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ABSTRACT

After 20 years, the "green revolution" is generally referred to as a milestone in the international agricultural movement. The introduction of new varieties of wheat and rice, along with fertilizers, pesticides, and mechanized farm equipment has produced a dramatic increase in world food production. This paper assesses the successes of the green revolution in light of its effect upon third world countries. It cautions that the revolutionary gains in agricultural production have not been distributed evenly. This uneven distribution of productivity is discussed in the first chapter, "Productivity Reconsidered." The second chapter, "Beyond the Green Revolution," considers the need for new crop varieties and technologies (including biotechnologies) but argues that tomorrow's innovations must be more consistent with regional agricultural traditions. This approach will help to avoid some of the environmental and social costs associated with the agricultural technologies utilized during the green revolution. The third chapter, "Rediscovering Traditional Agriculture," examines the benefits and limitations of traditional methods of agriculture, indicating that these practices should provide the basis for new practices, rather than be swept aside as archaic. "Toward Appropriate Biotechnology" discusses some of the possible contributions offered by biotechnology as tools for more efficient and sustainable agriculture. The document concludes with a call for additional research in sustainable agriculture productivity. (TW)

Beyond the Green Revolution:

New Approaches for Third World Agriculture

Edward C. Wolf

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Table of Contents

After twenty years, the green revolution stands as a touchstone in international agricultural development. At a time when famine seemed imminent, new varieties of wheat and rice introduced to Asia and Latin America along with fertilizers, pesticides, and mechanized farm equipment dramatically increased harvests. This agricultural strategy, which transformed the lives and prospects of hundreds of millions of people, is considered the most successful achievement in international development since the Marshall Plan and the reconstruction of Europe following World War II. India, whose food prospects once seemed bleak, today holds grain reserves that provide insurance against famine. Indonesia, once the world's largest rice importer, is now self-sufficient and exports rice.

But the agricultural progress that made the green revolution possible has not been distributed evenly. New seeds, fertilizers, and pesticides boosted the crop yields of Asian and Latin American farmers who had access to irrigation systems and markets for their crops. The aggregate statistics hide a large group of Third World farmers who did not benefit from the new technologies: subsistence farmers raising food for their families on marginal, rainfed land. Because their agriculture remains unproductive and vulnerable to crop failure, drought, and natural catastrophe, these rural people remain among the poorest in their societies. Failing to address their needs has slowed economic progress in dozens of countries. The recurrent famines in Africa, and persistent pockets of starvation on that continent, demonstrate the unacceptable human costs of this neglect.

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High-yielding varieties of wheat and rice have been introduced to less than a third of the 423 million hectares planted to cereal grains in the Third World. The rates of adoption vary widely by region: 36 percent
6 of the grain area in Asia and the Middle East, 22 percent of Latin America's grain area, and only 1 percent of Africa's grain fields grow improved varieties of wheat and rice. Other crops including barley, sorghum, potatoes, and especially maize have also been improved by research and breeding, and new varieties distributed to farmers. The local contributions of these advances have been substantial. For example, Zimbabwe's maize surpluses in recent years stem largely from plantings of improved hybrids by commercial and communal farmers alike. But none of these crops have had an effect on total food production, average productivity, and rural incomes as widespread or significant as the green revolution wheats and rices.[1]

Not all wheat and rice farmers can afford the new seeds and the inputs they require. Others raise crops for which systematic research is just beginning. Overall, nearly 100 million people in Latin America, 280 million in Africa, and over 990 million in Asia raise food under difficult conditions at yields little changed since mid-century. But grain yields in more agriculturally advanced regions are already near their biological ceilings; thus this group of nearly 1.4 billion people holds the key to future increases in world food production.[2]

The case for increasing yields remains as compelling today as it was a generation ago. Over the next 13 years, world population will expand from today's 5 billion to over 6 billion. Few analysts expect a significant expansion of cultivated land by then. Just to maintain current consumption levels will require a 26 percent increase in the world's average grain yields. And by 2020, feeding the projected population of 7.8 billion will require grain yields 56 percent higher than 1985 levels. Unlike past yield increases achieved under favorable cropping conditions, future improvements in average yields must come from raising the productivity of traditional farmers who cultivate low-yield crops under marginal conditions—perhaps the most demanding challenge that national governments and the international development community have faced.[3]

"High-yielding varieties of wheat and rice have been introduced to less than a third of the 423 million hectares planted to cereal grains in the Third World."

Small farmers cultivate their crops under extraordinarily diverse ecological conditions, ranging from the rain-soaked volcanic archipelagos of Southeast Asia to the arid savannas south of the Sahara and Latin America's high altiplano. Farming methods, and staple foods, vary enormously as well. In Southeast Asia, for example, where one-third of the farms are less than half a hectare in size, most farmers depend exclusively on manual labor and draft power supplied by water buffalos to cultivate their rice. On Africa's small farms, cultivated more with hoes than plows, families grow root and tuber crops including cassava and yams as the primary staples. Despite such variety, subsistence farms around the world share common features: Farmers often mix different crops in the same field to reduce the risk if a particular crop fails, they grow a variety of staple crops and vegetables to meet family food needs, and they rarely purchase artificial fertilizers or pesticides.[4]

Green revolution approaches will only be part of the answer for the 230 million rural households in Africa, Asia, and Latin America that use farming methods almost identical to those of their ancestors. One reason is energy. Past advances have come from increasing the energy intensity of farming: fuel to run machinery, fossil-fuel-based artificial fertilizers, and diesel fuel or electricity to run irrigation pumps. Few of the rural poor can afford these costly materials and services. Even if they had the income to purchase such inputs, many farmers are not served by roads or markets that could reliably supply them.

In addition, subsistence farmers grow crops that have received comparatively little research attention. There is as yet no research base for achieving high yields in many staple crops. Third World farmers cultivate on poor soils under harsh climates that require finely tuned agricultural practices. As rural populations grow, these farmers will need agricultural advances that are labor-intensive, rather than capital- and energy-intensive. Such conditions demand different research approaches from those that raised yields in the past.

A new strategy of efficiency and regeneration could help meet the needs of subsistence farmers, and begin to address the environmental and economic problems linked to more intensive cropping practices as well. Such a strategy would stress the efficient use of fertilizers, chemicals, water, and mechanized equipment. As a supplement to efficiency, farmers would blend biological technologies and traditional farm practices to increase the contribution that the land's natural fertility makes to food production.

Two sets of technical opportunities, already stirring the agricultural research community, promise rapid progress toward better resource management and regenerative approaches. One is the reappraisal of traditional farming practices, once judged backward and unproductive. Shifting cultivation, multiple cropping, and traditional soil management methods, though often practiced under pressures that make them counterproductive today, are governed by ecological principles that can serve as models for sustainable farming.

Biotechnology can also offer new solutions to Third World farming problems. The ability to modify the genetic makeup of plants and animals poses environmental risks that must be carefully evaluated. But biotechnology's benefits lie in the potential to allow breeders to develop new crop varieties more quickly than conventional breeding. Crops may be tailored to use water and nutrients more efficiently, and to perform well in the mixed cropping practices that many poor farmers employ.

Joining biotechnologies with the ecological insights of traditional farming promises innovative solutions to agriculture's economic and environmental problems. Government policies do not fully recognize that promise yet. But opportunities have never been greater for moving agriculture toward sustainability and reaching the quarter of the world's people—and quarter of the world's cropland—left out of the green revolution.

