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Linking Global and Local Approaches to Agricultural Technology Development: The Role of Participatory Plant Breeding Research in the CGIAR

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E C O N O M I C S

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Abstract: This paper describes the current state of international plant breeding research and explains why the centralized approach to germplasm improvement that was so successful in the past is gradually being transformed by the integration of decentralized local breeding methods that incorporate the perspective of end users. The paper begins by identifying factors that contributed to past successes of international breeding efforts for major crops, describes shortcomings of the existing global approach to plant breeding, and explains why future successes will depend on researchers' ability to incorporate the knowledge and preferences of technology users. Next, the paper reviews participatory research methods and highlights a range of approaches that are currently being tested in different settings and with different crops. The paper then discusses synergies that can be achieved by linking centralized and decentralized methods. It concludes by describing technical, economic, and institutional challenges that will have to be overcome to integrate end-user based participatory approaches into the international plant breeding system.

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Acronyms

CGIAR	Consultative Group on International Agricultural Research
CIAT	Centro Internacional de Agricultura Tropical
CIMMYT	Centro Internacional de Mejoramiento de Maíz y Trigo
CIP	Centro Internacional de la Papa
ICARDA	International Center for Agricultural Research in the Dry Areas
ICRAF	International Center for Research in Agroforestry
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IITA	International Institute of Tropical Agriculture
IPGRI	International Plant Genetic Resources Institute
IPR	Intellectual property rights
IRRI	International Rice Research Institute
NARSs	National agricultural research systems
NGOs	Non-governmental organizations
PPB	Participatory plant breeding
WARDA	West Africa Rice Development Association

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Introduction

Modern crop varieties developed by international agricultural research centers (Future Harvest Centers) supported by the Consultative Group on International Agricultural Research (CGIAR) played a leading role in launching the Green Revolution in world agriculture. Traditionally, CGIAR plant breeding efforts have been based on a centralized global research model under which CGIAR breeders collect germplasm from many different sources, evaluate the germplasm under carefully controlled experimental conditions, and make crosses among superior materials.[1] The best progeny from these crosses are then distributed to collaborators in national agricultural research systems (NARSs) for testing. In the early years of the CGIAR, germplasm was exchanged mainly with public breeding programs. More recently, the emergence of private seed industries in many developing countries has led to increased collaboration with private seed companies as well. In return for doing the testing, collaborators are free to use the materials in their own breeding programs. This international breeding system has been very successful. It has enabled CGIAR breeders to develop materials capable of performing well under a wide range of environmental conditions, and it has provided an effective mechanism for distributing these materials worldwide.

Since the first modern varieties (MVs) were released during the late 1960s and early 1970s, the area planted to MVs has continued to expand. This expansion resulted both from growth in area planted to MVs of the original CGIAR mandate crops and from broadening of the CGIAR mandate to include many non-cereal crops, including roots and tubers, legumes, oilseeds, bananas and plantains, and forage crops. While it is indisputable that MVs developed using CGIAR germplasm have brought benefits to millions of producers and consumers, over time it has become evident that adoption of MVs has lagged in some areas, including many marginal environments of low production potential. Among the factors that have slowed the spread of MVs into marginal environments has been the unsuitability of many MVs for the specialized production and consumption requirements of people who live in these environments.

Faced with evidence that MVs developed for favorable production conditions have not always diffused readily into marginal environments, plant breeders at many Future Harvest Centers and in some national breeding programs have recently stepped up efforts to more

[1] Throughout this paper, the term *plant breeders* is used in a broad sense to mean plant breeders and other scientists involved in crop genetic improvement research (plant physiologists, plant pathologists, entomologists, molecular biologists, etc.).

actively involve end users in the varietal development process. The result has been a surge in interest in participatory plant breeding methods designed to incorporate the perspective of farmers[2]—usually by inviting them to participate in varietal evaluation activities, but sometimes also by teaching them formal selection techniques. Proponents believe that participatory breeding methods show great promise for making varietal development efforts more responsive to the needs of technology users, although many also acknowledge that the cost-effectiveness of these methods has never been subjected to rigorous scrutiny.

This paper describes the current state of international plant breeding research and explains why the centralized global approach to germplasm improvement that was so successful in the past is today being transformed by the incorporation of decentralized local breeding methods designed to better incorporate the perspective of end users into the varietal development process. The paper begins by describing international breeding efforts for major crops and identifying factors that have contributed to the success of the international breeding system. Next, it describes shortcomings of the global approach to plant breeding and explains why future successes will depend critically on researchers' ability to incorporate the knowledge and preferences of technology users. It then reviews a number of farmer participatory research methods that are currently being tested by plant breeding programs throughout the developing world, highlighting a range of approaches being used with different crops and in different settings. The paper concludes by describing synergies that can potentially be achieved by linking centralized global and decentralized local breeding models and discussing technical, economic, and institutional challenges that will have to be overcome to integrate end user-based participatory approaches into the international plant breeding system.

The Current International Plant Breeding System

Future Harvest Centers

Established in 1971, the CGIAR is an informal association of 58 public and private members that supports a global network of 16 Future Harvest Centers. Official co-sponsors of the CGIAR include the World Bank, the Food and Agriculture Organization of the United Nations, the United Nations Development Program, and the United Nations Environment Program. In 2000, the combined budgets of the Future Harvest Centers totaled US$ 338 million, two-thirds of which came from industrialized countries in the form of official development assistance grants (CGIAR 2001). The remaining one-third came from international organizations and foundations, developing countries, and other donors, including private corporations. The mission of the CGIAR is to contribute to food security and poverty eradication in developing countries. The research mandates of individual Future Harvest Centers include genetic improvement of plants and animals, development

[2] For simplicity, throughout this paper we discuss participatory breeding as involving *farmers*. In many developing countries, food crops are produced and consumed within the same household, so participatory breeding schemes will want to focus on production and consumption traits. Often it will be desirable to involve different types of end users, i.e., not only those who produce the crop but also those who process, prepare, and/or consume it.

of sustainable crop and resource management practices, and policy analysis. In addition to their direct involvement in research, the Centers engage in numerous other activities designed to protect the environment, preserve biodiversity, and strengthen local research and policy-making capacity.

Plant genetic improvement research, the subject of this paper, is a major focus of the CGIAR. Currently nine Future Harvest Centers conduct plant breeding research, and a tenth, the International Plant Genetic Resources Center (IPGRI), holds a mandate to advance the conservation and use of plant genetic diversity for the well-being of present and future generations (Table 1). The CGIAR breeding programs target crops that are widely produced and consumed by the poor in developing countries, including cereals (rice, wheat, maize, sorghum, pearl millet, barley), pulses (common bean, lentil, chickpea, faba, pigeon pea, cowpea), oilseeds (soybeans, groundnut), roots and tubers (cassava, potato, sweet potato, yam, Andean roots and tubers), and bananas and plantains. In addition, CGIAR breeding programs work on selected non-food species that contribute in important ways to improving and sustaining the livelihoods of the poor, such as forage crops and trees.

