Reseeding the Green Revolution

High-yielding varieties of wheat, rice, and maize helped double world grain production. A repeat performance is now needed, and that will require a new commitment to agricultural research

Searing images of Ethiopian children with bloated bellies and flies clinging to their faces spurred the world in 1984 to combat that nation's devastating famine. To publicize their plight, which was exacerbated by the country's raging civil war, UNESCO filmed actresses Liv Ullman and the late Audrey Hepburn touring camps full of starving children. Pop icons Michael Jackson and Lionel Richie raised millions for the cause by gathering U.S. musicians to sing "We Are the World." In the United Kingdom, rock star Bob Geldof launched a similar campaign, called Band Aid. His arrival in Addis Ababa with a planeload of food sealed Ethiopia's reputation as the epitome of a country incapable of feeding itself.

Things have changed. The civil war ended in 1991, and since then Ethiopia has almost doubled its production of grain. Last year it exported about 200,000 tons of grain to neighboring Kenya, which was hard hit by drought. "Even people in Africa can't believe that Ethiopia is *exporting food*—do you have any idea what a change that is?" asks Nobel Peace Prize-winning plant geneticist Norman Borlaug of CIMMYT, the Mexican cereals-research center.

Borlaug was a captain of the Green Revolution—the potent combination of higher-yielding grain varieties, greatly increased use of chemical fertilizer, and the techniques to demonstrate their use to poor farmers—that enabled much of Asia and Latin America to achieve agricultural self-sufficiency in the 1960s and 1970s. While acknowledging that many Ethiopians still go hungry because of poverty and poor food distribution networks, he says the nation's turnaround shows that Green Revolution ideas can help Africa feed itself in the 1990s. "If African political leaders put agriculture high on their order of priorities, rather than military hardware, and if foreign assistance programs are reasonably well funded, we could see some really dramatic improvements in the next 5 to 6 years."

But Borlaug—like many agricultural researchers—is less optimistic about the prospects for rapidly boosting crop yields in the rest of the world. The Green Revolution has already transformed agriculture in most of Asia, Europe, and the Americas, with enormous impact on human well-being. Globally speaking, a child is less likely to be malnourished today than ever before. "The problem is that population growth hasn't stopped, so the Green Revolution has to happen all over again," says agricultural economist Lester R. Brown, president of Worldwatch Institute, an environmental advocacy group in Washington, D.C. "And that won't be easy."

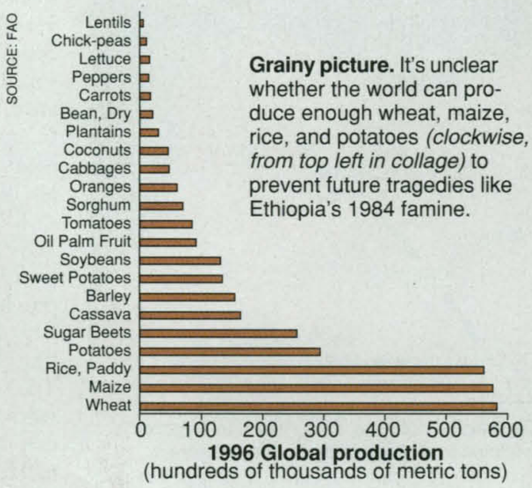
By the year 2030, the United Nations predicts, today's world population of 5.9 billion will likely jump to 7.1 billion. The impact of 1.2 billion additional mouths will be compounded by affluence, which drives up consumption of meat, requiring high volumes of grain for animal feed. "So you're not just increasing the load on what land we have, you're multiplying it," says William C. Paddock, a retired Iowa State University plant pathologist who has written about potential food shortfalls since the 1960s.

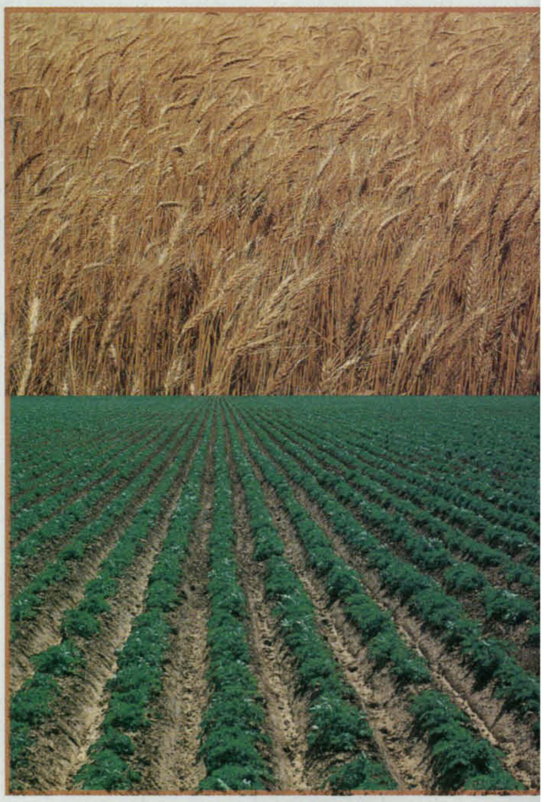
The surge in demand will occur even as evidence suggests that the Green Revolution is petering out. In recent years grain yields have stopped rising as fast, and plant scientists agree that they are facing physical limits as they try to coax plants to produce ever more of their weight in grain. Supplies of fresh water are growing scarce. Soil quality is deteriorating. There is little unplanted arable land left to exploit. "We're running out of gas at the time we most need it," Paddock says.