Productivity Reconsidered

The pursuit of productivity has been central to agriculture since farmers first selected the wild grasses ancestral to today's crops. In recent years, harvests have outpaced population growth, not only because more land has been brought under the plow, but because different plant varieties, more irrigation, fertilizer, and improved tools and equipment allow farmers to produce more from each hectare of land and each hour worked. World grain production increased from 620 million tons in 1950 to 1,660 million tons in 1985, and the average yield per harvested hectare climbed from 1.1 tons to 2.6 tons. These rapid increases have no precedent.[5]

The postwar increase in yields rested on a simple formula. Researchers and extension agents encouraged farmers to use more fertilizers, pesticides, and irrigation in combination with newly bred crop varieties. According to the conventional approach, substituting these capital- and energy-intensive inputs for the traditional resources of land and labor would allow farmers to expand harvests each year.

Some countries succeeded handsomely; hundreds of millions of people are better fed and better off than they would have been without these gains. But because of their exclusive focus on improving yields, policymakers and researchers emphasized regions where the economic return on investment in fertilizers would be highest, rather than seeking to distribute inputs more widely. This approach naturally overlooks farmers on marginal land, for whom raising yields may not be as important as increasing resistance to drought and other natural catastrophes.

Despite its drawbacks, enthusiasm for the conventional productivity formula is understandable. The increase in world food production in the last decade has been associated with a comparable increase in the use of artificial fertilizers. Regions that have used the most additional fertilizer have reaped the largest benefits. (See Table 1.) Asia and North America, the areas that harvested nearly four-fifths of additional world grain production, accounted for 56 percent of the increase in fertilizer use. And while North America's average harvested area also expanded over this period, virtually all the growth in Asian harvests came from fertilizer. Yet Eastern Europe and the Soviet Union demonstrate that additional fertilizer alone does not necessarily mean proportionately larger harvests. Relying on central planning rather than farmers to allocate fertilizer supplies accounts for much of the inefficiency.

Table 1: Increase in Average Grain Production and Fertilizer Use by Region between 1970-74 and 1980-84

Region	Grain Production Total Increase	Grain Production Share of World Increase	Fertilizer Use Total Increase	Fertilizer Use Share of World Increase
	(MMT)[1]	(percent)	(MMT)	(percent)
Asia	200.3	55	19.2	45
North America	86.0	23	4.6	11
Western Europe	31.3	9	2.8	7
Latin America	23.9	7	3.2	8
Eastern Europe and Soviet Union	8.8	2	10.7	25
Oceania	8.4	2	0.6	1
Africa	8.2	2	1.5	3
World	366.9	100	42.6	100

[1]Million metric tons.
Sources: U.S. Department of Agriculture, Economic Research Service, "World Indices of Agricultural and Food Production 1950-85," unpublished printout, Washington, D.C., April 1986; U.N. Food and Agriculture Organization, *Fertilizer Yearbook* (Rome: 1982 and 1984).

Average grain yields in the world's most populous countries reflect in part variations in rainfall and soil fertility, but they also illustrate the productivity gap that must be closed in the effort to raise the world's average yield above 2.6 tons per hectare. (See Table 2.) The 11 countries shown in Table 2 are home to nearly two-thirds of the world's

Table 2: Land Productivity in World's 11 Most Populous Countries, 1985

Country	Average Grain Yield	Population
	(tons per hectare)	(million)
Japan	5.8	122
United States	4.8	241
China	3.9	1,050
Indonesia	3.7	168
Bangladesh	2.2	104
Mexico	2.1	82
Brazil	1.8	143
India	1.6	785
Pakistan	1.6	102
Soviet Union	1.6	280
Nigeria	0.8	105
Total Population		3,182

Sources: Population Reference Bureau, *1985 World Population Data Sheet* (Washington, D.C.: 1985); U.S. Department of Agriculture, "World Indices of Agricultural and Food Production 1950-85," unpublished printout, Washington, D.C., April 1986.

population and represent the entire economic and ecological spectrum. Slightly fewer than a third of the world's people live in four countries where land productivity, measured as tons of grain harvested per hectare of agricultural land, exceeds 3.5 tons, well above the world average. Another third live in the five countries where productivity is less than 2 tons per hectare. While the highest yields occur in affluent industrial nations, China and Indonesia demonstrate that low income need not be associated with low yields.

The first step most countries can take to increase harvests is to correct the inefficient application of chemical fertilizers. Even China's high grain yield conceals a substantial opportunity to expand total harvests by distributing fertilizers more equitably to Chinese farmers. China's remarkable increase in food production from less than 200 million tons in the mid-seventies to over 300 million tons by 1985 was made possible in large part by an equally dramatic increase in fertilizer use. By 1983, Chinese farmers were applying 115 kilograms of artificial fertilizers per hectare planted, about as much as U.S. farmers. But according to Bruce Stone of the International Food Policy Research Institute, most of this was destined for just a third of Chinese cropland, that in the country's most fertile and most market-oriented areas. Adding another sack of fertilizer to these fields now produces much less additional grain than fertilizing neglected areas. Distributing fertilizer to the other two-thirds of Chinese cropland could yield three to 15 times more grain per ton of additional fertilizer than the state and market-oriented farms could produce under the existing distribution system.[6]

In addition, farmers achieve less than optimum production when they apply the nitrogen, phosphorus, and potash in artificial fertilizers in incorrect ratios. Nitrogen is often in short supply in Chinese soils, but if other nutrients are also lacking, just adding nitrogen cannot raise yields. Addressing the inequities in fertilizer distribution and correcting nutrient imbalances can increase food output faster and at lower cost than simply expanding fertilizer supplies, even in countries that now use little fertilizer.[7]

Another reason for using fertilizer more efficiently is the high environmental costs linked to heavy use. Government subsidies in Europe, Japan, and North America encourage farmers to expand production by applying more fertilizer than either sound agronomic practices or world market conditions warrant. One result of this subsidized overfertilization is that as much as one-fourth of the nitrogen fertilizers used in these regions leaches into groundwater. Increasing concentrations of nitrates in drinking water, which pose a health threat to bottle-fed infants, have been reported in Denmark, England, France, Germany, and the Netherlands. Ironically, at the levels of fertilizer applied by European farmers, the losses of nitrogen may

> "The first step most countries can take to increase harvests is to correct the inefficient application of chemical fertilizers."

amount to 30 to 45 kilograms per hectare—more fertilizer than is applied to cropland in many Third World countries.[8]

Farmers in Africa, Latin America, and Oceania have used the least additional fertilizer and contributed least to expanded food supplies. In Latin America, the challenge of managing enormous external debts has forced many countries to curtail imports of fertilizers in an effort to conserve foreign exchange for interest payments. In Africa, few farmers can afford conventional fertilizers, and limited water supplies often make them unprofitable. Yet, African and Latin American farmers need to expand food production, which has fallen behind population growth in both regions. Using additional fertilizer more efficiently would help, but these farmers also need less costly alternatives to the conventional methods of raising productivity.

Correcting inefficiencies in the use of purchased resources is not the only way to raise and sustain agricultural productivity. As the circumstances facing Africa and Latin America suggest, helping farmers achieve more stable yields, manage soils and water supplies more effectively, and control spending on costly chemicals could make farming practices in many settings more sustainable. Redefining productivity to encompass these concerns could broaden options for poor farmers in developing countries and suggest new directions for financially strapped farmers in industrial countries.

