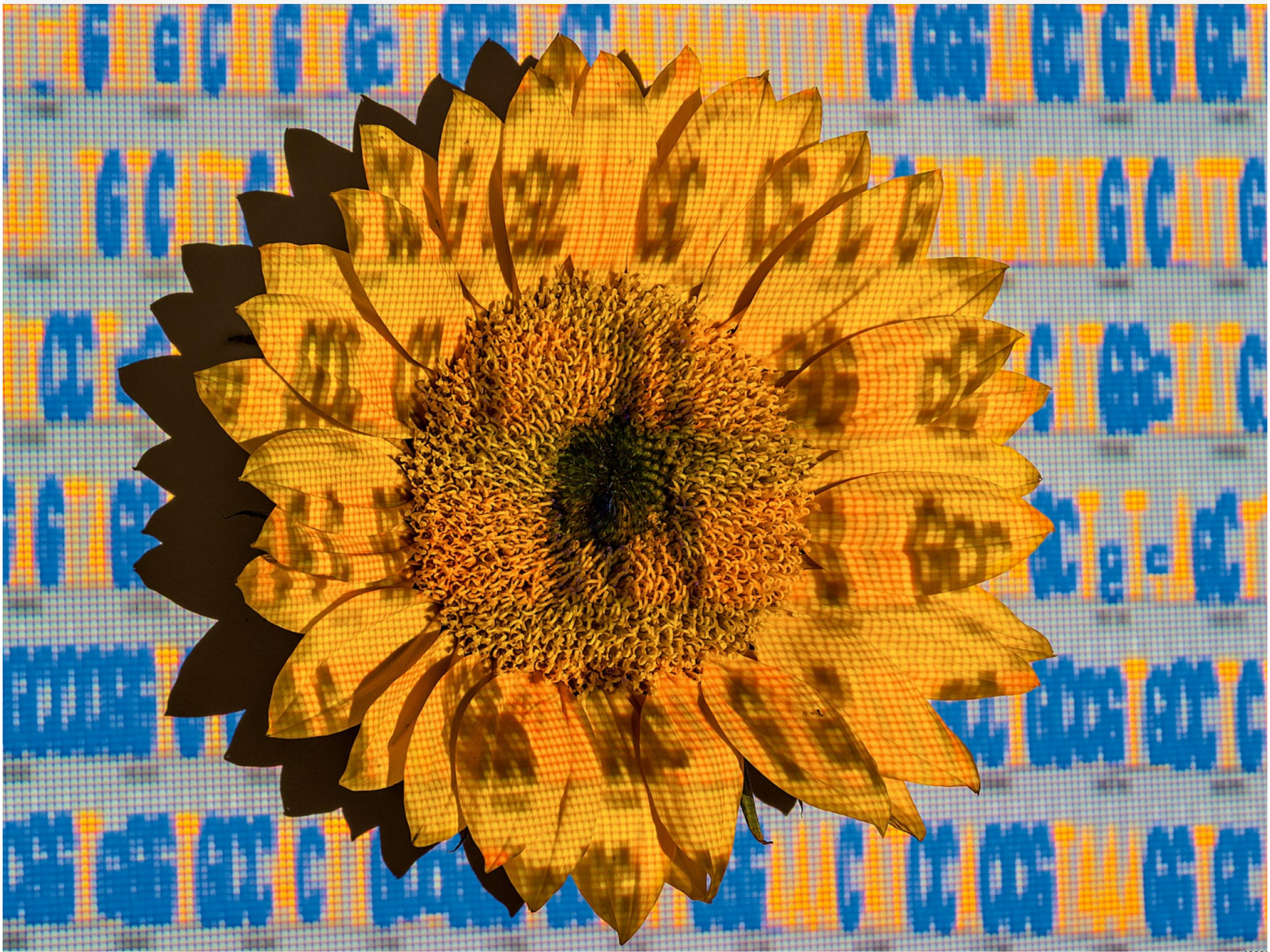


The genes of all living things on Earth—including the sunflower, a valuable oil crop—consist of varying sequences of four chemical compounds: adenine, thymine, cytosine, and guanine, abbreviated as A, T, C, and G. By identifying genes and manipulating them, scientists hope to create new crops that will help us face the challenges of global warming and population growth.

The Next Green Revolution

BY TIM FOLGER

PHOTOGRAPHS BY CRAIG CUTLER

Modern supercrops will be a big help.
But agriculture can't be fixed by biotech alone.

Something is killing Ramadhani Juma's cassava crop. "Maybe it's too much water," he says, fingering clusters of withered yellow leaves on a six-foot-high plant. "Or too much sun." Juma works a small plot, barely more than an acre, near the town of Bagamoyo, on the Indian Ocean about 40 miles north of Dar es Salaam, Tanzania. On a rainy March morning, trailed by two of his four young sons, he's talking with a technician from the big city, 28-year-old Deogratius Mark of the Mikocheni Agricultural Research Institute. Mark tells Juma his problem is neither sun nor rain. The real cassava killers, far too small to see, are viruses.

Mark breaks off some wet leaves; a few whiteflies dart away. The pinhead-size flies, he explains, transmit two viruses. One ravages cassava leaves, and a second, called brown streak virus, destroys the starchy, edible root—a catastrophe that usually isn’t discovered until harvest time. Juma is typical of the farmers Mark meets—most have never heard of the viral diseases. “Can you imagine how he’ll feel if I tell him he has to uproot all these plants?” Mark says quietly.