Will humankind ultimately be able to feed itself? Interviews with plant breeders, crop physiologists, and botanical geneticists in Africa, Asia, Europe, and North America suggest that the answer is yes. Life can be sustained, and at a relatively healthy level. But, they caution, it can happen only if the world engages in a gigantic, multiyear, multibillion-dollar scientific effort—a kind of agricultural "person-on-the-Moon project," says Kenneth G. Cassman, a crop physiologist at Nebraska State University, Lincoln, who specializes in rice.

To feed the world, Cassman and other researchers say, scientists will have to bring modern agricultural methods to areas where they are not now used, as Borlaug and others are trying to do in Africa. At the same time, they will have to squeeze more productivity from every piece of arable land where the Green Revolution has already taken place by developing "high-precision farming" techniques that optimize every step from seed to harvest.

Unfortunately, there is little evidence that society—or science—will embrace this heroic task in time. "The stakes are huge," Cassman says, "but when you look at it in terms of the global agenda of science, most people aren't even aware of it. People are more concerned about the impact of an asteroid." Worldwide funding for agricultural science is flagging, and several major research institutions are laying off staff. As a result, Cassman says, "I think that science could feed the world, but I'm quite worried that it won't be allowed to."



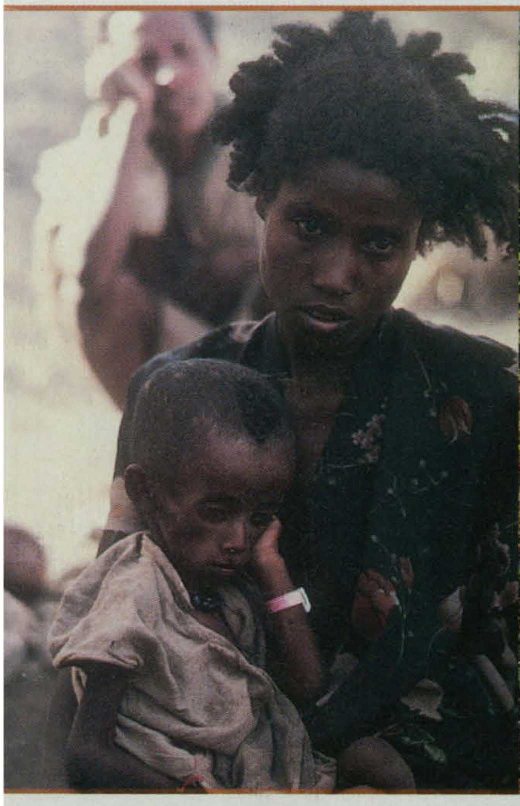


Grainy picture. It's unclear whether the world can produce enough wheat, maize, rice, and potatoes *(clockwise, from top left in collage)* to prevent future tragedies like Ethiopia's 1984 famine.

Defusing a bomb

Ecologist Paul Ehrlich, author of *The Population Bomb*, forecast in 1969 that within a decade, Japan would starve and a horde of famished Chinese would invade Russia. "Most of the people who are going to die in the greatest cataclysm in the history of man have already been born," he warned.

Back then, according to the U.N. Food and Agricultural Organization (FAO), 56% of the human race lived in nations with average per-capita food supplies of 2200 calories per day or less, a level barely enough to get by. As human numbers climbed relentlessly, population seemed destined to outstrip food production in the classic Malthusian scenario. Instead, grain harvests soared. By 1992–1994, FAO estimates, the percentage of the world's population living at or below 2200 calories/day had fallen to 10%. Ehrlich hadn't included the Green Revolution in his apocalyptic scenario.



MOTHER AND CHILD: U.N. CROPS: GRANT HEILMAN

It began in 1943, when Borlaug, funded by the Rockefeller Foundation and the Mexican Ministry of Agriculture, headed a program to breed high-yielding wheat varieties that resisted stem rust, a fungus that then plagued Latin American agriculture. The program set up two labs separated by 10 degrees of latitude and 2600 meters in altitude. By simultaneously testing wheat strains in both stations, the program developed high-yielding, rust-resistant hybrids that were insensitive to climatic variables such as temperature and day length.

