ISBN 958-694-053-5

Biotechnology-Assisted Participatory Plant Breeding: Complement or Contradiction?

PPB Monograph No. 3

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ISBN 958-694-053-5
Press run: 500
Printed in Colombia
December 2003

Thro, Ann Marie
Biotechnology-assisted participatory plant breeding : complement or contradiction? / A.M. Thro and C. Spillane. -- Cali, CO : CGIAR Systemwide Program on Participatory Research and Gender Analysis for Technology Development and Institutional Innovation ; Cassava Biotechnology Network (CBN), 2003.
153 p. -- (PPB monograph ; no. 3)
ISBN 958-694-053-5

AGROVOC descriptors in Spanish:
1. Fitomejoramiento. 2. Biotecnología vegetal. 3. Investigación participativa. 4. Análisis de costos y beneficios. 5. Propiedad intelectual. 6. Bioseguridad.

AGROVOC descriptors in English:
1. Plant breeding. 2. Plant biotechnology. 3. Participatory research. 4. Cost benefit analysis. 5. Intellectual property. 6. Biosafety.

I. Tit. II. Spillane, Charlie. III. CGIAR Systemwide Program on Participatory Research and Gender Analysis for Technology Development and Institutional Innovation. IV. Cassava Biotechnology Network. V. Ser.

AGRIS subject categories: F30 Genética vegetal y fitomejoramiento / Plant genetics and breeding
A50 Investigación agrícola / Agricultural research

LC classification: SB 123 .T47

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Preface

To achieve an impact that benefits poor people, the participation of farmers (especially women) is critical in technology development. In poor countries, women's access to technology appropiate for their needs vitally affects household food security, and especially the well being of children. For this reason, the Consultative Group on International Agricultural Research (CGIAR) system decided to strengthen, consolidate, and mainstream its participatory research and gender analysis. Thus it formed the Systemwide Program on Participatory Research and Gender Analysis for Technology Development and Institutional Innovation (the PRGA Program) a high-priority, high-visibility program that recognizes farmer participation as an important strategic research issue.

The program's goal is to improve the ability of the CGIAR system and other collaborating institutions to develop technology that alleviates poverty, improves food security, and protects the environment with greater equity. This goal will be accomplished through collaborative research to assess and develop methodologies and organizational innovations for gender-sensitive participatory research. The Program's overall strategy is to introduce and strengthen the appropriate use of PRGA approaches and methods in the CGIAR's and partners' core research areas.

The Program focuses on participatory approaches to technology development and institutional innovation that use action research. The latter is defined as research conducted via hands-on involvement in processes of developing technologies or institutional innovations, in contrast to only studying or documenting this development. Priority is given to two main thrusts: (1) the participation of farmers, particulary rural women, in farmer-led research, and (2) the participation of profesional scientists in farmer-led research.

Over the last 10 years or so, substantial work has been done to introduce a user perspective into adaptive research. Recent evidence suggests that user participation can be critical in the **preadaptive** stages of certain types of research. This is when it brings users into the early stages of technology development as researchers and decision

makers who help set priorities, define criteria for success, and determine when an innovation is "ready" for release. This new role changes the division of labor between farmers and scientists, and may dramatically reduce the cost of applied research. We have evidence that this novel approach can significantly improve the impact of research for poor farmers, especially women. However, evidence is patchy and how to replicate success on a large scale is not well understood. A key contribution of the Program is to develop clear guidelines on how to achieve this end, and to build the capacity to put novel approaches into practice.

Acknowledgements

The authors are grateful for the time and thought of several hundred colleagues who contributed ideas and observations to this paper and to the panel of readers who commented on the first draft. Contributors included farmers, participatory research experts, plant breeders, biotechnologists, research managers, and donor representatives. They were drawn from public national and international research and development programs, the private sector, and non-governmental organization. Without their contributions, the paper would not exist. The authors have made every attempt to be accurate. However, omissions or errors in representation of views may have occurred. Responsibility for such errors, and for the text in its entirety, rests with the authors.

Executive Summary

Contemporary plant biotechnologies and farmer participatory plant breeding (PPB) have evolved from different disciplines and along different trajectories. As approaches to improving rural livelihoods in developing countries, *could they complement one another?* The very existence of PPB suggests that farmers' landraces do not contain all that farmers need; and biotechnology offers new tools for getting and managing variation.

Among these new tools are marker-assisted selection, inducible promoters, controllable male sterility, inducible apomixes, visual markers, and more to come. Can these tools *increase the range of options* from which farmers can choose? Can they provide *new types of plants* or traits, that meet farmers needs? Can biotech tools *empower farmers*? that is, can they increase *farmers' ability to recombine and select from their own germplasm*, or to *manage biological processes at work in their farming systems*?

This paper is the record of an exploration of international thinking on biotechnology and farmer PPB. The authors' goal was to encourage and inform discussion about:

- Whether and how biotechnology can benefit small-scale, resource-poor farmers in developing countries;
- Whether farmers can more fully participate, as colleagues or leaders, in shaping and creating the benefits;
- The potential of specific biotechnologies to strengthen farmer participatory research.

The study included an extensive series of interviews, discussions, and surveys throughout 1999 and 2000, involving at least *500 farmers, participatory researchers, plant breeders, and biotechnologists in developing and developed countries*. The authors conclude:

- There is *real potential for synergy* between plant biotechnology and participatory research to assist resource-poor small-scale farmers
- *Farmer participation could strengthen biotechnology* research with a 'reality check' to sharpen its focus

- *The opportunities are unrealized.* Only a handful of biotechnology-assisted participatory projects existed. Most of these used tissue culture, an inexpensive biotechnology that can provide benefits quickly.

Successful application of biotechnology-assisted PPB will depend on:

- **Communication.** Mechanisms for sustained communication between biotechnologists, plant breeders, participatory research practitioners, farmers, and the public.

- **Investment.** *Public investment requires public support* in donor and developing countries. There is little interaction with the public about agricultural research needs of developing countries. An opposing view, that research is harmful, is actively presented. This imbalance has created a polarized opinion climate in which public investment was not sufficient even during the unprecedented prosperity of the late 20th Century. *Win-win commercial investment* or joint ventures are conceivable—farmers are themselves private investors—and may have advantages in sustainability and choices. Polarization of opinion constrains private investment also.

- **Short-term benefits for farmers.** To compensate farmers for risks and costs of experimentation, and address their most *pressing needs*, without sacrificing opportunities for long-term benefits.

- A **social vision** that is explicit and *clearly articulated* and shared among project partners; and, a shared understanding of what a given project would mean for that vision.

- **Effective "problem transfer".** A problem has been "transferred" when researchers identify with farmers' needs as their own. Problem transfer can happen through appropriate public-sector rewards; private enterprises that depend on mutual benefit; or direct control for farmers' groups over research funds and objectives. *Accountability* mechanisms support problem transfer.

- **Access to enabling technologies** via negotiation with proprietary sources, development of a public biotechnology tool-box, or strategic alliances with key public research institutions.

- **Effective and efficient regulatory systems.** Regulatory systems are designed to ensure responsible use of transgenic biotechnology. They also create costs, often exceeding research costs, that directly affect what technologies are developed for and with resource-poor farmers. *Some of the innovations discussed in this study would incur regulatory costs*, particularly innovations to *enable farmers to manage on-farm biological processes.*

- **Initiative and continuity.** A rare blend of realism, idealism, and stability will be required. Highly heterogeneous partnerships must be formed and kept *focused and motivated.*

Over a half-century of experience in motivating interdisciplinary research networks is available in the centers of the Consultative Group on International Agricultural Research (CGIAR). The centers pioneered *participatory networks* working with resource-poor rural people to *articulate and achieve local goals*. They have *created neutral spaces for cooperation* among groups that in other situations are rivals, or inaccessible to each other. These achievements make the centers a valuable resource as coordinators of biotechnology-assisted participatory projects.

Polarized public opinion has, however, *severe consequences* to CGIAR centers and other entities that could provide leadership. Funding has been insufficient, and—most difficult to overcome—messages from stakeholders are contradictory. Without *pro-active communication between farm and city, opportunities are highly constrained* for any partners wishing to explore benefits from biotechnology-assisted PPB for small-scale farmers in poor rural areas.

1. Introduction

Background

It is less than 20 years since modern biotechnologies and farmer participatory research techniques were first applied to agricultural research and crop improvement. Since then, many questions have arisen regarding the potential social and economic impact of both approaches. Modern biotechnology emerged from the natural sciences and participatory research from the social sciences. Their different starting points have led to separate evolution in markedly different directions. Even today, there is often little communication between the biotechnology and farmer participatory research communities. As a result there may be unexplored complementarities between the two approaches that can be harnessed to improve farmers' livelihoods. It is vital that institutional and educational strait-jackets do not prevent us from exploiting these complementarities.

This working paper examines current thinking on two questions: (i) can modern plant biotechnologies offer benefits to small-scale, resource-poor farmers in developing countries? (ii) can and should these farmers and their organizations more fully participate in creating and shaping those benefits? Specifically, the paper aims to explore and advance understanding of how modern biotechnologies might assist farmer participatory crop improvement by improving the latter's products and/or processes.

Private-sector biotechnology companies cannot answer these questions, because their existence depends on responding successfully to commercial opportunities in capitalized agriculture. It is therefore up to the public sector, which has a mandate to address the needs of resource-poor farmers, to do so. Accordingly, the Systemwide Program on Participatory Research and Gender Analysis (SWP-PRGA) of the Consultative Group on International Agricultural Research (CGIAR) invited the authors to engage a broad range of participants in interviews, discussions, and surveys on this subject. Approximately 500 people, including farmers, plant biotechnologists, plant breeders, and participatory research experts, took part. This working paper is the result. The paper is still preliminary, and the authors would

welcome readers' comments, whether to correct errors, present additional views, or further advance our thinking.

The authors' survey showed that the biotechnology/plant breeding and participatory research sectors have no common fora in which to interact, speak different professional languages, and in most cases are unaware of how each other's work might be relevant or useful to their own. It is questionable whether it is merely the lack of communication channels that has led to the dearth of collaboration between the two groups. It may be that the close links of many public-sector biotechnologists with the commercial sector has led to a schism, in which researchers working with poorer social groups feel there is no point in trying to work with biotechnologists (E. Friis-Hansen, pers. comm.).

A list of the constraints to collaboration was proposed by A. Sutherland (pers. comm.). Potential barriers include: negative attitudes on both sides (either of on-farm researchers towards biotechnologists or of biotechnologists to sharing knowledge, methods and materials with non-specialists), organizational distance (it is rare to find both types of researcher in the same organization), geographical distance, the movement of personnel (many on-farm researchers are on short-term projects and, in the CGIAR system, tend to be pre- or post-docs with uncertain futures), lack of support for collaboration from senior management, no budgets or terms of reference for linkage activities, and on-farm researchers' fears of being stigmatized for being associated with biotechnology, even if they themselves have no ethical reservations.

In the face of such constraints, the authors believe that much more discussion and communication will be needed between the two groups if collaboration is to increase and the complementarities between their two approaches are to be realized.

Focus on Small-Scale and Resource-Poor Farmers

Small-scale and resource-poor farmers in developing countries number some 1000-1400 million, compared to 50 million farmers in the developed world (Francis, 1986; Jazairy et al, 1992; Alexandratos, 1995). While resource-poor farmers produce only 15%-20% of the world's food, they are responsible for about 80% of agricultural production in developing countries (Francis, 1986; Daw, 1989). The agrarian workforce in most developing countries consists mostly of poor women (Quisumbing et al, 1995; Dankelman and Davidson, 1988), in many cases with very high demands on their labor and the labor of their children (White, 1996).

Throughout this paper, the word 'farmers' will refer to small-scale and resource-poor farmers in developing countries, unless otherwise

specified. Such farmers include both those in relatively isolated subsistence farming systems—the areas where low-external input agriculture (LEISA, as defined by Haverkort and Hiemstra, 1993) is practised—and those whose agriculture is linked to varying degrees to external markets, such as nearby urban areas or exporters, and who therefore tend to use a somewhat higher level of external inputs.

The paper asks how plant biotechnology research might be made more relevant to the needs of these farmers. In particular, it explores how farmer participatory research approaches might be used to impart a 'pro-poor' bias to existing biotechnology research, especially in the public sector.

Plant Breeding, Participatory Research, and Biotechnology

Less than 200 years ago, all plant breeders were farmers. The division of labor by which plant breeding became a separate specialized activity conducted by scientists occurred gradually during the 19th century (Duvick, 1996). Centralized scientific plant breeding, conducted largely on research stations, has been hugely successful. However, mainly because of the context in which it evolved and operates, its products have in some cases not been adopted by, or are not accessible to, resource-poor farmers in developing countries (Lipton and Longhurst, 1989). Decentralized farmer participatory plant breeding (PPB) has been developed and promoted as a way of improving the service and delivery of crop improvement research to the poorest, most marginalized peoples and areas. Its aims are to develop locally adapted technologies and distribute them more effectively (technology transfer) and/or to support local capacity for generating such technologies. The latter aim encompasses 'empowering' or 'self-help' approaches to rural development (Ashby and Sperling, 1994).

Farmer participatory agricultural research—of which PPB forms a part—emerged during the 1980s as a means of better understanding and meeting the needs of poor or marginalized rural people. In such research, farmers are considered to be active participants who may lead the process and whose ideas and views influence its outcome, rather than passive bystanders or objects of research. Much participatory research seeks to empower local people to develop their own solutions to problems. The issues raised by such research have been extensively reviewed and discussed (Chambers and Jiggins, 1986; Biggs, 1989; Fox, 1990; Cornwall et al, 1993; Gubbels, 1993; Mosse, 1993, 1995; Okali et al, 1994; Ashby and Sperling, 1994; Mayoux, 1995; Carney, 1996; Farrington, 1997). The use of farmer participatory research in plant breeding has been the subject of a number of recent compilations and reviews (de Boef et al, 1993; Okali et al, 1994; Eyzaguirre and Iwanaga, 1996; Sperling and Loevinsohn, 1996; UPWARD, 1996; CIAT, 1997; Veldhuizen et al, 1997; Witcombe et al,

1996; Witcombe, 1999a, 1999b, 2000a). For a review of PPB per se, see other papers in this series.

A distinction should be made between PPB and participatory varietal selection (PVS), although the two approaches often overlap and borrow or learn from each other. PVS is really a form of PPB, which is the larger of the two concepts. While PPB tends to involve farmers at all stages of the research process, farmer involvement in PVS tends to be somewhat more limited. In PVS, farmers play a role in selecting within stabilized materials already developed mainly by formal researchers and in feeding back their reactions to those who decide which varieties should be promoted and distributed.

Modern plant biotechnologies have emerged over the past 2 decades as powerful tools for crop improvement, especially when integrated with proven conventional plant breeding methods. For the purposes of this paper, they are held to include both plant molecular biology techniques and tissue culture techniques. The plant molecular biology techniques discussed are genomics, marker-assisted selection (MAS), diagnostics, and transgenesis (also known as genetic transformation, genetic modification, or genetic engineering). The plant tissue culture techniques covered include in vitro selection, embryo rescue, and anther culture, as well as clonal thermotherapy and micropropagation. While biotechnology is now often equated in the popular media (e.g., in Europe) with so-called 'genetically modified' foods, the authors wish to stress that only a sub-set of modern biotechnologies result in transgenic products. Biotechnologies which generate products of both a transgenic and a non-transgenic nature are considered in this paper, but the paper does not review the pros and cons of genetic modification per se.

Just as farmer participatory research approaches are diverse, so also plant biotechnologies vary greatly in their technical complexity and in the resources needed to apply them. Among the factors that need to be considered in selecting and defining an approach to biotechnology-assisted PPB are:

- Cost-benefit analyses of alternative research approaches. Several approaches to an agronomic problem may be possible, each with different costs, time-frames, and chances of success. Should biotechnology be the approach of last resort, only when all other approaches have failed? Or are there situations in which it should be given priority because it can provide the most cost-effective solution? Who decides which approaches are best?
- The provision of information about biotechnology to farmers. If farmers are to decide whether or not biotechnology should be used, do they need to understand what it is and how it works? How can relevant information regarding biotechnological options be supplied to them efficiently and objectively?

- The provision of information about farmers to biotechnologists. If biotechnologists are to develop products for farmers, they need to know the different needs of different groups of farmers and hence the circumstances into which those products must fit. They also need a greater understanding of how to deliver biotechnologies to farmers
- How to implement biotechnology research for non-commercial markets. There is an urgent need to enable and persuade biotechnologists to conduct research for poorer clients who offer neither research grants nor substantial opportunities for academic publication. The private sector may be involved in finding some of the solutions, but primary responsibility for proposing and developing the necessary incentives rests with the public sector
- Risk assessment and biosafety protocols. While biosafety review systems are necessary to regulate the deployment of transgenic products, too stringent a system can delay or prevent farmers' access to biotechnology innovations. So also can the absence of a functional system
- Intellectual property considerations. What are the implications of any existing or planned intellectual property rights (IPRs) for the availability of biotechnologies to resource-poor farmers? Can or should IPRs be claimed for the products of participatory research?

Biotechnology-Assisted Participatory Plant Breeding: Putting It All Together

Biotechnology-assisted PPB is little more than a concept at present. Its realization as a widely used research approach requires, first, the successful integration of biotechnology as a new tool in conventional plant breeding, and second, the successful integration of participatory research methods with conventional plant breeding methods. Neither of these conditions has yet been fully met. To enable that to happen, it is essential to understand how each approach—participatory research methods and biotechnology—can be valuable to formal or informal (farmer) plant breeders.

Over time, many biotechnologies which facilitate plant breeding are likely to become more cost-effective (Spillane, 1999). It is conceivable that some of the 'downstream' biotechnology tools that formal plant breeders are now adopting might now or in the future also prove useful to expert farmer-breeders working either by themselves at field level or with the support of researchers in a participatory breeding project. However, this possibility has not yet been properly explored. Nor has there been any exploration of whether new biotechnologies might be developed which are tailored specifically for use in PPB.

The integration of participatory research techniques with conventional plant breeding is embryonic. However, it is clear that these techniques can be applied in 'problem transfer'—the business of

relaying farmers' needs to formal breeders so that the latter will take them into account when setting research priorities. The techniques have also proved useful as a 'reality check', allowing breeders to evaluate what they are already doing in terms of its relevance to farmers' needs. This is especially useful given the long time-frame of much breeding research.

The authors believe that biotechnology techniques may have much to contribute to participatory research, and vice versa. Farmer participatory research has in some cases generated over-optimistic expectations (Farrington, 1997). The authors wish to stress that they do not see either participatory research or biotechnology as a panacea for agricultural development, rather as additional methodologies that help solve certain problems.

Research Partnerships in Biotechnology-Assisted Participatory Plant Breeding

What sort of institutions or researchers will initiate, plan, fund, and implement biotechnology-assisted PPB projects? Farmer-initiated projects are considered the ideal in participatory research. But in the case of biotechnology-assisted projects, farmer initation would require that farmers already possess a practical understanding of biotechnology, as well as an idea of where to request research support. It is unrealistic to expect resource-poor farmers to have such an understanding of a newly emerging technology that is often physically and intellectually remote from their world.

Clearly, access to research facilities, funding, human resources, and training will be vital for biotechnology-assisted PPB. So too will be attention to the links between upstream biotechnology and downstream applied research.

Farmers tend to request comprehensive projects that integrate biological and socio-economic activities and criteria (Thro et al, 1999b). These are difficult to fund due to the long time-frames they require to conduct biological research and achieve impact. The funding mechanisms used at present have imbued agricultural research with discontinuity and fragmentation—problems to which biotechnology-assisted PPB will also be prone. Developing the appropriate tools for such research, together with the necessary relationships between farmers and biotechnologists, will take time. Achieving an impact will take still more time. Sustained public funding will therefore be necessary.