National Agricultural Research Systems (NARSs)

Future Harvest Centers remain at the forefront of international germplasm improvement activities, especially in developing countries, but they do not in and of themselves constitute the global plant breeding system. The success of CGIAR plant breeding programs depends critically on the contribution of thousands of local public plant breeding institutes and university crop science departments, and, increasingly, private seed companies and non-governmental organizations (NGOs). Many of these organizations collaborate actively with Future Harvest Centers, and indeed relationships between the Centers and these organizations can be considered true partnerships.

Table 1. Plant breeding programs in the CGIAR.

Future Harvest Center	Full name	Year founded	Headquarters location	Plant breeding programs
CIAT	Centro Internacional de Agricultura Tropical	1967	Cali, Colombia	Common bean,cassava, rice, tropical forage
CIMMYT	Centro International de Mejoramiento de Maíz y Trigo	1966	Mexico City, Mexico	Maize, wheat, triticale
CIP	Centro Internacional de la Papa	1970	Lima, Peru	Potato, sweet potato, Andean root and tubercrops
ICARDA	International Center for Agricultural Research in the Dry Areas	1975	Aleppo, Syria	Barley, wheat, lentil, chickpea, faba, forage legumes
ICRAF	International Center for Research in Agroforestry	1977	Nairobi, Kenya	Agroforestry trees
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics	1972	Patancheru, India	Sorghum, pearl millet, chickpea, pigeon pea, groundnut
IITA	International Institute of Tropical Agriculture	1967	Ibadan, Nigeria	Cassava, maize, yam, cowpea, soybean,banana and plantain
IPGRI	International Plant Genetic Resources Institute	1974	Rome, Italy	
IRRI	International Rice Research Institute	1960	Los Baños, Philippines	Rice
WARDA	West Africa Rice Development Association	1970	Bouaké, Ivory Coast	Rice

Source: Compiled by authors.

No attempt will be made here to describe in detail the organization of plant breeding research in the developing world. Until recently, developing countries offered relatively few commercial opportunities for private seed companies, so investment in plant breeding came mainly from the public sector. Within individual countries the level of public investment targeted at a given crop and the focus of that investment varied with the importance of the crop. In large countries and major crops, it is not unusual to see governments investing in the complete range of "upstream" and "downstream" research activities. In small countries and minor crops, governments tend to concentrate on the "downstream" end of the research spectrum, relying on technology spill-ins to capture benefits from investments in "upstream" research carried out elsewhere, e.g., by larger NARS and/or Future Harvest Centers (see Byerlee and Traxler 1996; Maredia and Byerlee 1999; Traxler and Pingali 1999).

Impacts of Current International Plant Breeding System

The impacts of CGIAR breeding programs are well known. Modern varieties developed using improved germplasm from Future Harvest Centers today are grown on millions of hectares throughout the developing world (Table 2). Widely publicized Green Revolution success stories involving wheat and rice were followed in subsequent years by similar success stories involving many other crops—not only cereals, but also legumes, oilseed, roots and tubers, and bananas and plantains. Over the past four decades, MVs developed using improved germplasm from Future Harvest Centers have fueled important gains in global food production and generated billions of dollars of benefits for producers and consumers (Evenson and Gollin 2001).

Modern varieties have had an enormous impact throughout the developing world, but the benefits have not been distributed evenly. Productivity gains associated with adoption of MVs have been concentrated in favorable production environments characterized by fertile

Table 2. Impacts of CGIAR plant breeding programs.

Crop	Future Harvest Centers with breeding programs	MV area planted in developing countries (million ha)	Proportion of total area planted (%)
Wheat	CIMMYT, ICARDA	103.4	81
Rice	IRRI, WARDA	102.1	71
Maize	CIMMYT, IITA	70.7	52
Sorghum	ICRISAT	NA	NA
Pearl millet	ICRISAT	24.2	NA
Cassava	IITA, CIAT	16.5	18
Barley	ICARDA	19.0	14
Potato	CIP	7.5	6
Common bean	CIAT	SSA 1.7	49
		LAC 4.4	15
Lentil	ICARDA	2.7	62
Groundnut	ICRISAT, ICARDA	22.4	NA

Note: NA = not available. SSA = Sub-Saharan Africa. LAC = Latin America and the Caribbean. CIAT = Centro Internacional de Agricultura Tropical. CIMMYT = Centro Internacional de Mejoramiento de Maíz y Trigo. CIP = Centro Internacional de la Papa. ICARDA = International Center for Agricultural Research in the Dry Areas. ICRISAT = International Crops Research Institute for the Semi-Arid Tropics. IITA = International Institute of Tropical Agriculture. IRRI = International Rice Research Institute. WARDA = West Africa Rice Development Association.
Source: Evenson and Gollin (2001).

soils, adequate and reliable water supplies, ready access to input and output markets, effective extension services, and economic policies that encouraged investment in improved crop production technology. These conditions were present in many original Green Revolution sites, including northwest Mexico, the Punjab regions of India and Pakistan, the Mediterranean coast of Turkey, central Luzon in the Philippines, and southern China.

Some Green Revolution critics claim that MVs have had little impact in marginal environments, but this is not entirely correct. In the case of wheat and rice, for example, while it is true that semi-dwarf MVs that spearheaded the Green Revolution initially made little headway in non-irrigated zones, over the past 25 years most of the expansion in area planted to wheat and rice MVs occurred in rainfed areas, beginning first in wetter areas and spreading gradually into drier areas (Lipton and Longhurst 1989; Byerlee 1994). In many cases, the expansion of wheat and rice MVs into marginal environments has depended on availability of varieties that are suitable for more difficult production conditions and that satisfy the special requirements of people who live in these environments. Development of such varieties usually depends on the presence of a strong local breeding program capable of taking exotic germplasm and adapting it to local environmental conditions and end-user needs.

The Traditional Global Approach to Plant Breeding

Most Future Harvest Centers that engage in plant breeding research hold global mandates. In a few cases, the mandates are regional. Although the size of the mandate varies by crop, it is not unusual for a CGIAR breeding program to serve many millions of hectares. Given limited resources relative to the large size of their mandates, most CGIAR breeding programs concentrate on activities that are likely to generate maximum possible benefits. Many also consciously avoid activities performed by other organizations, including public agencies, private companies, and NGOs.

CGIAR Plant Genetic Improvement Activities

What types of activities are carried out by CGIAR plant breeding programs? Plant genetic improvement research can be classified into four general categories: (1) genetic resources conservation, (2) strategic research, (3) pre-breeding, and (4) cultivar development. Although the level of investment in each category varies by Center and by crop, a number of trends can be discerned across the CGIAR system.

