
Green Revolution: Impacts, limits, and the path ahead

Prabhu Pingali

Deputy Director, Agricultural Development
Bill & Melinda Gates Foundation

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Prabhu L. Pingali[1]
Bill & Melinda Gates Foundation, Agricultural Development, Seattle, WA 98102

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A detailed retrospective of the Green Revolution, its achievement and limits in terms of agricultural productivity improvement, and its broader impact at social, environmental, and economic levels is provided. Lessons learned and the strategic insights are reviewed as the world is preparing a "redux" version of the Green Revolution with more integrative environmental and social impact combined with agricultural and economic development. Core policy directions for Green Revolution 2.0 that enhance the spread and sustainable adoption of productivity enhancing technologies are specified.

global public goods | nutrition | poverty | technology | agricultural development

The developing world witnessed an extraordinary period of food crop productivity growth over the past 50 y, despite increasing land scarcity and rising land values. Although populations had more than doubled, the production of cereal crops tripled during this period, with only a 30% increase in land area cultivated (1). Dire predictions of a Malthusian famine were belied, and much of the developing world was able to overcome its chronic food deficits. Sub-Saharan Africa continues to be the exception to the global trend.

Much of the success was caused by the combination of high rates of investment in crop research, infrastructure, and market development and appropriate policy support that took place during the first Green Revolution (GR). I distinguish the first GR period as 1966–1985 and the post-GR period as the next two decades. Large public investment in crop genetic improvement built on the scientific advances already made in the developed world for the major staple crops—wheat, rice, and maize—and adapted those advances to the conditions of developing countries (2).

The GR strategy for food crop productivity growth was explicitly based on the premise that, given appropriate institutional mechanisms, technology spillovers across political and agroclimatic boundaries could be captured. However, neither private firms nor national governments had sufficient incentive to invest in all of the research and development of such international public goods. Private firms operating through markets have limited interest in public goods, because they do not have the capacity to capture much of the benefit through proprietary claims; also, because of the global, nonrival nature of the research products, no single nation has the incentive to invest public resources in this type of research.

International public goods institutions were needed to fill this gap, and efforts to develop the necessary institutional capacity, particularly in plant breeding, were a central part of the GR strategy. Based on the early successes with wheat at the International Maize and Wheat Improvement Centre (CIMMYT) in Mexico and rice at the International Rice Research Institute (IRRI) in the Philippines, the Consultative Group on International Agricultural Research (CGIAR) was established specifically to generate technological spillovers for countries that underinvest in agricultural research, because they are unable to capture all of the benefits of those investments (3). After CGIAR-generated knowledge, invention, and products (such as breeding lines) were made publicly available, national public and private sectors responded with investments for technology adaptation, dissemination, and delivery.

Despite that success, in the post-GR period, investment in agriculture dropped off dramatically into the mid-2000s (4). However, the need for continued investments in agricultural innovation and productivity growth is as important today as it was in the early years of the GR. Low income countries and lagging regions of emerging economies continue to rely on agricultural productivity as an engine of growth and hunger reduction (5–7). However, sustaining productivity gains, enhancing smallholder competitiveness, and adapting to climate change are becoming increasingly urgent concerns across all production systems.

Since the mid-2000s and heightened after the 2008 food price spikes, there has been renewed interest in agricultural investment, and there are calls for the next GR, including those calls made by the former Secretary General of the United Nations Kofi Annan and Sir Gordon Conway (3, 8). Simultaneously, there is recognition of the limitations of the first GR and the need for alternative solutions that correct for those limitations and unintended consequences (5). GR 2.0 must address these concerns both where the GR was successful and in low income countries and lagging regions, where agricultural productivity is still low. This paper reviews the evidence on the diffusion and impact of GR crop genetic improvements and the limitations and unintended environmental, social, and institutional consequences of the GR strategy for productivity growth. Then, I turn to the current period and the renewed interest and investment in agricultural development, and I give the technology and institutional priorities for a GR 2.0.

First GR: Diffusion and Impact of Crop Genetic Improvements

Positive impacts on poverty reduction and lower food prices were driven in large part by crop germplasm improvements in CGIAR centers that were then transferred to national agricultural programs for adaptation and dissemination. The productivity gains from crop germplasm improvement alone are estimated to have averaged 1.0% per annum for wheat (across all regions), 0.8% for rice, 0.7% for maize, and 0.5% and 0.6% for sorghum and millets, respectively (9). Adoption rates of modern varieties in developing countries increased rapidly, reaching a majority of cropland (63%) by 1998 (9–15).

