've just got to keep priming the pump of the research.”

No quick fix

Submergence-tolerant rice shows the years of effort it often takes to produce a new variety. Flooding costs South Asia about $1 billion a year in rice losses. Although paddy rice is grown in standing water, most varieties die if submerged for 3 or 4 days. Researchers had long known of varieties that apparently evolved to withstand monsoon flooding. An Indian variety known as FR (flood resistant) 13A can recover and produce rice even after 3 weeks underwater.

Despite that advantage, farmers have largely abandoned such varieties in favor of modern cultivars that produce double or more grain under normal conditions. In the 1970s, IRRI tried crossing FR13A with high-yield varieties. But farmers rejected the resulting cultivars because they didn't like the taste and had difficulty adapting the plants to local conditions, says David Mackill, head of plant breeding at IRRI.

In the early 1990s, Mackill, then at USDA's Agricultural Research Service in Davis, California, and colleagues at the University of California (UC), Davis, set out to identify the gene or genes in FR13A responsible for submergence tolerance. His team hybridized a variety derived from FR13A and an intolerant rice cultivar and tested hundreds of plants to see which recovered from submergence. Using molecular markers, or segments of easily identifiable DNA, they compared the genomes of the tolerant and nontolerant offspring, linking a region of chromosome 9 to submergence tolerance.

They enlisted colleagues at UC Riverside and IRRI to isolate the gene responsible, Submergence 1A (Sub1A). The group determined that Sub1A is expressed in FR13A only when the plant is submerged and that many nontolerant rice varieties don't have Sub1A. To confirm its role, they introduced Sub1A into an intolerant variety lacking the gene and got submergence tolerance. The group reported its findings in *Nature* in 2006.

IRRI plant physiologists, meanwhile, concluded that Sub1A inhibits stem and leaf elongation and the loss of chlorophyll that typically occurs in submerged plants. Limiting elongation conserves energy, and preserving chlorophyll, essential for photosynthesis, enhances chances of recovery.

Mackill joined IRRI in 2001 and 2 years later started working to get Sub1A into commercial varieties. Using marker-assisted selection, which links a DNA segment to a trait of interest, his team screened crosses for plants with Sub1A but otherwise identical to the target variety. The Swarna variety popular in India and Bangladesh was one of the first to get Sub1A, and germ plasm was given to BRRI and its counterpart in

India in 2005. This year, BRRI has four varieties with the Sub1A gene in field trials, Salam says. They will ramp up seed production of the best candidate, which will take another 2 years. Varieties are being tested in eight other Asian countries. Production of submergence-tolerant rice will become appreciable sometime after 2010, Dobermann says.

It's fortunate that a single gene confers a high degree of submergence tolerance. Researchers aren't always so lucky. In 2002, a team at IRRI, the Philippine Rice Research Institute in Muñoz, BRRI, and UC Davis identified Saltol, short for salt tolerance, on rice chromosome 1. A rice variety carrying Saltol is now in field trials in Bangladesh. But Saltol confers tolerance only during the seedling stage. This works for wet-season rice, because adult plants are saved by monsoon rains that reduce soil salinity as the season progresses. But dry-season varieties face increasing salinity during the critical flowering period in spring, when coastal groundwater turns brackish. Researchers are probing for other genes that might protect these types.

Scientists are using molecular techniques to boost resistance to diseases and pests as well. “But with biotic stresses, it is more complicated because you're defending the plant against pathogens or insects that are evolving,” says Dobermann.

Getting durable resistance to insects often requires several genes with different properties, continual improvement, and wise farming practices, as illustrated by the fight against the brown planthopper. The tiny insect sucks the sap from rice stalks and often infects the plant with viruses. Infestation can be deadly. In the 1970s, the planthopper was brought to heel through integrated pest management—which encourages the use of natural predators—and the development of resistant varieties.

But in just 10 years, planthoppers developed an ability to attack resistant plants as well as resistance to a widely used pesticide. Annual losses in China are estimated to run 2.77 million tons and in Vietnam about 700,000 tons, says Kong Luen Heong, an IRRI entomologist. The root problem is overuse of pesticides, which kill off the planthopper's natural predators. “This is a problem of unsustainable practices,” Heong says. Breeding resistant varieties might help, he says, but to be effective, new varieties must be integrated with changes in farming practices. IRRI is planning a pest-management demonstration project in China in 2009 that minimizes pesticide use.