The new varieties produced so much grain, in fact, that they "lodged"—that is, the plants became top-heavy and fell over, ruining the crop. So the researchers sought out wheat strains with shorter, stouter stalks, screening the entire U.S. Department of Agriculture (USDA) wheat collection before learning of some "dwarf" varieties in Japan. Except for its size, however, the Japanese wheat was unpromising. It produced unusable grain, was often sterile, and was so susceptible to disease that the first year's experimental crop was wholly lost to rust. After seven more years, Borlaug's team introduced the dwarfing genes without the undesirable characteristics. And there was an unexpected bonus: The dwarfing genes ultimately had synergistic effects on yield, increasing harvests to as much as 8 tons per hectare (t/ha)—a staggering increase from the previous average of 0.75 t/ha.

In 1960, the Rockefeller Foundation, the Ford Foundation, the U.S. Agency for International Development, and the Filipino government launched a similar campaign for rice. The International Rice Research Institute (IRRI), based in Los Baños, the Philippines, duplicated the Mexican success by breeding high-yielding, disease-resistant strains of rice and crossing them with dwarf varieties to prevent lodging. Meanwhile, Borlaug's program—renamed the International Center for Maize and Wheat Improvement, but known by its Spanish acronym, CIMMYT—adapted the new wheat strains for Pakistan and India. Largely because of the introduction of hybrid wheat and rice, says USDA, farmers around the world raised grain yields by an average of 2.1% a year between 1950 and 1990, almost tripling grain harvests during that period.

Recently, though, the rate of increase has slowed. Since the harvest of 1989–1990, world grain yields have risen by just 0.5% per year. As a result, cereal stockpiles plunged from 383 million tons in 1992 to an estimated 281 million tons in 1997—"well below … the minimum necessary to safeguard world food security," according to the May/June FAO "Food Outlook" report. And cereal stocks held by developing countries have declined for 3 years in a row.

To Brown, the declining stocks are "clear signs" that humankind is running into "a fundamental biological phenomenon—the S-shaped growth curve—where enormous increases in productivity hit a wall and level out." He believes the shortfalls are the harbinger of a widening, long-term, and nearly unavoidable "gap between the demand and supply of grain."

Others dismiss these gloomy predictions. According to Timothy Roche, grain chair at the USDA Production Estimates and Crop Assessment Division, the primary cause of the slippage in world productivity gains was the collapse of the Soviet Union, where grain harvests fell from 180 million tons in 1989–1990, the last year of Communism, to an estimated 116 million tons in 1996–1997. Far from signaling the approach of ecological limits, Roche says, the drop in the ex-Communist states "is 100% economics." Indeed, had Soviet yields remained at the levels attained in 1989—an average year—until today, global grain yields would have risen at an annual clip of 1.6%, more than triple the apparent rate. And many agriculturists expect that as the economies stabilize in the former Soviet Union, yields will gradually bounce back.

Although 1.6% per year still represents a decline, economist Nikos Alexandratos, chief of FAO's global perspective studies in Rome, says it may not be a problem. "One does not need to continue the growth at the same rate we have in the past for the simple reason that today a much higher proportion of the world population is well fed," says Alexandratos. Because production in rich countries doesn't need to increase, he says, "the aggregate will not grow as fast [as it did] in the past. If you observe slower growth today than yesterday, it could be good"—an indication of success, not failure.

Spreading the revolution

To Borlaug, worrying about the Green Revolution slowing is less important than recognizing that it has never been fully applied to some of the world's poorest areas, especially Africa. To be sure, Africa is an especially hard case—much of its soil is eroded, nitrogen-deprived, and lacking in organic matter. With sufficient water, fertilization could overcome many of these deficiencies. But arid Africa does not have the water. "It's more difficult there in

Saving Sorghum by Foiling the Wicked Witchweed

Civil war, genocide, corruption, and political incompetence have conspired to keep entire regions of Africa on the brink of famine, earning it the sad reputation as the hungry continent. But even if these dreadful socioeconomic problems were alleviated, African agriculture would still suffer from a host of more traditional problems—insects, birds, and plant diseases. Indeed, one of the greatest sources of crop losses in Africa is not war or corruption, but three species of the parasitic plant *Striga hermonthica*.

Commonly known as witchweed, *Striga* feeds on the roots of cereals and legumes in much of Africa and South Asia. Estimates of crop losses caused by *Striga* range from 15% to 40% of Africa's total cereal harvest; many areas lose two-thirds or more of their crops every year. Gebisa Ejeta, an agronomist at Purdue University, says *Striga*—which attacks maize, sorghum, and millet, Africa's three most important cereals—has long been the "strongest biological constraint to crop production" in the continent.


G. EJETA

Crop killer. A *Striga*-infested sorghum field in Ethiopia, which has started to use resistant seeds.