The rest of this paper is organized as follows:

- Chapter 2 looks briefly at existing plant breeding and participatory agricultural research and how these approaches merge in PPB. It

also looks at the 'why' of involving biotechnology when working with farmers

- Chapter 3 considers how the researchable needs of farmers have been or might be identified and better represented on research agendas
- Chapter 4 explores how specific biotechnologies might facilitate the **processes** of plant breeding, making research more efficient for the farmer or formal breeder
- Chapter 5 looks at some plant biotechnology research **products** that correspond to the needs expressed by farmers
- Chapter 6 briefly explores social and economic issues surrounding biotechnology-assisted PPB.

2. Farmer Participatory Research and Plant Breeding

An Analytical Framework for Farmer Participatory Plant Breeding

Over the past decade, a number of analyses and reviews of farmer participatory approaches to plant breeding have been published (de Boef et al, 1993; Okali et al, 1994; Eyzaguirre and Iwanaga, 1996; Sperling and Loevinsohn, 1996; UPWARD, 1996; CIAT, 1997; Veldhuizen et al, 1997). These and other works describe the evolution of concepts and practices in this field.

PPB aways involves scientists and farmers, and often a wide range of other people, including consumers, extensionists, NGO workers, traders, industrialists, rural businessmen and women, and the leaders of cooperatives or farmers' organizations. These people become co-researchers in that they: (i) help set research goals, decide on priorities, and define specific breeding objectives; (ii) make crosses, screen germplasm entries, and take responsibility for adaptive testing; (iii) organize seed multiplication and diffusion; and (iv) grow the crop and use, process, or market the resulting harvest (Sperling and Ashby, 1999). Key variables for analyzing PPB programs include the institutional context, the bio-social environment, the goals set, and the kind of participation achieved, including the division of labor and responsibilities (Sperling et al, 2000). Clear description of these variables is important when a project seeks to determine whether and how biotechnology can support its work.

A key institutional factor in PPB is the point of control or decision-making. Who decides the objectives, determines the approach, and specifies what results and data are needed? This will differ depending on whether farmers are invited by researchers to join breeding research initiated by formal programs ('formal-led PPB'), or whether scientists seek to support farmers' own systems of breeding, varietal selection, and seed multiplication and dissemination ('farmer-led PPB').

Formal-led PPB usually has certain distinguishing characteristics. It tends to be strongly linked to formal variety release and seed dissemination systems. It is usually required to provide feedback to the rest of the formal sector, implying the use of standard experimental

design and analysis. And it is expected to develop and test varieties or methods that will be applicable beyond an individual community. In farmer-led PPB, farmers bear the main responsibility, and often the costs, of conducting experiments and selecting and disseminating preferred materials. The objectives are first and foremost local, any broader applicability being fortuitous. And there is no obligation to provide information or germplasm to external or formal systems (Sperling et al, 2000).

Some commentators express skepticism that 'indigenous' farmer breeding practices can really be found (e.g., P. Richards, pers. comm.). However, by saving seed and resowing it the following season, many farmers practice what amounts to mass selection of landraces or improved varieties of grain crops. There is some evidence that farmers 'rusticate' both hybrids and improved open-pollinated varieties through such practices (Bellón and Brush, 1994; Wood and Lenné, 1997; Louette et al, 1997). D. Duvick (pers. comm.) notes that the reproductive biology of a crop (i.e., whether it is self- or open-pollinated) has a major bearing on the ease with which farmers can conduct plant breeding (in the sense of recombination followed by selection of useful genotypes). For instance, saving the seed of an open-pollinated variety of maize does not conserve the variety as surely as saving the seed of pure lines of wheat or rice, which are self-pollinating. Open-pollinated varieties lose their characteristics if selection is not rigorously maintained. Experience suggests that farmers achieve variable results when they try to maintain the quality of open-pollinated varieties. Research in China on the impact and subsequent history of open-pollinated maize varieties developed by the Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) (e.g., Song, 1998) shows that farmers need support in developing improved selection systems if they are to regenerate deteriorated open-pollinated varieties (N. Roling, pers. comm.).

Plant breeding projects typically include the following stages (modified from Schnell, 1982):

1. Setting breeding objectives
2. Obtaining genetic variation (from collections or farmers' fields, and/or through crossing)
3. Selecting among variable materials, such as segregating populations from crosses
4. Testing and characterizing the selections (experimental varieties)
5. Multiplying and disseminating seed (following regulatory and release procedures).

Biotechnologies may have implications for all of these stages. They may broaden the range of objectives that can be considered, making possible an objective that cannot be pursued through conventional breeding. They may increase the range of genetic variation available.

They can enhance the accuracy and efficiency of selection and testing. They may bring special regulatory and marketing considerations into play. And they can speed up the multiplication and dissemination of new planting materials (Box 1). Consequently, farmer participation in biotechnology-assisted plant breeding can certainly increase farmers' options, but it also entails a need to educate farmers, not only about the options themselves but also about the implications of choosing a biotechnology approach.

PPB involves farmer participation at various stages where it has not been traditional in conventional breeding, notably in stages 2 and 3. Farmers can also participate more fully in stage 1, their input to which in the past has often been limited to surveys of their farming systems. In addition, they can play a role not only in the later but also the earlier phases of stage 4, usually the preserve of formal researchers in the past. In stage 5, farmers may participate in both the formal and the informal seed delivery system.

Various frameworks have been developed for analyzing and evaluating the participation of end users or clients in agricultural research (e.g., Paul, 1986; Biggs 1989; Okali et al, 1994; Farrington, 1995). In practice, three kinds of participation are found: consultative

Box 1

Use of anther culture in participatory rice breeding

Anther culture is a form of micropropagation that can be used to speed up the delivery of improved grain crop materials to farmers.

A PPB scheme using anther culture has been proposed for the dissemination of rainfed rice in eastern India. The scheme involves the use of doubled haploid (DH) lines, which are uniform yet offer a wide range of phenotypic diversity from which farmers can select under their own conditions. It is essentially a modified version of bulk and pedigree methods, but delivers a wider range of individually uniform progeny to farmers' fields more rapidly (i.e., at the F_1-F_2 rather than the F_4-F_6 generations).

The scheme has the following stages:

- Characterization of parents
- Hybridization and generation of F_1 progeny (20-30 crosses)
- Production of DH populations from F_1 or F_2 generations, using anther culture
- Evaluation of DHs by farmers
- Overall performance assessment
- Replicated yield trials of the most promising DHs.

Farmers keen to get access to the seed of improved crop varieties quickly should find such a scheme very attractive.

SOURCE: Sarkarung et al (1996).

(information sharing), collaborative (task sharing), and collegial (sharing responsibility, decision making, and accountability) (adapted from Biggs, 1989; Sperling et al, 2000). The kind of participation at each research stage has also been examined (Farrington and Martin, 1988; Biggs, 1989; Sperling et al, 2000).

Rationales for Farmer Participation: Product or Process?

The participation of end users in research (including plant breeding) can either (i) be a means towards an end (that of improving research products) or (ii) be an end in itself. In the latter case, which could be called the 'process' approach to participation, the emphasis is not so much on achieving defined outcomes as on facilitating a process of empowerment, with the clients considered as agents rather than objects (Cornwall and Jewkes, 1995; R. Gerster, pers. comm.). In the former case, known as the 'functional approach', the tendency is to focus on a problem and generate solutions—as quickly as possible. In PPB, the functional approach would lead to the end being defined as the development of better adapted crop varieties more closely tailored to small-scale farmers' needs, whereas the process approach would aim to empower farmers to develop their skills as plant breeders. The functional approach is more common in the formal programs of government, research institutes, and the private sector, while the process approach tends to be more common among non-government organizations (NGOs) working for community development (Farrington and Nelson, 1997).

Process or empowering approaches tend to lead to broadly focussed research on a wide range of themes, since the livelihood constraints identified as research targets through such approaches are rarely sector- or technology-specific (Farrington et al, 1993) and the choice of themes tends to lie more firmly in the hands of farmers. This has implications for the mechanisms needed to enable participatory research to interact with plant biotechnology research, which typically has highly specific objectives. In theory, biotechnology research could support both the functional and the process approaches, but different biotechnologies might be employed and different products would doubtless result, since the functional approach tends to lead to more upstream research whereas the process approach more often avoids this. In practice, most current biotechnology research is targeted towards efficiency objectives, using a supply-driven approach.

The distinction between functional and empowerment-oriented participatory research may not always be clear cut. Research that begins with functional objectives can over time lead to empowerment as well. Ideally, the information generated through participatory methods, and the process of generating that information, builds local capacity in planning and organizing activities. An example of this outcome is the work of the Unión de Asociaciones de Trabajadores Agrícolas,

Productores y Procesadores de Yuca (UATAPPY), a cassava processing cooperative in Ecuador, which survived without external support through 2 years of natural disaster to contribute its own proposals to the design of a recovery plan (Thro et al, 1999b; see Box 10). Farmers' groups organized around commodities, such as cocoa production or cassava processing groups, are more likely to become involved in technology development and hence in functional or efficiency-oriented participatory research (Healy, 1987). Such groups may find it easier to interact with research institutions that are also commodity-based. As farmers become familiar with the potential benefits of research, their interests may shift from a process to a functional approach, as they identify needs that might be met through technology development. This is especially the case for more market-oriented farmers' organizations (Tendler, 1994; Collion, 1995; Collion and Rondot, 1998).

Since most PPB is still experimental, it is not yet clear whether the two approaches differ inherently in terms of the scale on which they can be applied and hence the impact that can be expected from them. It may be that smaller projects can be combined to create a mosaic of community-based activities covering much of the countryside (C. Iglesias, pers. comm.). The scale issue also has major implications for the cost-benefit analysis of participatory research. Such research is already costly in terms of time and other resources (Farrington et al, 1993; Farrington, 1997) and may become even more so when biotechnologies are involved. Functional participatory research may be possible on a large scale, but this is less likely to be the case for empowering research (Farrington, 1997), in which the frequency and intensity of contact between participants and external supporters of the process may be critical. There is a trade-off between the scale of farmer participation and its depth or intensity. It has been suggested that some kinds of NGO may have a comparative advantage over state institutions in promoting greater depth of participation (Farrington and Biggs, 1990; Okali et al, 1994), while state institutions may have both the capacity and the incentive to promote wider participation (Farrington, 1997).

Since resource-poor farmers operate under a wide range of environmental, social, and economic conditions (Francis, 1986), it is unlikely that single technical solutions can be developed to suit all of them (Ashby and Sperling, 1994; Chambers, 1983, 1987). Plant breeding has been highly successful in developing improved crop varieties suitable for large areas (Smale, 1997; D. Duvick, L. Sanint, pers. comms.). However, many such varieties have also been rejected as unsuitable by some groups of farmers (Clawson and Hoy, 1979; Ziegler, 1986). The costs of these cases of non-adoption can be high (Carr, 1989).

Resource-poor farmers are considered more likely to adopt technology if they are offered a range of prototype products from which

to choose according to their needs—a 'basket of options', in the words of Chambers (1987)—and which they can tailor to their specific circumstances (Ashby and Sperling, 1994). The basket may consist of different plant ideotypes, for example, or differing combinations and levels of fertilizer or pesticide applications. This 'prototype diversity' approach, which is also called 'decentralized technology development' (Biggs, 1995), is considered by many to be the most cost-effective for meeting the needs of farmers in complex, risk-prone environments (Ashby and Sperling, 1994; Sperling et al, 1993; Sperling and Berkowitz, 1994). To create a useful basket of options, researchers must have a relatively good idea of the broad range of clients' needs and constraints at the outset of the technology development process. These aims are best met through participatory research that involves farmers in both the diagnostic and the technology development stages of the research process.

Farmer Participation: Upstream versus Downstream Research?

At what points in the research spectrum can farmers or other end users interact with biotechnologists to make research and technology development more client-driven? Calls for client-driven research tend to focus attention and resources on 'downstream' applied or adaptive research (Ashby and Sperling, 1994). Not all research can be client-driven: basic research to increase knowledge is unlikely to be. Yet in the long term it too confers economic advantages on the countries that fund it (Wong, 1996), because at least some of the knowledge eventually gives rise to new technological options of one kind or another.

For some (e.g., J. Lewis, C. Martínez, K. Tamminga, pers. comms.), farmers' participation is seen as most useful at the initial priority setting and final testing stages of research (1 and 4, above); biotechnology research per se, which is usually conducted at stages 2 and 3, does not require it. According to this school of thought, farmers can have a meaningful input to defining needs and problems, setting priorities, and evaluating possible research approaches, in collaboration with scientists. Once the research agenda has been established, much of the upstream and mid-stream research, including biotechnology development, can then be conducted by scientists, who return to farmers only at the end of the research process, to obtain their reactions to the research product.

Most commentators find it difficult to foresee any meaningful role for farmers in laboratory experimentation. I. Potrykus (pers. comm.), for instance, believes that involving farmers in developing molecular markers would be too complicated, at least at the current stage of research. He advocates that farmers' participation in research involving transgenic varieties or MAS should, after initial priority setting, resume only when the results are transferred through breeding to potentially

interesting new varieties. K. Schmidt and K. Tamminga (pers. comms.) both felt that plant breeding could be made more participatory while still including a laboratory phase in which farmers do not participate directly, except perhaps through educational visits and discussions.

Activities at the downstream end of product development are likely to be more amenable to farmer participation. Farmers' organizations are often involved in adaptive research and technology transfer of 'off-the-shelf' technologies (Copestake, 1990; Mercoiret et al, 1990), while typically being excluded from most strategic and applied research (Bebbington et al, 1994; Muchagata et al, 1994). In public-sector research at least, there is typically little involvement of farmers and other end users (or intermediate users such as extension agents) in the process by which technologies get 'onto the shelf' in the first place. Indeed, one of the most difficult functions to institutionalize in public-sector on-farm research is feedback from the clients or users to upstream researchers (Merrill-Sands et al, 1991).

Challenges to the Participation of Resource-Poor Farmers

Much advocacy of participatory development is based on the assumption that the benefits of participation outweigh its costs to farmers (Mayoux, 1995; Mosse, 1995). However, time spent in participation has an opportunity cost to the poor, whose main economic resource is often their time (Sutherland et al, 1998). A vicious circle of exclusion can set in, whereby poverty and high-risk livelihoods are two of the most significant obstacles to poor peoples' participation in activities designed to alleviate their poverty and reduce the risks they face (Fox, 1990).

One commentator expressed concern that, all too often, researchers adopting a participatory approach merely co-opt a token 'participatory' farmer assistant, at greater cost to the farmer than gain (P. Richards, pers. comm.). The costs of participation to farmers must be offset by tangible and immediate benefits, over and above those obtained by investing their time in other activities. Unless they perceive these benefits, farmers may be unwilling to participate in voluntary projects (Finsterbusch and van Wicklin, 1987). This is one of the main limitations of PPB, which typically has a long time-horizon before farmers reap the rewards (Okali et al, 1994; Thro et al, 1997). It will certainly also be among the chief challenges to biotechnology-assisted PPB. The first pioneering projects will be particularly affected, since few biotechnology tools adapted to farmer participatory research are yet available 'on the shelf'. The requirement to develop these tools, such as molecular markers for farmer-specified traits, will add further to the time-horizon. In the longer term, once the tools have been developed, the capacity of biotechnology research to shorten the time-horizon may come into play, making participation once again more attractive to farmers.

The time constraint is as relevant to farmers' organizations as to individual farmers. The viability of many farmers' organizations depends on their capacity to provide members with goods and services in the short term. Consequently, they may be unwilling to become involved in 'upstream' research, even though it might help to meet their long-term strategic needs (Bebbington et al, 1994; Muchagata et al, 1994). Farmers' organizations usually focus on 'downstream' adaptive research and technology transfer (Copestake, 1990; Mercoiret et al, 1990). This focus is likely to steer the attention of client-driven researchers away from basic or long-term strategic research (Ashby and Sperling, 1994).

The technologies most likely to be adopted by resource-poor farmers are those that can deliver increases in land and labor productivity. Resource-poor farmers constantly face difficult choices in allocating their labor, shortages of which are especially severe in households headed by women. For the landless, labor is particularly precious because it is their main or only productive resource. If it is to appeal to farmers, biotechnology-assisted PPB and associated research needs to focus on the development of products or processes that reduce labor requirements, especially for the community's worst affected groups. In addition, reducing the labor time and intensity of key activities in plant breeding could be one way in which biotechnologies could contribute to PPB and make it more attractive to farmers.

Another challenge facing biotechnology-assisted PPB is the gap between formal and informal research cultures. Farmers are no strangers to experimentation, but their perceptions of and approaches to their experiments are often very different from formal scientific methods as developed in the West (S. Bickersteth, pers. comm.). Scientific methods are a requirement of most current plant breeding and biotechnology research. Aligning these methods with farmers' knowledge systems and practices in the field may be difficult. For instance, participatory approaches to plant pathology have been used to understand farmers' perceptions of the key disease constraints affecting bean production in the Great Lakes region of Africa (Trutmann, 1996). The farmers did not recognize individual diseases as such, but saw them as the result of certain types of rain. As a result farmers selected against varieties they considered 'susceptible to rain'—a statement that left pathologists none the wiser as to where their research priorities should lie. However, it is possible that the dichotomy of indigenous versus scientific knowledge systems has been overplayed and that it would be more useful to consider how the two systems could more effectively complement each other (Agrawal, 1995).

Lastly, the question of whether or not research will have a lasting impact in the farming community needs to be addressed for biotechnology-assisted PPB as for any kind of agricultural research. To meet this 'sustainability' challenge, the results of research—usually

enhanced germplasm—need to be of such a kind that they can either be multiplied and disseminated from the formal plant breeding program or seed sector once the researchers are no longer involved, or renewable over the longer term by the farmers themselves. Hence, 'exit strategies' are important and should be considered at the early stages of project formulation (Sutherland et al, 1998). Indeed, all external incentives and benefits provided by researchers, including biotechnology tools or products, should be critically evaluated for whether or not they can be accessed, generated or renewed by farmers alone in the longer term. This is a consideration that strengthens the case for including an 'empowerment' element in even the most functional types of participatory research.

Why Involve Biotechnology in Farmer Participatory Plant Breeding?

Adding biotechnology methods to PPB means adding more players, higher costs, extended time-frames (at first), and new regulatory issues to what is already a challenging form of research. Why do it?

From a plant breeder's point of view, the reason is: because biotecnology tools can increase genetic gain. That is, gain in whatever trait or combination of traits is of interest to the users of the crop under research. Any breeder—formal or informal—confronted with a possible new method will in effect ask, How does it help obtain genetic gain? To answer this question, researchers have developed the genetic gain equation (Box 2), an analytical tool for estimating the benefits of using biotechnology or any other new method in plant breeding.

By separating genetic gain into its components and quantifying them, formal breeders can use the equation to compare different breeding methods for the rate and extent of the progress that can be expected and the costs that will be incurred. They can then select the optimum method for their circumstances. Although farmers work without quantitative analytic tools, the same components of genetic gain underlie their breeding decisions: genetic variation, phenotypic variation (resulting from interaction of genetic variation with the environment), selection intensity, and time required for the gain. Generally, all breeders aim to maximize variation and selection intensity, while minimizing time (Fehr, 1987; Sprague and Eberhardt, 1977).