Farmers have another set of productive resources that publisher Robert Rodale has aptly labeled the "internal resources" of agriculture: the inherent fertility of the soil, rainfall and climate patterns, the dynamics of pest populations and their natural enemies—in other words, the natural resource base. The productive potential of these internal resources is sometimes masked or even diminished by heavy use of artificial fertilizers and other farm chemicals.[9]

"The rapid introduction of external inputs into agricultural production over the past century has unnecessarily diminished the strength, vitality, and usefulness of the internal resources of farmers," Rodale argues.[10] Research on nitrogen fixation by legumes shows how this can happen. Microorganisms in the roots of these crops convert nitrogen from the air into a form plants can use; the excess that remains in the soil can help nourish a subsequent grain crop. Soil scientist David Bezdicek and his colleagues at Washington State University have found that residual nitrogen from artificial fertilizer can reduce the amount of nitrogen fixed by a legume crop such as chickpeas. A heavy dose of fertilizer applied at the start of the growing season suppresses biological activity, while in some cases a small amount of fertilizer can actually stimulate nitrogen fixation. More nitrogen might be supplied by the correct balance of artificial fertilizer and biological nitrogen fixation than by using artifical fertilizers alone.[11]

The regenerative approach seeks to maximize biological contributions to agricultural productivity. It makes the most of natural sources of nitrogen, phosphorus, and potash, as well as the way these nutrients are cycled and conserved in natural ecosystems. Regenerative farming practices include sowing different crops together to use fully the soil's fertility, rotating food grains with nitrogen-fixing legumes, and planting trees and shrubs whose roots draw nutrients from deep soil layers to the surface. Purchased fertilizers and pesticides are used sparingly in these practices. Although regenerative methods require more careful farm management, they are less costly than conventional approaches.[12]

Agricultural research that emphasizes biological approaches to raising productivity can help poor farmers better cope with the risks imposed by erratic rainfall and less fertile soils. Conventional agricultural modernization, based on fossil fuels, is already beyond the means of many Third World farmers. Offered better methods for managing their internal resources, these farmers can reduce their vulnerability to crop failure and famine.

Beyond the Green Revolution

Two decades have passed since new, high-yielding varieties of wheat and rice were introduced to farmers in Mexico, the Middle East, and South Asia. The new varieties, which were more responsive to artificial fertilizers and irrigation than traditional varieties, "spread more widely, more quickly, than any other technological innovation in the history of agriculture in the developing countries."[13]

> "Research that emphasizes biological approaches can help poor farmers better cope with erratic rainfall and less fertile soils."

Modern grain varieties were quickly taken up in Bangladesh, India, Pakistan, and throughout Southeast Asia. (See Figures 1 and 2.) In Latin America, the area planted to new wheat and rice varieties increased from 270,000 hectares in 1970 to 9.6 million hectares by 1983. By the mid-eighties, roughly half the wheat area and nearly 58 percent of the rice area of all developing countries had been sown to high-yielding varieties. In major wheat- and rice-growing regions, the percentages are far higher: 82 percent of Latin America's wheat area and 95 percent of China's rice area were sown to high-yielding varieties in 1983.[14]

The amount of rice and wheat grown in developing countries increased 75 percent between 1965 and 1980, while the area planted to those crops expanded by only 20 percent. The ability to harvest two crops a year with the new seeds contributed to these increases. In 1980, the additional wheat and rice produced by green revolution technologies were worth an estimated $56 billion, of which $10 billion was due to the improved genetic potential of the new varieties. This expansion of the food supply is crucial to many countries with rapidly growing populations. As Michael Lipton of the University of Sussex wrote in 1985, "If the farmers of the Third World today used the same cereal varieties as in 1963-64, and everything else were unchanged, then tens of millions of people would this year die of hunger."[15]

Africa benefited least from the green revolution. Few of Africa's 50 million rural families grow wheat or rice, and only in the last decade have researchers turned their attention to millet, sorghum, cassava, yams, and cowpeas that are the subsistence staples of most rural Africans. Only 6 percent of sub-Saharan Africa's wheat and rice area is planted to modern varieties. Improved maize varieties and hybrids have boosted harvests in countries including Kenya, Zimbabwe, and South Africa, but on the whole, scientific plant breeding has not decisively changed the continent's food prospects. And Africa's conditions are not unique; many farmers in Latin America and Asia are still prevented from planting improved varieties by poor soils, erratic water supplies, and poverty.[16]

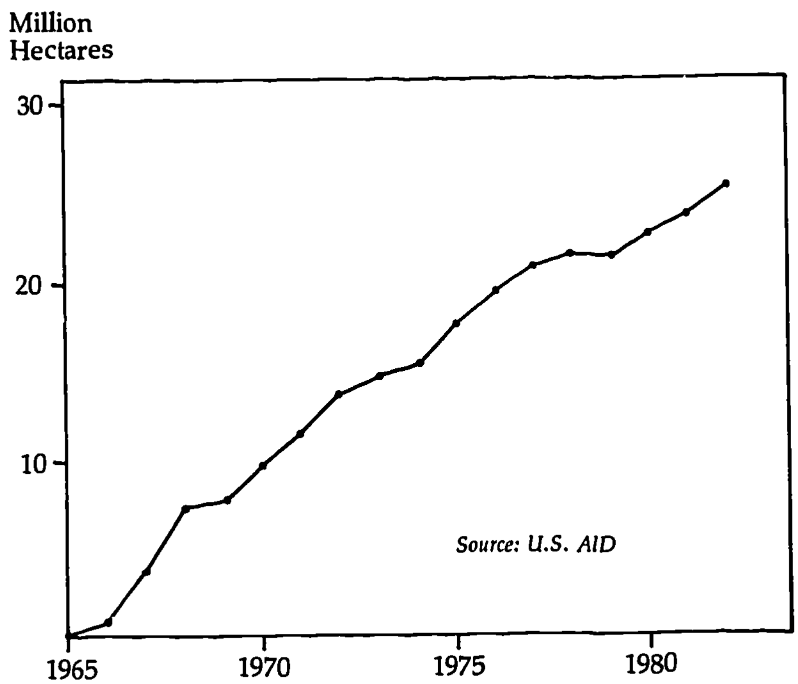

Figure 1: Area Planted to High-Yielding Varieties of Wheat in South Asia, 1965-82

High-yielding varieties of wheat and rice are still spreading, however. Though the early green revolution seeds were planted almost exclusively by farmers with well-irrigated land who could afford to purchase the necessary supplements of fertilizers and pesticides, modern varieties are now grown by farmers under less-favored circumstances. More than half of the high-yielding wheat in Bangladesh is watered only by rain, as is about 85 percent of the high-yielding rice in the Philippines. Varieties bred and released today perform better than traditional varieties even without costly inputs.[17]

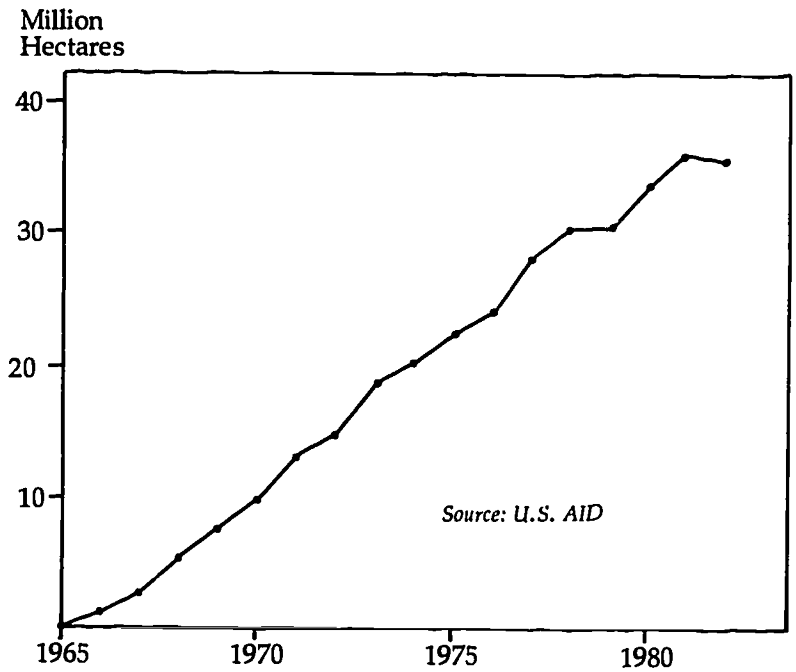

Figure 2: Area Planted to High-Yielding Varieties of Rice in Southeast Asia, 1965-82