All efforts to control what Ejeta calls "this scourge" failed until he and his Purdue colleague, the late Larry Butler, developed the first *Striga*-resistant sorghum. Introduced in 1995, the new varieties are now grown in such desperately poor places as Chad, Mali, Niger, Rwanda, and the Sudan. According to Marco Quiñones, an agronomist in Addis Ababa, Ethiopia, the Ejeta-Butler sorghum was so successful that it spread throughout Sudan despite a civil war. Farmers in neighboring Ethiopia wanted *Striga*-resistant sorghum badly enough to smuggle the seeds across the hostile border. "They are growing sorghum in areas that were abandoned to *Striga* for years," Quiñones says. "The change is enormous."

From a biological perspective, *Striga* is a fascinating problem. Once established, witchweed is almost impossible to eradicate—the United States has spent millions in an attempt to contain a single small outbreak in the Carolinas. Each plant produces 40,000 to 100,000 seeds, although production of half a million seeds has been observed. The seeds, smaller than grains of sand, lie dormant in the soil for as long as 20 years, germinating only when stimulated by a specific chemical exudate given off by the root of the host plant. After germination, a second host exudate triggers the development of a root-like organ called a haustorium, which the parasite uses to penetrate the host and siphon away nutrients. Dozens of plants can attack the same host, stunting or killing it. Although *Striga* eventually grows into an 80-cm plant with bright pink or red flowers, it wreaks most harm while still invisibly underground. "Before farmers know they have the parasite in their farms," Ejeta says, "the damage has been done."

S. hermonthica and *S. asiatica* parasitize cereals; *S. gesneroides* targets cowpeas and tobacco. But all three rapidly adapt to new hosts—one reason that *Striga* losses are growing. Barley and the Ethiopian grain teff, once perceived as immune, are now attacked. Pearl millet was introduced to eastern Sudan, where sorghum crops had been wiped out by *S. hermonthica*, the largest and most virulent species. Within a few years *Striga* was wiping out millet, too.

In the past, African farmers shifted their planting from one plot to another, rotating crops with long fallow periods between. "If a problem came up with *Striga*," Ejeta says, "they had the luxury of leaving the field alone for a few years." With populations rising, farmers now often stay put, cropping the same land—ideal conditions for *Striga*.

Having left his native Ethiopia in 1974 just before a military coup deposed Emperor Haile Selassie, Ejeta finished his doctorate in the United States and then went to the Sudan office of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), an agricultural think tank headquartered in Hyderabad, India. At ICRISAT, he developed Hageen Dura-1, the first commercial sorghum hybrid in sub-Saharan Africa, and introduced it to Sudanese farmers. Although the new variety was drought-tolerant and yielded as much as 150% more than traditional varieties, it was plagued by witchweed. When Ejeta came to Purdue in 1984, he was determined to do something about this parasite.

Believing the interactions among parasite, host, and environment are too complex to control in field conditions, Ejeta decided to unravel the basic biology of *Striga*. He teamed up with Butler, a biochemist, hoping that understanding the specific biochemical signals between host and parasite would allow farmers to disrupt them. In 1992, Bupe Siame, a Zambian graduate student working with Ejeta and Butler, identified the exudate—sorgolactone—that activated germination of *Striga* seeds in sorghum, maize, and millet.

Dale Hess, another Purdue graduate student, meanwhile developed a simple agar assay that separated sorghum genotypes on the basis of their ability to germinate *Striga*. He spread *Striga* seeds evenly over a petri dish and placed a growing sorghum seed in the center. By measuring at intervals the distance of the furthest germinated *Striga* seed from the sorghum, the researchers determined the host's level of sorgolactone.

Using this technique, Hess and Ejeta discovered that one sorghum line, SRN-39, had a recessive gene that limited sorgolactone production. "The ability to produce this chemical compound was under simple Mendelian control," Ejeta says. "So we were able to extract the gene through conventional plant breeding and put it into eight varieties of cultivated sorghum." Field testing took place in Niger, Sudan, and Mali. (Field studies of *Striga* are usually performed in Africa, for fear of letting witchweed escape into new territory.) In the United States, Ejeta and Butler mapped the gene on the molecular linkage map for sorghum, the first step in cloning the *Striga*-resistance gene and transferring it to other crops.

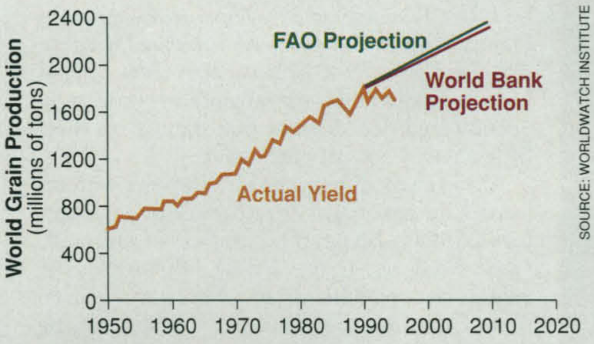
By 1999, Ejeta believes, some 200,000 farms should be growing *Striga*-resistant sorghum in 12 African countries. "We were lucky," he says. "Usually varieties perform well in one environment but fail in others. Ours seem to be doing well throughout arid Africa."