An important difference between formal and informal plant breeders lies in their management of spatial phenotypic variation. A formal breeding program developing varieties for a large target area will select those with minimal variation among locations, whereas a farmer whose target is one small farm or even one field will seek the varieties that do best in that site, regardless of their performance elsewhere. All

Box 2

The genetic gain equation

$$G_y = \frac{k\,\sigma^2_A}{y\,\sqrt{\sigma^2_e/rt + \sigma^2_{ge}/t) + \sigma^2_g}}$$

where the terms are:

G_y	genetic gain per year	σ^2_A	additive genetic variation
k	selection intensity	y	years (other units of time can be used, such as seasons)
σ^2_e	experimental error (uncontrolled variation)	r	number of replications
σ^2_{ge}	genotype x environment interaction	t	number of test environments (years, locations, or a combination of these)
σ^2_g	total genotypic variation		

SOURCE: Fehr (1987).

breeders, however, tend to seek to minimize the temporal component of phenotypic variation.

Heritability is the ratio of two of the components of genetic gain for a given trait: genotypic variation and phenotypic variation (Lush, 1945; Feldman, 1992). Low heritability characterizes some of the traits most important to farmers at all times and places, such as yield per se, yield stability, cooking quality, and processing quality. A significant proportion of the variation in these traits is caused by the environment, so repeated measurement of the traits across locations and/or years is required to identify desirable genotypes accurately. Conversely, traits with high heritability and little environmental effect require less effort in selection. Stem and flower color are examples of traits with high heritability.

Any biotechnology tool intended to facilitate plant breeding can be evaluated for its effect on the components of genetic gain and on heritability. Although the vocabulary they use may differ, both formal and informal plant breeders will ask whether the tool can:

- Increase genetic variation (by introducing new traits or extending the range of variation)
- Reduce phenotypic variation (or otherwise reduce the number of locations or years needed to assess the stability of a trait)
- Increase selection intensity or accuracy
- Reduce the amount of time required to complete a cycle of crossing and selection
- Deliver the results of research (e.g., a variety, a plant population) to farmers.

For example, a breeder, whether formal or informal, might ask if biotechnology can offer ways of enhancing the selection process so as to circumvent an age-old problem that has led to the steady reduction of varietal diversity in farmers' fields: the requirements of both traditional and industrialized agriculture for key market traits that often have low and complex heritability (e.g., bread-making quality in wheats). These requirements limit the amount of diversity that can be retained by breeders, because the use of crosses with diverse parents to broaden the genetic base of the crop will break up the favorable genetic linkage blocks that create the desired market quality (Spillane and Gepts, 2000). The resulting progeny are unusable, even if they have other desirable traits. For example, the red seed color of beans required in some Central American countries is a highly complex trait that tends to get lost when crosses are made, with the result that many otherwise desirable progeny are unusable (S. Beebe, pers. comm.). The preferred cooking quality that limits farmers on Colombia's north coast to one disease-susceptible variety of cassava is similarly lost in the progeny of crosses (Thro et al, 1997). If biotechnology can increase the precision with which these traits can be handled, many more breeding populations could be moved off the research station and on to farmers' fields, promoting in situ variation considerably (S. Beebe, pers. comm.).

Costs and Benefits of Biotechnology-Assisted Participatory Plant Breeding

Because biotechnology-assisted PPB will require significant investments of time and other resources from both farmers and biotechnologists, it becomes both important and difficult to weigh its costs against its potential benefits.

Conventional plant breeding has proved highly cost-effective for some environments and farmers. The costs and benefits of PPB and PVS have not yet been comprehensively evaluated (J. Sumberg, pers. comm.; Okali et al, 1994), although studies are under way and firm results are expected by 2002 (L. Sperling, pers. comm.). A similar question pertains to the costs and benefits of plant biotechnology, because of its relative youth as an applied science. Even in the developed countries, where extensive biotechnology research is under way, there are many more products in the pipeline than there are in farmers' fields.

Farmer participation in research may not always be absolutely necessary or represent best value for money (Magrath et al, 1997). Some commentators noted that, where upstream research is seeking guidance, quicker and cheaper methods, such as literature review, consultation with local experts, and focussed workshops, may give as good or better results than extensive dialogue between farmers and researchers (A. Sutherland, pers. comm.).

Participation has a high opportunity cost for both researchers and farmers. For farmers, PPB must be worked in alongside existing crop production activities. The experimental plots are often part of the family's production plots. Any activity that reduces production in even a portion of the farm is keenly felt. Farmers may not wish to participate in a project if its benefits cannot be reaped in the short term (Finsterbusch and van Wicklin, 1987). Should participating farmers be compensated for their time and other contributions? There is no established 'best practice', but many practitioners agree that providing farmers with too many incentives to participate masks the crucial question of whether or not the innovations developed and tested will be continue to be used after the project has ended. Most researchers, too, lack institutional support or finances for participatory research. Projects will require time allocation and budget lines for these activities (C. Ives, pers. comm.).

3. Needs Assessment and Priority Setting

Why Involve Resource-Poor Farmers in Priority Setting for Biotechnology Research?

Involving farmers or their organizations in setting research priorities helps ensure that formal plant breeding develops material that will be in popular demand (Ashby and Sperling, 1994). A relatively small proportion of global agricultural biotechnology research is currently targetted specifically at the needs or even to the crops of resource-poor farmers in developing countries (Spillane, 1999; Nuffield Council on Bioethics, 1999). Among the few examples are the work of the international agricultural research centers (IARCs), the Center for the Application of Molecular Biology to International Agriculture (CAMBIA), Canberra, Australia, the Plant Science Programme of the UK's Department for International Development (DFID), the Cassava Biotechnology Network (CBN) coordinated by the Centro Internacional de Agricultura Tropical (CIAT), and the Rockefeller Foundation's Rice Research Network. Just as some plant biotechnologies may be able to facilitate PPB, so farmer participatory research could help make public-sector biotechnology research more demand-driven.

Although many resource-poor farmers in developing countries have heard of biotechnology through the popular press (L. E. Herazo, pers. comm.), few have a practical grasp of what it might mean for them or how to access its products and services. Similarly, relatively few of the world's agricultural biotechnologists have any direct contact with resource-poor farmers or even with other researchers working on farmer participatory approaches to agricultural development. Biotechnology-assisted PPB could help break down this isolation, allowing farmers access to the potential of biotechnology to provide them with useful innovations. Needs assessment and priority setting with farmers are first steps in bridging the gap.

There are numerous variants of and synonyms for participatory needs assessment methodologies. These include participatory technology development (PTD), rapid rural appraisal (RRA), participatory rural appraisal (PRA), and so on (Chambers, 1983). Even the farming systems research and extension (FSRE) approaches of the 1970s and 1980s had elements of a participatory approach in the

baseline and systems surveys from which their subsequent component research was derived. In recent years, more rapid and less costly methodologies have been developed (Cornwall and Jewkes, 1995). Originally developed for single locations, they have recently been adapted for more extensive use (I. Guijt, pers. comm.). The CGIAR institutes have a long history of promoting participatory approaches, including on-farm research (used by virtually all the centers), local research committees developed by CIAT and the farmer back to farmer approach used by the Centro Internacional de la Papa (CIP) (e.g., Rhoades and Booth, 1982).

These methodologies typically look at the constraints and opportunities of different sectors of the community (Mosse, 1993) by gender, age, social status, religion, ethnic group, livelihood system, and so on, in an attempt to better understand resource allocation, control, and use. Many of them also include the development and implementation of 'empowering' action plans by the community (Cornwall and Jewkes, 1995). The emphasis of these plans is on local priorities, knowledge, and perspectives (Chambers, 1983), which are not merely acknowledged but actually form the basis for all subsequent research and development (R&D) activities (Chambers, 1983; Chambers and Jiggins, 1986).

Many commentators feel information about these methodologies and competence in using them remain as 'craft knowledge' in the hands of a relatively small number of social scientists, who become advocates of these approaches (Jiggins and Röling, 1994). Descriptions of specific methods, the skills needed to use them, and documentation of the contexts in which they have proved useful are circulated largely through informal networks or in the form of 'grey' literature. When research for this paper began, few biotechnologists contacted by the authors were aware of participatory approaches or of why or how they might be linked to them. In the meantime, the participatory approach has become better known, but until very recently opportunities for professional contact and dialogue between biotechnologists and farmer participatory research practitioners were almost non-existent.

The result is that few participatory techniques have been adapted for use by biotechnologists, so that they can feed them into their work (Compton, 1997); and there are few recorded instances in which RRAs or PRAs have been used to identify farmers' priorities and selection criteria for the purposes of biotechnology research (Joshi and Witcombe, 1995; Weltzien et al, 1996). Bunders et al (1996) called for greater commitment to shared learning and the creative process of interactive problem solving between farmers and biotechnologists.

Much biotechnology research is considered to be technology-driven, with the emphasis on what research can do rather than on what should be done. On the other hand, some farmer participatory

development approaches tend to assume that all problems can be solved at the local level, without any outside assistance. While some needs can be met entirely through local activities, there will always be others that cannot be (Loevinsohn, pers. comm.). Many agricultural problems cannot simply be 'participated' out of existence (Compton, 1997). A better use of participatory methodologies is to apply them objectively across the technology spectrum, allowing the more widespread development of demand-driven research that may or may not include biotechnologies.

A number of organizations promoting and developing methodologies for farmer participatory research do so within concepts of 'sustainable' or 'organic' agriculture that may not be open to the use of modern biotechnologies such as transgenic organisms. Among these are the International Federation of Organic Agriculture Movements (IFOAM), CARE, the Southeast Asia Regional Institute for Community Education (SEARICE) and the Intermediate Technology Development Group (ITDG) (M. Altieri, pers. comm.). There is no agreement on what constitutes sustainable or organic agriculture (e.g., Ngoc Hai, 1998; J. Jones, pers. comm.). Some argue that biotechnology approaches, so often presented as the antithesis of organic approaches, could in fact allow reduced use of chemical inputs and should therefore be classified as organic.

A technology is considered neutral when its adoption does not change existing social and economic relations between different groups in a community. How can we determine which biotechnologies (and other technologies) are neutral and which are not. And how can we predict the impact of those that are not? Participatory needs and opportunities assessment can help examine these issues at an early stage of the research process.

Whose Needs Are Being Assessed?

Small-scale farmers can be classified in many different ways. Some are share-croppers, others freeholders; some farm mainly for subsistence, others are market-oriented; some sell only into local markets, others to regional or international markets. Other criteria for differentiation include age, gender, wealth or farm size, ethnic or religious group, households headed by women, by single men or by couples who share decision making (L. Chiwona-Karltun, pers. comm.). Within the household, different members have different roles and responsibilities, such as work in the field or in the house, food production or the generation of a cash income. They may also have different objectives, such as livelihood security, high yields, risk aversion, market access, and others. Households and their members can also be classified according to their different access to resources and skills, such as water, land, the labor of other household members, and so on (U. Murray, pers comm.).

In many cases these groups will have different needs. For example, a participatory needs assessment conducted with farmers by researchers at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) found that the pearl millet harvest index (HI) preferred by small-scale dryland farmers dependent on livestock differed from the HI preferred by larger farmers, who did not rely on livestock as much (A. Gupta, pers. comm.). A subsistence farmer may be willing to forego a variety with a high yield potential if another variety is more reliable in bad years. A farmer may want several varieties of the same crop: varieties with yield stability, varieties with the family's preferred flavor, high-yielding varieties, varieties with a high value in local or regional markets. Farmers linked to exporters will want varieties that meet export demands or criteria. Men and women in the same household often name different attributes of a crop as ranking higher in importance to them (U. Murray, pers. comm.). Consequently, a fundamental question in participatory needs assessment is, Whose needs are being assessed? A second question follows this first one: What criteria should be used to select farmers or groups of farmers to participate in the research process?
(A. Sutherland, pers. comm.).

Consulting each group, both separately and in interaction with others, will yield maximum information about the range of needs and help ascertain whether they can be met through a single research approach or will require completely separate efforts. It will then be possible to decide which research approaches should be given priority, bearing in mind the objectives of the project, which may be to maximize impact through the development of technology that will benefit everyone, or to try to meet the needs of a smaller, less privileged group or sub-group.

Restricting participation to farmers and formal plant breeders may exclude other relevant actors (C. Ives, pers. comm.). Needs assessments and priority setting should therefore involve other stakeholders involved in crop production, processing, marketing, and consumption. For example, local processors or traders may wish to specify important quality criteria that determine whether or not they will purchase a crop. The preferences of urban consumers are also becoming increasingly important, both within a country and when exporting. Especially in countries with a food surplus, consumer issues may have more impact on the use of some technologies, particularly transgenic methods, than any technical or cost factor (J. Jiggins, pers. comm.). The policy makers (or their representatives) who determine the incentives to produce a crop may also need to be included, particularly if the 'policy environment' is currently adverse (B. Stockli, C. Ives, J. Lewis, pers. comms.).

Needs assessment should probably not be done by individual researchers but rather by groups or teams, allowing different needs to

be communicated to those team members with the greatest ability to address them. Assessments of this kind carry relatively high costs, which would need to be budgeted for (C. Ives, pers. comm.).

The increasing precision of plant biotechnologies can allow the development of products tailored to specific markets or groups (M. Loevinsohn, P. Eyzaguirre, pers. comms.). Indeed, the long-term commercial potential of much molecular marker and transgenic technology is considered to lie in the development of value-added output traits that will address a wide range of specific needs or market niches (Shimoda, 1998). The product differentiation that is possible through biotechnology research is evident, for example, in the specialty starches and oils being developed in crops such as maize, soybean, and rapeseed. Small-scale farmers in developing countries can also benefit from varieties tailored for their content of specific nutrients, such as vitamins, essential fatty acids, sugars, proteins, and oils, or for the absence of anti-nutritional components, such as erucic acid or nitrates.

Does Biotechnology Require Special Needs Assessment Methods?

Setting priorities for biotechnology-assisted PPB requires cross-boundary interaction and the sharing of specialized knowledge. Does this mean that special priority setting methods are needed?

Opinions vary widely and there is as yet little experience to go on. We have grouped opinions under two broad viewpoints, for and against (see viewpoints A and B below). The debate on this subject may provide opportunities to develop better procedures for participatory needs assessment and priority setting in general (de Kathen, pers. comm.).

Viewpoint A: Special methods are not required

The main argument against the need for special priority-setting methods when biotechnology is one of the research options is that farmers' needs remain the same irrespective of the kind of research or technology that is applied to meeting them (M. A. Jorge, J. Lewis, pers. comms.). Differences among sub-groups within a farming community require more attention at this point than the tool-box of technologies that may or may not be used.

One concern is that including biotechnology as a possible option in the early stages of needs assessment may elicit calls for biotechnology interventions when less expensive or more familiar approaches might achieve the same objective. Needs assessment exercises typically identify a range of needs, whose solutions may require anything from plant breeding to road building. Adjustments to national or international policy may be as important as technology in providing

solutions. Only a sub-set of needs may require a research approach, whether local or external. For example, a project in eastern Kenya identified 16 different possible research approaches that could be used to address a range of problems related to household food security (Sutherland et al, 1998; Kang'ara et al, 1997). Only after needs have been identified and if plant breeding is found necessary does the question arise as to whether biotechnology may offer advantages as part of the breeding approach. (Some commentators also feel that only at that point is it time to consider whether a participatory approach will be advantageous in the research phase, e.g., L. Sanint, pers. comm.).

Viewpoint B: Special methods are required

To participate in decisions related to biotechnology, farmers need some knowledge about it. Collaborative or farmer-led decisions about whether or not to use biotechnology require that farmers and researchers understand each other's vocabulary and typologies, and have at least a rudimentary grasp of the areas in which the other is expert. Consequently, priority setting when biotechnology is an option has unique requirements.

If some biotechnologies offer breeders options that were previously inconceivable to them, needs assessments that avoid discussion of research approaches may ignore these options. Conversely, if farmers choose products that imply the use of biotechnologies but remain unaware that they are doing so, they may also fail to appreciate the other implications that biotechnology may have for the outcome of the research process (biosafety considerations, research time and cost implications, and so on). If these shortcomings are not recognized and dealt with, it may be because of an implicit assumption that farmers exhibit no preferences for one technological approach over another, or that they should be the passive objects of technological prioritization by other decision makers or interest groups. Farmers familiar with the debate on biosafety issues may become concerned if they learn accidentally or from sources other than the PPB program that biotechnology solutions are an option under consideration by researchers.

The ability of biotechnology to allow the development of entirely new traits and plant types implies that farmers and researchers may need to participate in brainstorming or some other activity designed to identify these new options, which may represent opportunities rather than mere solutions to existing problems. Methods are needed that go beyond 'wish lists' to the realm of the entirely new departure or venture (such as adding value to cassava through the synthesis of plastics precursors in the plants' roots). These methods may be considered exploitative by purists, but they may also expose resource-poor farmers to new sources of income and new routes out of poverty.

The challenge is how to inform farmers about biotechnology options without influencing them towards the choice of such options and without raising false expectations that products will be easy to develop when they may not be. (Some forms of biotechnology research are longer term and less certain of technical success than others.) Conversely, when participatory research practitioners do not inform farmers about all the available technological options, they may be accused of biasing the outcome of the needs assessment process by deliberately keeping certain technological options off the agenda (Lukes, 1974).

How to supply intelligible, relevant information about biotechnology to farmers objectively is not immediately evident. The more marginalized or poorer farmers are, the greater the challenge posed by the information gap. CBN and the Dutch Ministry for Development Cooperation (DGIS) have experimented with ways of closing it. A possible method for presenting alternative technology approaches to farmers has also been developed through work on the establishment of small-scale micro-enterprises supported by the German Bundesministerium für Zusammenarbeit (BMZ) and Gesellschaft für Technische Zusammenarbeit (GTZ). This method was originally developed to help farmers visualize and compare potential new products from their farms (Ostertag and Gracia, 1997; R. Best, J. Ashby, pers. comms.). These efforts are only a beginning, however, and much more work is needed.

The authors know of little experience in needs assessment or priority setting with resource-poor farmers specifically for the purpose of biotechnology research. Two groups with some experience are CBN and the DGIS Special Programme for Biotechnology and Development Cooperation.

When CBN began priority setting for farmer-oriented biotechnology research in 1988, it first consulted national and international scientists expert in cassava production and processing. This provided global coverage and was rapid and relatively inexpensive. However, it was realized that the results were conditioned by the perceptiveness and imagination of the scientists and limited by the lack of interaction with farmers.

In 1992, in search of direct interaction with farmers, CBN turned to rapid participatory needs assessment methods, which it applied in several countries (Henry and Howeler, 1995; Thro et al, 1994, 1997). In each country, farmers were visited in their fields and villages over a 1- to 4-week period and asked about their experiences, opinions, and wishes concerning their cassava crop. At this stage, no references were made to the technologies that could be used to develop solutions to problems. The priorities that emerged from these exercises were:

- In Tanzania: drought tolerance, cooking quality, insect resistance, nutritional value, and cyanogenesis (safety), all combined with high yield
- In southeast China: high yield, and traits contributing to low production costs and high market value
- In northern Colombia: disease resistance coupled with traditional cooking quality, high yield, insect resistance, and post-harvest keeping qualities
- In Uganda: resistance to African cassava mosaic disease, combined with locally desired plant type and cooking and market qualities.