The green revolution's early benefits were by no means equally shared. Relatively prosperous farmers who controlled more land, and so had the financial means to purchase fertilizers, pesticides, and equipment, gained most by adopting high-yielding wheat and rice. Small farmers in areas favored by abundant water, who tended to adopt new varieties and technologies later, also profited, but not as much. Grain prices dropped because of bigger harvests on the larger landholdings. Consumers enjoyed the lower food prices—or at least the brake on price increases—that expanded harvests made possible.

Governments also gained. India, for example, used the expanded production of the late sixties to offset its dependence on costly grain imports rather than to significantly increase food consumption among its poor. A drain on the country's treasury was plugged but there was little progress in raising per capita food consumption.[18]

Others, however, lost from the new technologies. The biggest losers were farmers in areas where the new varieties performed poorly, and those growing crops primarily for subsistence. These farmers earned no new income from bigger harvests, and may have become poorer as prices for their occasional marketable surpluses declined. On some 300 million hectares in the Third World, supporting over a billion people, productivity has not measurably improved.[19]

That the record of the green revolution is mixed should come as no surprise. The scientists who developed the new varieties of wheat and rice never expected their work to provide an open-ended solution to the world's food problems. Many believed that the new technologies offered a means to buy time until population growth rates could be slowed. Harvests could not increase indefinitely; birth rates would have to fall. Twenty years later, countries like China that both promoted new seeds *and* instituted economic reforms and national family-planning programs to lower birth rates have done the most to improve the welfare of their people.

The unique research network launched by the Rockefeller Foundation in Mexico in 1943 may be a more significant contribution of the green revolution than the expanded harvests achieved so far. Supported by the Rockefeller and Ford Foundations, plant breeders developed new crop varieties appropriate for conditions in Mexico, Pakistan, India, and Turkey. Success in these countries led to the creation of the Philippines-based International Rice Research Institute (IRRI) in 1962, the International Center for the Improvement of Maize and Wheat near Mexico City in 1965, and ultimately to the creation of a system of 13 international agricultural research centers funded through the Washington-based Consultative Group on International Agricultural Research (CGIAR). The research agenda of the centers today covers 21 food crops, conservation of the genetic resources used for plant

"Scientists never expected their work to provide an open-ended solution to the world's food problems."

breeding, animal husbandry and livestock diseases, and policy issues related to agricultural research.[20]

A high priority of the CGIAR centers is the need to defend the gains already achieved. Farmers who plant high-yielding varieties of wheat and rice need continuous research to sustain their yields. This "maintenance research" emphasizes breeding crop varieties to increase their natural ability to resist pests and disease. Maintaining stable yields at high levels can be a more complex task than raising yields in the first place. New plant varieties must be on hand to replace old ones that succumb to pests and disease. This requires a vast breeding program and an extensive system of gene banks.[21]

National and international research programs are turning to a new challenge: developing crops and technologies for farmers who do not irrigate their fields and who lack the income to purchase fertilizers and pesticides. The rice-breeding agenda at IRRI illustrates the shift in research priorities that will help meet their needs. In the sixties, the effort to raise yields of irrigated rice led to IR-8, IRRI's first widely planted high-yielding variety. When IR-8 began to experience serious pest infestation, breeders sought a wider variety of agronomic traits. IR-36 combined high yield with broad genetic resistance to pests, and it matured even more quickly than earlier varieties, permitting two crops to be harvested each year. IRRI's next successful rice strain, IR-64, was selected both for its broad resistance to pests and disease and for its more flavorful grain.[22]

In the eighties, breeders have further expanded their goals to developing rice varieties suited to adverse growing conditions—varieties that will be profitable for marginal and disadvantaged farmers. IRRI's breeding goals have evolved from a nearly exclusive emphasis on achieving peak yields with inputs of water and fertilizer to dependable production under a range of farming conditions.

In addition to appropriate crop varieties, poor farmers need alternative sources of plant nutrients. IRRI has begun to investigate opportunities to substitute farm-grown nutrient sources for purchased artificial fertilizers. Promising approaches for Asian farmers include the nitrogen-fixing blue-green algae sustained by a fern called *Azolla* that thrives in flooded rice paddies, and types of bacteria that could enhance soil fertility. Chinese farmers already use some of these

methods quite successfully, and researchers in the Philippines have found that farmers who grew *Azolla* in their paddies were able to reduce their use of purchased fertilizer by 50 percent without lowering yields.[23]

Such innovations are not restricted to Asia. Scientists at the International Institute of Tropical Agriculture in Nigeria have identified a leguminous African shrub called *Sesbania* that may prove to be a low-cost nitrogen source for African rice farmers. Research in Colombia indicates that farmers can cut their needs for phosphate fertilizers in half by using certain fungi that help plant roots absorb phosphorus. IRRI recently created the International Biofertilizer Germplasm Conservation Center at its Philippines headquarters, where promising microbial sources of plant nutrients can be evaluated, stored, and distributed to researchers all over the world for testing.[24]

A range of other food crops is beginning to receive deserved research attention. Wheat and rice tend to be grown under relatively homogeneous conditions. Breeders of these crops drew on an enormous backlog of improved wheats and rices already available in Japan and North America, varieties whose pedigrees predated World War II. By contrast, improving the staple crops widely grown in Africa, and the potatoes, yams, and legumes grown throughout the Third World, is a much more challenging task. Such crops grow under widely divergent conditions, and have no comparable history of improvement. Systematic work on cassava and cowpeas in West Africa or potatoes in the Andes is little more than a decade old.

Efforts to raise the productivity of all staple crops in the years ahead depend on gathering a wide range of traditional varieties, crop relatives, and wild plants for breeding. Breeders need this genetic sampling to select the traits that strengthen resistance to pests and disease, and to tailor crops to grow under varied ecological conditions. Collecting and storing crop germplasm is coordinated by the International Board for Plant Genetic Resources (IBPGR). It is now a major responsibility of all the international centers. The value of distant crop relatives is likely to increase as biotechnology techniques are introduced that can speed up and simplify the tasks of breeding new varieties. IBPGR has initiated genetic resources programs in 50 countries, and national committees concerned with conservation of germplasm have been set up in over two dozen others.[25]

For most major food crops, germplasm collections of modern and traditional crop varieties are impressively broad. (See Table 3.) Except for wheat, however, scientists have not thoroughly investigated or collected the wild relatives of these crops. The unique genetic com-

Table 3: Estimated Number of Germplasm Samples Collected for Major Food Crops, and Coverage of Traditional Varieties and Wild Species

Crop	Samples in Major Genebanks	Estimated Share of Diversity Collected: Traditional Varieties	Wild Species
	(thousands)	(percent)	
Wheat	400	95	60
Rice	200	70	10
Maize	70	90	—
Barley	250	40	10
Sorghum	90	80	10
Potato	42	95	—
Cowpea	18	75	1

Source: Adapted from Consultative Group on International Agricultural Research, "International Agricultural Research Centers: Achievements and Potential," unpublished draft, Washington D.C., August 1985.

binations of wild crop relatives are often lost as modern varieties and monocultures replace traditional farming methods. Such wild species may hold the key to improvements in the productivity of crops like sorghum and cowpeas that are crucial to Africa's food prospects.