The success was marred by Butler's unexpected death after surgery for prostate cancer last February. "To get these kind of breakthroughs—first in Sudan with the hybrid sorghum and then this one—I've been very fortunate to have it happen," Ejeta says. "My greatest sadness is that Larry isn't here to cherish it with me."

–C.M.

every way," says Nebraska's Cassman.

Still, Borlaug believes that Africa has been "unjustly neglected." Indeed, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), in Hyderabad, India—the equivalent of IRRI and CIMMYT for African staples like sorghum and millet—was not founded until 1972, more than a decade after its fellows. And even when research was done, Borlaug says, the world made "no major effort to move the technology to farmers' fields."



Yield of dreams? Worldwatch's Brown says World Bank and FAO predictions about future yields are overly optimistic.

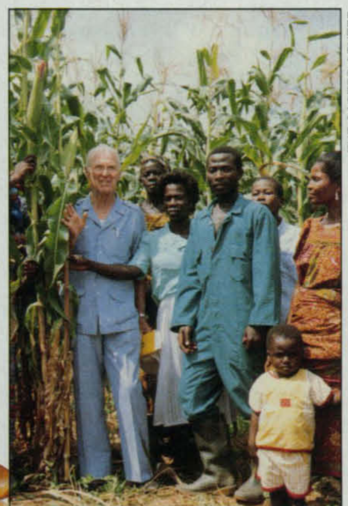
Dismayed by the slow progress, the late Ryoichi Sasakawa, a Japanese industrialist-philanthropist, asked Borlaug in 1986 to come out of retirement and bring the Green Revolution to Africa. With Borlaug and former President Jimmy Carter on board, Sasakawa created Sasakawa Global 2000 (SG2000), hoping to do in Africa what the Rockefeller Foundation did in Latin America 40 years before. Today, Borlaug says, SG2000 has set up between 350,000 and 400,000 demonstration plots where Green Revolution approaches are compared to traditional, current practices. "What this has shown is that you can always at least double the yields—and frequently triple them—and in some cases quadruple them by the application of the best package of technology that you can put together," he says. "Very simple steps can have a dramatic impact." Africans rarely use commercial fertilizer, for example, and the first high-yield sorghum was only brought to the continent in 1991.

A recent, dramatic success story has been Ethiopia, says Marco Quiñones, an SG2000 agronomist in Addis Ababa. Until 1991, the ruling military cabal favored heavy industry over farming. Partly because of urgings by Carter—who helped convince the prime minister to view SG2000 demonstration plots in 1994—the new government has emphasized agriculture, lending money for improved seed and fertilizer to the country's millions of small private farms.

As a result, Quiñones says, Ethiopian grain production went from less than 6 million tons in the 1994–1995 harvest season to an estimated 11.7 million tons in the 1996–1997 harvest season. "And that's with fertilizer levels typically less than half of what they are in the United States, ... with many farmers still not having access to improved varieties of maize and sorghum, and no improved varieties of teff [a traditional Ethiopian grain] yet available." Quiñones believes further increases will occur as farmers adopt new innovations such as parasite-resistant sorghum (see sidebar, p. 1040).

Researchers in Africa emphasize, however, that the continent's social and economic problems remain a major obstacle to development. SG2000 refuses to work in countries without stable governments, which bars it from many nations. It didn't begin operations in Mozambique, for instance, until the 1995–1996 season, a year after the end of a disastrous civil war. Based in the capital city of Maputo, the foundation selected 40 1-ha farms for demonstration plots, half near the border with Zimbabwe, half in the far North. It provided each farm with 100 kilograms of fertilizer and disease-resistant white maize seed. Harvests from the region near the Zimbabwe border usually averaged less than 1 t/ha, according to Wayne Haag, the SG2000 representative in Maputo. "With just this little bit of fertilizer and better seed," he says, "their yields were over 3 t/ha."

In the North, though, the results were less beneficial, but not because the improved seed and fertilizer failed to produce—the farms averaged 4.7 t/ha. The northern farmers were unable to take advantage of the surplus. The cash-strapped Mozambican government didn't fulfill its promise to buy excess production for about \$120/t. Worse, the poor condition of local roads prevented farmers from transporting their produce. The northern area ended up awash in maize; with stockpiles rotting, the price fell to a ruinous \$40/t. Meanwhile, a drought hit southern Mozambique, which paid \$160/t to import maize from South Africa. "It made economic sense," Haag says. "If you figured in paying the transportation costs, which are fairly high due to the poor infrastructure, and the high interest rates, it probably would have cost nearly \$200/t to take the grain produced in the North to the South."


THE CARTER CENTER

Dr. Green Revolution. Norman Borlaug *(left)* with farm family in Ghana.