Of the priorities that CBN had identified earlier through its consultations with researchers, some (e.g., healthy planting material and virus resistance) were corroborated by the farmer participatory exercise. Others (e.g., cyanogenesis) were seen somewhat differently when the farmers were involved. And in some cases, entirely new priorities were revealed. For example:

- Cyanogenesis: new information from the participatory exercise revealed that toxic cassava is deliberately used by farmers in some areas, despite the risks and high labor demands for processing noted by researchers. As a result of the exercise, the scope of research was expanded to include an effort to understand the ecological role of cyanogens in cassava, together with the development of new plant types. The latter consisted of plants in which cyanogens are expressed only at certain times or in certain tissues, and plants with substitute compounds that are not toxic to humans. Toxin-free varieties, the original research priority, remained an objective for specific areas.
- Cassava bacterial blight (CBB): because research had shown that CBB can be controlled by cultural practices, resistance had not been considered a priority for genetic improvement. The participatory exercise revealed that in some situations—share-cropping, for example—farmers do not control their land from one cropping cycle to the next are therefore unable to implement recommended cultural practices. Genetic resistance is their only hope of controlling yield losses. Research is now being conducted on host-pathogen relationships and the mechanisms governing susceptibility and resistance, on molecular markers for resistance, and on the development of transgenic resistant varieties.
- Cooking quality: priority setting with farmers revealed many cases in which farmers would like plants with new traits, but only if these can be combined with the desired cooking quality, which is generally a complex, quantitative trait. Meeting this need requires the development of molecular markers for cooking quality. A proposal for research on this subject is pending.

Sometimes, the speed with which farmers can obtain new materials turns out to be more important to them than the high-priority traits they have identified. For example, cassava farmers in Colombia requested varieties having locally preferred cooking qualities combined with resistance to bacterial blight, their number one disease priority, and to stem borers, an insect pest with lower but nevertheless signficant priority. Because cooking quality is a complex trait with low heritability, this combination had proved unobtainable using conventional breeding. After hearing the farmers' views, researchers presented two options: the first was to use MAS followed by traditional breeding to combine cooking quality with bacterial blight resistance, while the second was to develop a transgenic variety with insect resistance only. The researchers might have preferred the MAS option, which would have yielded new information and materials from which to develop new varieties. However, the farmers unhesitatingly chose the transgenic option, even though the resulting product would not meet their top priority. They chose this option because, at that time, it seemed the faster and the more certain to lead to the desired outcome. Their choice overturned months of careful participatory priority setting following all the orthodox recommended procedures (Thro et al, 1997).

How Much Interaction Is Necessary to Determine Priorities?

Despite their cost advantages, rapid participatory needs assessment methods inevitably provide only a superficial 'snapshot' of a farming system. As such they may reflect farmers' preoccupations at the time of the survey, but fail to capture changing needs over time. The priorities identified by farmers often reflect recent experience. For example, cassava farmers in Tanzania, who had opted for resistance to mealy bug as their priority, switched to drought tolerance when a new survey was carried out in a dry year (Thro et al, 1994). Changing market opportunities may also alter farmers' priorities.

These methods also fall short of providing the farmers' full perspective on potential solutions to problems. For example, in the CBN exercise, farmers in Tanzania identified 'poor soil fertility' as a problem in cassava cultivation (Thro et al, 1994). What is the best approach to overcoming that problem? Applying commercial fertilizer or animal manure? Switching to crops more tolerant of poor soils? Or transgenic approaches designed to improve our understanding of nutrient use efficiency as a basis for breeding superior varieties? Further discussions with farmers and experienced national program staff are needed to answer these questions.

In another example, a 1987 survey of women farmers in Malawi ranked the following criteria, in descending order, as most important for their selection of bean varieties: (i) yield, (ii) taste, (iii) cooking quality, (iv) marketability, (v) date of maturity, (vi) health-related

issues, (vii) insect and disease resistance, and (viii) ability to withstand environmental stresses (Ferguson et al, 1997). But is such information specific enough to guide biotechnology or breeding research? This is a key issue that should be addressed when training researchers in farmer participatory techniques. It is also worth noting that farmers' knowledge of the underlying biology of their farming systems may be limited, as also may that of outside researchers (Trutmann, 1996).

All this means that needs assessment will need to be continuous, or at least periodic, rather than a one-stop shop. To provide opportunities for extended dialogue between researchers, farmers, and the public, DGIS has used the participatory technology development (PTD) method (ETC, 1992; ILEIA, 1989) and the 'bottom-up approach' (Bunders and Broerse, 1991). Both approaches were tested in Kenya, India, Colombia, and Zimbabwe through the DGIS Special Programme on Biotechnology and Development Cooperation. With its emphasis on participatory dialogue, this program seeks to go beyond RRA/PRA methods to define the optimum approach or technology that might be applied. In each country, biotechnology options were introduced and discussed with farmers, after which priorities were set. The process, which took 2-4 years, involved farm visits, reports, and meetings at which farmers, researchers, policy makers, and the general public were all widely represented. The crop improvement priorities determined to date are:

- Kenya: high-quality planting materials of specific crops; increased legume production via rhizobial and mycorrhizal inocula; pest and disease resistance in maize; high yield combined with drought tolerance in all crops
- Zimbabwe: drought tolerance and insect resistance in specific crops, particularly maize
- Colombia: high-quality disease-free planting material of specific crops; and disease and pest resistance combined with desirable processing and cooking quality in cassava.

CBN took a different approach. Instead of initiating an independent dialogue with farmers, it developed links with existing participatory projects which already had such dialogues. These projects covered integrated pest management (IPM) in north-eastern Brazil and West Africa, integrated crop management in five Southeast Asian countries, and human health in Mozambique. Links were also forged with some essential participants not represented in the projects, including biotechnologists, research directors, and policy makers, who were brought in through mechanisms such as site visits to the projects and CBN's biennial technical meetings.

The advantages of the CBN approach were (i) the relatively low additional investment required; (ii) the opportunities to create dialogue between farmers, biotechnologists, and applied researchers in a

problem-solving context, and (iii) maximum use of comparative advantages of each specialization. Dialogue in problem-solving contexts has proved especially fruitful, since it can be tightly focussed on what is practically achievable. For example, farmers and researchers in Brazil and Colombia are currently developing descriptions of cassava quality preferences (W. Fukuda, C. Iglesias, pers. comms.) to help national and CIAT breeders and biotechnologists retain locally preferred qualities when breeding for yield, drought tolerance, and other traits.

After 5 years of work with farmers, CBN invited eight representatives of resource-poor cassava farmers and processors to attend a meeting with biotechnologists, other researchers, and representatives from other cassava stakeholders in Latin America, including industrial processors. A farmers-only session was arranged the day before the full meeting. Following a half-day briefing on biotechnology methods, the farmer representatives together discussed their needs and prepared a statement of their views (Box 3) for the subsequent interdisciplinary meeting.

The priorities subsequently agreed on by the full meeting were similar, though not identical, to the list initially presented by the farmers. Planting material was in first place on both lists. Marked differences between the full group and the farmer sub-group were the priority afforded to drought tolerance and to how varieties fit into cropping systems, which came high on the farmers' list and lower on the plenary list. (A subsequent meeting of Latin American cassava researchers added the conservation and characterization of cassava genetic resources, which they considered fundamental to all other objectives.)

How Can Resource-Poor Farmers' Needs Be Translated Into Research Activities?

Effective problem transfer

Between participatory priority setting and research implementation lie the hurdles of problem transfer (Jefferson, 1993a, 1993b) and control over research decisions. The term 'problem transfer' expresses the idea that problems identified in participatory priority setting must not only be communicated to biotechnology researchers but also taken up by them in their research proposals and funding requests, leading to 'shared ownership' of the problem. Some commentators feel that problem transfer may be more of a constraint than technology transfer in the development and delivery of technologies tailored to the needs of resource-poor farmers (Jefferson, 1993a, 1993b). Merrill-Sands et al (1991) argue that institutionalizing feedback from clients or users to upstream researchers is especially difficult in public-sector agricultural research.

Box 3

Latin American farmers' recommendations to CBN

Given on 17 March 1998, Pirinopolis, Brazil by representatives of associations of small-scale producers and processors of cassava from Brazil, Colombia, and Ecuador:

Group A: Most important recommendations

- Identify the most urgent problems (see below for examples)
- Work on topics of highest importance and immediate urgency, in 'PP' (practical and participatory) projects
- Seek more opportunities for collaboration between biotechnologists, applied researchers, and farmers: 'together from the gene to the market'
- Work at the local level to: (i) sensitize farmers, technical personnel, and all those involved in the cassava sector; (ii) identify, publicize, and respond to local problems (iii) using locally available materials.

Group B: Also desirable

- Prioritize technologies and knowledge that can help solve problems now, while recognizing that better technologies may come in the future
- Add value in cassava processing systems. Topics to be covered include alternative uses of waste products that will add directly to food security and reduce contamination levels (e.g. fish culture using waste water). Participatory biotechnology-assisted research should take into account the whole system of the local producer.

Group C: Other useful initiatives

- Training in relevant technologies
- Information about biotechnology and its advantages and disadvantages.

Examples of urgent (Group A) problems include:

(i) Common problems identified by all participants:
  - Drought, planting materials, credit, markets.

(ii) Problems of specific locations:
  - Northeast Brazil: root rots, cassava green mite
  - Northern Colombia: perishability, bacterial blight, frogskin virus, insects
  - Manabi, Ecuador: water quality for processing, waste water management.

In many cases, biotechnology research is still not considered a realistic option in the communication of most needs assessments to researchers. The results of assessments are typically communicated to agronomists, extensionists, even IPM specialists—but seldom to biotechnologists. How can problem transfer to the biotechnology community be improved? It is not realistic to conduct needs assessments and then expect some scientist, somewhere, to take on a technology development or dissemination role spontaneously. There is a real danger that needs will constantly be reassessed and never actually met, since no one is prepared to take responsibility for doing so. Institutional frameworks that separate needs assessment from

extension and extension from technology supply and development are likely to be ineffective (Sutherland et al, 1998). Yet most public-sector plant biotechnology research is separated in just this way from extension and needs assessment.

Who decides what research is funded?

Problems have to be transferred not just to upstream researchers but also to the agencies that fund them (and to the individuals who advise the agencies). Can the participatory process reach back this far? If participatory priority setting is to do more than educate researchers and raise farmer expectations, attention must be paid to these links.

The agencies themselves can do much to ensure that the needs and priorities identified through farmer participatory priority setting are translated into research. They can actively seek biotechnology projects for funding which are firmly based on addressing needs 'as identified by farmers'. Researchers find it easier to generate technology-driven project proposals than demand-driven ones, so if demand-driven projects are not actively sought it is highly likely that they will be, or at least seem to be, in the minority. Funding exclusively technology-driven proposals can only widen the gaps between biotechnologists, small-scale farmers, and the public, as the recent public relations problems of several private-sector companies show.

The originators of participatory needs assessment intended it to differ from conventional methods, not only in the quality of information provided but also in terms of shifting the balance of power in research planning. Questions of power make a real difference in determining the outcome of the planning process (Lukes, 1974; A. Sutherland, pers. comm.). In most cases, research follow-up on priority setting remains an external decision, dependent on actors other than the farmers. The DGIS has gone further than most agencies in putting decisions into farmers' hands. But even in these programs, the final 'green light' rests with the funding agency.

Interdisciplinarity and the division of labor

Like all skills, participatory research cannot be done well without training and practice (Farrington, 1997; Hagmann et al, 1998). Yet few plant breeders and biotechnologists have trained in, or had an opportunity to practise, participatory research methods. If all specialized biological scientists were to conduct participatory research to identify needs in which their specialization might make a difference, this would be wasteful, because it would negate the comparative advantages due to research specialization (G. Henshaw, pers. comm.). Yet if biotechnologists do not get involved in needs assessment, they lay themselves open to the accusation of being 'remote from the needs of the farmer'. From there it is but a step to the widely held opinion

that biotechnology has nothing to offer resource-poor farmers. This merely perpetuates the existing failure to communicate the results of needs assessments to biotechnologists: why bother?

Interdisciplinary collaboration between 'upstream' biotechnologists or other specialists and 'downstream' on-farm participatory researchers probably offers the best way forward. It may well be more effective to involve upstream researchers through better communication than by trying make them come out of the laboratory to enter directly into the participatory research processes. Other researchers may be better at this.

A critical mass of interdisciplinary researchers organized as a team or in a decentralized network may be the most efficient approach (Compton, 1997). The capacity for such work exists only in a few research institutions, such as the CGIAR centers. Some commentators have suggested that certain teams could serve as go-betweens for laboratories and farmers and as fora for interdisciplinary communication and research planning (G. Henshaw, pers. comm.). These fora or teams could serve multiple functions:

- Collection, synthesis, debate, and dissemination of experiences and information relating to best participatory practices and farmers' needs, for and to the broader research community
- Continuous opportunities for interaction between farm-level programs and laboratory scientists to assess needs and weigh alternative research approaches
- A platform from which farmers and researchers can together inform and influence the broader research community, public opinion, and funding sources (this is being done by some NGOs working exclusively with traditional technologies)
- In some situations, a contact point for farmer representatives in charge of community funds for research.

An interdisciplinary team that served as a more or less stable link between downstream and upstream research would have access to biotechnologists with different specializations, to whom would be circulated the range of problems identified through participatory research with farmers. These biotechnologists could then involve themselves and their colleagues according to their comparative advantage. This approach could provide continuity of attention and interaction, while alleviating the time-drain on individual farmers, biotechnologists, and other resource persons.

In the long run there may be an opportunity to re-design institutions by creating structures in which participatory priority setting is linked to research planning and financing in ways that change internal accountability. This may be more effective than trying

to achieve responsive research by persuasion (P. Richards, A. Gupta, pers. comms.) or by the example of a few special projects. Many commentators pointed to the isolating effect of current institutional arrangements, suggesting a widespread need for, and a growing acceptance of, a research environment that actively promotes farmer contact and research responsiveness (M. Altmann, M. A. Jorge, pers. comms.). However, although institutions can change, they tend to so only slowly, even in response to crisis. More interim solutions, such as task-dedicated interdisciplinary teams, are therefore needed.

Research agendas

It has been said that a difficulty with the uptake of resource-poor farmers' priorities by the biotechnology research community is often not that needs cannot be sufficiently generalized to make biotechnology investment practical but that most biotechnologists continue with a pre-determined agenda regardless of needs assessment exercises (S. Bickersteth, pers. comm.). Often, however, an agenda that may be labelled 'pre-determined' simply reflects institutional circumstances that favor other uses for extremely limited funds.

Throughout the public sector, most needs assessment with resource-poor farmers is institutionally separated from biotechnology research planning and, especially, financing (Sutherland et al, 1998). In the private sector, R&D funds are allocated wherever it is thought they will generate the best return on investment. The DGIS has made an explicit attempt to link participatory priority setting to research planning and financing, through an advance budget allocation to its country programs for the collaborative development and implementation of projects based on farmers' priorities. Similarly, DGIS provided a budget for competitive 'seed money' grants for projects to follow up CBN's participatory priority setting.

Most biotechnologists specialize in one or a few topics and are thus a highly differentiated group regarding research objectives and agendas. The more specialized a researcher, the stronger the cost-benefit implications that prevent him or her from taking on a new area of research. The 'research topic inelasticity' of many researchers means that involving a 'token' biotechnologist in a team intending to use a needs assessment to develop a more relevant research agenda may be less effective than having access to a 'portfolio' of biotechnogists with different specializations. CBN's experiences demonstrate that linking a broad range of complementary and networked biotechnology expertise to farm-level needs assessments can play a useful part in priority setting and the transfer of identified problems to the most relevant researchers.

Incentives for scientists

Simply attaching a socio-economist or a biotechnologist to a team does not necessarily make it interdisciplinary (e.g., Maxwell, 1984; Horton, 1984). Appropriate incentives to work in this way must be in place.

Many scientists whose professional rewards depend on scientific accuracy, academic publications, and access to grants tend to avoid involvement in farmer participatory research because the loss of control over research variables may jeopardize publications and other measures of professional success (Baker, 1991). Few public-sector agricultural research institutes have incentive systems which reward teamwork or those scientists who meet the needs of clients (Collion and Rondot, 1998). The adoption rates of crop varieties by farmers and other indicators of client satisfaction with the products of crop improvement research are valid research variables (Farrington, 1994), but data on them only become available long after the research has been done. Innovative ways are needed of using such data to construct reward systems for scientists involved in PPB.

Can priorities expressed by farmers be sufficiently generalized?

The authors have argued that biotechnology can provide useful tools to help PPB address site-specific and differentiated target group needs. Some commentators (J. Jiggens, S. Beebe, pers. comms.) have pointed to the problems associated with seeking to identify generalized research objectives for PPB. This can be seen as tantamount to pre-judging the needs of farmers in locations other than that in which the research is being conducted—precisely the opposite of the underlying philosophy of participatory research (J. Jiggens, pers. comm.). But if needs are interpreted as purely location-specific, the broad applicability that justifies investment in research to meet them is lost (S. Beebe, pers. comm.).

Few laboratories will be able to devote resources to projects with results that will be only narrowly applicable. If, by working together, farmers, professionals in plant breeding, and experts in participatory research and the social sciences can define valid large-scale objectives, participation by laboratories becomes much more likely. The link to a specific location need not be lost; in fact it becomes, for the laboratory, the model system in which the real-world applicability of the innovation can be tested.

One principle for involving upstream laboratories will be to link them to projects that extend all the way to the local level, including participatory activities with farmers. On-site collaborators in PPB projects, including farmers and professional breeders from national or international programs, will be vital in the process of adapting upstream innovations to local germplasm requirements, practices, and

systems, and feeding information back to the laboratory on what works. These collaborators will also play a vital role in analyzing whether the project can scale up successfully.

A generalized list of priorities would, then, be helpful in harnessing limited global biotechnology capacity cost-effectively in the interests of resource-poor farmers. In biotechnology it is often the case that an approach to solving a problem, once developed, can be transferred to other varieties or species. In these circumstances a generalized list might be especially useful. Such lists can be tentatively drawn up on the basis of common features in the results of the participatory needs assessments so far carried out. For example, the DGIS found common priorities among farmers in different countries for planting material, yield, drought tolerance, disease resistance and quality characteristics. Similar results were obtained from CBN's needs assessment with farmers over 5 years (Box 4).

Findings on needs in these biotechnology-specific priority-setting exercises are similar to the needs and priorities identified through other participatory exercises. For example, the priorities identified for phaseolus beans in Malawi included yield, cooking quality, maturity, and yield stability. Thus, for most crops, a list similar to the following generalized list of resource-poor farmers' priorities might ultimately emerge:

- Yield stability (generally via tolerance of stresses such as drought, flood, salinity, toxic or deficient soil minerals)
- Multiple disease and/or pest resistance
- Suitability for the cropping system (flexibility, maturity, crop architecture, etc.)

Box 4

Summary of cassava farmers' concerns expressed to CBN

Sub-Saharan Africa (food security)

- Planting material, virus resistance, insect resistance, drought tolerance, cooking quality with high yield, cyanogenesis management (human health)
- Improved products, markets and prices.

Southeast Asia (cash crop on non-rice soils)

- Markets, prices (for starch and new products), cyanogenesis management
- Yield per se, production costs including labor, acid soil tolerance.

Tropical Americas (food security and cash crop)

- Markets, prices (starch, new products, supply)
- Planting material, quality, yield, drought tolerance, resistance to bacteria, fungi, insects and viruses
- Cyanogenesis management (water quality).

- Planting material (quantity, quality, storage life)
- Yield per se
- Processing and marketing qualities and new or improved products
- Nutritional value, taste, appearance
- Reduced labor requirement for cultivation or processing.