(1) Genetic resources conservation. Most Future Harvest Centers that engage in plant breeding research maintain gene banks for their mandate crops (Table 3). These gene banks house extensive collections of genetic resources, including landraces, domesticated species, and sometimes wild relatives of domesticated species that could potentially serve as sources of useful traits. Some accessions in CGIAR gene banks were donations from public gene banks in developing and developed countries, some were collected from the wild by CGIAR and NARS researchers, and some are products of CGIAR breeding programs. Information about the physical characteristics and agronomic performance of gene bank

Table 3. Summary of accessions held in CGIAR gene banks (food crops).

Future Harvest Center	Crops	Number of accessions
CIAT	Common bean	27,595
CIAT	Cassava	5,728
CIMMYT	Wheat	79,912
CIMMYT	Maize	19,548
CIP	Potato	5,057
CIP	Sweet potato	6,415
ICARDA	Wheat	30,270
ICARDA	Barley	24,218
ICARDA	Lentil	7,827
ICARDA	Chickpea	9,116
ICARDA	Faba bean	9,075
ICRISAT	Sorghum	35,780
ICRISAT	Pearl millet	21,250
ICRISAT	Chickpea	16,961
ICRISAT	Groundnut	14,357
IITA	Cassava	2,158
IITA	Yam	2,878
IITA	Cowpea	15,001
IITA	Soybean	1,909
IITA	Banana, plantain	283
IRRI	Rice	80,618
WARDA	Rice	14,917

Note: CIAT = Centro Internacional de Agricultura Tropical. CIMMYT = Centro Internacional de Mejoramiento de Maíz y Trigo. CIP = Centro Internacional de la Papa. ICARDA = International Center for Agricultural Research in the Dry Areas. ICRISAT = International Crops Research Institute for the Semi-Arid Tropics. IITA = International Institute of Tropical Agriculture. IRRI = International Rice Research Institute. WARDA = West Africa Rice Development Association.

Source: CGIAR System-wide Genetic Resources Program (SGRP), February 2000.

accessions ("passport data") is made available to breeders worldwide, who may request seed of specific accessions for use in their own breeding programs. Most Future Harvest Centers provide seed free of charge, subject to availability.

(2) Strategic research in plant biology, molecular biology, and genomics. Scientists at Future Harvest Centers carry out a certain amount of strategic research, defined here as research designed to generate information about basic plant biological processes, as well as research leading to the development of novel breeding techniques and selection methods. Generally speaking, however, strategic research makes up a small portion of the CGIAR portfolio. Most Future Harvest Centers prefer to leave strategic research to organizations that are in a better position to incur large up-front investments with uncertain prospects of success, such as public universities and private corporations. Given their limited budgets and competing demands for their services, most Future Harvest Centers avoid strategic research, positioning themselves instead to be users of information, methods, and tools developed by others. In cases where technologies considered vital for the success of the CGIAR mission are unlikely to become available from alternative sources, however, Future Harvest Centers have not hesitated to engage in strategic research in an effort to overcome critical constraints.

(3) Pre-breeding. Pre-breeding research, defined as the development of improved germplasm that will be used by other plant breeders as a source of desired traits, remains a major focus of CGIAR plant genetic improvement work. Some Future Harvest Centers focus exclusively on pre-breeding, in the sense that they do not try to produce finished varieties that can be released directly to farmers. The CIMMYT Maize Program, for example, does not release its own varieties or hybrids. Instead, it produces intermediate products for use by public and private national breeding programs—improved materials showing superior yield potential, good agronomic characteristics, resistance or tolerance to important diseases and pests, and/or acceptable consumption qualities.

At many Future Harvest Centers, pre-breeding research is accomplished with the help of networks of international nurseries. An international nursery consists of a set of experimental materials sent to local collaborators in many different test locations. Local collaborators grow these experimental materials under carefully controlled levels of management, along with one or more local checks. They then collect performance data for each entry in the nursery and report back to the Future Harvest Center. By analyzing these data, Center breeders are able to identify superior materials, both widely adapted materials that perform well across a range of locations, as well as narrowly adapted materials that perform well only in specialized locations.

International nurseries managed by Future Harvest Centers serve as important two-way conduits through which germplasm moves from Centers to collaborating breeding programs, and information moves from collaborating breeding programs back to the Centers. In return for growing the nursery, monitoring the performance of each entry, and reporting back results, collaborators have an opportunity to observe a set of promising experimental materials assembled, in many instances, from all over the world. If they wish, local collaborators may also retain seed of interesting materials for use in their own breeding programs.

(4) Cultivar development. Cultivar development involves assembling the precise combination of traits desired by end users (including producers, consumers, and sometimes industrial processors) within individual varieties. To the extent that CGIAR breeders know about desirable combinations of important traits, and to the extent that they can assemble these desirable combinations of traits within the same germplasm background, varieties produced by CGIAR breeding programs may be suitable for release as finished cultivars. Many semidwarf wheat and rice varieties that spearheaded the Green Revolution owed their success to the fact that they combined many desirable traits, including superior yield potential, responsiveness to high levels of management, resistance to important diseases and pests, and acceptable consumption quality. Significantly, these traits were in demand in many different countries, which meant that the same varieties could be introduced successfully over extensive areas throughout the developing world.

Materials distributed through multi-locational testing networks such as CGIAR nurseries can sometimes be released "as is," but often this is not the case. More commonly, additional selection is needed to ensure that the materials are well adapted to local production conditions and end-user needs. The amount of cultivar development work done at Future Harvest Centers varies. For major crops of widespread global importance (e.g., wheat, rice, maize), Centers frequently lack the resources needed to develop separate cultivars for thousands of distinct, specialized target environments. But for minor crops that tend to be grown in concentrated areas (e.g., pearl millet, chickpea, lentils, pigeon pea, cowpea), cultivar development breeding may be justified.

Advantages of Global Plant Breeding

The extensive diffusion of MVs developed using CGIAR-improved germplasm shows that centralized plant genetic improvement research can be very effective. Indeed, the global model of international plant breeding in which Future Harvest centers serve as hubs of extended global networks for germplasm improvement and exchange has a number of obvious advantages.

Elimination of redundant activities. Because they operate at the regional or global level, Future Harvest Centers achieve important efficiencies for the international breeding system by eliminating activities that would be redundant if performed at the country level. Gene banks are a good example. For crops of global importance, if every country in which the crop is grown were to establish its own gene bank, inevitably there would be a large amount of wasteful duplication as the same accessions were collected and maintained in multiple locations. Security considerations dictate that at least two copies of all materials be maintained in separate sites (to provide protection in case of catastrophic loss at one site), but maintenance of multiple copies of the same germplasm at many different sites is unnecessary and inefficient.