Researchers have cultivars that are resistant to other stresses—including drought, cold, and iron toxicity—in the R&D pipeline. Teams are also working on genetically modified (GM) varieties. Public antipathy, particularly in Asia, has kept GM rice confined to labs. A variety modified to produce pro- vitamin A could force governments to come to terms with transgenic crops (*Science*, 25 April, p. 468). IRRI now has the so-called golden rice in a field trial, and trials in farm fields in Bangladesh could start in about 2 years, Dobermann says. But he thinks it will take at least a decade for GM rice to have a significant impact on production.

Another factor slowing work on new varieties is the structure of the rice market. Private companies conduct a lot of research on crops such as maize and soybeans because there is a thriving seed business. Rice farmers, on the other hand, retain part of each season's crop as seed for the next crop, so there is a smaller seed business and advances depend heavily on public-sector efforts. Pardey says little public spending in advanced countries goes to increasing grain productivity; instead, it is spent mostly on fruits and vegetables and environmental concerns. Contributions to organizations like IRRI have waned: IRRI's budget has eroded from a peak of $44.4 million in 1993 to $27.9 million in 2006. And few developing countries, aside from China and India, have been ramping up spending as quickly as they need to, Pardey says. As a result, over the past 10 years maize yields have risen by nearly 1.8% per year while growth in rice yields has slipped below 1% annually and is virtually nil across Asia, Dobermann says.

Closing the gap

Reducing losses to stresses can only partly ameliorate a crisis. Varieties tolerant to submergence, drought, and salinity are useful in environments that account for about 25% of global rice production. “If we want to do something in terms of food security,” says Dobermann, “we need to invest much more in improving varieties” for the 75% of rice grown in favorable environments.

Recent improvements in potential rice yields have been incremental in part because breeders have already picked the low-hanging fruit. In a sign of the challenges ahead, Qifa Zhang, a rice geneticist at Huazhong Agricultural University in Wuhan, China, identified a gene on chromosome 7 that plays a key role in boosting yield potential. He found, however, that most modern cultivars already carry the gene. Understanding how it works might lead to yield gains, says Zhang, whose findings appeared in *Nature Genetics* last May. “But we'll have to be creative in deciding how to make use of it.”

Higher yields could come from greater reliance on hybrid rice. Hybrids of genetically diverse plants benefit from heterosis, or hybrid vigor, which produces yields up to 20% greater than inbred varieties. China pioneered the use of hybrid rice in the 1970s and now plants it on 16 million hectares, or 57% of its total rice area. Last year, hybrid rice accounted for about 65% of China's 186 million ton rice production, according to Longping Yuan, director-general of the China National Hybrid Rice R&D Center and a professor at Hunan Agricultural University in Changsha. The average yield of hybrids is 7.1 to 7.2 tons per hectare versus 5.8 to 5.9 tons per hectare for inbred varieties.

But several factors have limited the spread of hybrid rice. Yuan's hybrids are indica varieties suited for the tropics. His team has not yet produced an effective japonica hybrid for temperate regions. In addition, Yuan admits, the hybrid rice he introduced in 1976 “was just so-so” in taste and quality. It was promoted by a central government anxious to feed its people, he says. His center is striving to improve the rice's taste.

Because of quality concerns, breeders in other countries have been slow to adapt hybrids to local conditions. Hybrid rice also requires a change in farming culture and infrastructure. The practice of retaining part of a crop as seed works for inbred varieties that are self-pollinating. But the yield benefit of heterosis is seen only in first-generation crosses. This means new hybrid seed must be purchased for each crop.

The drawbacks have limited hybrid rice to about 4 million hectares outside China. But Dobermann foresees that total rising to as much as 20 million hectares in a decade as varieties improve.

Precious cargo.

A dozen countries have restricted rice exports to protect domestic consumers, pushing export prices to record levels.