A biotechnology laboratory wishing to contribute to resource-poor farming in developing countries might examine this list for topics related to its expertise. However, although such a list can be produced for use as a first step in planning, it is only a first step and too general for the purpose of developing collaborative projects. Biotechnology research for resource-poor farmers should be linked whenever possible to the needs of a target location. Contact and interaction—participation, in fact—are necessary to verify that the solution offered will meet a real need or open up a new opportunity. Laboratories can efficiently access farmers for participation through relevant networks, if these exist, or through contact with a regional or national interdisciplinary forum, center or program. Research that is so far upstream that it cannot yet be linked to specific farmers could still be conducted interactively with such fora to ensure relevance and ultimate uptake.

Doing the Work or Directing It?

It is not yet certain that farmer participation in the time-consuming day-to-day tasks of plant breeding is 'empowering' in the sense that farmers perceive it to improve their lives. Giving farmers a say in public-sector research directions and decision making may be much more 'empowering' than expecting such farmers to actually conduct the research (Bebbington et al, 1994; Gubbels, 1993; Merrill-Sands and Collion, 1994; Tendler, 1994). There is a danger that over-advocacy of the latter approach could, if the resulting research were perceived to be ineffective, lead to reduced funding.

Some say that R&D would become more demand-driven if institutions and individuals were made more accountable for the relevance of the technology they develop. But perhaps the best way forward is to give resource-poor farmers a publically subsidized voice in decision making. This could help orient plant breeding and biotechnology towards their interests (Haugerud and Collinson, 1990).

4. Biotechnology as a Set of Tools for Formal and Informal Plant Breeding

Introduction

PPB faces many of the same limitations as conventional formal plant breeders have faced for decades and farmer breeders have faced for millennia. Biotechnologies that can assist conventional plant breeding may also be found helpful in researcher-led PPB. A sub-set of biotechnologies may even prove applicable by farmers (or farmers' groups) in farmer-led PPB.

As yet there are very few examples of the use of biotechnology in PPB (de Boef et al, 1993; Okali et al, 1994; Eyzaguirre and Iwanaga, 1996; Sperling and Loevinsohn, 1996; UPWARD, 1996; CIAT, 1997; Veldhuizen et al, 1997). This chapter looks at some of the biotechnology tools that are or could be used. Because some of the applications discussed require the use of genetic transformation, biosafety and other emerging regulatory considerations will affect their development and deployment. These are discussed in Chapter 6.

Genetic variation is the essential raw material for the generation of improved crop varieties through plant breeding. Breeders obtain useful genetic variation in many ways: through access to existing diverse parental lines or populations of crops, their wild relatives, or even unrelated organisms; through increased understanding of patterns of diversity in crop-environment and host-pathogen interactions; by inducing random mutation; or (in a more directed fashion) by altering the expression of existing genes and/or discovering 'new' genes. Biotechnology provides useful new tools to aid the generation and analysis of variation by all these methods.

Farmers' control over key biological processes

Farmers attempt to control or manage many physical and biological variables in their crop production systems. The tools for this purpose typically include inputs such as seeds, fertilizers, pesticides, mechanization, and human labor. Resource-poor farmers by definition have less access to the external inputs that can reduce their labor inputs. For example, for many such farmers, labor-intensive 'hands-on' weeding is often the only means of weed control (see Box 14). Several

recently developed approaches to crop husbandry, such as IPM, seek to increase farmers' control over their systems by adding to their knowledge and substituting their labor for external inputs, often consisting of gene-based technology.

In theory, plant biotechnologies could be developed that would increase farmers' control or management of key biological processes. Needs assessment would have to be an integral part of such 'control-oriented' technology development, to identify what processes are most important to specific farmers (Mosse, 1993).

Dependency and empowerment: Product versus process?

A rough distinction can be made between (i) providing finished products to farmers and (ii) facilitating research (whether formal or informal) through the provision of what are called 'process' or 'enabling' traits or tools. The latter include traits and tools such as male sterility, inducible promoters, MAS, transposon mutagenesis, and in vitro techniques.

The range and ease of use of these tools is increasing. Originally developed for use by plant breeders or biotechnologists, some of them at least could be adapted for use by farmers in a way that increases their control over biological processes. Although this has been proposed, to the authors' knowledge no examples yet exist of such adaptation (Jefferson, 1993a, 1993b). This may reflect either biotechnologists' lack of knowledge of or contacts with PPB, or lack of funds for the necessary research, or both.

Instead of providing finished products to farmers, it is possible to develop enhanced germplasm 'prototypes', which are locally replicable and modifiable using locally available expertise and resources. This is an under-researched area in plant biotechnology. It probably requires the development of enabling tools that are specially designed and packaged to support farmers' decision making, rather than the tools developed for use by formal breeders (M. Loevinsohn, pers. comm.). This approach has been promoted as a potentially empowering form of biotechnology research for resource-poor farmers (Jefferson, 1993a, 1993b). The experiences of existing PPB programs could be useful in guiding the development and adaptation of some enabling tools for use by farmers.

Some commentators felt it was an open question whether such adapted tools and traits will ever be developed, since there is no commercial market for process-oriented end products of farmer-led research in systems where most farmers still depend on saved seed. Even if a significant amount of research towards such objectives were under way, it would be at least a decade before farm-level tools could be made widely available (R. Jefferson, pers. comm.).

Can biotechnology tools be made more user-friendly?

The authors recognize that the laboratory stages of plant biotechnology research, involving complex and specialized tasks, such as DNA sequencing and analysis or genetic modification, are not for the most part conducive to farmer participation. Such research is likely to be relatively inaccessible not only to farmers but also to other (non-biotechnology) specialists.

In formal plant breeding, biotechnology now offers certain definite advantages over conventional methods. Examples include virus elimination through meristem culture, breaking tight genetic linkages, speeding up backcrosses, adding new traits or enhancing existing ones, micropropagation, the identification of heterotic groups, the manipulation of breeding systems through male sterility or self-incompatibility, and so on. In theory, similar advantages could accrue to farmer-led breeding, if the development and use of the necessary tools could be made cost-effective.

Certain biotechnology tools are likely to be used only in laboratories. These include the tools for cloning genes, identifying their functions, and developing genetic constructs. Other tools could be used in the field by farmer breeders. These tools range from locally adapted tissue culture techniques for vegetatively propagated crops, through simple diagnostic kits for detecting viruses, to 'intermediate' or 'facilitator' genotypes engineered to simplify farmer-managed recombination or selection.

This crude categorization reflects current, still limited, experience and imagination. It also implies a broad interpretation of what could be considered a biotechnology tool, as opposed to a biotechnology product. For instance, a research product such as a transgenic variety harboring a gene for inducible male sterility could, in the hands of a farmer breeder, be a useful research tool at the field level for the purpose of increasing recombination (Bidinger et al, 1994). Cost considerations aside, the authors contend that some of the biotechnology tools that can now be used directly in the field by conventional plant breeders could be equally useful in existing or adapted form to some farmer breeders. It is difficult to generalize and there will bg many different outcomes from broadly similar attempts to test their use. A clearer picture will emerge as more thought is given to this subject, as more shared experiences are gained, and as more robust field-level tools become available.

The sections that follow explore how some biotechnologies might be useful at certain stages of either the plant breeding or the crop production cycle. Most of them would require significant support from formal scientists, at least at the outset. The opportunities and constraints associated with each are highlighted, using real examples

to illustrate the relevance to small-scale farmers wherever possible. In cases where no biotechnology-assisted PPB work has been done, possibilities for the future are outlined. Real and imagined examples are supplemented with observations drawn from our consultations with experts. These observations reflect the range of current opinion, as a basis for further discussion and experimentation.

Tools for Understanding Diversity

Biotechnology offers tools for analyzing the genetic variation among plant individuals, accessions, populations, and species (Wu and Tansley, 1993; McCouch et al, 1997; Olufowote et al, 1997) and for monitoring genetic diversity over time and space (Smith and Beavis, 1996; McCouch et al, 1997). These tools have sometimes been used to generate greater understanding by outsiders of farmers' management of crop genetic diversity. Some commentators felt that this mode of research, typically involving the molecular analysis of genetic variation in crop plant populations, is the most, or even the only, appropriate use of biotechnology in support of farmer breeders (B. Visser, J. Jiggins, pers. comms.).

Molecular marker analysis could improve the methodologies used by PPB programs. Information on the relationship between phenotypic and genetic diversity and the dynamics of functional and redundant genetic diversity in different crop reproduction systems is essential if PPB is to move beyond the promotion of mass selection. Molecular studies may be helpful in assessing the recent concept of a 'theatre of evolution' in and around the fields of small-scale farmers in developing countries (Dempsey, 1992).

There is now a growing body of information on how farmers' selection and seed exchange processes may affect the phenotypic characteristics of crop varieties over time and space (e.g., Louette and Smale, 1998; Longley, 1999; Soleri et al, 1999). Studies on this subject are complex, as geneflow can be conditioned by many biological, physical, and social factors. Nonetheless, it is thought that farmers' management of crop varieties can be highly dynamic, involving open systems with a large turnover of local and introduced germplasm over even a few crop generations (Louette et al, 1997; Wood and Lenné, 1997). This has been reported for crops such as rice (Dennis, 1987), maize (Bellón and Brush, 1994), beans (Sperling and Loevinsohn, 1993), and potato (Brush et al, 1981). Indeed, the 'half-life' of landraces in traditional systems may be even shorter than that of modern varieties in high-input systems (Wood and Lenné, 1997), a factor which PPB programs would do well to take into account since it emphasizes the need to provide a stream of useful materials to meet changing environmental conditions and the changing needs of farmers (D. Duvick, pers. comm.). In some cases geneflow can occur between introduced modern varieties and local landraces, leading to

the 'rustication' or 'criolloization' of the introduced varieties (Smale et al, 1991; Bellón and Brush, 1994; Louette et al, 1997; Wood and Lenné, 1997).

However, little of predictive scientific value is currently known about how farmers' selection practices affect local-level geneflow. Among the handful of studies known to the authors are those on Andean potato landraces (Zimmerer and Douches, 1991), cassava in Malawi (Box 5), maize in Mexico (J. Berthaud, pers. comm.), and pearl millet in West Africa (Box 6). Studies have also been done on poorer farmers' (or consumers') knowledge and perceptions of the usefulness of exotic cultivated germplasm or crop wild relatives in plant breeding (Louette et al, 1997; Wood and Lenné, 1997; Longley, 1999). A number of studies have been conducted on the extent and partitioning of genetic diversity between landraces (Spillane and Gepts, 2000). However, for reasons to do with the ease of sampling, the majority of such studies use accessions from genebanks, which have been separated from the farmers who may (or may not) have continued to manage both the landraces and the environments in which they evolved (e.g., Olufowote et al, 1997). Integrated approaches involving molecular analyses to facilitate understanding and enhancement of farmers' landraces were also presented at a 1997 Workshop on the Management of the Genetic Resources of the African Savannah, held in Bamako, Mali (Anon, 1993).

A cooperative of small-scale farmers in coastal Ecuador plans to develop a farmers' collection of cassava as part of a disaster relief project funded by the United States Agency for International Development (USAID) (see Box 10). This project will use molecular markers to characterize the collection's landraces, so as to support the identification of clones and match them correctly to associated traditional knowledge. From the few other studies of this kind conducted so far, it is evident that useful insights on farmers' germplasm conservation and enhancement strategies can be obtained (Zimmerer and Douches, 1991; Busso et al, 1998). A local-level study of the partitioning of genetic diversity in Andean potato landraces demonstrated high levels of geneflow between commercial landrace populations as a result of seed tuber exchange among farmers, but lower levels for types used solely for subsistence (Zimmerer and Douches, 1991). Molecular characterization of farmers' germplasm could help farmers' groups to monitor their situation and researchers to understand the farmers' methods, the better to target any future support (B. Visser, pers. comm.).

Molecular marker analyses have been used to analyze genetic change and inform decision making in a long-term French program for the dynamic in situ conservation and enhancement of wheat germplasm (Goldringer et al, 2000). This 'evolutionary breeding' program established a highly diverse meta-population of wheat with

Box 5

Molecular anthropology: Markers for understanding the spread of cyanogenic cassava

Cassava toxicity is a paradox. Few of the 500 million people who daily consume the crop are at risk from its toxicity. Tragic consequences tend to occur only in populations where severe deprivation, unvaried diet, social instability, and food insecurity all occur together. But due to its built-in pest protection and ability to provide food under difficult conditions, toxic cassava is crucial for survival in precisely these situations.

The biological bases of toxicity—precursor compounds of cyanide called cyanogens—are found in all cassava. Toxic cyanide is released when these cyanogens come into contact with an enzyme released by damaged cell walls when cassava is chewed or chopped. In cassava-dependent cultures, processing to remove cyanogens is typically women's principal activity. Processing is lengthy and labor-intensive, but if toxic cassava is eaten after rushed or inadequate processing, paralysis or death can result, especially if the consumer already has poor general nutrition.

In some of the world's most disadvantaged areas, particularly in sub-Saharan Africa, farmers deliberately grow toxic cassava as their basic staple. They explain their choice by describing this crop as more drought-tolerant, higher-yielding, superior in processing quality for traditional foods, and disease- and insect-resistant. Moreover, in these areas, the higher the toxicity of the varieties, the lower the risk of theft of plants from the fields of vulnerable female-headed households. Processing bulky cassava roots is a difficult operation to hide in a small community, and the perishability and bulkiness of the roots makes it difficult to carry away stolen roots to process them elsewhere. In a survival economy, where trade is not an option due to remoteness and civil unrest, these protective advantages may outweigh the accompanying disadvantages.

Appropriate biotechnology interventions may exist that could benefit women coping with such situations. But what they would be is not immediately obvious to outsiders. Possible objectives are to alleviate the toxicity risk, reduce the labor burden on women caused by processing, and promote marketing, while at the same time supporting local food security strategies.

With support from the Swedish International Development Agency (SIDA), researchers from the Swedish Agricultural University (SLU) of Uppsala, and the Ministries of Agriculture of Malawi and Tanzania are using sociological and molecular data to elucidate women farmers' objectives and processes in the use of toxic cassava. The practice of growing toxic cassava has apparently spread into Malawi and Tanzania from West and Central Africa, although 'sweet' (low-cyanogen) cassava is also grown by all farmers. The two countries are now among those most affected by the paradox between cyanogen toxicity and the essential role of cyanogens in food security. Cassava varieties are commonly renamed as they pass from farmer to farmer, so researchers working without molecular markers have been unable to assess and validate oral histories of the spread and value of toxic cassava. The better understanding of farmers' objectives achieved by the study will, it is hoped, form the basis for appropriate support to farmers' diversity management strategies, probably through farmer-led PPB.

SOURCES: H. Rosling (pers. comm.); Chiwona-Karltun et al (1997, 2000); Thro et al (1994).

Box 6

Molecular markers throw light on farmers' selections of pearl millet landraces in West Africa

A molecular marker study of farmers' landraces of pearl millet in West Africa revealed that the crop management practices of neighboring farmers led to the selection of different genotypes of the same named landrace, and similar genotypes of different-named landraces.

Eight samples were collected of each of four landraces of pearl millet. The four landraces were identified by name by the local farmers and were visually distinct. Samples were from the fields of four different farmers in two villages in Ghana; no field was less than 200 meters away from any other.

Molecular analysis showed that, while the phenotypic characteristics which identified a landrace were maintained across farmers, the genetic profiles of two different landraces grown by the same farmer were more similar than those of the same landrace grown by two different farmers. Farmers' conscious or subconscious selection practices were shaping genetic diversity at the farm level. While holding a few major genes constant, they were selecting for specific phenotypic traits that indicated adaptation to their own fields or micro-sites.

This study has important implications for the maintenance of on-farm genetic diversity and also for on-farm crop improvement. It suggests that, in addition to the names of landraces, the names of farmers, farmers' evaluation of the variety, dates of sampling, and eco-geographic details are equally important for the purposes of germplasm identification and genebank records. It also suggests that diversity, at least in these areas of Ghana, is better represented by samples from each farmer than by samples of each 'variety'. In the case of a disaster, if materials had to be re-supplied to an area, researchers would know that the name of the variety a farmer grew before might not be enough information to get locally adapted seed back into that farmer's field, since a variety with a different name could conceivably be closer to the original genotype.

SOURCE: Busso et al (1998).

subsequent management of the population in many different environments under natural or weak selection pressures (Goldringer et al, 2000). Molecular marker analyses allowed adaptive changes in pathogen resistance and multilocus diversity to be tracked across populations and over time. In addition, outcrossing rates were determined in order to assess the optimal levels of geneflow that might be promoted between different sub-populations. Although no individual farmer selection pressures were applied to the populations, the program's approach and findings are similar to those of the study on local-level geneflow in maize conducted by Louette et al (1997). Goldringer et al (2000) suggest that their evolutionary breeding model may be suitable for PPB where uniformity of the materials produced is not required.

The choice of a cost-effective molecular marker technique depends on program objectives (Karp et al, 1997). Some techniques (e.g., isozymes, RAPDs) are simpler to use, while others are more difficult but also more accurate or sensitive (e.g., AFLPs, microsatellites, SCARs, etc.). Where there is sufficient polymorphism, isozyme analysis may yield enough information to be the technology of choice. For instance, 12 isozyme systems allowed the differentiation of 95% of cultivated clones of *Hevea* (Leconte et al, 1994). A 'portable laboratory' based on these enzymes has been developed, allowing nursery fingerprinting of high-yielding clones used in industrial plantations. For other species or objectives, other DNA markers may be required to achieve sufficient resolving power. Most PPB programs would need the assistance of an advanced biotechnology laboratory to conduct DNA analysis of germplasm. Many such laboratories may be interested in the analysis of selection by farmers (e.g., Busso et al, 1998).

The advent of DNA chip, micro-array, and nanomachine technology is likely to increase the throughput of molecular marker and DNA analyses in the coming years, by increasing the speed and lowering the cost of processing large numbers of samples (e.g., Walter et al, 2002; Gibson, 2000; Chee et al, 1996). This could open the way to simpler evaluation of gene frequencies in a single mixture of DNA representing a population, greatly facilitating the spatial and temporal monitoring of the molecular events underlying either dynamic conservation or PPB efforts (Second et al, 1997). It should be possible to bulk many plants in samples for analysis and so to obtain information on many loci in one or a few high-throughput experiments. However, such technologies are still well beyond the reach of most biotechnology researchers, many of whom are competing to conduct the initial experiments on the first-generation DNA chips currently under development.

Understanding the dynamics of farmer-directed genetic change, especially among resource-poor farmers, may not rank high compared to other research objectives. To the authors' knowledge, no farmers' groups have spontaneously chosen the understanding of genetic variation and gene-flow processes in their material as a priority research objective. Paradoxically, therefore, such research—although conducted at the field level—may be as 'upstream' as many laboratory projects, in the sense that it is not perceived as providing short-run benefits by its end users. However, farmers have a keen sense of urgency regarding varietal improvement and have in many cases requested outside intervention in support of this. D. Duvick (pers. comm.) notes that studies of population dynamics of farmers' varieties can become over-academic because of the fascinating data they generate for specialists. It is at this point that they run the greatest danger of losing practical relevance for farmers. He suggests that all such studies should be guided by the question, Are molecular marker-assisted methods the most efficient way of helping farmers get the germplasm they want?

Tools for Selecting Germplasm

Relating farmers' criteria to researchers' tools

Farmers may use very different selection criteria from formal breeders and biotechnologists to evaluate germplasm. The fact that some modern crop varieties are not adopted is a clear indication of the gap. Indeed, the very concept of 'adoption' implies that formal breeders and biotechnologists need to improve their understanding of what farmers mean by a 'preferred variety' (M. Fregene, pers. comm.). If different social groups of farmers (i.e., disaggregated by sex, income, ethnicity, age, etc.) have different preferences, then breeders need to understand these as well (K. Schmidt, P. Eyzaguirre, pers. comms.).