Extensive exchange of germplasm. Most plant breeders who work for Future Harvest Centers travel extensively, interact frequently with scientists from public and private breeding programs, and regularly exchange germplasm with colleagues from all over the world. These breeders are well placed to take advantage of breeding gains made elsewhere because they are exposed to large amounts of diverse germplasm. By introgressing exotic materials into their crossing blocks, they can exploit genetic gains made in other locations. Over the long run, genetic gains achieved by CGIAR breeding programs are greatly enhanced by regular introgression of exotic materials.

Multi-locational testing. Thanks to their close links to colleagues in national breeding programs, Future Harvest Centers' plant breeders are able to test experimental germplasm in many different locations around the world. This provides them with an important advantage when selecting superior materials, which are more easily identified with the help of performance data collected in a wide range of production environments. Plant breeders working in national programs generally do not have access to nearly as many testing sites, which complicates the selection task.

Exploitation of technology spill-outs. A key to the success of the global breeding system has been its ability to distribute improved germplasm to local breeding programs. International nurseries managed by Future Harvest Centers have proved to be very effective tools for disseminating improved materials. Virtually all NARSs breeding programs and most private seed companies regularly screen CGIAR nursery entries in search of useful germplasm, and many report that CGIAR nurseries represent their single most important source of new breeding materials. Numerous studies have confirmed that the international breeding system based on centralized CGIAR plant breeding programs generates enormous spillover benefits (Maredia and Byerlee 1999; Traxler and Pingali 1999; Byerlee and Traxler 1996).

In summary, CGIAR plant breeding programs have been successful in part because their large size and global reach allows them to capture important economies of scope and scale. Additional factors that contributed to the success of CGIAR plant breeding programs include the fact that its Centers have been able to attract and retain well-trained and highly motivated scientists and support them with sufficient resources to get the job done.

Shortcomings of Global Plant Breeding

While the global model of international plant breeding has many advantages, it also has some clear shortcomings.

Limited adaptation breeding. Consultative Group on International Agricultural Research plant breeding programs do not always have sufficient resources to do extensive local adaptation breeding. Most CGIAR breeding programs identify a core set of priority traits and work to incorporate these traits into a range of diverse germplasm backgrounds, which are then made available to national breeding programs and private companies. Traits that are commonly targeted include high yield potential, tolerance or resistance to major biotic and abiotic stresses, early maturity, fertilizer responsiveness, and food or feed quality. In some cases, CGIAR breeders also develop finished cultivars containing specific combinations of traits desired by particular groups of farmers in well-defined target environments. This so-called "cultivar development" work is justified when a crop is grown in large, ecologically homogeneous production environments, because successful varieties are likely to diffuse across a large area. More often, however, cultivar development work is left to local breeding programs, especially when a crop is grown in small, ecologically diverse target environments that require distinct varieties. When local breeding programs are weak or inadequately funded, cultivar development work often gets neglected.

Weak links to end users. Consultative Group on International Agricultural Research plant breeders often have weak links to the end user. This is partly due to their professional training: plant breeders receive rigorous instruction in the theory and practice of crop improvement and have little exposure to survey methods needed to elicit structured feedback from farmers. While most plant breeders—certainly most successful plant breeders—do make a point of frequently visiting farms and talking to farmers about the advantages and disadvantages of different varieties, information about farmers' varietal preferences is often collected in an informal and unsystematic manner from small and potentially non-representative samples of respondents. As a result, what plant breeders consider to be important in a variety may not correspond closely with what the majority of farmers in a target area consider to be important, in which case the breeding program may be selecting for a non-optimal combination of traits.

Inadequate farm-level testing. Consultative Group on International Agricultural Research plant breeding programs do not always have resources to test their products at the farm level. On-farm varietal testing tends to be very resource intensive, especially in developing country settings where the breeding program is targeting mainly subsistence-oriented farmers living in remote areas that are poorly served by roads and other forms of infrastructure. For this reason, few CGIAR breeding programs conduct extensive on-farm varietal trials; instead, most base their selection decisions on data generated through on-station trials. This can lead to problems, because research has shown that varieties often perform differently under farmers' management practices than they do under researchers' management practices.

In summary, despite its many advantages, the global model of plant breeding also has a number of shortcomings. These shortcomings relate mainly to the inability of a highly centralized breeding system to address the enormous diversity of environmental conditions and end-user needs. Varietal preferences often vary significantly from location to location, from season to season, and from farmer to farmer, particularly in subsistence-oriented farming systems. Most CGIAR plant breeding programs lack the resources to solicit the diverse varietal preferences of farmers in thousands of different locations, develop distinct varieties for all these locations, and test all varieties thoroughly at the farm level.

The Emerging Local Approach to Plant Breeding

In an effort to overcome limitations of the traditional global approach to plant genetic improvement, researchers in a number of Future Harvest Centers and national breeding programs are developing a new approach known as *participatory plant breeding* (PPB). Participatory plant breeding has been defined as a set of methods that involve close farmer-researcher collaboration to bring about plant genetic improvement within a crop (Weltzien et al. 2000). Participatory plant breeding is expected to produce more benefits than the traditional global breeding model in situations where a highly centralized approach is inappropriate (Weltzien et al. 2000). Situations in which PPB is expected to be particularly advantageous include the following:

- Improvement of crops that are mainly of local interest and hence do not attract the attention of commercial breeding programs.
- Improvement of crops grown in marginal environments characterized by subsistence-oriented agriculture.
- Improvement of crops grown in highly variable environments in which genotype-by-environment interactions preclude widespread use of individual varieties.
- Situations in which end users require uncommon traits.
- Situations in which end users require unusual combinations of common traits.

Participatory Plant Breeding (PPB): Modes of Participation
With PPB, farmers and plant breeders (including scientists from other disciplines engaged in crop genetic improvement research) can interact in a number of different ways, known as *modes of participation*. These modes of participation can be thought of as points along a continuum representing different levels of interaction between farmers and breeders. Each mode of participation can be characterized in terms of how farmers and plant breeders

interact to set objectives, take decisions, share responsibility for decision-making and implementation, and generate products. In practical terms, these four factors affect three key parameters of the breeding process:

1. the *stage of the breeding process* at which farmers interact with breeders,
2. the *location* where selection and testing of germplasm takes place, and
3. the *design and management* of the germplasm evaluation process.