Juma is wearing torn blue shorts and a faded green T-shirt with “Would you like to buy a vowel?” printed on the front. He listens carefully to Mark’s diagnosis. Then he unshoulders his heavy hoe and starts digging. His oldest son, who is ten, nibbles a cassava leaf. Uncovering a cassava root, Juma splits it open with one swing of his hoe. He sighs—the creamy white flesh is streaked with brown, rotting starch.

To save enough of the crop to sell and to feed his family, Juma will have to harvest a month early. I ask how important cassava is to him.

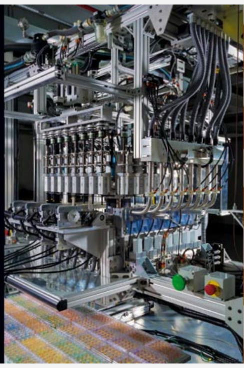
“Mihogo ni kila kitu,” he replies in Swahili. “Cassava is everything.”

Most Tanzanians are subsistence farmers. In Africa small family farms grow more than 90 percent of all crops, and cassava is a staple for more than 250 million people. It grows even in marginal soils, and it tolerates heat waves and droughts. It would be the perfect crop for 21st-century Africa—were it not for the whitefly, whose range is expanding as the climate warms. The same viruses that have invaded Juma’s field have already spread throughout East Africa.

Before leaving Bagamoyo, we meet one of Juma’s neighbors, Shija Kagembe. His cassava fields have fared no better. He listens silently as Mark tells him what the viruses have done. “How can you help us?” he asks.








Click here to launch gallery.

Answering that question will be one of the greatest challenges of this century. Climate change and population growth will make life increasingly precarious for Juma, Kagembe, and other small farmers in the developing world—and for the people they feed. For most of the 20th century humanity managed to stay ahead in the Malthusian race between population growth and food supply. Will we be able to maintain that lead in the 21st century, or will a global catastrophe beset us?

The United Nations forecasts that by 2050 the world’s population will grow by more than two billion people. Half will be born in sub-Saharan Africa, and another 30 percent in South and Southeast Asia. Those regions are also where the effects of climate change—drought, heat waves, extreme weather generally—are expected to hit hardest. Last March the Intergovernmental Panel on Climate Change warned that the world’s food supply is already jeopardized. “In the last 20 years, particularly for rice, wheat, and corn, there has been a slowdown in the growth rate of crop yields,” says Michael Oppenheimer, a climate scientist at Princeton and one of the authors of the

IPCC report. “In some areas yields have stopped growing entirely. My personal view is that the breakdown of food systems is the biggest threat of climate change.”

Half a century ago disaster loomed just as ominously. Speaking about global hunger at a meeting of the Ford Foundation in 1959, one economist said, “At best the world outlook for the decades ahead is grave; at worst it is frightening.” Nine years later Paul Ehrlich’s best seller, *The Population Bomb,* predicted that famines, especially in India, would kill hundreds of millions in the 1970s and 1980s.

Before those grim visions could come to pass, the green revolution transformed global agriculture, especially wheat and rice. Through selective breeding, Norman Borlaug, an American biologist, created a dwarf variety of wheat that put most of its energy into edible kernels rather than long, inedible stems. The result: more grain per acre. Similar work at the International Rice Research Institute (IRRI) in the Philippines dramatically improved the productivity of the grain that feeds nearly half the world.

From the 1960s through the 1990s, yields of rice and wheat in Asia doubled. Even as the continent’s population increased by 60 percent, grain prices fell, the average Asian consumed nearly a third more calories, and the poverty rate was cut in half. When Borlaug won the Nobel Peace Prize in 1970, the citation read, “More than any other person of this age, he helped provide bread for a hungry world.”

To keep doing that between now and 2050, we’ll need another green revolution. There are two competing visions of how it will happen. One is high-tech, with a heavy emphasis on continuing Borlaug’s work of breeding better crops, but with modern genetic techniques. “The next green revolution will supercharge the tools of the old one,” says Robert Fraley, chief technology officer at Monsanto and a winner of the prestigious World Food Prize in 2013. Scientists, he argues, can now identify and manipulate a huge variety of plant genes, for traits like disease resistance and drought tolerance. That’s going to make farming more productive and resilient.

The signature technology of this approach—and the one that has brought both success and controversy to Monsanto—is genetically modified, or GM, crops. First released in the 1990s, they’ve been adopted by 28 countries and planted on 11 percent of the world’s arable land, including half the cropland in the U.S. About 90 percent of the corn, cotton, and soybeans grown in the U.S. are genetically modified. Americans have been eating GM products for nearly two decades. But in Europe and much of Africa, debates over the safety and environmental effects of GM crops have largely blocked their use.

Proponents like Fraley say such crops have prevented billions of dollars in losses in the U.S. alone and have actually benefited the environment. A recent study by the U.S. Department of Agriculture found that pesticide use on corn crops has dropped 90 percent since the introduction of Bt corn, which contains genes from the bacterium *Bacillus thuringiensis* that help it ward off corn borers and other pests. Reports from China indicate that harmful aphids have decreased—and ladybugs and other beneficial insects have increased—in provinces where GM cotton has been planted.

The cassava plants in this petri dish have been genetically engineered to resist brown streak virus, a disease that's spreading across sub-Saharan Africa, where cassava is a staple for 250 million people. Field tests began last spring in Uganda. Only four African countries allow the planting of genetically modified crops.