Some say that farmers are biased towards selecting traits that are easy to distinguish visually in a parental or progeny plant (Wood and Lenné, 1997). Such selection has, for example, led to extreme phenotypic diversity in the color of bean seeds and maize kernels. These 'peacock' traits may be either qualitative or quantitative. Conversely, it is difficult for farmers to select for traits that are not easy to see, such as resistance to sheath blight in rice. Farmers are probably aware of desirable quantitative traits (e.g., high yield) which are difficult to control and retain between generations. However, they are unlikely to be interested in subjecting their crops to major losses in order to select for phenotypic traits whose evaluation requires destructive testing, such as pest and disease resistance.

The extent to which farmers can visualize or 'perceive' different traits will have a bearing on their success in selecting for individual traits. While it may seem obvious that farmers interpret the look and performance of a plant as desirable or undesirable for certain traits, it is not obvious how they do this and how they use this information in their selection efforts. Very little is known about how the phenotypic descriptors that farmers use for selection correlate with those used by plant breeders or genebank curators. For instance, there is little information on how farmers perceive the phenotypic trait markers used in conventional genetic linkage maps (e.g., Kinoshita, 1995) or on how they characterize germplasm accessions. Detailed farmer participatory research work has, however, been done on the definition of Brazilian farmers' selection criteria in cassava (C. Iglesias, L.A. Hernández, W. Fukuda, pers. comms.; Iglesias and Hernández-Romero, 1997). The objectives of identifying farmers' descriptors and definitions were to enable farmers and formal breeders to 'speak the same language' and, when possible, to 'translate' farmers' descriptors so that a given descriptor (or a highly correlated trait) can be measured and quantified in order to study inheritance and design effective breeding strategies. Integrated multidisciplinary approaches involving crop geneticists, anthropologists, agronomists, and socio-economists are likely to be valuable in gaining a better understanding of farmers' selection criteria.

Without new selection tools and techniques for farmers, interaction between farmers and researchers to improve the efficiency of trait selection will, then, tend to be limited to traits that farmers can easily 'visualize' or 'perceive' through non-destructive evaluation, such as heading date, plant height, seed weight, and so on. But if simple diagnostic tools that increase throughput can be developed for use by farmers as well as formal-sector breeders, this would widen the variety of traits that could be evaluated. For instance, where farmers have to meet exacting food safety standards, diagnostic tools for detecting undesirable compounds, such as aflatoxin in groundnut, could be useful. These and other tools can help resource-poor farmers create a surplus of uniform, high-quality produce, enabling them to enter new markets (Box 7).

Similarly, the use of MAS is likely to be most powerful when it is integrated with social and agronomic studies of the phenotypic criteria used by farmers. The advent of molecular and linkage maps may allow collaborative participatory selection efforts that complement or integrate farmers' 'visible' criteria with the invisible ones that are also important for many traits.

Box 7

Biotechnologies that help small-scale farmers enter new markets

Many resource-poor farmers have inadequate access to markets for their produce, especially the more lucrative markets. The barriers to entry into such markets often include product quality and uniformity standards.

Quality standards tend to be highly specific, requiring measurement (e.g., minimum levels of a given vitamin, freedom from insect damage, a specific dry matter, starch, or protein content). Some biotechnologies can help farmers meet these standards. For instance, diagnostic kits can allow farmers to test for levels of desirable and undesirable compounds, such as starch or aflatoxins. Several modern biotechnologies can help farmers or farmers' groups involved in seed multiplication and dissemination improve the quality of their seed (Cromwell et al, 1993). The application of simple diagnostic tests for seed-transmitted diseases can allow farmers' groups to sell disease-free seed at a premium. Using tissue culture, farmers can generate large amounts of disease-free planting materials, especially in vegetatively propagated crops.

As regards uniformity standards, double haploid lines of landraces could allow phenotypically uniform varieties to be developed and maintained by farmers. Transgenic approaches to the reduction of levels of undesirable compounds may also be possible. Pioneer Hi Bred has developed the use of genetic modification to reduce mycotoxin contamination of foods by incorporating fumonisin-metabolizing transgenes into the plant's genome.

SOURCE: J. Duvick (pers. comm.).

So far there has been little exploration of whether farmers' 'descriptors' can be integrated with germplasm descriptors or with existing linkage maps as a starting point for enhancing farmer-researcher collaboration in plant breeding. Only researchers with a detailed knowledge of farmers' selection criteria and practices are likely to be able to relate these to criteria usable by formal breeders or biotechnologists, and vice-versa. If farmers' selection criteria change over time or vary from place to place, then these relationships, and the process of establishing them, may become complex. Nonetheless, as MAS enters the genomics and phenomics era, it is vital that this task be addressed.

Marker-assisted selection

Conventional plant breeding has typically used phenotypic observations, sometimes backed by sophisticated statistical analysis, to select for improved germplasm in breeding populations. Although this approach is still valid, there are limitations to what can be achieved by phenotypic selection alone. Some agronomically useful traits are either very difficult to select for (and maintain) on the basis of phenotype, or cannot be selected for on this basis alone (e.g., yield). These traits show continuous phenotypic variation because they are controlled by several genes, the individual effects of which are relatively small (Yano and Sasaki, 1997). This has made breeding for such traits difficult.

The use of molecular markers and genetic maps to select for genes rather than for phenotype could, in theory, overcome many of the limitations of conventional breeding (Caetano-Anollés and Trigiano, 1997). These tools are already revolutionizing breeding through the identification of the quantitative trait loci (QTLs), the relatively large segments of DNA that underlie many key agronomic traits (Smith and Beavis, 1996; Yano and Sasaki, 1997; McCouch et al, 1997). A wide range of markers and maps are now available (Caetano-Anollés and Trigiano, 1997; Xiao et al, 1998; Ayres et al, 1997; Blair and McCouch, 1997). In addition, molecular maps are being integrated with linkage maps based on observable phenotypes (Yoshimura et al, 1997). This will allow phenotypic selection to be complemented by MAS for traits of interest. This approach could prove cost-effective in PPB programs using phenotypic selection for traits not easily selected for on this basis alone.

Some field-level practitioners find that farmers are at a disadvantage when attempting to identify and select effectively for useful genes found at low frequency in populations, particularly when the associated traits are hidden (J. Lenné, pers. comm.). By identifying and mapping molecular markers, formal breeders and biotechnologists can help select such genes.

Finding the loci of these traits in one crop provides guidance to where they might be in other related crop species (e.g., Kowalski et al,

1994; Lin et al, 1995; Ming et al, 1998). The close functional and evolutionary relationships between many resistance genes is making it easier to search for them in germplasm collections (e.g., Leister et al, 1996).

A crucial question is whether individual molecular markers can be 'translated' into visual markers or other easily selectable markers, allowing MAS to be applied at field level by formal breeders or farmers. For instance, a single gene that provides a visible morphological marker such as red pigment color (i.e., a more penetrant version of the currently available anthocyanin Lc marker) could conceivably be linked as a reporter, via transgenic techniques (T-DNA tagging) and/or molecular marker-assisted backcrossing, to a major allele for a hard-to-see trait such as drought tolerance or resistance to a cyclic pest. This could be particularly useful in open-pollinated populations. Even in a year when the stress is absent, the red pigment from the marker would help the farmer identify stress-tolerant plants and save enough seed from them to maintain the trait in the population at a level sufficient to stabilize year-to-year performance. However, while reporter genes such as the GUS and GFP are routinely used to great effect in laboratory research, very few such genes are yet available for use at field level.

If markers can be linked to major agronomic alleles, the allele itself does necessarily have to be visually selectable. Use of selectable markers (such as herbicide resistance genes) could allow farmers to select for the allele. However, at least at the current level of technology development it is questionable whether the cost of such an approach would be justified by the benefits (M. Gale, pers. comm.).

Developing molecular markers for QTLs is important in improving selection for phenotypic traits. QTL analysis looks at the underlying genetic basis of such traits (Ribaut and Hoisington, 1998). Consequently, there is likely to be room for considerable interaction between researchers and farmers, who will need both to identify desirable traits and to test germplasm enhanced by this means. Some commentators believe that, in breeding for quantitative traits, farmer participatory selection, either among finished varieties or within segregating populations, could replace MAS, since both end up with the same thing—a product in which you can 'see' or otherwise experience the desired results. However, this seems unlikely, since quantitative traits have traditionally been difficult for breeders to select for on the basis of phenotype, even with the support of complex biometrical and genetic analyses. The reality may lie somewhere in between, with farmer selection criteria proving a useful complementary source of information for DNA marker-based selection, and vice-versa.

The development of suitable populations for mapping, as a prelude to the development of markers, is best done through collaboration between

farmers and locally based plant breeders (S. Hughes, pers. comm.), with regional or international inputs where necessary. Fregene (pers. comm.) suggests that a team of breeders, molecular geneticists, and farmers could handle perhaps four breeding populations at a time.

In the near term, molecular markers might facilitate PPB through the generation of trait-enriched populations at an early stage of the selection process. Molecular markers can be used to increase the frequency of certain traits, such as QTLs for drought tolerance (Ribaut et al, 1996, 1997), or of desirable individuals in an otherwise variable population, creating an 'enriched' population for further selection by farmers (S. Beebe, pers. comm.). MAS can enhance total genetic gain and the choices available to farmers for difficult-to-select traits, particularly tolerance or resistance to biotic or abiotic stresses that may require special stress environments to be fully expressed, and traits that require slow and/or costly sampling methods, such as cooking quality or photosynthetic rate (M. Lee, 1998).

For crops in which molecular mapping is at an advanced stage, where the underlying genetics of important agronomic traits are becoming increasingly clear, it may be possible to develop sets of markers that could act as 'sieves' to enrich germplasm populations for linked agronomic traits. The use of these molecular sieves would help reduce breeding populations to a manageable level (M. Fregene, pers. comm.). The chances of a farmer creating desirable material by crossing two interesting parents would be increased, since the amount of 'junk' or apparently useless diversity (M. Loevinsohn, pers. comm.) would have been reduced by 10 times or more (S. Beebe, pers. comm.). This could, it is thought, change farmers' perceptions of the costs and benefits of becoming involved in early generation selection efforts in PPB. As Witcombe et al (1996) found in the Chitwan Valley of Nepal, farmers' lack of interest in selecting for early segregating populations is a barrier to their participation in the early stages of crop improvement. In such situations they find themselves being asked to deal with too wide a range of prototypes of too low a quality.

Farmers participating in research want to see results fast (B. Visser, pers. comm.) and often express a sense of urgency (e.g., Thro et al, 1997). The use of MAS requires additional time early in the research process, when the markers are first developed (this takes 2 to 4 years, depending on the complexity of the trait and previous knowledge). This time-lag is 'anathema' to many farmers involved in participatory research (J.K. Lynam, pers. comm.). Yet one of the main attractions of biotechnology to conventional breeders is that, once the tool development stage is over, it can greatly speed up the breeding cycle. As more markers become available over time as a result of genome mapping and sequencing efforts, the 'tool development' time-lag is likely to shorten.

In addition, discoveries made in comparative mapping have shown that markers from closely related (e.g., rice and wheat) or even distantly related (e.g., dicot and monocot) species can be successfully used across species (Paterson et al, 1996). This has greatly increased the diversity and genome coverage of the markers now available, reducing both their costs and the time required to apply them. Costs will probably continue to decrease as molecular marker assays become cheaper per unit of information gained (Xie and Xu, 1998). In the longer term, technology spillovers from human genetics (notably the human genome project) should further increase the potential of DNA technology for crop improvement, leading to even more favorable cost:benefit ratios. However, this depends on sufficient public-sector funding being made available for technology adaptation and dissemination (Smith and Beavis, 1996).

DFID's Plant Sciences Research Programme is establishing a project in the semi-arid regions of India and Nepal that will combine PPB with the use of molecular marker techniques in rice (J.R. Witcombe, pers. comm.). The project will evaluate the participatory approach, which will be applied to a range of crosses mostly involving the popular variety Kalinga III as one parent. The end products from the crosses will be tested using molecular markers to identify linkage blocks representing genomic regions preferred by farmers or producing the best results in specific environments. Progeny from a wide cross between the Asian and African rice species *Oryza sativa* and *O. glaberrima* will also be evaluated, so that useful genomic regions of *O. glaberrima* can be introgressed into the *sativa* varieties preferred by farmers. QTLs for root growth and drought resistance are being introduced into Kalinga III through MAS. The results of this project should shed more light on the usefulness of molecular markers in PPB projects.

Optimizing local genotype x environment interactions

Some PPB programs promote the use of a decentralized farmer selection-based approach to the development of germplasm specifically adapted to different micro-environments (Ceccarelli and Grando, 1996; Ceccarelli et al, 1991, 1994; Simmonds, 1991). These practitioners believe that selection for specific adaptation to local conditions will result in varieties that require reduced levels of inputs and are more robust in the stress-prone environments typically used by resource-poor farmers. This reflects a long-standing debate among plant breeders as to whether or not high genotype x environment interactions can be usefully exploited to develop germplasm adaptation to marginal or heterogeneous environments (Gauch and Zobel, 1997). The specific adaptation approach is considered by some to stand in opposition to the centralized development of varieties exhibiting broad adaptation to a wide range of environments (Ceccarelli, 1989; Link et al, 1996). For cost-benefit reasons, most centralized breeding has successfully concentrated on developing varieties adapted to large geographic areas.

Many widely adapted varieties have been bred to exhibit low G x E interactions for agronomic traits and are very successful in homogeneous high-potential environments in which fertilizers and irrigation are used. It has, however, been suggested that the success of widely adapted commercially bred varieties is due less to the inputs they receive than to the amount of breeding and testing invested in their development (D. Duvick, pers. comm.). Some widely adapted varieties have been developed for small-scale farmers' conditions, where they perform well despite the absence of buffering inputs. Experience with rice breeding in South America suggests that rice varieties bred for wide geographic adaptation are used by resource-poor farmers because these varieties adapt as well to the extremes occurring under farmers' management regimes as they do to the variability found across geographical locations. For example, the varieties yield well even when sown too late because of competing requirements for labor (L. Sanint, pers. comm.)

One of the problems in breeding for stressful and unpredictable environments is the reduced heritability of complex traits such as yield in such environments (Ceccarelli et al, 1991). MAS has become a factor in the high versus low G x E debate (Kang, 1990). It now allows breeders to distinguish between low QTL x E and high QTL x E loci, QTL x E being analogous to G x E interactions (Hoisington et al, 1996; Fry et al, 1998; Stratton, 1998; Paterson et al, 1991; Stuber et al, 1992; Melchinger et al, 1998; Yan et al, 1998). The majority of work with QTLs is likely to concentrate on low QTL x E effects. However, a PPB project seeking to exploit high G x E effects for adaptation to a specific environment could assemble germplasm containing QTLs exhibiting high G x E effects from existing MAS efforts and test them.

Some formal breeders feel that, as recent advances in MAS methods allow traditional plant breeding objectives to be met more efficiently, resources should become available for pursuing other goals that were previously considered too costly—including, perhaps, location-specific breeding (L. Sanint, M. Gale, K. Schmidt, pers. comms.). Strategic research to create the necessary biotechnology applications could improve the cost:benefit ratio of plant breeding targetted to the location-specific needs of resource-poor farmers in developing countries. In addition, geographical information systems (GIS) could be used to search for similar micro-environments that might form part of the 'adaptation domains' of varieties bred for local adaptation (G. LeClerg, pers. comm.), enabling the results of location-specific PPB to be scaled up.

Providing 'baskets' of easily identified varietal options

As we have already seen, where farmers are operating in heterogeneous, risk-prone, marginal environments, a single crop

variety (or technology) is unlikely to meet all their needs (Chambers, 1983). In the past decade there has been a shift in research and extension practices towards providing a 'basket' of options from which such farmers can choose according to their needs (Witcombe et al, 1996, 1998, 1999; Ashby and Sperling, 1994).

The reproductive processes of germination, vegetative growth, flowering, and seed maturation are vital to resource-poor farmers. Many minimize their risks by planting different varieties or crops which mature at different times of the year, ensuring a steady supply of food (Gilbert, 1995). Farmers can be offered varieties with a mix of maturation periods and alternative storage and processing characteristics. Intensive research is currently being conducted on the genetics of flowering time (Laurie, 1997). Biotechnology could be used to expand the range of varietal maturity options.

MAS can help breeders transfer the loci associated with maturity into otherwise desirable genetic backgrounds with minimal alteration in other varietal characteristics (W. Beversdorf, pers. comm.). More genes and loci controlling flowering time will doubtless be identified over the next decade, and knowledge generated on how they operate and interact. Other possibilities include the linkage of flowering time genes to promoters so that flowering can be induced, shortening generation times. This will be especially useful in the early stages of breeding programs, when rapid progress needs to be made and demonstrated, and wherever there is a need to avoid continuing or imminent stresses (Laurie, 1997).

The relationship between flowering time (heading date), crop adaptation, and yield is critical. Clawson (1985) pointed out that tropical farmers often use different colored varieties, which are associated with different maturation periods. He concluded that farmers' adoption of modern varieties would accelerate if they were offered multiple high-yielding varieties of staple food crops of varying seed color and maturation periods.

At any rate, farmers may be unwilling to adopt any of the new options they are presented with unless they can easily distinguish them visually (S. Morin, K. Longley, pers. comms.). A considerable amount of work on human cognition and the relationships between classification, cultivation, and selection has recently been done. The model of 'selection for perceptual distinctiveness' developed by Boster (1985) suggests that, if farmers cannot distinguish between varieties, they will not be maintained in local farming systems. At present, the Boster model applies mainly to root crops that reproduce vegetatively and is less relevant to out-breeding grain crops.

Similarly, improved rice varieties developed through conventional crop breeding often have very similar phenotypic characteristics,

making it difficult for farmers to distinguish between them (S. Morin, K. Longley, pers. comms.). Many of these varieties display excellent qualities and in theory offer farmers a much wider choice. But this choice may not be exercised in practice if the varieties are not phenotypically distinct. Work is under way to adapt the Boster model to rice (Longley, 2000).

Molecular markers can be used to maintain or increase genetic diversity at a locus or range of loci that are neutral for agronomic traits, while selecting for such traits at other non-neutral loci (Ribaut and Betran, 1999). This approach could be used to maintain allelic series or a range of non-agronomic visual phenotypes (e.g., flower color, seed color) during the early stages of a breeding program, so as to increase the likelihood that the final products will be phenotypically distinct.

Farmer-friendly specialized collections?

The provision of a range of existing varieties to interested farmers is an important function for genebanks (FAO, 1996). The practical difficulty of screening large numbers of germplasm accessions will be felt just as acutely by farmers as by formal plant breeders, or even more so. To make screening cheaper and easier, many genebanks have established core collections, designed to represent a crop's maximum genetic diversity through the minimum possible number of accessions (Hodgkin et al, 1995). At least 63 different core collections of 51 crops have been established worldwide (Spillane et al, 1999). Plant breeders and biotechnologists have, in addition, developed specialized experimental collections, such as near-isogenic lines and special genetic stocks, to facilitate their research.

There has been little systematic thinking about how these specialized collections might be adapted to meet the needs of PPB. Several end-user oriented variations on the concept of specialized collections have been proposed, but not yet tested (e.g., van Hintum, 1999). Van Hintum et al (2000) have developed an on-line selector which allows users to define their own collection (see www.cpro.dlo.nl/cgn/corecoll/usercore.htm).