The stage at which farmers interact with breeders can range from very early in the breeding process (e.g., during selection of source materials or when the germplasm being improved still shows a high degree of genetic variability) to very late in the breeding process (e.g., during evaluation of near-finished or finished varieties). Selection and testing of germplasm may take place at the experiment station, farmers' fields representative of the target area for improvement, or both. By planting breeding materials in several different locations, plant breeders and farmers are able to evaluate varieties under a range of biophysical conditions. The design and management of the germplasm evaluation process can be done by plant breeders alone, by farmers alone, or jointly by both groups. Interactions between the location where selection and testing of germplasm takes place and the design and management of the germplasm evaluation process are particularly important, because they provide breeders and farmers with the opportunity to assess genotype-by-environment interactions (with the environment defined to include not only biophysical conditions in the target environment, but also management conditions that are relevant to farmers).[3]

Table 4 presents examples of different modes of participation, ranked from the least amount of farmer participation to the greatest. The examples in Table 4 represent arbitrarily selected points on a continuum; many other possible modes of participation are not shown. What is important, however, is that the continuum represents increasing participation by farmers in the breeding process, more frequent communication between farmers and scientists, and growing mutual trust.

For both farmers and breeders, movement along the continuum is not costless. As their participation increases, farmers must invest increasing amounts of time, energy, and resources; they must also provide increasing amounts of intellectual input and draw on increasingly sophisticated analytical skills. For scientists, movement along the continuum similarly entails costs, since traditional ways of organizing breeding programs may have to be modified substantially through the addition of new activities involving farmers.

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3 In the literature on PPB, farmer selection of finished or near-finished varieties is known as *participatory varietal selection*, while farmer selection with unfinished materials with a high degree of genetic variability is known as *participatory plant breeding* (Ceccarelli et al. 2000; Witcombe et al. 1996). Testing and selecting in different locations representative of the target breeding environment is known as *decentralized breeding* (Ceccarelli et al. 2000). As defined above, *decentralized breeding* can be done without farmer involvement and *participatory varietal selection* and *participatory breed*ing do not necessarily imply that they are done in multiple environments (decentralized). In the gradient of modes of participation presented here, we combine these three types to define them.

Table 4: Modes of participation in participatory plant breeding (PPB).

Mode of participation	Role of plant breeders	Role of farmers	Comments
Farmers are given finished varieties developed by plant breeders	• Set breeding objectives • Select source germplasm • Identify traits for improvement • Determine breeding methodology • Establish testing procedures • Evaluate finished cultivars on station	• Decide only whether or not to adopt the product	• Traditional breeding • Little direct interaction between farmers and breeders • Breeders knowledge of what farmers' want is not based on organized and direct interaction with farmers
Farmers provide source germplasm on which breeding process is based	• Collect and characterize source germplasm • Identify traits for improvement • Determine breeding methodology • Establish testing procedures • Evaluate finished cultivars on station • Basis for developing new varieties	• Provide source germplasm • Part of target population	• Source germplasm comes from farmers in target population, rather than gene bank • Well adapted material, hopefully with many traits farmers value • Tenuous relationship between farmers and breeders • Breeding process solely in the hands of breeders
Farmers identify traits to be improved and suggest selection criteria	• Set breeding objectives • Select source germplasm • Determine breeding methodology • Establish testing procedures • Evaluate finished cultivars on station	• Identify traits for improvement	• Better targeted varieties • Varieties more likely to respond to farmers' needs and constraints
Farmers evaluate finished varieties on station or in scientists-managed on-farm trials and help select varieties to distribute	• Set breeding objectives • Select source germplasm • Identify traits for improvement • Determine breeding methodology • Establish testing procedures • Finished cultivars evaluated on station or in farmers' fields but under breeders' management	• Actively participate in testing procedures • Identify finished or near finished varieties that are interesting to them • Farmers may be able to select for traits that they cannot easily describe in words	• Decision-making and responsibility for selection of germplasm shared between breeders and farmers • If varieties are planted on-farm in several different locations, breeders and farmers can evaluate them under a range of biophysical conditions
Farmers evaluate unfinished materials (lines, families, landraces) on station or in scientists-managed on-farm trials and select materials for further improvement	• Help set breeding objectives • May select source germplasm • Help identify traits for improvement • Determine breeding methodology • Establish testing procedures • Finished cultivars evaluated on station or in farmers' fields	• Identify interesting materials that still show a high degree of genetic variability for further improvement • Help set breeding objectives • Identify traits for improvement	• May lead to more diverse set of materials to be improved • Provides good idea of genotype-by-environment interactions if done in farmers' fields
Farmers conduct germplasm evaluation trials in their own fields and using their own management practices	• Help set breeding objectives • May select source germplasm • Help identify which traits will be targeted for improvement • Determine breeding methodology	• Farmers actively participate in testing procedures • Testing is done in farmers' fields and under their management • Identify near or finished varieties or interesting materials that still show a high degree of genetic variability for further improvement • Help set breeding objectives • Identify traits for improvement	• Materials could be finished varieties or unfinished materials in different stages of improvement • Provides a very good idea of genotype-by-environment interactions • Explicitly incorporates farmers' needs, interests, and constraints • Strong organized interaction between breeders and farmers • Sharing decision-making, responsibilities and activities
Farmers are trained in "scientific" breeding methods	• Train farmers in scientific breeding methods so they can: (1) maintain valued traits in their varieties, (2) modify existing traits, and/or (3) introduce new traits.	• Set breeding objectives • Select source germplasm • Identify traits for improvement • Determine breeding methodology • Establish testing procedures • Testing done on farmers' fields	• Trained farmers are able to carry out breeding process on their own, possibly with help from scientists

Source: Authors.

Advantages of Local Plant Breeding

Local approaches to plant breeding based on participatory methods offer a number of potential advantages compared to the traditional global approach to plant breeding.

Improved local adaptation breeding. Participatory plant breeding methods are well suited for niche breeding, or development of varieties that perform well in highly specialized environments. Niches can be defined not only by biophysical variables, but also by human preferences and needs. The advantage of PPB methods derives from the strong links that they generate between scientists and end users. By making selection criteria more relevant to end user needs, participatory breeding can reach poor households that have not yet benefited from modern varieties (Kornegay, Beltran, and Ashby 1996; Sperling, Loevinsohn, and Nabomvura 1993; van Oosterom, Whitaker, and Weltzien 1996).

Promotion of genetic diversity. Unlike the current global breeding model, which for the most part has concentrated on developing a limited number of varieties that are stable over time and adapted to a wide range of environments, the breeding model based on PPB methods encourages the maintenance of more diverse, locally adapted plant populations (Berg 1995; Ceccarelli et al. 1997; Joshi and Witcombe 1996). To the extent that these populations are taken up and grown by farmers, *in-situ* conservation of crop genetic resources is enhanced (Qualset et al. 1997). Participatory plant breeding methods could, however, lead to loss of genetic diversity if only a few genetically similar plant populations are taken up and grown by farmers, displacing an array of more diverse populations.