The particular GM crops Fraley pioneered at Monsanto have been profitable for the company and many farmers, but have not helped sell the cause of high-tech agriculture to the public. Monsanto's Roundup Ready crops are genetically modified to be immune to the herbicide Roundup, which Monsanto also manufactures. That means farmers can spray the herbicide freely to eliminate weeds without damaging their GM corn, cotton, or soybeans. Their contract with Monsanto does not allow them to save seeds for planting; they must purchase its patented seeds each year.

Though there's no clear evidence that Roundup or Roundup Ready crops are unsafe, proponents of an alternative vision of agriculture see those expensive GM seeds as a costly input to a broken system. Modern agriculture, they say, already relies too heavily on synthetic fertilizers and pesticides. Not only are they unaffordable for a small farmer like Juma; they pollute land, water, and air. Synthetic fertilizers are manufactured using fossil fuels, and they themselves emit potent greenhouse gases when they're applied to fields.

"The choice is clear," says Hans Herren, another World Food Prize laureate and the director of Biovision, a Swiss nonprofit. "We need a farming system that is much more mindful of the landscape and ecological resources. We need to change the paradigm of the green revolution.

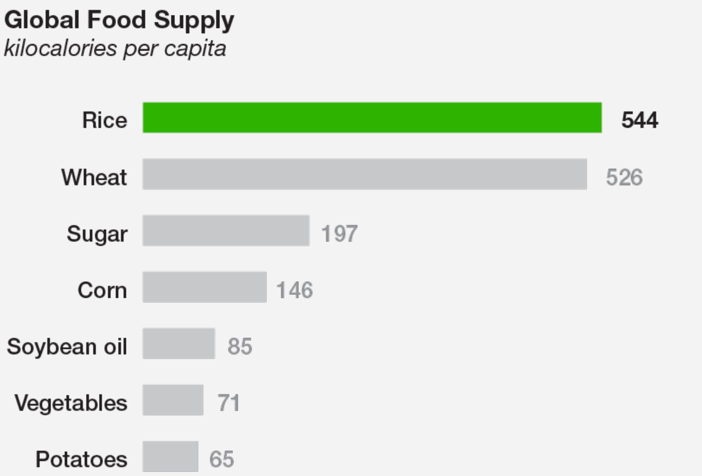
Heavy-input agriculture has no future—we need something different.” There are ways to deter pests and increase yields, he thinks, that are more suitable for the Jumas of this world.

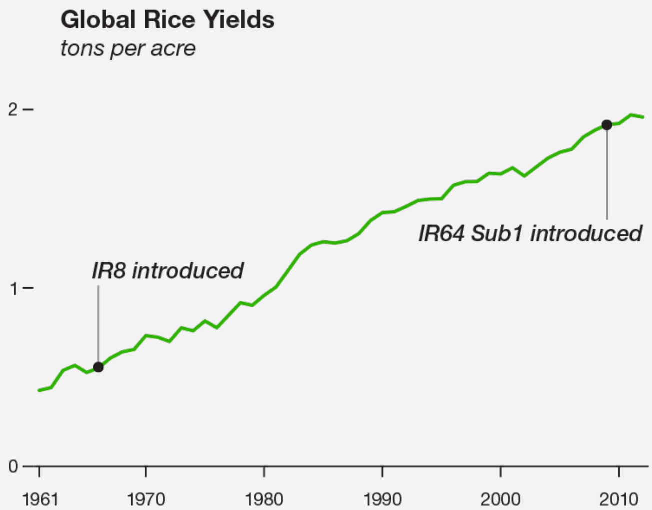
Click here to launch gallery.

Monsanto is not the only organization that believes modern plant genetics can help feed the world. Late on a warm February afternoon Glenn Gregorio, a plant geneticist at the International Rice Research Institute, shows me the rice that started the green revolution in Asia. We’re in Los Baños, a town about 40 miles southeast of Manila, walking along the edge of some very special rice fields, of which there are many on the institute’s 500 acres.

“This is the miracle rice—IR8,” says Gregorio, as we stop beside an emerald patch of crowded, thigh-high rice plants. Roosters crow in the distance; egrets gleam white against so much green; silvery light glints off the flooded fields. IRRI, a nonprofit, was founded by the Ford and Rockefeller Foundations in 1960. Two years later a plant pathologist named Peter Jennings began a series of crossbreeding experiments. He had 10,000 varieties of rice seeds to work with. His eighth cross—between a dwarf strain from Taiwan and a taller variety from Indonesia—created the fast-growing, high-yielding strain later known as India Rice 8 for its role in preventing famine in that country. “It revolutionized rice production in Asia,” says Gregorio. “Some parents in India named their sons IR8.”

Walking along the paddies, we pass other landmark breeds, each designated with a neatly painted wooden sign. The institute releases dozens of new varieties every year; about a thousand have been planted around the world since the 1960s. Yields have typically improved by just under one percent a year. “We want to raise that to 2 percent,” Gregorio says. The world’s population growth rate, now 1.14 percent a year, is projected to slow to 0.5 percent by 2050.