However, global aggregates mask great geographic disparities. In Asian countries (including China), the percentage of area planted to modern varieties was 82% by 1998, whereas improved varieties covered only 27% of total area planted in Africa (16). This difference may be, in part, because of the later introduction of CGIAR research programs focused on Africa as well as the lag in breeding efforts for the orphan crops—crops that did not benefit from a backlog of research conducted before the GR period but had improvement that came during the GR and post-GR periods, such as cassava, sorghum, and millets—which are of greater relative importance to the African poor (10). For

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[1] E-mail: prabhu.pingali@gatesfoundation.org.

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instance, the first CIMMYT maize program focused on Africa only began in the late 1980s. Although the International Institute for Tropical Agriculture research for cassava started in 1967, its impact was felt only since the 1980s (10). Although it lagged behind in the GR period, Africa has witnessed positive growth in the post-GR period. Adoption of improved varieties across sub-Saharan Africa reached 70% for wheat, 45% for maize, 26% for rice, 19% for cassava, and 15% for sorghum by 2005 (17).

Impact on Productivity and Food Prices. The rapid increase in agricultural output resulting from the GR came from an impressive increase in yields per hectare. Between 1960 and 2000, yields for all developing countries rose 208% for wheat, 109% for rice, 157% for maize, 78% for potatoes, and 36% for cassava (18). Developing countries in southeast Asia and India were the first countries to show the impact of the GR varieties on rice yields, with China and other Asian regions experiencing stronger yield growth in the subsequent decades (19). Similar yield trends were observed for wheat and maize in Asia (20). Analysis of agricultural total factor productivity (TFP) finds similar trends to the partial productivity trends captured by yield per hectare [TFP is defined as the ratio of total output to total inputs in a production process (20)] (21). For the period 1970–1989, change in global TFP for agriculture was 0.87%, which nearly doubled to 1.56% from 1990 to 2006 (21).

Crop genetic improvement focused mostly on producing high-yielding varieties (HYVs), but the decrease in time to maturity was also an important improvement for many crops, allowing for an increase in cropping intensity. The rapid spread of the rice–wheat system in the Indo-Gangetic plains (from Pakistan to Bangladesh) can be attributed to the shortening of the crop growing period (22). Other improved inputs, including fertilizer, irrigation, and to a certain extent, pesticides, were also critical components of the GR intervention. Asia had already invested significantly in irrigation infrastructure at the start of the GR and continued to do so throughout the GR and post-GR periods (2).

Widespread adoption of GR technologies led to a significant shift in the food supply function, contributing to a fall in real food prices (23, 24). Between 1960 and 1990, food supply in developing countries increased 12–13% (25). Estimates suggest that, without the CGIAR and national program crop germplasm improvement efforts, food production in developing countries would have been almost 20% lower (requiring another 20–25 million hectares of land under cultivation worldwide) (26, 27). World food and feed prices would have been 35–65% higher, and average caloric availability would have declined by 11–13% (28). Overall, these efforts benefited virtually all consumers in the world and the poor relatively more so, because they spend a greater share of their income on food (29).

Access to Crop Genetic Improvements. The CGIAR's numerous crop improvement networks allowed for the best breeding materials and knowledge to be widely and freely available and used across the developing world (30, 31). National Agricultural Research Systems (NARS) in developing countries generally used varieties or crosses from CGIAR centers as parents and then adapted those varieties for particular agroecological environments or preferences. Enabling such adaptive transfers significantly improved research efficiency, reduced research costs, and greatly expanded the pool of genetic resources and varieties available to the national programs. Such an uninhibited system of germplasm exchange with the best international materials allowed countries to make strategic decisions about investing in plant breeding capacity (32). In general, large NARSs engaged in adaptive transfers rather than direct use of CGIAR-generated varieties and crosses, whereas small NARSs used the material directly (33). The CGIAR content of modern varieties was high for most food crops; 36% of all varietal releases were based on CGIAR crosses, although it varies greatly by crop (34). In addition, 26% of all modern varieties had a CGIAR-crossed parent or other ancestor (9).