Most of the world's food is supplied by a handful of crops selected by our neolithic ancestors. While farming technologies have advanced steadily, there have been few significant botanical innovations since the origins of agriculture. Most international research deals with just 16 widely grown crops, although at least 3,000 plants have been used for food at one time or another in history. Crops like teff, a hardy grass grown as a staple grain in Ethiopia, or amaranth, a grain and vegetable crop native to the Americas that is both nutritious and drought-tolerant, may prove better-suited than conventional crops to the environmental and economic conditions facing many Third World farmers.[26]

The network of international research centers may not be the wellspring of work on promising but unproven crops. By their charters, the centers are instructed to work on the most widely grown food crops. Research efforts focus on crops with proven potential and regions where the return to research investment is likely to be high. But restricting research to familiar crops may foreclose some important agricultural opportunities.

Naturalist Gary Nabhan, who has studied traditional food and medicinal plants native to the Sonoran Desert in the southwestern United States, believes that research on unconventional crops may be as valuable for insights on how to manage familiar crops as for novel agronomic possibilities. He writes, "By evaluating native desert plants as potential economic resources, and comparing them with conventional crops, we stand to learn something about the tradeoffs between short-term productivity and long-term persistence in unpredictable environments."[27]

Independent research centers have an important role to play in pursuing the agricultural opportunities that fall outside the mainstream of international research. The privately funded Rodale Research Center in Pennsylvania coordinates worldwide research on amaranth and

"In pursuit of higher productivity, many agricultural scientists overlooked the need for long-term sustainability."

maintains a germplasm collection containing 1,300 amaranth samples from Asia and Latin America. Scientists at Rodale and at the Land Institute in Kansas are investigating perennial grain polycultures as possible alternatives to today's annual corn and wheat monocultures, particularly for marginal lands. Agriculture based on perennials, though probably decades away, would offer several advantages over current practices, including reduced soil erosion, simplified weed control, improved water management, and enhanced soil fertility. Understanding perennial-based cropping practices could shed new light on how to reduce the environmental impact of more conventional farming practices.[28]

New crop varieties and technologies for farmers in developing countries will be essential in the years ahead. Biotechnologies may provide new generations of crop varieties to farmers left out of the green revolution. But to avoid the environmental and social costs associated with the last generation of agricultural technologies, tomorrow's innovations will have to be more consistent with regional agricultural traditions and better matched to the ecological context into which they are introduced.

Rediscovering Traditional Agriculture

Agricultural research has been needlessly hindered for two decades by pejorative attitudes toward traditional farming. Some scientists assumed that because peasant farmers produced low grain yields, their practices had little relevance to twentieth-century agriculture. Until recently, few researchers recognized the ecological and agronomic strengths of traditional practices that had allowed farmers over the centuries to maintain the land's fertility. In pursuit of higher productivity, many agricultural scientists overlooked the need for long-term sustainability.

Economic analysis reinforced the belief that traditional practices had little to offer in solving contemporary agricultural problems. In *Transforming Traditional Agriculture*, published in 1964, University of Chicago economist Theodore Schultz argued that peasant farmers were rational and efficient individuals who had reached the limits of their technologies. His conclusion: No significant increase in harvests could be achieved using only the resources and methods that traditional farmers had at their command. Schultz advocated investments in agricultural research, new technologies, and rural education that would allow traditional farmers to choose innovations to increase their productivity.[29]

Many scientists and policymakers, however, saw traditional methods as an obstacle to be eradicated rather than a basis for introducing new seeds and farming methods. The food crisis in India and throughout Asia in the late sixties lent a sense of urgency to efforts to promote the green revolution. The strengths of traditional practices and the reasons for their persistence were swept aside. A report by U.S. President Lyndon Johnson's Science Advisory Committee warned in 1966 that "the very fabric of traditional societies must be rewoven if the situation is to change permanently."[30]

Agricultural scientists have recently begun to recognize that many farming systems that have persisted for millennia exemplify careful management of soil, water, and nutrients; precisely the methods required to make high-input farming practices sustainable. This overdue reappraisal stems in part from the need to use inputs more efficiently, and in part from the growing interest in biological technologies. The complex challenge of Africa's food crisis in the early eighties forced scientists to look more closely at the methods used by peasant farmers. Many researchers today seek to "improve existing farming systems rather than attempting to transform them in a major way," according to William Liebhardt, director of research at the Rodale Research Center.[31]

Traditional farming systems face real agronomic limits, and can rarely compete ton for harvested ton with high-input modern methods. It is important to recognize these limitations, for they determine both how traditional practices can be modified and what such practices can contribute to the effort to raise agricultural productivity.

First, most traditional crop varieties have limited genetic potential for high grain yields. They are often large-leaved and tall, for example. These traits help farmers meet nonfood needs, supplying thatch,

> "Agroforestry systems offer improvements in water-use efficiency and soil fertility that subsistence farmers can afford."

fuel, and fodder as well as food to farm households. Traditional varieties respond poorly to the two elements of agronomic management that make high grain yields possible: dense planting and artificial fertilizer. Despite these limitations, traditional varieties also contain genetic diversity that is invaluable to breeders in search of genes for disease- and pest-resistance and for other traits.[32]

Second, peasant farmers often have to plant in soils with serious nutrient deficiencies, where crop combinations and rotations are needed to help offset the limitations. Many tropical soils, for instance, lack sufficient nitrogen to sustain a robust crop. Soils in vast areas of semiarid Africa are deficient in phosphorus. High-yielding varieties, more efficient in converting available nutrients into edible grain, can rapidly deplete soil nutrients if they are planted in monocultures by peasant farmers who cannot afford to purchase supplemental fertilizers.[33]

Traditional agriculture, practiced under biological and physical limitations, often breaks down under growing population pressure. As rural populations grow, farmers try to squeeze more production from existing fields, accelerating the loss of fertility. Or they may cultivate new, marginal, or sloping land that is vulnerable to soil erosion and unsuited to farming.

Nonetheless, traditional methods can make an important contribution to efforts to raise agricultural productivity. They offer what Gerald Marten of the East-West Center in Hawaii calls "principles of permanence." They use few external inputs, accumulate and cycle natural nutrients effectively, protect soils, and rely on genetic diversity. "Neither modern Western agriculture nor indigenous traditional agriculture, in their present forms, are exactly what will be needed by most small-scale farmers," says Marten. "The challenge for agricultural research is to improve agriculture in ways that retain the strengths of traditional agriculture while meeting the needs of changing times."[34]

Farming methods like the traditional agroforestry systems of West Africa's Sahel region offer improvements in water-use efficiency and soil fertility that subsistence farmers can afford. Sahelian farmers traditionally planted their sorghum and millet crops in fields interspersed with a permanent intercrop of *Acacia albida* trees. Acacia trees fix nitrogen and improve the soil. In the Sahel, grain yields are often highest under an acacia's crown.[35]

Fields that include acacia trees produce more grain, support more livestock, and require shorter fallow periods between crops than fields sown to grain only. *Acacia albida* naturally enhances productivity by returning organic matter to the topsoil, drawing nutrients from deep soil layers to the surface, and changing soil texture so rainwater infiltrates the topsoil more readily. All of these benefits make farming on marginal lands more productive and profitable without requiring the farmer to purchase fertilizers year after year.[36]

Equally important, such improvements in soil structure, organic matter content, water-holding capacity, and biological nitrogen fixation allow the most productive application of conventional fertilizers. Programs promoting acacia-based agroforestry could complement fertilizer extension in semiarid countries—agroforestry playing a role analogous to irrigation. Governments that have modest fertilizer-promotion programs may find that they can maximize the benefits from fertilizer by promoting agroforestry as well.[37]

Legume-based crop rotations and traditional intercropping systems husband organic material and nutrients much more carefully than do modern monoculture practices. While organic manures and composts contribute significant amounts of nutrients in their own right, they can, like agroforestry, also magnify the contribution of small amounts of artificial fertilizers.