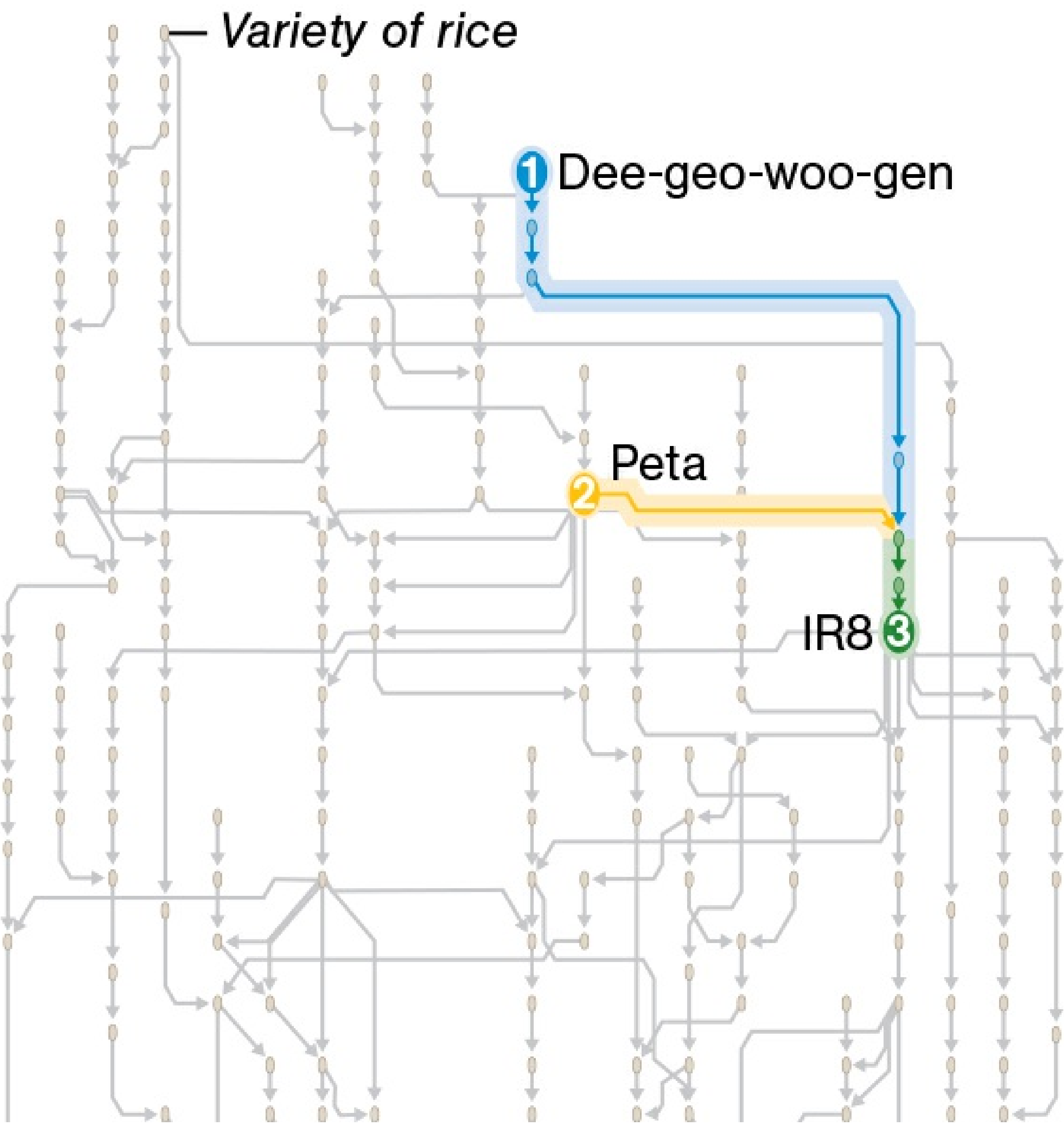


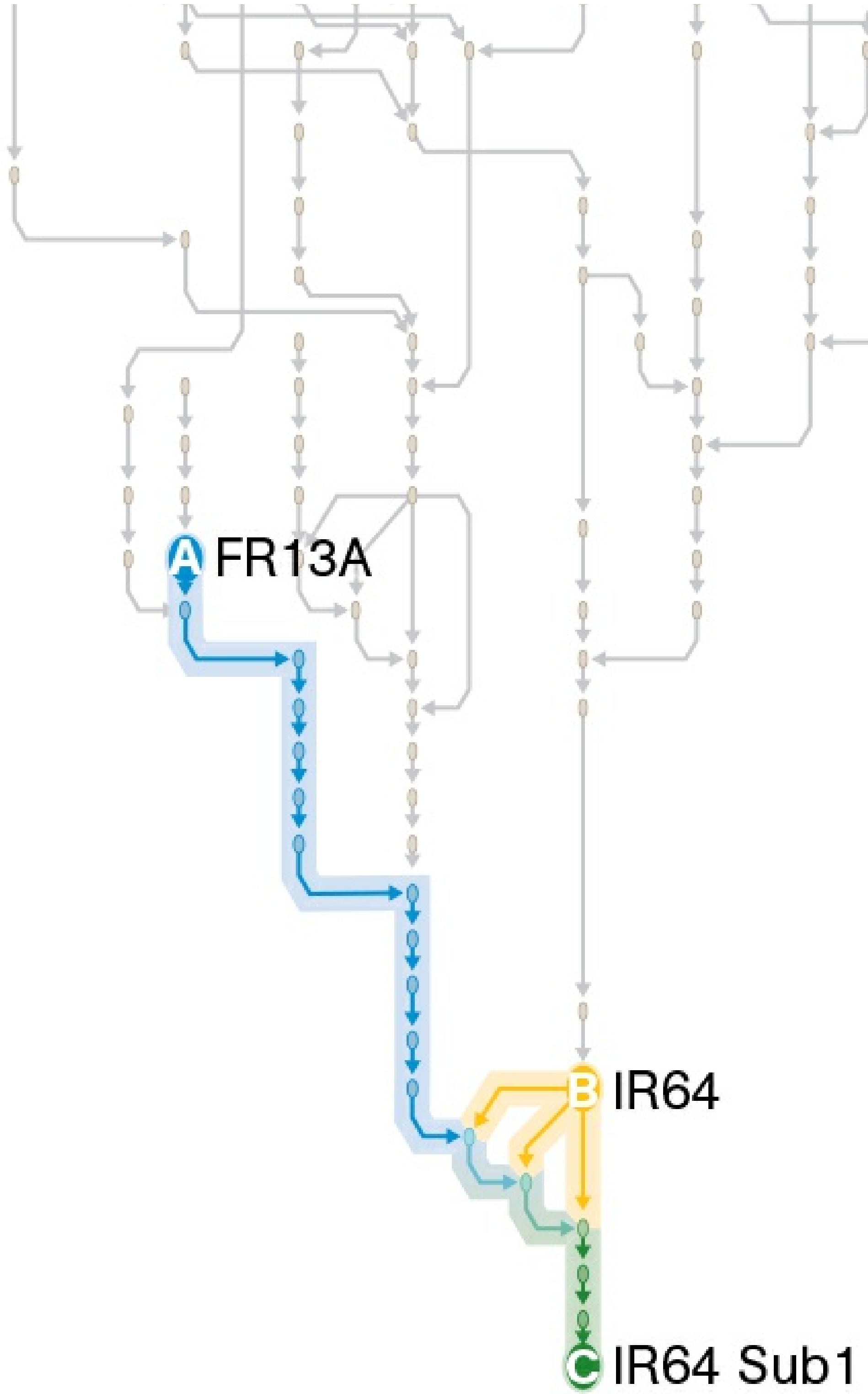
Rice is the most important food crop in the world, providing more energy to humanity than any other *food source. Rice yields have more than tripled since 1961, keeping up with Asia's growing population.*