Returns to Crop Improvement Research Investment. The returns to research investments in the GR strategy of germplasm improvement have been measured in great detail by several economists over the last few decades (10). These studies have found high rates of returns that, for the most part, compare favorably with alternative public investments. A recent meta-review of trends and characteristics of the rates of return to agricultural research and development, examining 292 case studies with 1,900 estimated rates of returns, found a median annual rate of return estimate ranging from 40% to 60%, consistent with the broad literature. More importantly, it found no evidence that the rates of return to research had declined over time (35). The overall benefits of CGIAR contributions to crop genetic improvement are estimated in billions of dollars—mostly because of the benefits from the improved three main staples (10). Spring bread wheat, rice (in Asia only), and maize (CIMMYT contribution only) have produced estimated benefits of $2.5, $10.8, and $0.6–0.8 billion, respectively (36).

As these studies show, there is evidence of continuing high rates of return for crop breeding improvements that have wide adaptability, such as those improvements for wheat, rice and maize. The more recent evidence also shows high returns for improvements in orphan crops in the post-GR period (10). No studies have found evidence of significant decline in rates of return to agricultural research in the post-GR period, likely because of continued investment in breeding for improved stress tolerance in addition to yield growth. For example, a recent estimate of the total benefits of resistance to all types of wheat rust was estimated to generate between $600 million and $2 billion per year (37). The spread of crop genetic improvement for marginal production environments and orphan crops adds to the continued high returns that have been observed in the post-GR period. In Africa, for instance, the internal rates of return to CGIAR investments from 2000 to 2020 in the dual purpose cowpea, which was developed through a collaboration between International Institute for Tropical Agriculture and the International Livestock Research Institute, have been estimated between 50% and 103%, depending on the assumptions used (10).

Limitations of GR-Led Growth Strategies

The GR contributed to widespread poverty reduction, averted hunger for millions of people, and avoided the conversion of thousands of hectares of land into agricultural cultivation. At the same time, the GR also spurred its share of unintended negative consequences, often not because of the technology itself but rather, because of the policies that were used to promote rapid intensification of agricultural systems and increase food supplies. Some areas were left behind, and even where it successfully increased agricultural productivity, the GR was not always the panacea for solving the myriad of poverty, food security, and nutrition problems facing poor societies.

Poverty and Food Insecurity Persisted Despite the GR Success. There is a large econometric literature that uses cross-country or time series data to estimate the relationship between agricultural productivity growth and poverty. These studies generally find high poverty reduction elasticities for agricultural productivity growth (2). In Asia, it has been estimated that each 1% increase in crop productivity reduces the number of poor people by 0.48% (38). In India, it is estimated that a 1% increase in agricultural value added per hectare leads to a 0.4% reduction in poverty in the short run and 1.9% reduction in the long run, the latter arising through the indirect effects of lower food prices and higher wages (39). For low income countries in general, the impact on the poverty headcount has been found to be larger from agricultural growth relative to equivalent growth in the nonagriculture sector at a factor of 2.3 times. In sub-Saharan Africa, agriculture's contribution to poverty reduction was estimated to be 4.25 times the contribution of equivalent investment in the service sector (40).

Because the GR strategy was based on intensification of favorable areas, its contribution to poverty reduction was relatively lower in the marginal production environments. In South Asia, the poorest areas that relied on rain-fed agriculture were also the slowest to benefit from the GR, contributing to widening interregional disparities and an incidence of poverty that still remains high (34, 41). Technologies often bypassed the poor for a number of reasons. Among these reasons were inequitable land distribution with insecure ownership and tenancy rights; poorly developed input, credit, and output markets; policies that discriminated against smallholders, such as subsidies for mechanization or crop and scale bias in research and extension; and slow growth in the nonfarm economy that was unable to absorb the rising numbers of rural unemployed or underused people (42). Migration from less-favored rural areas has been cited as a strategy for poverty reduction; however, when migration out of rural areas occurs faster than the growth in employment opportunities, only a transfer of poverty results rather than true poverty reduction associated with agricultural transformation (43).

Sex played a major role in determining the distribution of benefits from the GR. Women farmers and female-headed households are found to have gained proportionally less than their male counterparts across crops and continents (44, 45). Technology transfer largely focused on male farmers, with few measures to address women's technology needs or social conditions, and thus, they largely missed women farmers (46). Cross-country empirical evidence shows that women farmers are no less efficient than their male counterparts when using the same productive assets; however, women consistently face barriers to accessing productive resources and technologies (47).