Increased breeding efficiency. Returns to investment in breeding research will increase if use of PPB methods increases overall MV adoption levels. Similarly, important economic benefits will be created if use of PPB methods accelerates adoption of MVs by reducing the time required to develop new varieties (Pandey and Rajataserrekul 1999). No matter how excellent the science, if improved germplasm is not adopted, the breeding process that generates MVs must be considered inefficient.

Empowerment of rural communities. Participatory plant breeding allows rural communities to maintain germplasm they value and enables them to participate in the development of new varieties that suit their needs. Participatory plant breeding methods thus can empower groups that traditionally have been "left out" of the development process (McGuire, Manicad, and Sperling 1999).

Shortcomings of Local Plant Breeding

While PPB has a number of potential advantages, it also has several potential shortcomings.

High overall cost for breeding programs. One advantage of PPB methods is that they can generate varieties targeted to specific niches. This advantage comes at a cost, however: the recommendation domain for each individual variety will often be limited. For this reason, PPB methods are well suited for village-level work involving small numbers of farmers, but it is not clear that it will always be feasible to scale them up to involve large numbers of farmers, especially when these farmers are distributed over a wide area. It may be relatively inexpensive to work with a few dozen farmers located in a small, well-defined production environment (e.g., a small mountain valley), but very expensive to work with hundreds of thousands of farmers scattered across an enormous area (e.g., the Indo-Gangetic Plains). Scaling up PPB methods for work at the regional, national, or international level could require large investments in time, money, and human capacity.

High cost for participating farmers. Unlike traditional approaches to plant breeding in which most work is done by scientists, farmers participating in PPB have to invest resources—their time and intellectual capital, and sometimes traditional production inputs such as land, labor, and capital. The amount of resources farmers must invest increases in proportion to their degree of participation. This may be a particular problem for poor farmers, who by definition have few resources to contribute. Poor farmers therefore may be unwilling or unable to participate in participatory breeding schemes because participation tends to be relatively costlier for them.

Additional training needed for scientists. Scientists require specialized skills that are not normally taught in traditional plant breeding programs to be proficient at using PPB methods. These specialized skills require additional training. At a time when many NARSs are downsizing, this additional training will not always be readily forthcoming. Currently there is limited local capacity within most NARSs for carrying out PPB, and prospects are limited for quick improvement. Unfortunately, it also seems unlikely that such training will be provided by the private sector. While PPB is particularly well suited to serve the needs of farmers in marginal areas of high environmental variability, these areas offer limited commercial incentives for private firms.

Linking the Global with the Local

The global approach that has traditionally characterized international plant breeding efforts and emerging new local approaches epitomized by the PPB movement both have unique strengths and weaknesses. In future, the international plant breeding system will be greatly strengthened if new local approaches can be combined with existing global approaches in ways that exploit the advantages of both, while at the same time eliminating (or at least reducing) their respective disadvantages. For this "hybridization of approaches" to succeed, three types of challenges will have to be overcome: technical, economic, and institutional.

Technical Challenges

If emerging local approaches to plant breeding are to gain wide acceptance, data generated by these approaches will have to be considered credible. Many methods being developed in PPB are still evolving, and data generated using these methods therefore lack credibility in certain circles. Some "old school" plant breeders think that participatory methods are so informal that data generated using these methods are not amenable to rigorous statistical analysis. Justified or not, attitudes such as this diminish the professional standing of breeders who use PPB and act as a disincentive to adoption of PPB methods. Unfortunately, the credibility problem extends beyond the plant breeding profession. Regulatory authorities in many countries are still not willing to consider data generated using participatory methods when they evaluate varieties for registration and release. Seed company representatives may also be reluctant to market varieties generated through PPB. Even farmers who have evaluated the performance of varieties grown in researcher-managed trials are skeptical that their own rankings will hold up when the same varieties are grown under farmer management.

One of the main advantages of PPB is that it provides a means of assessing "subjective" traits. In food crops these include taste, aroma, appearance, texture, and other characteristics that determine the suitability of a particular variety for culinary use. These traits are difficult to measure quantitatively because they are a function of human perceptions. This poses a major problem for plant breeders, because before they can select for a trait, it must be well identified and subject to measurement.[4] Identification and evaluation of subjective traits requires close collaboration between plant breeders, social scientists, and farmers. Social scientists traditionally have played a minor role in plant breeding, but when it comes to identifying subjective traits their contribution is fundamental, because they specialize in the study of human perceptions and preferences.

This is not to suggest, however, that all social scientists are necessarily experts in this field. Much methodological work still needs to be done in developing efficient and reliable methods for eliciting and analyzing end-user preferences. Bellon (2001) has reviewed methods being developed by PPB practitioners to help in identifying and analyzing subjective traits. Focus group interviews and matrix ranking techniques can be useful for eliciting and prioritizing traits of importance to selected groups of end-users. Since these methods rely on group interviews, however, the data they generate generally cannot be used to analyze variability in the preferences of individual group members. Also, while group interviews often help to build consensus among members, consensus building can hide important differences of opinions between individuals. Partly for this reason, group interviews are increasingly being complemented by systematic elicitation of scores or rankings from individuals as a way to capture intra-group variability in knowledge and preferences. If respondents are selected using valid sampling methods, these scores or ratings can be analyzed in a statistically rigorous way.

To achieve better integration of global and local approaches to plant breeding, data generated by PPB methods will have to be recognized as valid not only by supporters of participatory breeding, but also by skeptics. The technical challenge facing the PPB movement is to develop varietal evaluation methods capable of generating credible data of widespread acceptability. Efforts are currently underway to refine specialized trial designs that can generate different types of data tailored to specific needs of different groups of users. Following Franzel at al. (2001), it is possible to distinguish three types of varietal evaluation trials distinguished in terms of objectives, design, and manner of implementation. Type 1 trials, whose objective is to assess the biophysical properties of

[4] Depending on the context, the concern of the plant breeder may be to improve these "subjective" traits, or simply to maintain them while other traits are being improved. In either case, however, the breeder will need to be able to identify these subjective traits and evaluate them.

different materials, are researcher-designed and researcher-managed. Type 2 trials, which are designed to elicit farmer perceptions about different materials, are researcher-designed and farmer-managed. Type 3 trials, whose objective is to determine the acceptability of different materials and/or promote farmer innovation, are farmer-designed and farmer-managed. Depending on the research objectives, two or more of these trial types can be combined. For example, the "Mother-Baby" varietal evaluation system combines Type 1 and Type 2 trials in different locations within the same target area (CIMMYT 2000; Snapp 1999). The Mother-Baby system has become popular in recent years, even though its technical and economic merits remain unproven. Some breeders think that the Mother-Baby system provides a cost-effective approach for generating data that are credible to all involved in the plant breeding process.