JASON TREAT, NGM STAFF. SOURCES: JANELLE JUNG, IRRI; FAOSTAT

[illegible]

When the green revolution began in the 1960s, it was before the revolution in molecular genetics: IR8, the first miracle rice, was bred without knowledge of the genes that blessed it with high yields. Breeders today can zero in on genes, but they still use traditional techniques and ever more complex pedigrees. That's how they've created rice varieties adapted to rising sea levels—including Swarna-Sub1, popular in India, and IR64 Sub1, whose pedigree is shown here.





For many decades IRRI focused on improving traditional varieties of rice, grown in fields that are flooded at planting time. Lately it has shifted its attention to climate change. It now offers drought-tolerant varieties, including one that can be planted in dry fields and subsist on rainfall, as corn and wheat do. There’s a salt-tolerant rice for countries like Bangladesh, where rising seas are poisoning rice fields. “Farmers don’t realize the salt water is coming into their fields,” says Gregorio. “By the time the water is salty enough to taste, the plants are already dying.”

Only a few of the rice varieties at IRRI are GM crops, in the sense that they contain a gene transferred from a different species, and none of those are publicly available yet. One is Golden Rice, which contains genes from corn that allow it to produce beta-carotene; its purpose is to combat the global scourge of vitamin A deficiency. Last summer an IRRI test plot of Golden Rice was trampled by anti-GM activists. IRRI creates GM varieties only as a last resort, says director

Robert Zeigler, when it can’t find the desired trait in rice itself.

Yet the institute’s entire breeding operation has been accelerated by modern genetics. For decades IRRI breeders patiently followed the ancient recipe: Select plants with the desired trait, cross-pollinate, wait for the offspring to reach maturity, select the best performers, repeat. Now there’s an alternative to that painstaking process. In 2004 an international consortium of researchers mapped the entire rice genome, which comprises some 40,000 individual genes. Since then, researchers around the world have been pinpointing genes that control valuable traits and can be selected directly.

In 2006, for example, plant pathologist Pamela Ronald of the University of California, Davis, isolated a gene called *Sub1* from an East Indian rice variety. Seldom grown now because of its low yields, the East Indian rice has one remarkable characteristic: It can survive for two weeks underwater. Most varieties die after three days.

Researchers at IRRI cross-pollinated *Sub1* rice with a high-yielding, flavorful variety called Swarna, which is popular in India and Bangladesh. Then they screened the DNA to determine which seedlings had actually inherited the *Sub1* gene. The technology, called marker-assisted breeding, is more accurate and saves time. The researchers didn’t have to plant the seedlings, grow them, and then submerge them for two weeks to see which would survive.

The new flood-tolerant rice, called Swarna-Sub1, has been planted by nearly four million farmers in Asia, where every year floods destroy about 50 million acres of rice. One recent study found that farmers in 128 villages in the Indian state of Odisha, on the Bay of Bengal, increased their yields by more than 25 percent. The most marginal farmers reaped the most benefit.

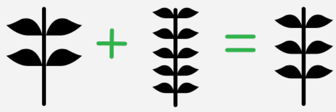
“The lowest castes in India are given the worst land, and the worst lands in Odisha are prone to flooding,” says Zeigler. “So here is a very sophisticated biotechnology—flood-tolerant rice—that preferentially benefits the poorest of the poor, the Untouchables. That’s a helluva story, I think.”

The institute’s most ambitious project would transform rice fundamentally and perhaps increase yields dramatically. Rice, wheat, and many other plants use a type of photosynthesis known as C3, for the three-carbon compound they produce when sunlight is absorbed. Corn, sugarcane, and some other plants use C4 photosynthesis. Such crops require far less water and nitrogen than C3 crops do, “and typically have 50 percent higher yields,” says William Paul Quick of IRRI. His plan is to convert rice into a C4 crop by manipulating its own genes.