In Haag's view, such woes demonstrate that the success of the African Green Revolution will depend on investment in infrastructure. But, he says, agencies like the International Monetary Fund are demanding that African governments "follow a very tight, austere public-financing policy, so there's no money." At the same time, foreign aid is being cut back, especially from U.S. sources. Says Haag: "Years ago, to start the Green Revolution there was a lot of external assistance. Now there's almost none and people stand back saying 'Africa is hopeless.' Well, Africa is not hopeless. You give the farmers here a chance and they respond magnificently."

Growing pains

If African nations make the necessary investments in agriculture—and Borlaug, for one, is confident that they eventually will—the region's poor soils and lack of water still make it unlikely that, even with the Green Revolution, Africa will ever produce enough surplus food to help meet the growing planetwide need. That task, says Takeshi Horie, an agronomist at Kyoto University, requires regions that have better soils, water, and climate. "To feed the world, we will have to take areas that have already increased yields greatly—Japan, California, Europe—and make them repeat it a second time," says Horie. "It will be a big job."

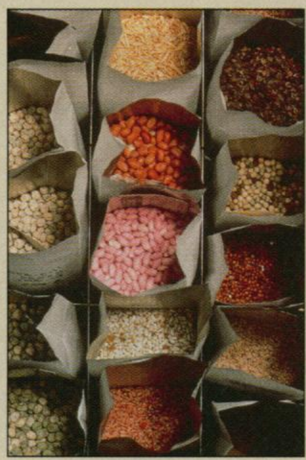
Just how big a job will depend in part on how fast demand for grains is likely to grow—a topic of considerable debate. In 1994, Lester Brown of Worldwatch caused an international uproar by predicting that China's growing appetite for grain would set off a worldwide economic convulsion. Brown argued that China is losing arable land and exhausting its water supply, while explosive economic growth and a shift in consumption from rice and wheat to meat will drive up its demand for grain. Brown forecast that China would have to import "massive quantities" of rice, wheat, and maize. This extraordinary demand would "trigger unprecedented rises in world food prices," he said, tipping the world food balance "from surplus to scarcity" and leading to mass starvation.

Most agricultural economists agree that

Cashing in on Seed Banks' Novel Genes

In 1970, an epidemic of Southern corn leaf blight ravaged farms throughout North America, causing the biggest economic losses ever recorded for a single crop in a single year. Nothing seemed able to stop the fungus that caused the blight—until scientists discovered that a wild variety of maize was resistant to it. By crossing the wild and cultivated maizes, researchers created resistant varieties, saving thousands of farmers from ruin.

The blight spread so rapidly because 70% of the maize in the United States had the same genetic susceptibility to the disease. This stark evidence of the dangers of genetic uniformity led to an international effort to conserve crop diversity. Today, collections hold more than 6 million germ plasm samples, mostly seeds, covering some 100 crop species and their wild relatives. But as Cornell University plant breeders Steven Tanksley and Susan McCouch contend in an article on page 1063 of this issue, plant breeders have failed to exploit seed banks.



USDA-ARS

Going to seed? Banks hold untapped riches.

"The embarrassing, paradoxical fact is that we've made this major investment in biodiversity but—except for corn blight—hardly ever used it," says Tanksley. "Seed banks are supposed to be storehouses of important genetic traits, but breeders pay practically no attention to them." Ronald Phillips, chief scientist for the competitive grants program at the U.S. Department of Agriculture, says the article "provides a great service by alerting people to the value of hidden genes in seed banks and by pointing out the newer methods for their detection."

In part, breeders have ignored seed banks because conventional breeding involves eliminating all but the most desirable traits. As a result, breeders tend to regard seed banks as botanical *salons des refusés*: storehouses of rejected traits. But Tanksley's own work shows how useful these storehouses can be. Tanksley began hunting through seed banks for novel genes 6 years ago, eventually teaming up with his Cornell colleague McCouch and Jiming Li and Longping Yuan of the National Hybrid Rice Research and Development Center, in Hunan, China. This group now has bred rice that may yield 20% to 40% more than conventional high-yielding strains—all by capturing genes from uncultivated rice varieties that themselves show little obvious sign of being useful.

Using methods pioneered by Tanksley with tomatoes, the researchers crossed a weedy, unpromising wild Malaysian rice (*Oryza rufipogon*) with cultivated Asian rice (*Oryza sativa*), hoping that the wild species might have some unknown beneficial traits. Of the 300 test plants they bred by crossing these species, about 15% outyielded the cultivated strain, a few by as much as 50%. At Cornell, Tanksley and McCouch genetically mapped the high-yielders and found two wild genes that seemed to be responsible for the increased yield. Such a finding, McCouch says, "flies in the face of traditional breeding, where the best parents give the best children. Here, Steve [Tanksley] was taking parents with poor phenotypes and using them to improve yields in elite varieties."