Research in Burkina Faso illustrates the complementary effect. (See Table 4.) This study looked at the contributions of straw, manure, and compost to sorghum yields with and without the addition of small amounts of artificial nitrogen. The results show that the most productive organic method, applying compost, can increase sorghum yields from 1.8 tons per hectare to 2.5 tons. Artificial fertilizer alone produced grain yields slightly higher than any of the organic practices. But the best result was achieved by combining compost with artificial fertilizer; this raised sorghum yields to 3.7 tons per hectare. The three

Table 4: Complementary Effect of Artificial and Organic Fertilizers on Sorghum Yields in Burkina Faso, 1981

Treatment[1]	Sorghum Yield	
	Without Artificial Nitrogen	With 60 kg/ha Nitrogen
	(metric tons per hectare)	
No Organic Treatment	1.8	2.8
Sorghum Straw	1.6	3.4
Manure	2.4	3.6
Compost	2.5	3.7

[1]All organic materials applied at a rate of 10 tons per hectare.

Source: M. Sedogo, "Contribution à la valorisation des résidus culturaux en sol ferrugineux et sous climat semi-aride," doctoral thesis, Nancy, France, 1981, quoted in Herbert W. Ohm and Joseph G. Nagy, eds., *Appropriate Technologies for Farmers in Semi-Arid West Africa* (West Lafayette, Ind.: Purdue University International Programs in Agriculture, 1985).

organic practices increased the efficiency of nitrogen application by 20 to 30 percent. Given responsive crop varieties and small amounts of artificial fertilizer, traditional practices that cycle organic materials effectively would raise yields in the same manner.[38]

Some conventional analysts looking at the study would argue that fertilizer outperforms the organic practices. Yet exclusive reliance on fertilizer would sacrifice a significant part of the additional harvest. As French researcher Christian Pieri, who has worked in West Africa, points out, "Fertilization is a prime technique for increasing agricultural productivity in this part of the world, but in order to obtain a greater and lasting production it is indispensable to combine the effects of mineral fertilizers, the recycling of organic residues and biological nitrogen fixation, and also to optimize the use of local mineral resources such as natural phosphates."[39] Neglecting the local internal resources can undermine a farmer's investments in conventional inputs.

Intercropping, agroforestry, shifting cultivation, and other traditional farming methods mimic natural ecological processes, and the sustainability of many traditional practices lies in the ecological models they follow. This use of natural analogies suggests principles for the design of agricultural systems to make the most of sunlight, soil nutrients, and rainfall.

Shifting cultivation practices, such as bush-fallow methods in Africa, demonstrate how farmers can harness the land's natural regeneration. Farmers using bush-fallow systems clear fields by burning off the shrubs and trees. Ashes fertilize the first crop. After a couple of seasons, as nutrients are depleted, harvests begin to decline, so farmers abandon the field and move on to clear new land. Natural regeneration takes over; shrubs and trees gradually reseed the field, returning nutrients to the topsoil and restoring the land's inherent fertility. After 15 to 20 years, the land can be burned and cultivated again.[40]

The bush-fallow system has obvious limitations. It requires enormous amounts of land, and when population growth pushes farmers to return too quickly to abandoned fields, serious environmental deterioration can result. Declining land productivity in crowded countries like Rwanda is testimony to this danger. But even disintegrating systems offer a basis for designing productive and sustainable farming practices.

Researchers at the International Institute of Tropical Agriculture, for instance, have adapted the principles of natural regeneration in bush-fallow systems to a continuous-cultivation agroforestry system called alley cropping. Field crops are grown between rows of nitrogen-fixing trees; foliage from the trees enhances soil organic matter, while nitrogen fixed in root nodules increases soil fertility. A high level of crop production is possible without a fallow interval. Traditional shifting cultivation provided the model for this system.[41]

> "The sustainability of many traditional practices lies in the ecological models they follow."

Conventional research tools can also be used to overcome the agronomic constraints that have limited traditional systems to low productivity. For decades, crop breeders have tailored varieties to respond to high levels of artificial fertilizers, assured water supplies, and dense monoculture plantings. Working with the genetic diversity available in traditional crop varieties, they can apply the same breeding methods to produce varieties better matched to the conditions faced by subsistence farmers. At an Agency for International Development workshop on regenerative farming practices, Charles Francis of the University of Nebraska concluded, "A new generation of varieties and hybrids adapted to marginal conditions and to intercropping could be the start of a new revolution aimed at meeting the needs of the majority of limited resource farmers in the developing world."[42]

Traditional practices exemplify efficiency and the regenerative approach to agricultural development. Yet until recently, a kind of myopia has kept the research community from recognizing the opportunities for agricultural innovations that lie in traditional practices. In West Africa, for example, 70 to 80 percent of the cultivated area is sown to combinations of crops in traditional intercropping systems. Cowpeas, one of Africa's most widely grown food staples, are always planted as an intercrop. But only about 20 percent of the research effort in sub-Saharan Africa focuses on intercropping.[43]

As the African examples described here show, researchers can use traditional principles to develop new techniques that preserve the land's stability and productivity even as populations increase. Though traditional methods have limitations, they are not archaic practices to be swept aside. Traditional farming constitutes a foundation upon which science can build.

Toward Appropriate Biotechnology

Most agricultural innovations of the past have been based on gradual refinements of technologies known at least since the Industrial Revolution and in some cases since the dawn of farming. But the 1953 discovery of the structure of DNA and the 1973 development of "recombinant DNA," or gene-splicing techniques, promise to change irretrievably the familiar landscape of agricultural development. Biotechnologies based on these insights allow scientists to identify the genes that control certain physical traits and to combine the genes of distantly related or unrelated plants and animals—two barriers that conventional plant breeders have never been able to overcome. Many analysts believe that agricultural applications of biotechnology will mark a watershed in the effort to raise productivity.

From 1920 to 1950, agriculture in industrial countries was dominated by mechanical technologies that dramatically increased the amount of food produced per worker and per hour. Shortly after World War II, the mechanical age gave way to the chemical age as farmers worldwide began to adopt artificial fertilizers and synthetic chemical pesticides, which vastly expanded their harvests per hectare. Biotechnologies shift the focus of research toward crop plants themselves. They have inaugurated a new era of agriculture likely to reshape research, development assistance, and farmers' choices. Biotechnologies may offer cheaper and quicker ways to improve Third World staples—including millet, cassava, and yams—than the costly innovations of the mechanical and chemical eras.[44]

Biotechnology encompasses an array of tools and applications that allow researchers to manipulate the genetic material of plants, microbes, and animals. These methods provide ways to modify the characteristics that are passed from one generation to the next. The vaccines, antibiotics, and reproductive technologies created through biotechnology and genetic engineering are already revolutionizing animal husbandry. Biotechnologies are not yet as widely applied to cultivated crops, in part because scientists understand less about plant genetics and physiology than about domestic animals.