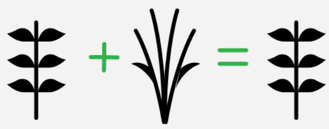
C4 photosynthesis, unlike the submergence tolerance of *Sub1* rice, is controlled by many genes, not just one, which makes it a challenging trait to introduce. On the other hand, says Quick, “it has evolved independently 62 times. That suggests it can’t be that difficult to do.” By “knocking out” genes one by one, he and his colleagues are systematically identifying all the genes responsible for photosynthesis in *Setaria viridis,* a small, fast-growing C4 grass. So far all the genes they’ve found are also

Breeding Better Crops

Genetic modification gets the public attention—and the controversy—but plant breeders today have numerous tools for creating crops with new traits. The goal: continually increasing yields in an increasingly challenging climate.



Traditional Breeding
Desired traits are identified in separate individuals of the same species, which are then bred to combine those traits in a new hybrid variety.



Interspecies Crosses
Breeders can also cross different yet similar species. Modern wheat comes from such hybridizations, some of which happened naturally.

Marker-Assisted Selection
When genes for a trait aren’t precisely known, targeting a DNA marker near them can speed up breeding: It identifies plants with the trait even before they mature.

Genetic Modification
Genes identified in one species can be transferred directly to

present in C3 plants. They're just not used in the same way.

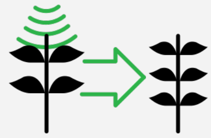
Quick and his colleagues hope to learn how to switch them on in rice. "We think it will take a minimum of 15 years to do this," Quick says. "We're in year four." If they succeed, the same techniques might help enhance the productivity of potatoes, wheat, and other C3 plants. It would be an unprecedented boon to food security; in theory yields could jump by 50 percent.

Prospects like that have made Zeigler a passionate advocate of biotechnology. White-bearded and avuncular, a self-described old lefty, Zeigler believes the public debate over genetically modified crops has become horribly muddled. "When I was starting out in the '60s, a lot of us got into genetic engineering because we thought we could do a lot of good for the world," he says. "We thought, These tools are fantastic!

"We do feel a bit betrayed by the environmental movement, I can tell you that. If you want to have a conversation about what the role of large corporations should be in our food supply, we can have that conversation—it's really important. But it's not the same conversation about whether we should use these tools of genetics to improve our crops. They're both important, but let's not confound them."

Zeigler decided on his career after a stint as a science teacher in the Peace Corps in 1972. "When I was in the Democratic Republic of the Congo, I saw a cassava famine," he says. "That's what made me become a plant pathologist."

an unrelated species, giving it an entirely new trait—resistance to a pest, say, or to a weed killer.



Mutation Breeding
Seeds are irradiated to promote random mutations in their DNA. If a mutation happens to produce a desirable trait, the plant is selected for further breeding.

ART: OLIVER MUNDAY. SOURCE: JANELLE JUNG, INTERNATIONAL RICE RESEARCH INSTITUTE (IRRI)

Video: Breeding Factory *Inside the Donald Danforth Plant Science Center in St. Louis, plants get the phenotyping treatment, while scientists explain how the technology could benefit crops in a shifting climate.*

Which vision of agriculture is right for the farmers of sub-Saharan Africa? Today, says Nigel Taylor, a geneticist at the Donald Danforth Plant Science Center in St. Louis, Missouri, the brown streak virus has the potential to cause another cassava famine. “It has become an epidemic in the last five to ten years, and it’s getting worse,” he says. “With higher temperatures, the whitefly’s range is expanding. The great concern is that brown streak is starting to move into central Africa, and if it hits the massive cassava-growing areas of West Africa, you’ve got a major food-security issue.”

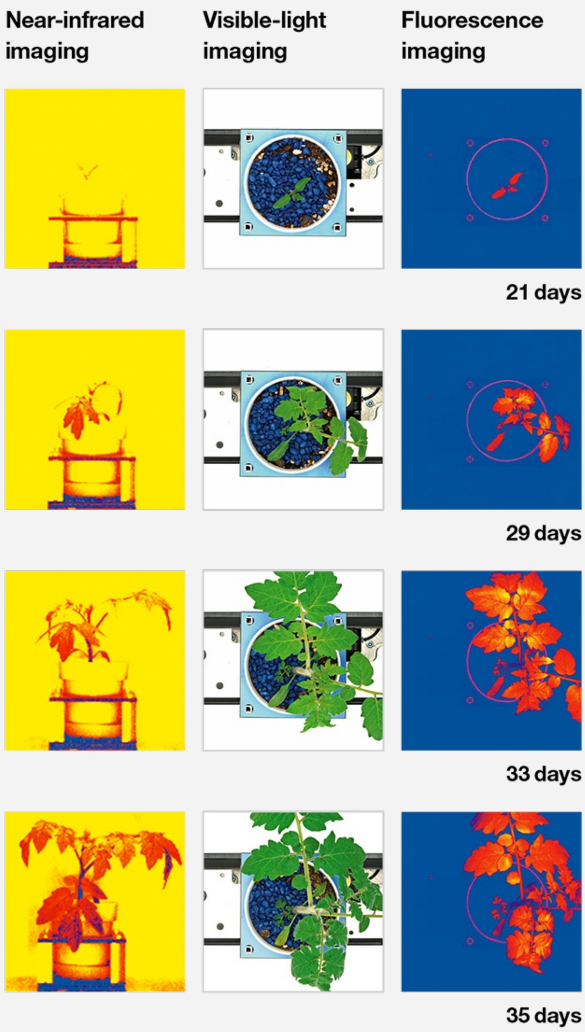
Taylor and other researchers are in the early stages of developing genetically modified cassava varieties that are immune to the brown streak virus. Taylor is collaborating with Ugandan researchers on a field trial, and another is under way in Kenya. But only four African countries—Egypt, Sudan, South Africa, and Burkina Faso—currently allow the commercial planting of GM crops.