Although Tanksley believes that the hybrid rice will be useful, he is most pleased by the larger implications of the new method. Maintaining but not using seed banks, he says, "was like having this huge bank account in Switzerland, but nobody had given us the password, so we couldn't tap into it. The genes that passed the muster of evolution for millions of years are sitting there, waiting to be used. And now maybe we can start using them." –C.M.

China's appetite for grain will surge, but they believe—surprisingly—that the world can increase production fast enough to satisfy it, and with relative ease. World Bank analysts Donald O. Mitchell and Merlinda D. Ingco, for example, predicted in a widely cited 1993 study that future yields would "continue along the path of past growth." And Alexandratos's 1996 model for FAO argues that eliminating malnutrition in the world's poorest nations by 2010 "would certainly not tax the capacity of the world."

Agricultural scientists, although tending to dismiss Brown's scenario as overly apocalyptic, are considerably less sanguine than the economists are. "The ones that predict higher yields forever, I keep asking them, 'How are we going to do this?'" says Thomas R. Sinclair, an environmental horticulturist at the University of Florida-Gainesville's Agricultural Research Center.

With his colleagues, Sinclair has been assessing the maximum potential yields of individual wheat and maize plants—the harvest index, as it is known. "To grow corn," he points out, "you have to have leaves, stalks, and roots, so there's got to be mass committed to what you don't harvest." The question is how small the nongrain proportion needs to be. "At the beginning of this century," he says, "many crops had harvest indexes on the order of 0.25 of their weight in grain, and now many crops are approaching 0.5." Sinclair says the index can't rise much higher. "Maybe you could go up to 0.6 or 0.65," Sinclair says, "but beyond that you can't have a viable plant."

Nor, he believes, can farmers keep dumping ever-greater quantities of fertilizer on their fields. Maximum yields at IRRI experimental stations declined from 10 t/ha in the tropical dry season to 6 t/ha as overuse of fertilizer reduced the level of easily decomposable organic compounds in the soil, in turn reducing its nitrogen-supplying capacity. With less ability to hold nitrogen, overfertilized soils let it wash into rivers and groundwater, polluting them. Partly for this reason, fertilizer use in Europe—where runoff is a problem—declined from 169 kg/ha in 1988 to 116 kg/ha in 1993, the latest year for which FAO statistics are available.

These fundamental physical constraints mean that researchers can no longer easily apply the old Green Revolution paradigm—breed shorter plants with more grain per stalk, provide lots of fertilizer, and watch yields triple—to wheat, rice, and maize, the main cereal crops. "Producing higher yields will no longer be like unveiling a new model of a car," Nebraska's Cassman says. "We won't be pulling off the sheet and there it is, a two-fold yield increase."

An example is the "new plant type" rice under development at IRRI. Cultivated rice grows as a clump of almost 30 stemlike "panicles" that bear the flowers and grain. But only half the panicles produce grain, so Gurdev S. Khush, the principal plant breeder at IRRI's base in the Philippines, and coworkers selected for those and thickened their stems. IRRI scientists hope that the new plant type, which should be in field tests within 3 years, will push the current 0.55 harvest index of rice to 0.6 or 0.65—a 10% to 20% increase, not the 200% to 300% increases of the past.

But even this modest rise may be unattainable. Cassman and his collaborators reviewed the literature on the new plant type at the end of 1993. "We did not find a strong scientific paper trail, based on published data, that would justify or support the supposition that there's an untapped 25% yield potential," he says. (For another approach to increasing the rice-harvest index, see sidebar, p. 1042.)

Because increasing the harvest index will be difficult, progress will lie in combining a variety of approaches—breeding strains that better resist disease, tolerate acidic or metallic soils, or provide better nutrition. Borlaug is particularly excited about the aluminum-tolerant breeds of corn, soybeans, rice, wheat, and pasture grass now being tried on the highly leached Brazilian cerrado. Hopeful of finding useful new genes, U.S. cereal geneticists are proposing a federally funded project to spend more than $100 million on mapping the genomes of wheat, rice, and corn (*Science*, 27 June, p. 1960). But Cassman cautions that these "good and useful" efforts "will be expensive, compared to the past," and are unlikely "to shoot up yields overnight." Increasing crop yields, in his estimation, will be "incremental, tortuous, and slow."

Given that current varieties are approaching their biological limits, Russell Muchow of the Commonwealth Scientific and Industrial Research Organization, in Brisbane, Australia, believes that "the big opportunities lie not in raising maximum yields but in getting actual yields closer to the maximum." To find places where crop production falls below the maximum potential yield, Kyoto University's Horie factors in variables such as water availability, temperature, the length of day, and the harvest index. In the temperate California desert, Horie has calculated, the potential rice harvest is 19.3 t/ha. "The actual yield is only about 8 t/ha or 9 t/ha, so there is room for improvement by yield management," Horie says. Japan and Australia, he says, have similar possibilities. But in other areas, like China's Yunan province, Horie sees little opportunity. "The farmers get something like 13 to 15 tons per hectare, a very high yield. But there is no deficiency of nutrients or water, no insect damage, and it's very carefully managed, so the yield is very close to potential."