Economic Challenges

In a world of limited resources, all research must be cost-effective. Managers of plant breeding programs must determine how global and local approaches can be combined in ways that make sense economically. Intuition suggests that it would not be efficient for the international plant breeding system to consist *only* of global breeding programs or *only* of local breeding programs; rather, efficiency could be improved by adopting some combination of the two. But what combination? In economic terms, the challenge is to allocate resources in such a way that global and local breeding programs generate similar benefits at the margin. This promises to be difficult, because relatively little is known about the economics of plant breeding. Numerous case studies have assessed returns to investment in conventional plant breeding programs, but the results tend to be location, commodity, or institution specific. Almost no empirical work has been done to assess the returns to investment in PPB programs, which is not surprising given that participatory breeding methods are still new. A major economic challenge will thus be to generate improved knowledge about the economics of plant breeding—both global breeding and local breeding—so that the integration of global and local approaches can be based more explicitly on considerations of economic efficiency.

Economic efficiency considerations are important not only at the level of entire plant breeding programs, but also at the level of individual participants in the plant breeding process. By definition, PPB depends on participation by farmers. Proponents of PPB often seem to overlook the fact that this participation entails costs. In many cases, farmers who participate in PPB must contribute land, labor, and/or other inputs, and may also be required to incur additional risk. At the very least, they must contribute time, which could have been devoted to other activities. The idea underlying PPB is that by involving farmers in the genetic improvement process, plant breeding programs will be able to produce better varieties that will be adopted more widely and generate greater benefits on aggregate. But what benefits can participating farmers expect to realize? Although everybody seems to assume that participating farmers will be rewarded, the benefits realized by individual farmers who participate in PPB schemes are not always obvious—and even when they are obvious, they may not be large enough to justify participation. Thus, another challenge will be to determine modes of participation that ensure equitable compensation for participating farmers without imposing undue costs. For every level of expected benefits, there presumably exists an optimal level of participation, but we still do not understand the economics of PPB well enough to be able to say much about the costs and benefits of participation.

Institutional Challenges

A third set of challenges that will have to be overcome to achieve integration of global and local approaches to plant breeding relates to institutions. The term "institutions" is used here in a broad sense to include not only organizations, but also laws, regulations, "rules of the game," and standard operating procedures that govern the current international plant breeding system.

One set of institutions that will have to be modified to accommodate new types of information generated by PPB are national and international regulatory frameworks that govern the evaluation, approval, and release of new plant varieties. Most countries currently have well-defined varietal testing and release procedures in place; before a new plant variety is approved for official release, it must undergo a long and often cumbersome evaluation process (Tripp 1997; Morris 1998). In most countries, new plant varieties are approved for release only if it can be shown that they differ in some significant way from varieties already in the market. Evidence of significant difference generally consists of data generated through conventional varietal evaluation trials conducted under the supervision of duly certified testing authorities. Subjective performance data such as data generated through PPB are usually not recognized in varietal approval guidelines, suggesting that existing regulatory procedures will have to undergo major revisions to accommodate products of PPB programs.

Another set of institutions that will have to be overhauled to accommodate new PPB realities are the rules and procedures to assign credit for genetic improvement efforts and determine compensation. Under intellectual property rights (IPR) regimes currently prevailing in most countries, credit for breeding accrues to the breeder or breeding program that made the final selection or selections. The key criterion for claiming IPR is that the selection or selections must have created "novelty" in the resulting cultivar, i.e., modified it in some way that makes it recognizably distinct from cultivar or cultivars from which it was derived. Usually a breeder working in a specific location performed the selection or selections that created the novel cultivar, so assignment of credit is relatively straightforward. But with PPB, the nature of the breeding process can change fundamentally, depending on the mode of participation. In cases in which farmers are asked to evaluate materials developed by breeders, one can argue that there is really little difference from the existing system. But in cases in which participating farmers not only evaluate materials but also select plants for further improvement, the line becomes blurred, and it is difficult to deny participating farmers a share of the breeding credit.

Once it is acknowledged that farmers share the credit, the issue of compensation arises. How should farmers who participate in PPB programs be compensated for their contribution? Currently in most countries, IPR systems afford little recognition to the role played by farmers in plant breeding. Recently attempts have been made to acknowledge farmers' contribution in improving cultivars commonly referred to as "landraces" or "farmers' traditional varieties," but efforts to link this recognition to formal compensation have made little headway. Discussions have become bogged down because of the enormous practical difficulties involved in determining what would be an equitable level of compensation and who should receive payment. While the lack of progress is perhaps understandable, at the same time, it shows the inadequacy of existing intellectual property laws and points to the enormous challenges that have to be overcome to establish revised IPR regimes capable of equitably assigning credit in the more participatory breeding system of the future.

Discussion

By any reasonable standard, the international plant breeding system has been very successful. Modern varieties of wheat, rice, maize, barley, sorghum, pearl millet, potatoes, sweet potatoes, cassava, beans, and many other important crops developed by scientists from Future Harvest Centers of the CGIAR, working in collaboration with colleagues in national breeding programs, are today grown on millions of hectares throughout the developing world. Productivity gains attributable to adoption of these MVs have helped raise incomes and improve living standards of hundreds of millions of poor rural households. Increased crop production resulting from MV adoption has helped depress the prices of most major food staples, benefiting additional hundreds of millions of poor urban consumers who spend a large proportion of their income on food.

A key factor that contributed to the success of the international breeding system has been its centralized organization. By serving as hubs of international networks for the improvement, evaluation, and exchange of germplasm, Future Harvest Centers have been able to foster synergies among thousands of public and private national breeding programs and facilitate technology spillovers. Wherever one goes, one is likely to find farmers growing MVs whose pedigrees include exotic source materials that at one point or another have moved through a CGIAR-administered germplasm exchange network.

In addition to its strengths, however, the international plant breeding system also has a number of weaknesses. Chief among these has been its limited success in producing locally adapted cultivars for many specialized niche environments. Stated bluntly, the task is simply too big to be taken on by a centralized global breeding system. Given the vast number of distinct production environments and the enormous variability in end-user requirements, it is simply not possible for CGIAR plant breeders to identify every combination of desirable traits. Even if were possible to identify every combination, Future Harvest Centers lack the resources needed to carry out local adaptation breeding on a global scale. Unable to address the needs of all potential users, CGIAR breeders have tried to maximize the impacts of their work by focusing their efforts on dominant types of widely grown crops. This strategy has resulted in the development of MVs that have been successfully adopted over extensive areas, but it has also resulted in the neglect of many smaller niche environments for which mainstream MVs are unsuitable.

The recent emergence of the PPB movement represents a response to this perceived weakness of the traditional global approach to plant breeding. As we have seen, the term "participatory plant breeding" does not refer to a single, well-defined method for plant genetic improvement; rather, the term refers to a set of breeding methods characterized by many different potential forms of interaction between farmers and breeders. What these many forms of interaction have in common, however, is that all are designed to shift the locus of plant genetic improvement research toward the local level by more directly involving the end user in the breeding process.