In Africa, as elsewhere, people fear GM crops, even though there’s little scientific evidence to justify the fear. There’s a stronger argument that high-tech plant breeds are not a panacea and maybe not even what African farmers need most. Even in the United States some farmers are having problems with them.

A paper published last March, for instance, documented an unsettling trend: Corn rootworms are evolving resistance to the bacterial toxins in Bt corn. “I was surprised when I saw the data, because I knew what it meant—that this technology was starting to fail,” says Aaron Gassmann, an entomologist at Iowa State University and co-author of the report. One problem, he says, is that some farmers don’t follow the legal requirement to plant “refuge fields” with non-Bt corn, which slow the spread of resistant genes by supporting rootworms that remain vulnerable to the Bt toxins.

In Tanzania there are no GM crops yet. But some farmers are learning that a simple, low-tech solution—planting a diversity of crops—is one of the best ways to deter pests. Tanzania now has the fourth largest number of certified organic farmers in the world. Part of the credit belongs to a young woman named Janet Maro.

Maro grew up on a farm near Kilimanjaro, the fifth of eight children. In 2009, while still an undergraduate at the Sokoine University of Agriculture in Morogoro, she helped start a nonprofit called Sustainable Agriculture Tanzania (SAT). Since then she and her small staff have been training local farmers in organic practices. SAT now receives support from Biovision, the Swiss organization headed by Hans Herren.



The Search for a Less Thirsty Tomato *To find out how tomato plants resist drought, Danforth Center researchers cut their water ration 18 days after planting, then monitor them using three kinds of imaging. Near-infrared images show the plant's water content. Fluorescence images show where photosynthesis is occurring. Tomatoes are typically grown in hot, dry climates with a lot of irrigation water—more than 13 gallons per tomato on average. To create less thirsty varieties, Dan Chitwood's team at the Danforth Center are crossing tomato plants with a wild relative from Peru's southern coastal desert, one of the driest places on Earth.*

Morogoro lies about a hundred miles west of Dar es Salaam, at the base of the Uluguru Mountains. A few days after my visit with Juma in Bagamoyo, Maro takes me into the mountains to visit three of the first certified organic farms in Tanzania. "Agricultural agents don't come here," she says as we lurch up a steep, rutted dirt road in a pickup. Greened by rains drifting in from the Indian Ocean, the slopes remain heavily forested. But increasingly they've been cleared for farming by the Luguru people.

Every quarter mile or so we pass women walking alone or in small groups, balancing baskets of cassavas, papayas, or bananas on their heads. It's market day in Morogoro, 3,000 feet below us. Women here are more than porters. Among the Luguru, landownership in a family passes down the female line. "If a woman doesn't like a man, out he goes!" Maro says.

She stops at a one-room brick house with partially plastered walls and a corrugated metal roof. Habija Kibwana, a tall woman in a short-sleeved white blouse and wraparound skirt, invites us and two neighbors to sit on her porch.

Unlike the farmers in Bagamoyo, Kibwana and her neighbors raise a variety of crops: Bananas, avocados, and passion fruit are in season now. Soon they'll be planting carrots, spinach, and other leafy vegetables, all for local consumption. The mix provides a backup in case one crop fails; it also helps cut down on pests. The farmers here are learning to plant strategically, setting out rows of *Tithonia diversifolia,* a wild sunflower that whiteflies prefer, to draw the pests away from the cassavas. The use of compost instead of synthetic fertilizers has improved the soil so much that one of the farmers, Pius Paulini, has doubled his spinach production. Runoff from his fields no longer contaminates streams that supply Morogoro's water.

Perhaps the most life-altering result of organic farming has been the liberation from debt. Even with government subsidies, it costs 500,000 Tanzanian shillings, more than $300, to buy enough fertilizer and pesticide to treat a single acre—a crippling expense in a country where the annual per capita income is less than $1,600. "Before, when we had to buy fertilizer, we had no money left over to send our children to school," says Kibwana. Her oldest daughter has now finished high school.

And the farms are more productive too. "Most of the food in our markets is from small farmers," says Maro. "They feed our nation."