Maximizing yields, researchers believe, ultimately requires an expensive global effort to wring the last bit of productivity from plant genomes and employ "high-precision farming" techniques to realize the gains in the field. Martin Kropff, a theoretical ecologist at Wageningen Agricultural University in the Netherlands, says that lengthening the grain-filling period between flowering and maturity of the crop is one key. Temperate environments have cooler nights, naturally providing a longer grain-filling period. "[That's] one reason why the U.S. Midwest has such high yields," says Kropff. Hotter places like Africa may be able to partly overcome their disadvantage if breeders create new varieties with longer grain-filling periods, but they will have to be precisely managed. "Having a longer grain-filling period will depend on supplying the nitrogen at exactly the right time and in exactly the right amount," he says.

R&D is starving

Most of the optimistic forecasts of farm production depend crucially on a single variable: investment in R&D. "Science is not a panacea," says Per Pinstrup-Andersen, director-general of the International Food Policy Research Institute (IFPRI). "It will take more than that. But without it, we won't make it."

Modelers bank on R&D not only providing future productivity rises, but on maintaining current agricultural conditions. Biological systems are constantly changing, as pests and diseases evolve, soil conditions change from irrigation and cropping practices, and people heat up the earth with carbon dioxide. "You have to run harder and harder just to stand still in agriculture," says IFPRI researcher Philip G. Pardey. "It's not only a matter of generating more input, it's a matter of running to keep what we have now."

The trend, however, is worrisome. Public agricultural research funding has been declining for years, according to a new analysis by Pardey, Julian M. Alston of the University of California at Davis, and Johannes Roseboom of the International Service for National Agricultural Research at The Hague. In 1985 dollars, the three researchers reported at a 10 August international gathering of agricultural economists, global research spending doubled between 1971 and 1991, from $7.3 billion to $15 billion. But the average annual rate of increase fell from 4.4% in 1971–1981 to 2.8% in 1981-1991. A continuation of this trend, warns economist Pierre Crosson, a senior fellow at Resources for the Future, a Washington, D.C.–based think tank, "would pose a major threat to the achievement of a successful supply response to [the] rising world demand for food."


IRRI

Food for thought. Breeders saw big yield jumps from traditional *(left)* to modern rice plants *(center)*, but newer advances *(right)*, are less dramatic.

Privately funded research will not come to the rescue. Although private money funded 53% of all agricultural research in 1993, the last year for which data are available, the IFPRI researchers calculate that just 12% of the money went to direct crop improvement. For self-pollinating crops like wheat and rice, Pardey explains, industry has trouble recouping its investment in new varieties, because farmers only purchase the seed once. (Industry is more interested in corn, which in the United States is mostly grown from sterile hybrid seed.) Economics thus drives private R&D to focus on drugs, pesticides, food processing, and mechanization.

The slowdown has especially hit international R&D. The principal vehicle for such research is the Consultative Group on International Agricultural Research (CGIAR), a group of 43 public- and private-sector donors that supports 17 research centers, including CIMMYT, IRRI, IFPRI, and ICRISAT. Although CGIAR funding accounts for just 2% of all agricultural R&D, its catalytic role is disproportionately important, especially in the Third World. The chief focus of many national research institutions in poor nations is developing local adaptations to CGIAR technologies. Today, CGIAR is a victim of donor fatigue. Since 1993, its budget has remained roughly constant, at about $315 million. But because that money is parceled out to an increasing number of institutions, budgets on a per-organization level have fallen. IRRI, for instance, lost almost a quarter of its $30 million budget in the last 2 years; it recently laid off 550 people, half its staff. "There is so little investment to use science to solve poor people's problems," Pinstrup-Andersen says.

Pardey is especially concerned about the level of funding in Africa. "We're not talking slowdown there," he says, "we're talking retreat from R&D. Some [of the loss] was picked up by donors, but now those donor funds are not even there." Annual research spending from all sources increased by only 0.8 % in the 1980s, about a third of the average worldwide rate. An analysis of funding as a percentage of agricultural gross domestic product paints an even bleaker picture: The United States is about 2.5%, while Africa is only 0.5%. "And the gap between the intensity ratio of the developed and developing world is widening," says Pardey.

IFPRI economist Mark Rosegrant and three colleagues are refining an econometric model they unveiled in June to factor in the impact of different levels of R&D investments. But the overall picture seems clear. "We can, I think, feed everyone, even if we will continue to have problems distributing it equitably," Rosegrant says. "That's what the model indicates. But everything I'm saying could be destroyed if people stampede out of research funding." If that happens, he says, "the jig might be up."

–Charles Mann