Nutrition: Calorie Availability Increases but Micronutrient Intake Is Still Lagging. Between 1960 and 1990, the share of undernourished people in the world fell significantly (25). Improved availability and decreased staple food prices dramatically improved energy and protein consumption of the poor (2). The pathways through which the GR improved nutritional outcomes depended on whether a household was a net producer or net consumer; however, for virtually all consumers, the supply shifts and GR-driven rise in real incomes had positive nutritional implications (48, 49). A 10-y study in southern India found that increased rice production resulting from the spread of HYVs accounted for about one-third of the substantial increase in energy and protein consumption of both farmers and landless workers, controlling for changes in nonfarm income sources (50).

The fall in staple prices as a result of the GR also allowed for more rapid diet diversification, even among poor populations, because savings on staple food expenditures improved access to micronutrient-dense foods (51). In Bangladesh, for example, the steady fall in real rice prices from 1992 to 2000 led to greater expenditures per capita on nonrice food and a significant improvement in child nutrition status. The amount of rice consumed did not change, but households spent more on nonrice foods as their rice expenditures declined (51).

Nutritional gains of the GR have been uneven; although overall calorie consumption increased, dietary diversity decreased for many poor people, and micronutrient malnutrition persisted. In some cases, traditional crops that were important sources of critical micronutrients (such as iron, vitamin A, and zinc) were displaced in favor of the higher-value staple crops (25). For example, intensive rice monoculture systems led to the loss of wild leafy vegetables and fish that the poor had previously harvested from rice paddies in the Philippines (52). Price effects of such supply shifts also limited access to micronutrients, because prices of micronutrient-dense foods rose relative to staples in many places (53, 54). In India, the increasing price of legumes has been associated with a consequent decline in pulse consumption across all income groups (25).

Policy and structural impediments, as well as a weak private sector, limited the supply responsiveness for vegetables and other nonstaples. Policies that promoted staple crop production, such as fertilizer and credit subsidies, price supports, and irrigation infrastructure (particularly for rice), tended to crowd out the production of traditional nonstaple crops, such as pulses and legumes in India (55). More recent evidence does suggest that diets are shifting in urban and rural Asia to include fewer cereals and more milk, meat, vegetables, and fruits. Evidence from India shows a marked increase in protein and fat intake between 1975 and 1995 across all income groups, suggesting that all consumers have benefitted from some nutritional improvements (56). However, micronutrient deficiencies among the poor persist, indicating that this dietary shift has not yet fully compensated for the decline in vitamin intake associated with cereal-dominant diets (2). Biofortification (breeding micronutrients into staple crops, such as the vitamin A-enhanced, orange-fleshed sweet potato) offers a new solution for improving nutrition outcomes, particularly for the rural poor, who depend on their own production for a large proportion of their daily caloric intake (57).

Environment: Impacts Have Been Mixed. GR-driven intensification saved new land from conversion to agriculture, a known source of greenhouse gas emissions and driver of climate change, and allowed for the release of marginal lands out of agricultural production into providing alternative ecosystem services, such as the regeneration of forest cover (58). HYVs more responsive to external inputs were central to the productivity achievements; however, in many cases, appropriate research and policies to incentivize judicious use of inputs were largely lacking (29). Unintended consequences in water use, soil degradation, and chemical runoff have had serious environmental impacts beyond the areas cultivated (59). The slowdown in yield growth that has been observed since the mid-1980s can be attributed, in part, to the above degradation of the agricultural resource base. These environmental costs are widely recognized as a potential threat to the long-term sustainability and replication of the GR's success (25, 60).

The environmental consequences were not caused by the GR technology per se but rather, the policy environment that promoted injudicious and overuse of inputs and expansion of cultivation into areas that could not sustain high levels of intensification, such as the sloping lands. Output price protection and input subsides—especially fertilizer, pesticide, and irrigation water—distorted incentives at the farm level for adopting practices that would enhance efficiency in input use and thereby, contribute to sustaining the agricultural resource base. Where the policy incentives were corrected, farmers quickly changed behavior and adopted more sustainable practices. For example, the removal of pesticide subsides in Indonesia in the early 1990s led to a dramatic drop in insecticide use (46, 58).