Technical hurdles are not the only constraints on agricultural applications of biotechnology. So far, advances have been made in industrial countries, where public scrutiny is intense. The environmental risks posed by releasing gene-spliced microbes or plants into the environment remain poorly understood. Developing guidelines for the newly emerging technologies has led to a contentious public debate about genetic engineering. In the United States, debate has centered on proposals to release bacteria modified to retard the formation of frost on strawberry and potato plants. Because the bacteria could reproduce in the natural environment and thus spread beyond the fields where they were released, predicting environmental impacts is both more crucial and more complex a task than with many other technologies. Developing the "predictive ecology" that critics say is necessary for thorough environmental review, and enacting regulations that guard against the uncertainties will slow the marketing of commercial biotechnology products to industrial country farmers.[45]

The genetic engineering of plants is far more complex than modifying microbes, but it is also less controversial on environmental grounds. Crops with modified traits are under a farmer's direct control, and their reproduction and spread in the environment are both slower and more predictable. Crop characteristics like drought-tolerance, ability to withstand salty water, and pest resistance—the traits that have always concerned breeders—are a likely focus of the new technologies.

Thus, the major applications of biotechnologies to Third World crops will complement rather than replace conventional plant breeding. Developing new crop varieties can be an extraordinarily complex and time-consuming process. Identifying desirable characteristics, crossing parents, planting and growing the first generation of the cross, selecting the progeny that have the right mix of desired traits, and refining those characteristics through further breeding and screening can easily take a decade or longer. Conventional breeding of a new variety of wheat may involve thousands of carefully selected crosses.

By contrast, tissue culture, gene transfer, and other genetic techniques allow much of this work to be done in the laboratory, because researchers can manipulate single cells rather than entire plants. This saves space and time. Gene-splicing techniques allow researchers to transfer only specific traits into a crop. Such precision can help reduce the need to identify and eliminate full-grown plants carrying undesired genetic baggage—a problem when distantly related species or varieties are crossed.

Tissue culture techniques may revolutionize international gene banks by making it easier to store and manipulate crops that do not reproduce by setting seeds. These methods—which allow single plant cells to be sustained in laboratory flasks, multiplied, and regenerated into adult plants—are especially important for crops that propagate by roots or cuttings, such as cassava, potatoes, and yams. Tissue culture is also useful for propagating slow-growing species, including trees that hold promise for reforestation.[46]

Given the ability to modify virtually any plant characteristic and to tailor plants in precisely defined ways, biotechnology would seem to offer tools well-suited to agricultural development strategies that emphasize resource efficiency and farming's internal resources. According to the U.S. Office of Technology Assessment, "Most emerging technologies are expected to reduce substantially the land and water requirements for meeting future agricultural needs."[47] For example, it should eventually be possible to modify a plant's physiology to improve its efficiency in photosynthesis, enabling grains to produce more carbohydrate and thus, higher yields. The adaptations that allow some plants to lose very little water through their leaves in transpiration, transferred to more widely grown crops, could reduce irrigation needs. Developments like these could indeed diminish pressures on marginal lands and perhaps eliminate the need for costly capital investments in water supply projects.

There is nothing in the nature of biotechnologies that renders them inherently appropriate to a strategy of efficiency and regeneration, however. Many biotechnology innovations pose trade-offs rather than clearcut benefits. Although increasing photosynthetic efficiency could raise yields, it would likely lead to accelerated depletion of soil nutrients and heavier dependence on artifical fertilizers.

Another trade-off centers around herbicide resistance, a relatively uncomplicated genetic trait, which makes it an attractive research target. Researchers have already put considerable effort into developing crop plants that resist herbicides, allowing farmers to apply more of these chemicals. Much of this work is supported by the chemical companies that market herbicides.[48]

"The most significant factor that will affect the direction of agricultural biotechnology is the rapid shift of research to the private sector."

Herbicides have come to play a major role in industrial-country farming in recent years. High fuel costs and the need to conserve soil have prompted U.S. farmers to adopt reduced-tillage practices on 42 million hectares. These methods, which involve less plowing and leave topsoil covered with crop residues, employ herbicides rather than cultivation to control weeds. Conservation tillage is no longer restricted to industrial countries; scientists at the International Institute of Tropical Agriculture are also investigating more labor-intensive forms of these practices for small farmers to protect fragile tropical soils. In both industrial and developing countries, the soil- and energy-saving benefits of conservation tillage practices could be offset by the hazards of increased reliance on chemical herbicides.[49]

The most significant factor that will affect the direction of agricultural biotechnology is the rapid shift of research from the public to the private sector. This is especially evident in the United States. For nearly a century, public agricultural experiment stations and land grant universities sponsored by the U.S. Department of Agriculture (USDA) performed most agricultural research. Private seed companies often used the plant varieties developed by government-supported breeders. Over the last three decades, however, the private sector has assumed control of research efforts. Private companies now perform two-thirds of U.S. agricultural research.[50]

In biotechnology, the deck is stacked even further in favor of the private sector. USDA's Agricultural Research Service and Cooperative State Research Service support most public work in agricultural biotechnology, and these two federal programs spent less than $90 million on biotechnology research in 1984-85. Monsanto, which has the largest but by no means the only plant biotechnology research program among private U.S. corporations, has already invested $100 million in agricultural biotechnology development. Biotechnologies that affect agriculture in the years ahead will have a decidedly private-sector cast. With the exceptions of mechanization and the development of hybrid corn, that has not generally been true of important innovations in agriculture.[51]

Leaving research priorities to the marketplace may eclipse promising opportunities. Research efforts on crops will be proportional to the value of the crop and the size of the market. Because improving crops for small farmers in developing countries means producing low-cost agronomic innovations, many of which must be site-specific and thus not suitable for mass-marketing, crop improvement for the vast majority of the world's farmers offers little profit. Few private companies are likely to enter such an unpromising market. Consequently, investigations of minor crops like sorghum and millet, grown primarily by Third World subsistence farmers, will be neglected.

National research programs and the international research centers have an obvious stake in applying biotechnology. Refinements in plant breeding, technologies for germplasm storage and for plant evaluation and propagation, and new alternatives in pest control are exactly the kinds of innovations scientists need to extend research on developing-country food crops. It took decades of work to produce high-yielding varieties of wheat and rice. With biotechnology, comparable improvements in millet, sorghum, cassava, or tropical legumes could come more quickly.

The private-sector domination of biotechnology raises questions about the role new technologies will play in international research programs. Private companies may become competitors with the CGIAR-sponsored centers, particularly when it comes to improvements in major, widely traded crops like wheat and rice. The full exchange of scientific information that is essential to the international centers may be curtailed if it appears to compromise proprietary corporate research. Moreover, international centers may increasingly have to purchase or license new technologies that were formerly freely available through public channels. Finally, private firms will compete with the centers for scientific talent, and the centers may be unable to match the salaries, facilities, and security that corporate laboratories offer.[52]

Uncertainties cloud the prospects for national biotechnology programs as well. A few developing countries, notably Indonesia, the Philippines, and Thailand, have established national programs in agricultural biotechnology. The Philippines views its program as the first step toward an industrialization strategy based on biological materials that can help free the country from dependence on im-

"For Third World farmers who never shared in the agricultural advances of the green revolution, the issue is economic survival."

ported oil. Philippine scientists hope to use crop residues and by-products as raw materials to produce liquid fuels and industrial chemicals, and to develop food-processing industries with biotechnology methods. W.G. Padolina, of the National Institute of Biotechnology and Applied Microbiology at the University of the Philippines, writes, "The national strategy is to transform biomass biologically into food, fuel, fertilizers, and chemicals."[53]

Achieving these goals is certain to be costly. Few countries can afford the investment in equipment that major biotechnology programs entail, and some countries lack sufficient trained scientists to staff such programs. Agricultural biotechnology contrasts sharply in this regard with conventional plant-breeding programs, which require relatively modest capital investment.