CREDIT: RAYMOND PANALIGAN/IRRI

One alternative—looking to wild and exotic strains—promises to boost yields of inbred varieties. For decades, breeders have worked with a limited number of rice varieties chosen for observable traits, says Susan McCouch, a rice geneticist at Cornell University. Wild and exotic varieties were ignored, she says, because they yield less rice than modern cultivars and thus were not obvious sources of beneficial genes.

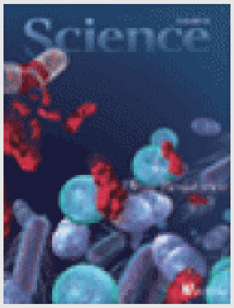
In the 1990s, McCouch and Cornell colleague Steven Tanksley crossed wild and exotic rice varieties with modern cultivars and then used molecular linkage maps to identify genes in offspring that increased yield. They almost always found some yield-boosting genes from the wild parent, McCouch says. They then added targeted genes from the wild parent to modern cultivars. This strategy appears to have an effect similar to heterosis, but the desired trait is fixed and boosts yields in later generations.

Now about a dozen groups around the world are using wild rice genes in this way to improve local varieties. Sang-Nag Ahn, a rice breeder at Chungnam National University in Daejeon, South Korea, and his colleagues crossed four elite Korean rice cultivars with wild species. Some offspring yielded 10% to 20% more grain than the parents, says Ahn. The most promising lines are in field trials; he expects to release the first of these crosses to farmers in 3 to 5 years.

A more ambitious plan is to convert rice from a C3 to a C4 plant that's better at bulking up on carbon. C3 plants—the majority of species, including wheat, barley, and potatoes—use the enzyme RuBisCO to turn carbon dioxide into a three-carbon compound that is fixed into the plant's biomass. Less common C4 plants, such as maize and sugar cane, have an additional enzyme, PEP carboxylase, which produces a four-carbon compound that RuBisCO fixes more efficiently. C4 plants, which probably evolved from C3 plants millions of years ago, are 50% more efficient at turning sunlight into biomass. John Sheehy, an IRRI plant physiologist, says that a C4 rice plant could boast 50% greater yield while requiring less water and fertilizer (*Science*, 28 July 2006, p. 423).

Sheehy and colleagues have screened wild relatives of rice and found some evidence of the close vein spacing in leaves, the large numbers of photosynthesizing chloroplasts, and the CO_2-absorption high-pay characteristics that are typical of C4 plants. “They are not C4 plants but are closer to C4 than normal C3 plants,” Sheehy says. He predicts it could take several years to prove that rice can be transformed into a C4 plant and a decade or more to produce a prototype. That's just the kind of long-term, high-payoff research that governments should be funding, says Pardey.

A meta-analysis of hundreds of studies that Pardey's group is preparing for publication shows “a pretty well-established relationship” between R&D and increasing yields. They also found that the peak effect of a discovery comes 20 to 25 years after the research was initiated. Conversely, sagging growth in agricultural productivity is the direct result of limited increases in R&D funding since the late 1970s, Pardey says. Reversing the trend requires “a decadal response,” he says, “not a political cycle response.” The rice crisis that caught the world off-guard may take many years to resolve.



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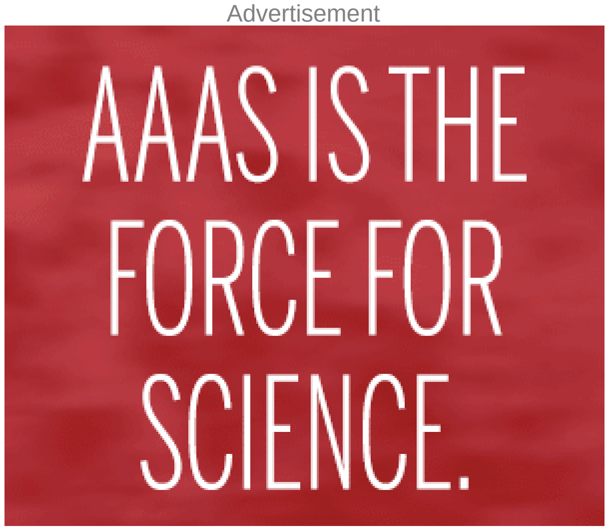

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