Marginal Production Environments. The original purpose of the GR was to intensify where returns would be high, with a focus on irrigated or high rainfall areas. The international breeding programs aimed to provide broadly adaptable germplasm that could then be grown across a wide set of geographies, but adoption was greatest in favorable areas. Technologies in the GR period did not focus on the constraints to production in more marginal environments, especially tolerance to stresses such as drought or flooding. Whereas HYVs of wheat provided yield gains of 40% in irrigated areas with modest use of fertilizer, in dry areas, gains were often no more than 10% (61). Almost full adoption of wheat and rice HYVs had been achieved in irrigated environments by the mid-1980s, but very low adoption in environments with scarce rainfall or poor water control (in the case of rice) had been achieved (62). In India, specifically, adoption was strongly correlated with water supply (3). Worldwide, improved seed–fertilizer technologies for wheat were less widely adopted in marginal environments and had less of an impact there than in favored environments (63).

More often than not, marginal environments were left behind, because the climate and resource constraints were such that returns to investment in GR varieties were low. Despite relatively low adoption of improved varieties, people living in marginal environments benefitted from the GR through consumption and wage linkages, such as lower food prices (64). Farm employment and growth in the nonfarm rural economy provided labor benefits to the landless rural poor and those people living in marginal production environments. Multicountry case studies of rice environments in Asia show that labor migration to more productive environments resulted in wage equalization and was one of the primary means of redistributing the gains of technological change from favorable to marginal areas (65). Similar results were found for wheat grown in high- and low-potential environments in Pakistan (66). There is also a growing body of evidence of spillovers from the productive regions that benefit the more marginal environments. These spillovers involve not only technology transfer and capital investments but also the software of development, such as local institutions, property rights, and social capital (67).

Poorly endowed environments, nevertheless, pose a tremendous challenge to researchers and policymakers alike to identify new agricultural research and development (R&D) opportunities and facilitate adoption of technologies and appropriate institutions to meet the needs of the poor living there. In the post-GR period, new investments in R&D for stress-tolerant crops and increased demand for feed grains have changed the prospects for agricultural production in marginal areas. Drought- and pest-resistant varieties, such as submergence-tolerant rice and drought-tolerant maize, provide options that reduce farmers' risk and improve incentives to invest in productivity-enhancing technologies (68). Changing market contexts also create new opportunities for farmers in more marginal areas to produce for the feed and biofuel markets (17).

Gains in Africa Lag Significantly but Are Catching Up. Africa was the main exception to the success of the GR in the developing world. The GR strategy was not appropriate where population densities were low and/or market infrastructure was poor. Also, the agricultural resource base could not sustainably support productivity growth, and the poor depended largely on orphan crops rather than the three main staple cereals. The package of innovations that spurred GR success in Asia was largely inappropriate for the African context at that time (25, 69). However, emerging success stories of agricultural productivity growth in recent decades show that (*i*) the context for agricultural development has shifted dramatically and (*ii*) investments in research to address the crops and constraints relevant to the continent's agriculture yield high returns.

First, during the GR period, the demand for intensification in Africa was quite low, because land was relatively abundant (9). Farmers had little incentive to intensify land use, because they had no incentive to save on land costs (69). However, there are some areas in Africa today where the land/labor ratios are now similar to what they were in Asia during the GR (70). For instance, in eastern and southern Africa, the amount of arable land has risen only marginally, but the percentage of households engaged in agriculture has grown threefold (71). The demand for yield-enhancing technologies is consequently rising in the region.

Second, improvements in rice, wheat, and maize largely addressed the main food security concerns in Asia. Africa, however, has huge diversity of cropping systems, and many orphan crops are central to food security (27). Even where the major cereals are grown in Africa, few suitable varieties were available for those agroecologies until the end of the GR and beginning of the post-GR period. In the 1960s and 1970s, national and international programs may have sought to short cut the varietal improvement process in sub-Saharan Africa by introducing unsuitable varieties from Asia and Latin America. This pattern remained until the 1980s, when more suitable varieties finally became available—based on research specifically targeted to African conditions (9). Improved varieties of sorghum, millet, and cassava also started to emerge around the middle to late 1980s (9). The productivity gains from such investments are now starting to emerge; benefits from CGIAR investments in Africa for maize alone are estimated to exceed $2.9 billion (10). Yields growth for roots and tubers rose sharply between 1980 and 2005, increasing 40% during this period (17).