Biotechnologies offer promising tools for more resource-efficient and sustainable agriculture. Technical hurdles must be overcome and environmental risks evaluated before that potential can be realized. But more troublesome from the standpoint of Third World agriculture is the degree to which the private sector will dominate agricultural biotechnologies. An expanded commitment to public research, at both the national and international levels, is needed to correct distortions of the research agenda and ensure that Third World priorities command attention. Public research in biotechnology consistent with resource-conserving and low-cost farming practices could counterbalance private-sector priorities.

Research for Sustainable Agriculture

The sense of urgency with which the green revolution was launched has largely disappeared from international agricultural development efforts. That several developing countries, formerly food importers, now have achieved food self-sufficiency has led some policymakers to question the value of assisting poor countries to increase food production further. But for Third World farmers who never shared in the agricultural advances of the green revolution, the issue is economic survival. Only by husbanding their scarce resources, regenerating their land, and raising their yields can these farmers improve their economic prospects. The reorientation of agricultural research and development assistance to meet their needs has begun, but deserves more attention and support.

An important bellwether of trends in international agricultural research is the funding of the world's 13 CGIAR-sponsored research centers. The budget grew from $21 million in 1972, when the system included just four centers, to over $100 million by 1980. This growth expanded the research mission to new crops and ecological zones. Spending increased more slowly to a level of about $170 million by the mid-eighties. While support for the centers remains strong, sufficient financial resources in the years ahead to underwrite more complex research tasks and changing technologies are by no means assured.[54]

CGIAR centers have established an important foundation of basic knowledge about staple food crops in the last 15 years. Opportunities to apply that knowledge could slip away if funding support stagnates. A large measure of responsibility for adapting crop research to local conditions rests with national research programs. Scientists at CGIAR hope that national programs will assume most of the responsibility for crop breeding in the years ahead. This would allow the international centers to focus on more "strategic" issues, including coordinating the conservation of crop genetic resources and applying biotechnology to staple crops.[55]

The international research agenda is shaped as much by new technologies as by critical agricultural needs. Biotechnology, now the principal focus of private-sector agricultural research, has captured the limelight; research administrators are scrambling to hire molecular biologists and redirect research programs. Taking this trend too far could be a serious mistake for public research institutions worldwide. As Cornell University sociologist Frederick Buttel counsels, "One must be cautious in assuming that there is only one scientific trajectory along which agricultural practices evolve."[56]

After supporting much of the work that led to the green revolution, the Rockefeller Foundation is now looking at ways to apply biotechnology to the crops overlooked by private-sector research. In 1983, the foundation redirected its program in agricultural sciences to emphasize biotechnology research on rice, the grain of least interest to private firms in industrial countries. In 1986, the foundation outlined a new agenda that included plans to extend biotechnology research to the improvement of sorghum, millet, and other neglected staple food crops—partly to counterbalance the private-sector emphasis on more widely grown commercial crops.[57]

The public research agenda can complement and compensate for the interests of the private sector in other ways as well. One way is to focus some portion of agricultural research on ecology. Robert Barker of Cornell University argues that public institutions like the U.S. land grant universities should shift their attention to the "development of the ecosystem sciences."[58] Agricultural technologies and practices that emphasize efficient use of resources and regenerative approaches are more likely to draw on the insights of ecology and evolutionary biology than on biochemistry.

In the past, responsibility for advances in resource efficiency and regenerative approaches has been left to independent institutions like the Rodale Research Center and some U.S. universities that have developed programs in agroecology. Participants in a 1980 Office of Technology Assessment workshop on biological technologies for agriculture noted that "much of the development of innovative technologies is occurring outside of, and perhaps in spite of, the national and international institutions normally considered responsible for maintaining natural resources and for dealing with problems of land quality and productivity."[59] That bias is slowly changing.

At the international level, the CGIAR centers have begun to acknowledge the importance of agricultural sustainability. The directors of the centers agreed in May 1986 to devote more research to raising crop productivity in ways that avoid environmental deterioration. The new emphasis on resource management goes beyond crop yield to encompass soil conservation, water management, and ways to help farmers reduce their reliance on purchased chemicals and fertilizers. In addition, the centers will work to develop technologies that can restore degraded croplands.[60]

The 230 million rural households in Africa, Asia, and Latin America that this research must reach are more isolated and face a far more complex set of agricultural constraints than their market-oriented counterparts. Actual conditions, rather than the ideal conditions in the experimental fields of research stations, determine the success or failure of new seeds, tools, or farming practices. Several international research centers have adopted a new approach to better understand the constraints faced by farmers on marginal lands. "Farming systems research" involves farmers and rural households directly in the research process. But how can the comparative handful of scientists in national and international research begin to reach a quarter of a billion households and refine technologies that match their individual circumstances? The answer must be a far more decentralized research effort that builds on farmer-scientist collaboration and equips farmers to produce innovations for themselves.[61]

The reappraisal of traditional practices is a step toward this collaboration. According to Paul Richards of University College in London who has worked with Nigerian farmers, indigenous agricultural knowledge is "the single largest knowledge resource not yet mobilized in the development enterprise." In his book, *Indigenous Agricultural Revolution*, Richards documents how traditional farmers in West Africa have modified farming practices on the basis of carefully controlled experiments, ranging from selection of rice varieties to the control of grasshoppers. He suggests that mainstream researchers have as much to learn from the partnership with small farmers as the farmers themselves.[62]

The challenge for agricultural research at all levels is no longer a problem of one-way "technology transfer," as so many people perceived the green revolution. Innovations and insights that help raise agricultural productivity will flow in both directions—between researchers and farmers, between developing and industrial countries. Success in the low-productivity fields of the Third World can suggest new ways of managing agricultural resources that farmers in Iowa or France could employ as well.

The conservation and use of crop genetic diversity illustrates the international convergence of interests in raising agricultural productivity in the Third World. The tools of biotechnology are needed to store, evaluate, and manipulate the genes in traditional crop varieties and wild plants needed for crop breeding. Yet much of the diversity itself still resides in farmers' fields, where crops are adapted to the idiosyncracies of local rainfall, soils, and cultivation methods. "Neither money, talent and technology, nor unimproved germplasm alone can create improved crop plants—the former must be applied to the latter," points out Steven Witt in his book *Biotechnology and Genetic Diversity*. "And that means cooperation between those who have the talent and technology and those with the necessary germplasm."[63]

The world is far from having solved the problems of agricultural productivity. The conventional approach to raising productivity—combining new crop varieties with fertilizers, pesticides, and heavy use of energy—succeeded dramatically in increasing food production in industrial countries and in parts of the Third World. But new approaches are needed to reach farmers who could not afford the conventional technologies, as well as to correct inequities in the distribution of resources and confront widespread environmental problems. Complementing the use of conventional resources with innovative biological technologies that maximize agriculture's internal resources can ensure the affordable and sustainable gains in agricultural productivity that the world needs in the years ahead.

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