Alternatively, after farmers have defined their criteria, breeders could search germplasm collections for corresponding genotypes and assemble them into source populations for farmer breeders. For example, the collection of cassava clones being developed by a cooperative of small-scale farmers in coastal Ecuador (see Box 10) will, at the farmers' request, include material from CIAT breeding populations. These materials are being selected by a CIAT breeder according to criteria specified by the farmers, which include high yield, drought tolerance, and good processing quality. GIS are an additional tool that can be used to support the assembly of sets of accessions adapted to specific environmental variables (D. Wood, pers. comm.).

Tools for Promoting Recombination

Commentators vary in their views on the optimal amount of recombination, or mutability in its largest sense, that should be included in PPB. Some feel that methods derived in the laboratory may not be superior to evolutionary processes in the field (J. Jiggins, pers. comm.). Others, however, such as Simmonds (1979), have felt that the limitations to recombination have been one of the major constraints to selection efforts by both formal and informal breeders.

Creating endogenous genetic variation

Farmer-led PPB is likely to face constraints in accessing and/or managing new genetic variation from outside the farming system. The fact that formal breeders have made considerable progress using endogenous genetic variation—variation available in limited or closed breeding populations—alone may be highly significant for farmer-led efforts (Leng, 1974; Wych and Rasmussen, 1983; Hallauer, 1986; Mac Key, 1986; Dudley and Lambert, 1992; Manninen and Nissila, 1997; Rasmussen and Phillips, 1997).

Chemical treatment or nuclear irradiation have been used to induce mutations for the purposes of crop improvement (FAO/IAEA, 1986). Commonly used mutagenic chemicals like EMS introduce point mutations, while X-ray irradiation leads to gross chromosomal changes. Because these techniques do not distinguish between human and plant DNA, highly controlled experimental conditions are required to protect users. For this and several other reasons, these methods could not easily be used by farmers.

Another mechanism for inducing mutagenesis is transposition (Wessler, 1988; Peterson, 1993). This relies on transposons, which are naturally occurring genetic elements (i.e., pieces of DNA) that move around the genome of most plant species. Transposons generate new genetic variation as they move. The rate at which different transposons move through particular genomes varies widely, and with it the rate at which variation occurs (Levy and Walbot, 1990). A recent study of maize demonstrated the importance of transposition in generating genetic variation (Fischer et al, 1995).

The advent of increasingly sophisticated and controllable transposon mutagenesis techniques has already revolutionized plant molecular biology research (Sundaresan, 1996; Izawa et al, 1997). In some plant species (e.g., *Arabidopsis*, maize, and rice), these techniques are now being used as experimental tools by biotechnologists, primarily to identify genes and/or phenotypes through insertional mutagenesis (Sundaresan, 1996; Izawa et al, 1997). They are proving more accurate and potentially useful than previous mutagenesis approaches. In theory, they could eventually be used to help farmers generate, augment

or 'release' useful variation within local germplasm (R. Jefferson, pers. comm.).

Transposon mutagenesis techniques can generate alleles associated with a gain or a loss of function for many phenotypic traits and have been primarily used to date in the identification of the loci associated with specific traits. At present a research group in Wageningen is using these techniques to over-express, mis-express or ectopically express candidate transgenes at different locations in the genome in order to generate new phenotypes (A. Pereira, pers. comm.). While most available transposon techniques are suitable only for laboratory-based line selection and screening, the techniques currently under development will enable selection and screening to be done in experimental fields. It is likely that field-level techniques such as promoter perturbation, gene knockouts, or activation tagging could be developed or adapted for use to generate genetic variation for PPB and PVS programs.

Some commentators feel that 'random' mutagenesis approaches of this kind will not be useful to farmer-breeders because they will generate more 'junk' variation than farmers can handle (D. Duvick, pers. comm.). They suggest that some pre-screening for desirable phenotypes would have to be done by formal researchers before farmers would be interested. The potential of transposon systems for generating genetic gain could probably be empirically tested against conventional breeding techniques. However, biosafety regulations make it unlikely that farmers will be allowed to experiment at field level with transgenic transposon mutagenesis techniques.

Controlling recombination rates

Another way of increasing endogenous genetic variation is through optimizing the process of recombination. This issue is considered by some to have been neglected in plant breeding compared to the techniques of selection and isolation (Simmonds, 1979). Recognizing that a high degree of genetic variability is required for major evolutionary advances, Stebbins (1959) argued that, when endogenous mutation rates are low, genetic recombination is the most likely source of such variability and that recombination-generated diversity could be maximized by hybridization between populations with different adaptive norms. Recombination within the sequence of a single gene and epistastic effects—the effects of one gene on another—have been identified as a potentially important source of new genetic variability in the development of elite germplasm (Schnable et al, 1998; Rasmussen and Phillips, 1997). For instance, the generation of new specificities through unequal crossing-over within complex resistance genes during recombination has been demonstrated, to date mainly in model systems such as the *Zea mays-Puccinia sorghi* interaction (Pryor and Ellis, 1993).

The level of recombination in farmer-led PPB is likely to be far from optimal for the purposes of generating endogenous genetic variation. Increasing it could help (Hanson, 1959a, 1959b; Rieseberg et al, 1996), but not always to the same degree. Crop plant genomes differ in their 'permeability' as regards the introgression of different genes or chromosomal regions, whether by wide-cross recombination with wild relatives or when crossed with other domesticates in the primary genepool (e.g., Rieseberg et al, 1996).

Mating strategies have a significant effect on recombination rates. They may be important for genetic enhancement or pre-breeding, especially where the resources to conduct marker-assisted introgression are not available (Tanksley et al, 1989). Improving farmers' mating strategies could prove cost-effective in PPB programs, (Spillane and Gepts, 2000).

Molecular mapping efforts are likely to increase knowledge of the genomics of recombination rates, both within and between crop genepools. The existence of genes that influence crossability in many species indicates that the presence or absence of these genes in farmers' populations may affect recombination rates as well as inter-specific hybridization (e.g., Luo et al, 1996). For instance, the genes kr1, kr2, kr3, and kr4 found in wheat cultivars such as Chinese Spring (and in some Chinese landraces) are known to facilitate crossability with species of other genera (Luo et al, 1996; Jiang et al, 1994).

Efforts are now under way to isolate the genes that promote or impede recombination (Moore, 1998). Once this is done, it may be possible to develop 'gene cassettes', in which these genes are controlled by inducible promoters. These cassettes would be used to generate experimental lines for use by farmers or formal breeders. Crossed into breeding populations, they would either enhance recombination or reduce it, to protect favorable gene combinations from rearrangement. Such approaches may give farmer-led PPB greater control over recombination rates within their populations.

Inducible apomixis

Apomixis is a naturally occurring phenomenon whereby some plant species produce true seeds without fertilization and recombination. It has been described in over 400 different plant species, only a few of which are crops. The harnessing of apomixis genetics for plant breeding may make it possible to develop true-breeding hybrids which retain their yield advantages over generations, making it unnecessary for farmers to buy new seed each year. In contrast to gene-based enhancements, the provision of an apomictic trait could permit new strategies based on the control of recombination in conventional breeding and selection. There have been significant advances in recent

years towards the goal of harnessing apomixis in a number of crop plants (Grossniklaus et al, 1998). However, a considerable amount of further research will probably be necessary to develop the technology for widespread use in breeding (Jefferson, 1994; D. Wood, pers. comm.).

The development of apomictic varieties will require the use of inducible promotors that can be switched on and off (Jefferson, 1994). Retaining the ability to switch back to a sexual phase of recombination will be necessary to permit the incorporation of new genes into the apomictic background. The genetic engineering of apomixis should make it possible to develop an inducible apomictic gene cassette, perhaps one that is independent of crop species.

Many commentators feel that the development of inducible apomixis could have a profound effect on PPB (Jefferson, 1994; P. Richards, T. Hodgkin, D. Wood, pers. comms.). Inducible apomixis-based plant breeding could be done on a modest scale at regional or local level, mainly by farmers' groups. Access to inducible apomixis through PPB would allow farmers to screen, select, and enhance germplasm much more efficiently and productively, with minimal outside intervention. One commentator suggested that, until inducible apomixis is fully developed, PPB projects involving clonally propagated crops with a sexual cycle could be used to provide insights into farmers' interest in the technology and the likelihood of widespread adoption (P. Richards, pers. comm.).

The authors of the 1998 Bellagio Apomixis Declaration expect easy-to-use apomixis to permit:

- New breeding procedures and strategies based on individual plants (existing methods are based on the synthesis of observations of entire plant families). An exceptional individual plant could immediately become a variety
- Immediate genetic fixation of any desired plant individual, including those generated by wide crossing two different species, which are often sterile at present. This could expand the accessibility and use of a wider diversity of genetic resources
- Fast and flexible plant breeding. Commentators have emphasized the advantages of apomixis for responding to changing micro-environments, cropping conditions, pathogen populations, and market opportunities. It is also felt that apomixis could promote more sustainable agro-ecosystem management (Jefferson, 1994)
- Development of hybrid cultivars in almost every crop species. Farmers sowing seed harvested from F_1 hybrids would experience minimal decrease in yield. The authors of the Bellagio Declaration and other commentators (e.g., A. Ebert, pers. comm.) feel that this will greatly increase resource-poor farmers' access to the yield benefits of heterosis, without changing traditional seed saving

practices. Farmers will still be able to select the best seed for the next cycle. As hybrid varieties are adopted by increasing numbers of farmers, large gains in crop production could be achieved

- Propagation by true seed of crops that are currently vegetatively propagated, such as cassava, potato, sweet potato, and yams, with concomitant reduction of the diseases transmitted during vegetative propagation
- Reduction of the micropropagation costs of horticultural crops, trees, and flowers. In some cases, apomictic seed could replace the need for cuttings and other forms of vegetative propagation
- Protection from horizontal transfer of transgenic characters into neighboring populations, through the introduction of apomixis into male-sterile varieties.

Some commentators warn of possible unwanted side-effects. If farmers using landraces turn to apomictic hybrids that maintain their yield advantage down the generations, they could become dependent on external sources to provide improved genotypes, just as they are when they adopt conventional improved varieties (Smale, 1997; S. Smith, R. Riley, D. Duvick, pers. comms.). There is a risk of loss of diversity and genetic stagnation (D. Duvick, pers. comm.). However, traditional landraces would not always be displaced; in many traditional farming systems, modern varieties and landraces are maintained together (e.g., Bellón, 1991; Brush, 1995; Smale and Heisey, 1995; Wood and Lenné, 1997). A number of seed industry commentators have expressed concern that the widespread use of apomictic varieties might lead to reduced investment in public- or private-sector formal breeding, including activities to source new germplasm and create new diversity. If this were to occur, then genetic progress would plateau, leading to stagnant yields, declining genetic diversity, and, over time, higher risk of crop failure caused by diseases and insects (S. Smith, R. Riley, pers. comms.).

The value of apomixis technology in the long term would depend greatly on what farmers (and their formal-sector partners) did with it, which in turn would depend on whether they find it easier to create improved apomictic hybrids than to use existing methods to improve pure lines or open-pollinated varieties, and on the extent to which they continue to access varieties from outside their farming systems (D. Duvick, pers. comm.).

Controllable male-sterility systems

Male sterility is a useful trait for promoting cross-pollination and recombination. It is also widely used in the production of F_1 hybrid seeds. However, male-sterile lines are not yet available for all crops. And there may be problems associated with its use in some crops, such as the lack of suitable restorer lines or the vulnerability to disease of genetically uniform cytoplasm in the progeny.

While nuclear male-sterile (NMS) mutants have been observed in many plant species (Kaul, 1988), the lack of homozygous breeding lines has precluded their use in hybrid seed production (Williams, 1995). Regardless of whether the NMS gene is dominant or recessive, at most 50% of the progeny of any cross will be male-sterile (Rao et al, 1998). The problem then arises of how to eliminate the 50% non-male sterile progeny. Simple and elegant genetic engineering technologies have been developed to overcome this problem, allowing 100% male-sterile progeny to be produced (Mariani et al, 1991). These technologies also incorporate the fertility restoration necessary for the production of F_1 hybrids. A number of potentially useful transgenic technologies in which male sterility can be induced in any crop species have now been developed (e.g., Yistra et al, 1994; Mariani et al, 1990). Early transgenic technologies had the disadvantage of requiring two lines for fertility restoration. Transgenic one-line male sterility technologies have now been developed, in which conditional male sterility can be induced by applying a non-toxic chemical (e.g., Kriete et al, 1996).

No male-sterility technologies appropriate for the production of F_1 hybrid seeds solely by farmers have yet been adopted by them, even if they have been developed (M. Gale, pers. comm.). However, single transgene-conditional male- or female-sterility technologies could be of use in some PPB applications, if directional cross-pollination is desirable but is not easy to achieve with existing germplasm. Bidinger et al (1994) have demonstrated that heterosis can be used to improve pearl millet landraces without any major loss in adaptation, by top-crossing locally adapted landraces with high-yielding male-sterile lines.

Coupled with emerging developments in field-level inducible promoters, advances in transgenic male- and female-sterility technologies suggest that simpler systems for the generation of hybrid seed could be developed. Current approaches to F_1 hybrid seed production are based on the strip-planting of female and male (pollen donor) inbred lines, which are then crossed. The female lines are emasculated by hand or chemically by spraying. The use of field-level inducible promoters linked to transgenes which promote male sterility (in the female inbred line) or female sterility (in the male inbred line) could allow breeders to plant a mixture of female- and male-sterile plants, induce sterility, and harvest the entire plot for hybrid seed. Such approaches could conceivably be used to facilitate heterosis breeding by farmers.

Tools for Enhancing Germplasm

Many farmers need germplasm containing variation that is unavailable to them in locally available germplasm, whether landraces or modern varieties (Wood and Lenné, 1997). Locally adapted varieties that are otherwise excellent may lack useful traits following genetic erosion

caused by events such as war or natural disasters (so-called 'bottlenecking events', see Boxes 10 and 11), as a result of genetic drift or simply because the traits are not found in that crop. In environments subject to extreme fluctuation, such as drylands that are marginal for cropping, some landraces may have a narrow genetic base due to past bottlenecking events (Spillane and Gepts, 2000). Suitable germplasm may even be lacking in the centres of diversity for a crop. For instance, local landraces of wheat in Ethiopia were shown to lack resistance to stem rust (*Puccinia graminis*) and leaf rust (*P. recondita*) and were consequently confined to highland areas where disease pressure was low (Belay et al, 1995).

Introducing exotic germplasm can bring substantial benefits to farmers. However, most plant breeders, formal and informal, are reluctant to use exotic or unadapted material due to its initially detrimental effects on their elite or adapted breeding material (Kannenberg and Falk, 1995; Duvick, 1996). Crosses with exotic material can result in the parallel introduction of inferior alleles and the disruption of useful co-adapted gene complexes (Duvick, 1984). Adaptation can be negatively affected by such changes. Such disincentives to use exotic germplasm may be felt more strongly by informal than by formal breeders, who do not have to eat or sell their early-generation progeny.

What starting materials to choose?

Choosing the starting genetic materials is the crucial first step for any PPB program (Witcombe et al, 1996; Witcombe and Virk, 2001). The choice will depend on the program's objectives. When the program wishes only to consider existing locally adapted landraces, the choice will be limited to these. But when important agronomic characteristics are lacking in locally available germplasm, the inclusion of exogenous material will be necessary. The extent to which farmers participate in making such decisions in existing programs, even the participatory ones, is often not clear.

Many PPB programs take as their point of departure an implicit assumption that the participatory approach will increase on-farm genetic diversity. However, this assumption may not be valid, because phenotypic diversity does not necessarily equate with genetic diversity (Wood and Lenné, 1997; Spillane and Gepts, 2000). Additionally, it has been suggested that widespread adoption by farmers of varieties from participatory projects could as easily lead to the contiguous planting of genetically similar varieties over large areas as conventional plant breeding has done, with the concomitant risk of genetic erosion and increased vulnerability to pests and diseases (Witcombe, 1999b).

The effects of PPB on phenotypic and genetic diversity can be investigated by conducting baseline surveys before the program is

launched and at periodic intervals subsequently. Molecular genetic characterization of farmers' material at different stages of the program would help monitor the situation over time, enabling researchers and farmers to identify the breeding activities most needed. For example, in mass selection of self-pollinated crops it may be important to maintain a number of individual lines to ensure adequate genetic diversity in the population. Molecular marker analysis of rogued versus selected plants would indicate the effects of selection on the genetic base over time and the relative importance of different genes to farmers.

For both formal and informal breeders, the surest way of achieving genetic gain is to cross genotypes that are already known to perform well under their target conditions. Consequently, a plant breeding program that needs to show early results may use only a modest amount of genetic variation in the initial crossing design to produce material that can be predicted to perform well (D. Duvick, pers. comm.). The need to obtain good results quickly is as common a constraint in PPB as in conventional breeding, particularly when resource-poor farmers with an urgent need to improve their livelihoods are involved. However, when a program has to meet a need that cannot be met using proven material, a greater range of genetic diversity is required, bringing in unadapted or even unrelated genotypes or genes. In this case, most progeny of crosses will prove unusable in the short term. Better selection tools (and often additional generations of recombination) are needed to extract the rare favorable recombinants of these crosses. Biotechnology can provide such tools (D. Duvick, pers. comm.), making it more feasible for PPB to incorporate new or unrelated genetic variation.

Introducing exogenous variation

In many cases exotic germplasm must undergo 'pre-breeding' or 'trait enrichment' before it can be useful (Simmonds, 1993). This is a strong argument for some degree of outside support to farmers' breeding efforts (D. Duvick, pers. comm.), including the use of biotechnology tools where these are the key to either providing new variation or making efficient use of it.

Recent progress using advanced backcross QTL methods has shown that DNA marker technology can be used to extract yield-enhancing traits from exotic germplasm such as wild relatives (Tanksley and McCouch, 1997). At present the cost:benefit ratios for developing the use of molecular marker technology in breeding programs are in the main only favorable for high-value commercial crops. Nonetheless, it is expected that costs will fall and that MAS will eventually become an integral part of modern plant breeding (D. Duvick, pers. comm.). The effect of the anti-transgenic food lobby on research funding and objectives (e.g., in the European Union) may steer future research in some regions towards the use of molecular markers to

manipulate germplasm within sexually accessible crop genepools, avoiding genetic modification.

Once the use of markers becomes routine, MAS may provide a powerful tool for promoting geneflow to locally adapted populations, since it allows the identification of individual QTLs for a specific trait not only in the donor but also in the recipient parent (deVicente and Tanksley, 1993; Tanksley et al, 1996; Tanksley and Nelson, 1996; Tanksley and McCouch, 1997). Recent advances in the use of molecular markers to identify QTLs may mean that 'trait-enriched' populations can be developed which will be easier to combine with locally adapted varieties or landraces. In sum, the innovative use of molecular maps and markers is likely to alter radically the way in which exotic germplasm is used in plant breeding and genetic enhancement in the decades ahead (McCouch, 1998).

Comparative molecular mapping is opening up hitherto unknown opportunities to capitalize on the similarity between different species in the grass family (McCouch, 1998). It may be possible to develop a unified genetic map of higher plants which spans both monocots and dicots (Paterson et al, 1996). These developments will make it possible to study the genetic basis of adaptation across different crop species and to apply the knowledge gained from one crop to the introduction of new genes into another crop (Devos and Gale, 1997; McCouch, 1998; Sasaki, 1998). The relatively small genome of rice has meant that this crop is likely to become the 'anchor genome' for the comparative mapping and isolation of all cereal genes. A number of public- and private-sector efforts are now under way to sequence the rice genome.