Depending on the circumstances, the locus of breeding activity can vary (Figure 1). Prior to the appearance of modern scientific breeding programs, all plant breeding was essentially local. Individual farmers saved seeds collected in their own fields or in their neighbors' fields for replanting the following season, and in so doing, performed the complete range of tasks associated with plant genetic improvement, including selection of source germplasm, trait improvement, cultivar development, and final evaluation of finished varieties (Model 1). Following the emergence of modern scientific breeding programs, plant breeding effectively became globalized. Under the current international plant breeding system, a small number of professional plant breeders develop MVs for distribution throughout the world, in the process assuming responsibility for all breeding tasks (Model 5). In between these two extremes lie many different possible approaches to plant breeding characterized by varying degrees of interaction between farmers and scientists at different stages of the breeding process. These range from "complete participatory breeding" (Model 2) in which farmers and scientists collaborate continuously throughout the breeding process to "participatory varietal selection" (Model 4) in which the initial stages of the breeding process are performed exclusively by scientists and farmer participation is restricted to evaluating finished cultivars.

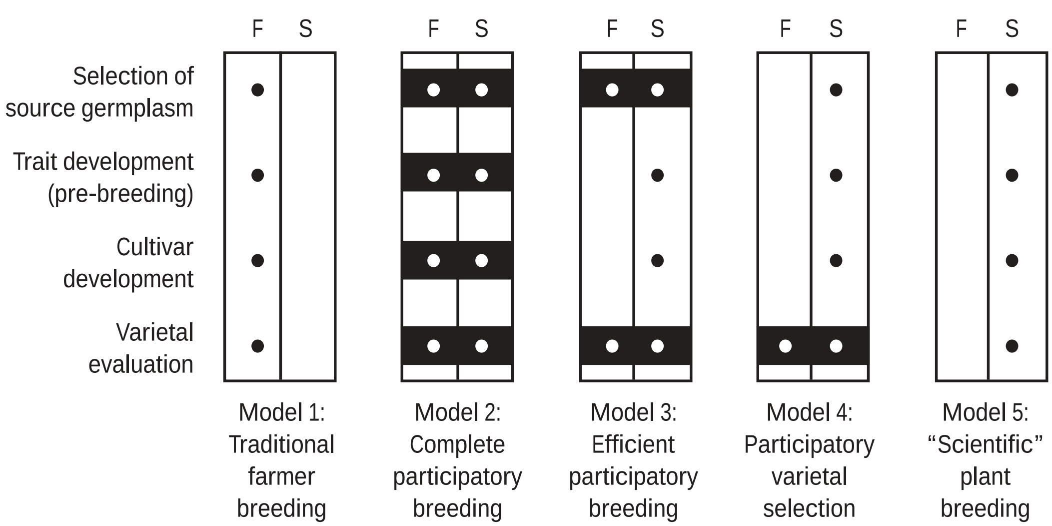

Figure 1. Integrating global and local approaches to plant breeding.
Note: F = farmer; S = scientist.

Participatory plant breeding clearly has potential to enhance traditional global approaches to plant breeding, but at this point it would be premature to say that the potential has been realized. Before the effectiveness of PPB is conclusively established, tangible evidence will be needed to demonstrate that participatory breeding methods can live up to the expectations of PPB proponents. A number of important questions still must be answered. Will varieties developed using PPB differ from those produced using conventional breeding methods? If they differ, will they be better? If they will be different and better, will the additional benefits justify the additional costs implied by PBB? How exactly will the costs and benefits of PBB be distributed? Will institutional plant breeders find it useful to adopt PBB methods? Will farmers find it worthwhile to participate in PPB schemes? Partial answers to some of these questions are beginning to emerge, but additional research is needed to clear many remaining uncertainties.

Questions concerning the cost-effectiveness of PPB are particularly important. Even if it turns out that PPB leads to the development of varieties that are not only different from conventionally-bred varieties but also better, development of these varieties is likely to entail added costs for not only for plant breeders, but also for end users. Thus, a major challenge facing managers of institutional breeding programs is to figure out ways to foster increased participation by end users, but only during those stages of the breeding process at which participation makes a difference. The term "participatory research" has become something of a mantra in some circles, but it is important to keep in mind that more participation is not necessarily better. Participation should not be seen as an end in itself; rather, it should be seen as a means to an end—namely, the production of varieties that are better adapted to the needs of end users.

Maintaining the distinction between ends and means is critically important. During some stages of the breeding process, there is no reason to believe that increased participation by end users will necessarily be beneficial. For example, most trait improvement work (pre-breeding) and even many types of cultivar development work can be carried out very efficiently by station-based plant breeders using well-established scientific selection strategies and statistically valid analytical procedures. It is difficult to imagine how involving farmers in these activities will lead to improvements in breeding efficiency. On the other hand, farmers often have unique knowledge of characteristics of existing varieties, especially landraces, so it is likely to be advantageous to involve them in the selection of source germplasm to be used in a breeding program. Similarly, the acceptability of a variety may depend on characteristics that are difficult for scientists to measure and quantify, so it is likely to be advantageous to ensure that farmers participate in the evaluation of finished cultivars before they are released.

Recognizing that farmers and plant breeders have comparative advantages for different aspects of the breeding process, and taking into account cost considerations, the most efficient PPB system (Model 3) is likely to fall somewhere in between "complete participatory breeding" (Model 2) and "participatory varietal selection" (Model 4). It is important to recognize, however, that no single "optimal" model exists, because the cost-effectiveness of end user participation will vary depending on the characteristics of the crop, the agroclimatic characteristics of the environments in which the crop is grown, the socioeconomic characteristics of those who produce and consume the crop, the institutional setting, and other factors.

Improved integration of global and local plant breeding methods has the potential to deliver better varieties to farmers in developing countries, especially poor households in marginal environments who grow mainly non-commercial food crops. Until now, such households have been bypassed by the international plant breeding system, leaving them vulnerable to periodic production shortfalls and chronic food insecurity. How to implement and sustain the integration of global and local breeding methods remains to be worked out, however, particularly in light of institutional asymmetries in the existing international plant breeding system. For many crops, especially food crops of limited commercial importance, global breeding presently is carried out by Future Harvest Centers. Meanwhile, local breeding is all too often left to national research organizations, many of which are poorly funded and inadequately staffed. Considerable challenges will have to be overcome to strengthen the latter without weakening the former. Global and local breeding are complementary activities, rather than substitutes, so simply reassigning resources away from the Future Harvest Centers and toward national research organizations cannot strengthen the international plant breeding system. The challenge facing the international community thus will be to strengthen local breeding programs while preserving the excellence of existing global breeding programs—especially those of the Future Harvest Centers.

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