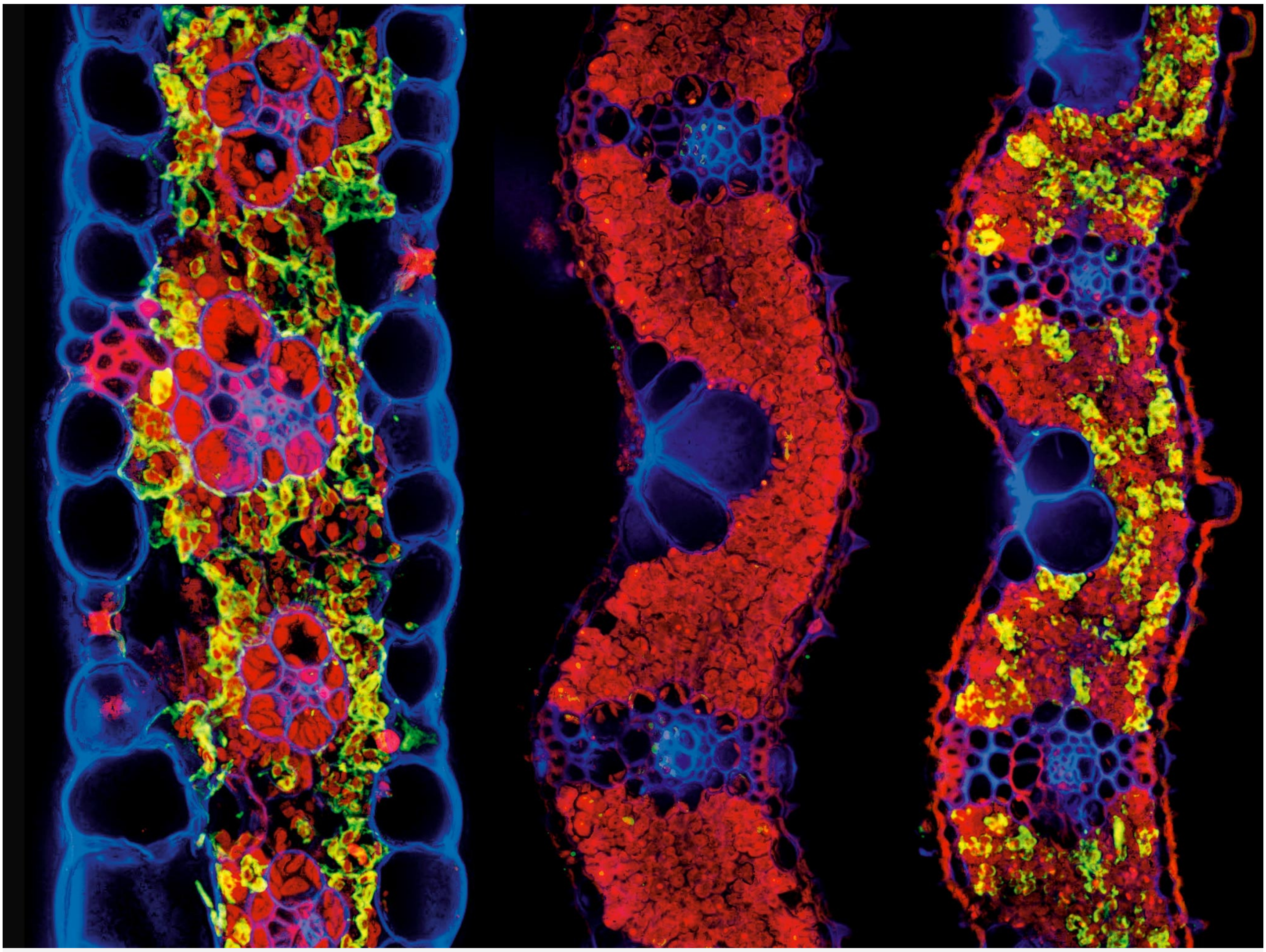
Wheat History Wagon *Counting from left to right: a wild ancestor from the Middle East; einkorn wheat, domesticated there 10,000 years ago; durum wheat; modern wheat, produced by crossing durum with goat grass; and a green revolution variety with shorter stalks and larger seeds. Wild wheat (in hand) has virtues scientists hope to tap: It can tolerate temperatures that kill its domesticated kin.*

When I ask Maro if genetically modified seeds might also help those farmers, she's skeptical. "It's not realistic," she says. How could they afford the seeds when they can't even afford fertilizer? How likely is it, she asks, in a country where few farmers ever see a government agricultural adviser, or are even aware of the diseases threatening their crops, that they'll get the support they need to grow GM crops properly? From Kibwana's porch we have sweeping views of richly cultivated terraced slopes—but also of slopes scarred by the brown, eroded fields of nonorganic farmers, most of whom don't build terraces to retain their precious soil. Kibwana and Paulini say their own success has attracted the attention of their neighbors. Organic farming is spreading here. But it's spreading slowly.

That's the central problem, I thought as I left Tanzania: getting knowledge that works from organizations like SAT or IRRI to people like Juma. It's not choosing one type of knowledge—low-tech versus high-tech, organic versus GM—once and for all. There's more than one way to increase yields or to stop a whitefly. "Organic farming can be the right approach in some areas," says Monsanto executive Mark Edge. "By no means do we think that GM crops are the solution for all the problems in Africa." Since the first green revolution, says Robert Zeigler, ecological science has advanced along with genetics. IRRI uses those advances too.

"You see the egrets flying out there?" he asks toward the end of our conversation. Outside his office a flock is descending on the green paddies; the mountains beyond glow with evening light. "In the early '90s you didn't see birds here. The pesticides we used killed the birds and snails and everything else. Then we invested a lot to understand the ecological structures of rice paddies. You have these complex webs, and if you disrupt them, you have pest outbreaks. We learned that in the vast majority of cases, you don't need pesticides. Rice is a tough plant. You can build resistance into it. We now have a rich ecology here, and our yields haven't dropped.

"At certain times of the day we get a hundred or so of those egrets. It's really uplifting to see. Things can get better."



Can rice be made to photosynthesize as efficiently as corn? If so, yields could rise 50 percent. In a magnified cross section of a corn leaf (left), photosynthesis proteins are stained fluorescent green. Ordinary rice (middle) makes none of the proteins—but rice that has been genetically manipulated by IRRI scientists (right) makes some. WILLIAM PAUL QUICK, IRRI

Tim Folger's last feature was the September 2013 cover story on sea-level rise. This is photographer Craig Cutler's first article for the magazine.

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