To a GR 2.0

GR 2.0 is already beginning to take place, and it is happening in low income countries as well as emerging economies. Low income countries, many of them in sub-Saharan Africa, still have very low productive agricultural systems. In these areas, chronic hunger and poverty continue to be daunting problems, and they face the age-old constraints to enhancing productivity growth, such as the lack of technology, poor market infrastructure, inappropriate institutions, and an enabling policy environment (17). Emerging economies, including much of Asia where gains from the first GR were concentrated, are well on their way to agricultural modernization and structural transformation (72). The challenge for agriculture now is to integrate smallholders into value chains, maintain their competitiveness, and close the urban–rural income gap (43). Enhancing staple crop supplies and sustaining productivity gains continue to be important, despite declining per capita cereal consumption, to meet the demands of population growth and demand for feed grain.

A confluence of factors has come together in recent years to generate renewed interest in agriculture and spur the early stages of GR 2.0. In the low income countries, continued levels of food deficits and the reliance on food aid and food imports have reintroduced agriculture as an engine of growth on the policy agenda. African leaders have acknowledged that agriculture plays a critical role in their development process and that lack of investment in the sector would only leave them farther behind. The Comprehensive Africa Agriculture Development Program (the agricultural program of the New Partnership for Africa's Development, an initiative of the African Union) declaration of 2006 and resulting pledges by African Heads of State to increase agricultural investments showed their commitment to improve the agriculture sector. There is also an increasing awareness of the detrimental impacts of climate change on food security, especially for tropical agriculture systems in low income countries (73–77).

In the emerging economies, growing private sector interest in investing in the agricultural sector has created an agricultural renaissance (43). Supermarkets are spreading rapidly across urban areas in emerging economies and encouraging national and multinational agribusiness investments along the fresh produce value chains in these countries (78). Consequently, traditional staple crop systems are diversifying into high-value horticulture and livestock production (79). Private sector has also made significant investments in other commercial crops for fiber and biofuel (80). For example, private R&D and supply chains have been the primary driver behind the rapid rise of Bt cotton production across Asia and Latin America (81). Despite these positive developments, interregional differences in productivity and poverty persist in many emerging economies. Rising demand for feed and biofuels and technological advances in breeding for stress tolerance could result in a revitalization of these areas. The rapid rise of hybrid maize production in eastern India is a case in point (82).

Finally, at the global level, there has been an increased tightening of food markets driven by population and income growth as well as diversion of food grain for biofuel and livestock feed. As a consequence, the long-term declining trend in real food prices, observed worldwide since 1975, leveled off by 2005 (5). The food price crisis of 2008, sustained high prices, and more recent peaks observed in 2011 and 2012 have brought agriculture back onto global and national agendas (83).

By 2050, global population is projected to increase by about one-third, which will require a 70% increase in food production (84). To meet this need, GR 2.0 must continue to focus on shifting the yield frontier for the major staples. Increasing cereal productivity not only meets demand for staples, it also allows for the release of land to diversify into high-value crops and movement of labor out of agriculture, where other economic opportunities provide greater returns. GR 2.0 must also focus on improving tolerance to stresses, both climatic and biotic (pest and disease). Improved varieties that are tolerant to drought or submergence enhance smallholder productivity in marginal environments and provide tools to adapt to climate change. Epidemics such as the recent UG-99 wheat stem rust infestation, a new virulent strain resistant to improved varieties that emerged at a time when research on rust resistance had largely stopped (assuming that the problem had been solved), underscore the necessity of continued investments to maintain resistance to pests and diseases to avoid future shocks (3). Finally, technologies to increase input use efficiency and improve management practices are necessary to ensure the competitiveness and sustainability of production systems.

International public goods research continues to play a critical role, but in contrast to the first GR, the context in which the CGIAR operates has changed significantly. NARSs in many emerging countries have become research leaders in their own right, which is especially true of China and Brazil (85). The multinational life sciences companies are now the leading source of innovation in agricultural science, especially biotechnology (86). New partnerships can channel the expertise of the private sector and advanced national programs in emerging countries to benefit the low income countries.

In 2007 the CGIAR began a major reform process to better address this changing context. It is still too early to say whether the system itself will be able to reorient itself, but there are definite signs that individual centers are starting to work innovatively. For example, IRRI partnered with the Beijing Genomics Institute to carry out genetic fingerprinting of IRRI's entire gene bank collection, which will then become publicly available data. Similarly, CIMMYT is developing drought-tolerant maize for Africa through a partnership with Monsanto, which provided proprietary germplasm that CIMMYT incorporated into high-yielding maize varieties adapted to African conditions (see textbox below).

There are also emerging examples of advanced NARSs leading global public good efforts with the CGIAR as a partner and collaborator. Exemplary cases include the partnership between IRRI and China to develop photosynthesis-efficient C4 rice as well as the global cassava partnership for genetic improvement, an international alliance of research institutes (see textbox below). The CGIAR also needs to become clearer in terms of the work on which it focuses and when it is hands off to the NARS. For instance, the CGIAR centers could hand over improved breeding material to the NARS and leave it up to them to complete the adaptation and varietal development process. The CGIAR should also devolve the activities associated with technology diffusion to the NARS, private sector, and nongovernmental organization partners (61).

The CGIAR has had limited success in generating and diffusing technologies and practices that enhance resource and input use efficiency, thereby contributing to improved competitiveness and sustainability (61). The call in the work by Conway (3) for a "Doubly Green Revolution," which is repeated in his latest book, is important for the CGIAR and the NARSs to heed (3). The point that this work (3) repeatedly makes is that understanding the underlying science is crucial to developing effective solutions. Improved understanding of tropical and subtropical agroecologies is an important global public good that contributes to innovation and new sustainable resource management practices. The emphasis of global public good research in resource management must be on such strategic knowledge generation rather than development of location-specific techniques and products.

The emerging Digital Revolution provides new opportunities for smarter use of agricultural resources. Remote sensing and spatial mapping technologies allow for better targeting and monitoring of agricultural investments. Cell phones and other information and communication technologies can contribute to smarter application of water, fertilizers, and other inputs. The adaptation of precision agriculture techniques for developing country

Additional resources*

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*All websites accessed June 20, 2012.

smallholder agriculture conditions could have significant global public good benefits.

Conclusions

Developing country agriculture is faced with a growing set of challenges: meeting the demands of diet diversity resulting from rapidly rising incomes; feeding rapidly growing urban populations; accessing technologies that are under the purview of proprietary protection; and gearing up for the projected negative consequences of climate change. Even as it absorbs the new challenges, the food policymaking community continues to grapple with its traditional preoccupation of the persistence of hunger and poverty in low income countries, particularly in sub-Saharan Africa, and lagging regions of emerging economies.

Harnessing the best of scientific knowledge and technological breakthroughs is crucial for GR 2.0 as we attempt to reestablish agricultural innovation and production systems to meet today's complex challenges. New global public goods are needed that focus on shifting the yield frontier, increasing resistance to stress, and improving competitiveness and sustainability.

The number of alternate suppliers of agricultural technologies, specifically seed-based technologies, has expanded rapidly over the last two decades. Strong NARSs and the private sector have become major players in the research, generation, and release of new varieties. Even nongovernmental organizations and civil society organizations are becoming active in developing community seed systems. Innovative partnerships are needed across the entire R&D value chain to channel the varied expertise to enhancing smallholder productivity growth.

At the country level, public policy can play an important role in ensuring that new innovations reach and benefit smallholders and encouraging the sustainable use of natural resources. This role requires policies that (*i*) emphasize agriculture as an engine of growth and poverty reduction, (*ii*) enhance competitiveness of modernizing agricultural systems, and (*iii*) focus on sustaining the resource base by correcting distortions that create incentives for unsustainable use. Both infrastructure investments and institutional reform can help create the enabling environment for smallholder productivity growth. Furthermore, a probusiness policy environment that includes intellectual property protection, reduced trade barriers, and a transparent biosafety procedure will lead to additional private sector research investments in the emerging economies.

However, the opportunities to meet these needs are not without concurrent challenges in the areas of international coordination of public good research, weak R&D and policy capacity among low income developing countries, and increasing demands for immediate results. Climate change will also stress agricultural systems in poor countries as well the capacity of the suppliers of public good R&D. Implementing a GR 2.0 will have to contend with all of these challenges and sequence innovations over time to succeed in achieving sustainable change.

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