Much plant biotechnology research is currently directed at the improvement of specific 'quality' traits in modern varieties (Mazur et al, 1999). It is likely that some landraces, both locally and widely adapted ones, can also be improved in this way. Paradoxically, deciding not to take this course may in the longer term only hasten the displacement of landraces by other crops or improved varieties that can provide such quality traits.

Increasing farmers' access to traits from wild relatives

As we have seen, farmers' varieties may lack genes for traits useful to farmers or other end users. The wild relatives of crops have already contributed many useful traits to crop production (Stalker, 1980; Prescott-Allen, 1988; Lenné and Wood, 1991). While the use of genes from wild species has so far been confined mainly to major cereal and cash crops, it is likely that almost all crops can benefit from the addition of agronomically desirable traits from this source, although these traits may not necessarily be easily accessible (e.g., Muehlbauer et al, 1994; Grimanelli et al, 1995; Singh and Ocampo, 1997).

There are examples of geneflow from wild relatives to domesticates (e.g., Oka and Chang, 1961; de Wet and Harlan, 1975; Longley, 1999), but farmers on their own seldom systematically access useful genes from wild relatives and related species. There are major barriers to such access, such as reproductive isolation, embryo breakdown, hybrid sterility, and limited genetic recombination (Spillane and Gepts, 2000). The disincentives faced by formal plant breeders in using wild relatives are felt even more acutely by farmers, who typically must sell or eat what they breed or select.

Nevertheless, access to useful genes from wild relatives can benefit resource-poor farmers. Baudoin et al (1997) demonstrated the usefulness of embryo rescue in tissue culture to achieve the wide-cross transfer of useful traits from wild strains of common bean (*Phaseolus vulgaris*) into the Andean cultivated genepool. Through on-farm trials and farmer participation, the best enhanced germplasm was then rapidly selected by farmers for incorporation into their existing bean-maize multiple cropping systems. Without the use of wide-cross embryo techniques it is highly unlikely that these Andean highland farmers would have had access to wild bean germplasm.

Conventional plant breeding has had major successes in transferring useful genes into cultivated varieties using either bridging crosses or wide crosses. For example, bridging crosses have often been used to access alien genetic variation in potato breeding (Iwanaga et al, 1991; Ortiz, 1998), while wide crosses have made significant contributions to wheat improvement (Jiang et al, 1994). Biotechnologies such as embryo rescue have also increased the opportunities for transfer (Sharma, 1995). One of the few examples of the farmer participatory dissemination of biotechnology products has occurred through the work of the West Africa Rice Development Association (WARDA), where progeny from an in vitro-facilitated inter-species cross between the indigenous African and Asian rice species have been entered into PVS trials (WARDA, 1999).

Wide crossing, especially of the less commercial crops, is considered by some to be a neglected area for research (Duvick, 1989). Yet advances in wide-crossing techniques such as hybrid embryo culture (Sharma et al, 1996) and the use of crossing strategies such as bridge crosses are making the wild relatives of many crops ever more accessible (Stalker, 1980; Muehlbauer et al, 1994). The success rate of gene transfer in wide crosses can be increased by knowledge of chromosome pairing mechanisms and their genetic control. This knowledge is essential to promote recombination between heterologous or homologous chromosomes if the size of the introgressed chromosome segment(s) needs to be either minimized or maximized (e.g., Luo et al, 1996). Continuing advances in structural genomics (e.g., comparative mapping) and genetic engineering (e.g., crossability transgenes) are likely to facilitate wide crossing still further in the coming years.

Although crop wild relatives are valued as a unique source of genetic variation, they have rarely been used to improve quantitative traits. It is acknowledged that exotic germplasm of this kind is infrequently used by breeders (Duvick, 1996; Spillane and Gepts, 2000). Achieving a wide cross is, of course, only the first step in successful gene transfer from wild to domesticated species. The problem of 'linkage drag' of undesirable genes with the desirable gene can only be solved by long cycles of repetitive backcrossing to break the linkage. Studies have shown that, even after 20 or more years of conventional breeding, a single gene transferred from a wild species can still be linked with enough chromosomal DNA to contain more than 100 other potentially undesirable genes (Young and Tanksley, 1989).

One example of how undesirable linkages limit access to useful traits is the low protein quality of cultivated maize kernels (Or et al, 1993). Storage proteins (zeins) containing high levels of the essential amino acids methionine and lysine have been identified in unselected wild germplasm, but not in domesticated germplasm. It is thought that undesirable genetic linkages between the zein loci and other loci have, since domestication, prevented both farmers and formal plant breeders from selecting for this trait using conventional breeding techniques (Swarup et al, 1995). MAS or genetic engineering may yet help to break this linkage.

New opportunities have been opened up by the recent development of a molecular marker-based technique that enables the transfer of QTLs conferring complex traits such as yield and organ size (Paterson, 1995; Tanksley and McCouch, 1997). This technique has now been demonstrated for rice (Xiao et al, 1998) and tomato (deVicente and Tanksley, 1993). Once its applicability to other crop/wild relative combinations is demonstrated, the technique may prove useful in developing trait-enriched germplasm populations for both conventional and PPB projects. One way forward may be the deliberate choice of diverse genotypes from crop core collections (collections of lines known to contain maximum levels of genetic diversity and to be adapted to different agro-environments) for inclusion in QTL analysis studies (van Hintum, 1999).

Providing useful traits through transgenesis

Transgenic approaches to providing the genetic variation needed to solve a plant breeding problem are usually tried only if suitable conventional approaches are lacking or do not work—for example, if germplasm conferring resistance to an important pest or disease has not been found or is very difficult to access in the genepool of a major commercial crop. Many crop genepools are poor in agronomically useful traits, such as protein quality or abiotic stress tolerance, that are available in the genepools of other crops or species. In some cases

transgenic approaches may be the only way of obtaining resistant or improved varieties (J. Tohme, pers. comm.).

A number of serious pests and diseases are already being tackled in this way. One example is soft rot or blackleg (*Erwinia carotovora*) in potato, which causes crop losses estimated at US$100 million per year worldwide (Perombelon and Kelman, 1980). Resistance is lacking in the potato genepool but has been identified in the wild species *Solanum brevidens*, which cannot be easily crossed with *S. tuberosum* (Austin et al, 1988; Williams et al, 1993). A transgenic route is thus the only possible one.

Some other examples of pests or diseases for which conventional resistance options are lacking include:

- Insects in cowpea (IITÅ, 1992)
- Leaf roll virus (PLRV) in potato (Corsini et al, 1994)
- Rice hoja blanca virus (Madriz et al, 1998)
- Rice grassy stunt virus (Swaminathan, 1982)
- Black sigatoka disease in banana (Swennen and Vuylsteke, 1991)
- Coffee seed weevil (CENICAFE, 1997)
- Bean golden mosaic virus (Hidalgo and Beebe, 1997)
- African cassava mosaic virus (Cours et al, 1997; Otim-Nape et al, 1997)
- Viruses in papaya (Gonsalves, 1998; Prasartsee et al, 1998)
- Insects in cotton (Estruch et al, 1997).

Similarly, crops contain no known genes for resistance against viroids (the smallest infectious agents of plants). At present, the only practical way of protecting crops from viroid epidemics is to diagnose infected plants and then to eliminate them from cultivation. Two genetic engineering strategies using antisense genes (Yang et al, 1997) or a yeast ribonuclease (Sano et al, 1997) have been developed to provide new sources of genetic resistance against specific viroids.

Although there are still problems in developing efficient transformation systems in many crops, a crop's accessible germplasm already extends in principle to many other organisms and could even include synthetic genes (e.g., Rotino et al, 1997). In particular, pest and disease resistance provides a multitude of examples in which transgenes have been obtained from diverse species and organisms.

A range of other agronomically useful genes have now been isolated and successfully transferred to crops. Many single plant genes are also now being transferred between sexually incompatible crop plant species (e.g., Whitham et al, 1996; Molvig et al, 1997; Wilkinson et al, 1997). For instance, pathogen resistance genes can be transferred from one plant species to another (e.g., tobacco to tomato, and vice-versa) and remain functional (Rommens et al, 1995).

While the majority of agronomic traits are quantitative and hence difficult to improve using existing transgenic technology, many monogenes are also known to confer major agronomic benefits (Table 1). In addition, monogene mutations are of major importance in breeding programs. Examples include 'opaque -2', which improves the nutritional value of maize kernels, 'nor', which increases the shelf life of tomatoes, and 'Rht1' and 'Rht2', which reduce the height of wheat plants (e.g., Lohmer et al, 1991). Indeed, the Rht-B1/Rht-D1 and dwarf-8 (d8) genes that were largely responsible for the Green Revolution have recently been shown to be mutant genes that are insensitive to certain growth hormones (Peng et al, 1999). The identification, isolation, and transfer of such monogenes between crop species or varieties may offer new opportunities to bring about genetic gain rapidly, in landraces as well as modern varieties.

Transferring desirable monogenic traits from exotic to adapted cultivated germplasm through conventional plant breeding can be highly time-consuming (Ronald, 1997). Transgenic technology is often equated with transferring genes between species, but it can equally well be used to transfer genes within a crop. For instance, if a desirable resistance gene homolog is available in a particular accession but not in the variety of choice, transgenic techniques can be used to move it. In some crops, once a resistance (or other) gene has been cloned (e.g., Kilian et al, 1997), transgenic cultivars can be generated within 2 years, compared with 5-7 or 10 years using a classical backcross approach (Ronald, 1997; C. Qualset, pers. comm.). Where PPB programs require access to specific monogenic traits, transgenic approaches can definitely help deliver them quickly.

Transgenic technology can be used to enhance landraces. For example, cassava farmers in Tanzania like both Mulundi/5, which is a selection from an on-station variety trial, and their local variety, Rushura. But they feel that Rushura cannot be recommended for more widespread cultivation because it is susceptible to cassava mosaic disease (de Piter et al, 1997). Gene transfer would be an effective way of adding resistance to Rushura, greatly enhancing an already useful variety known to be in demand by small-scale farmers.

Two routes are open to farmers and formal breeders wishing to enhance existing varieties using transgenes: (i) genetic transformation of the variety or (ii) backcrossing the transgene from a transgenic variety into a non-transgenic one. While route (i) may be faster, it requires either that protocols for efficient transformation of the particular variety have been developed, which is unlikely to be the case for most landraces, or the use of a suitable genotype-independent transfer method. Route (ii) is more time-consuming, and is unlikely to be an endeavor that farmers would wish to undertake, because of the yield and other problems in early-generation progeny. The costs and benefits of each route would have to be worked out on a case by case basis.

Table 1. Some examples of agronomically important single genes.

Major effect genes	Phenotype	Crop	References
HMW-GS 1Ax1	Breadmaking quality	Wheat	Altpeter et al, 1996
Hardness gene	Grain hardness	Wheat	Giroux and Morris, 1998
Rht_1, Rht_2	Dwarfing genes which contribute to increased harvest index	Wheat	Hoogendoorn et al, 1988 Waddington et al, 1986
Ppd_1, Ppd_2	Photoperiod insensitivity genes	Wheat	
Rye 1B/1R translocation (chromosome segment)	Yield increase and other effects (disease and insect resistance)	Wheat	Villareal et al, 1991, 1995
ph1 mutant gene (a deletion)	Controls homologous pairing, promotes chromosome pairing	Wheat	Gill, 1993
Vrn1	Vernalization response	Wheat	Galiba et al, 1995
Sh2	Vernalization response	Barley	Galiba et al, 1995; Laurie et al, 1995
Sp1	Vernalization response	Rye	Galiba et al, 1995; Laurie et al, 1995
Ppd-H1	Photoperiod response	Barley	Laurie et al, 1994
Ppd1	Photoperiod response, day length insensitivity	Most European wheat varieties	Worland and Sayers, 1996
Rpg1	Stem rust (*Puccinia graminis* f. sp. *tritici*)	Barley	Steffenson, 1992; Kilian et al, 1997

One option that might prove widely applicable would be to transform a basic set of genotypes (perhaps those that can be grown with at least some success in the broadest range of environments) with the most useful transgenes. After biosafety testing, the set could be made available as donor parents for crossing or backcrossing according to specific needs (M.J. Sampaio, D. Duvick, pers. comms.). This would be a 'low-tech' method for delivering transgenic innovations in a form readily usable by national programs or even directly by farmers.

If farmers were also provided with trait-linked selection markers for use in identifying transgenic progeny at the field level, they could in

theory shorten the amount of time spent on backcrossing, which might make them more willing to undertake it. In practice, however, farmers are unlikely to wish to take this route without the assistance of formal researchers, who are more able to sustain the risks of yield decline and quality deterioration associated with early-generation progeny.

As the technology progresses and more robust and efficient protocols become available, genetic transfer is likely to become applicable to a wider range of genotypes, as well as faster and more reliable (e.g., Clough and Bent, 1998; Komari et al, 1998; Mazur et al, 1999). It may become the preferred approach for adding single-gene desired traits to otherwise popular varieties, since unlike sexual crossing it does not disrupt the complex genetic balance of other traits, especially quantitative traits. It may prove particularly useful in clonally propagated crops, in which conventional breeding is difficult. Meeting biosafety requirements for containment in such crops is easier, because of the absence of natural seed dispersal. Efficient transformation systems may eventually become a service industry, in which varieties of a particular species can be transformed at core transformation facilities for that species.

MAS and transgenic techniques both have considerable potential for speeding up the 'upstream' germplasm enhancement or pre-breeding stages of crop improvement. They can also allow the development of enhanced germplasm populations more precisely tailored to the needs of end users (Tanksley and McCouch, 1997). For a while at least, non-transgenic germplasm enhanced by MAS may prove more popular with formal breeders and farmers who do not want or cannot afford the regulatory burdens and biosafety restrictions of working with transgenic material. But in the longer term it is clear that, used in combination, these advanced biotechnologies could yield tangible benefits for farmers and consumers.

Field-level 'gene switch' technologies to increase farmers' control

DNA elements called promoter sequences can be used to control the expression of a transgene by directing it to certain tissues (e.g., to pollen cells) or to specific developmental stages (e.g., at dehiscence) or to respond to specific inducing or repressing agents (e.g., virus infection, herbicide treatment). Inducible promoter systems allow researchers to switch genes on or off at particular times in their laboratory work. In theory, farmers or formal breeders could do the same thing at field level.

Combined with the use of transgenics, promoters are powerful tools for broadening farmers' choices and increasing their control over key biological processes. The challenge posed by cyanogen toxicity provides a good example (Box 8). The ability to control the expression

of selected genes in field-grown plants by applying inducer compounds to them could confer substantial agronomic benefits. Field-level intervention may be especially desirable for controlling the expression of transgenes.

Box 8

Seeking solutions to the paradox of cassava toxicity

Conventional plant breeding has been unable to produce cassava varieties that combine reduced labor requirements and reduced risk of toxicity with the advantages farmers require from toxicity. An alternative approach is to seek better processing methods, involving the distribution of improved (faster) fermentation starter cultures. But this approach faces daunting logistical and educational challenges. A genetic solution would be easier to implement. Can biotechnology tools help achieve a genetic solution?

Various biotechnology approaches have been suggested. If beneficial traits are linked to, but distinct from, the toxicity factors, then the linkage can be broken using precise new selection tools such as antibodies and molecular markers. However, it must be borne in mind that some benefits are conferred by the toxicity itself. These circumstances suggest a transgenic approach designed to increase the options available, together with farmers' control over them. Possible strategies include:

- Tissue-specific or developmentally controlled promoters inserted in front of the gene for cytochrome (P450), so as to limit synthesis of the toxin's precursor to certain tissues or specific periods of plant growth
- A promoter for the gene responsible for the breakdown of linamarin to toxic cyanide, to increase the speed of cyanide release during processing. Released cyanide would volatize rapidly and harmlessly in open-air processing areas, before the cassava is consumed
- For situations where toxicity is not needed and 100% safety is required, an antisense or gene-silenced construct of cytochrome P450 under the control of a strong constitutive promoter could be introduced. This would produce completely acyanogenic plants that lack the potential to become toxic under any circumstances.

Genetic tools are now available for pursuing these strategies. A cassava population on which to conduct the research to develop molecular markers for cyanogenic potential has been assembled at CIAT. Genes for cytochrome P450 and linamarase synthesis have been cloned. Constitutive and tissue-specific promoters and the technology for the genetic transformation of cassava are available. The promoters are patented, but free licensing is available to developing countries in the service of small-scale farmers.

SOURCES: Cassava Safety Group (1994); Hughes et al (1994, 1997); Hughes and Hughes (1994); White and Sayre (1997); Liddle et al (1997); Verdaguer et al (1996); Sarria et al (1995); Schopke et al (1996); Li et al (1996); Raemakers et al (1996); González et al (1998); Arias and Sayre (1998); R. Sayre, C. Iglesias, M. Fregene (pers. comms.).

A number of 'first-generation' inducible promoter systems have been developed (Table 2). Very few of these can be used on farmers' fields at present. Among them are the ethanol inducible promoter (Caddick et al, 1998) and the safener inducible promoter (de Veylder et al, 1997). More field-level systems will doubtless be developed over the next 5 years.

The ideal requirements for a farm-level inducible promoter were outlined by Jefferson (1993a, 1993b). For example, in a subsistence cropping system, where commercial inputs are not practical, the inducer would have to be an inexpensive, locally available substance. Jefferson et al (1999) suggests that no current systems meet all the necessary criteria for farmer use, but that systems could easily be developed that do.

Controversy has been aroused by the development of inducible promotor-based systems to restrict transgenic phenotypes to a single

Table 2. Some inducible promoters.

Promoter	Type	Reference
Gmhsp17.3 promoter (soybean)	Heat-shock promoter	
myb1 promoter (tobacco)	Virus-inducible promoter	Hong et al, 1996; Yang and Klessig, 1996
tet promoter?	Tetracycline inducible promoter	Masgrau et al, 1997
In2-2 promoter (maize)	Benzene sulfonamide herbicide safener inducible	De Veylder et al, 1997
EAS4 promoter	Pathogen-/elicitor-inducible promoter	Yan et al, 1998
lcA promoter	Ethanol inducible promoter	Caddick et al, 1998
Cu promoter	Copper inducible promoter	McKenzie et al, 1998
LAP promoter (tomato)	Methyl-jasmonate inducible	Ruiz-Rivero and Prat, 1998
wcs120 promoter (wheat)	Cold-inducible	Vázquez-Tello et al, 1998
pin-2 promoter	Insect feeding or wound inducible	Thornburg et al, 1990; Duan et al, 1996
GapC4 (maize) promoter	Anaerobic conditions inducible	Kohler et al, 1996
Steroid-responsive promoter	Glucocorticoid inducible	Schena et al, 1991; McNellis et al, 1998

generation (e.g., Moore et al, 1998). These systems, developed by Delta and Pine and the United States Department of Agriculture (USDA), were patented on the basis of their usefulness in protecting proprietary technology. They use a combination of inducible and growth stage-specific promoters in conjunction with other transgenes to limit access to proprietary 'embedded technology' to the first commercialized generation only (Jefferson et al, 1999). If second-generation seed is sown it does not germinate, leading to crop failure. This is the technology that was dubbed the 'terminator' by the Rural Advancement Foundation International (RAFI, 1998). During the Biosafety Protocol negotiations of 1999-2000, several developing countries expressed concern that second-generation transgenic seed carrying the technology could accidentally be sown, especially by resource-poor farmers, who often divert some of their food supply to this purpose at the start of the growing season. However, such seed could be a high-value product for specialized uses (J. Blalock, pers. comm.), in which case it would be too valuable to handle as a bulk commodity and would therefore be unlikely to become available for sowing.

A recently posited variant of these systems is the one in which farmers would be able to apply a specific compound to 'switch on' an agronomic transgene if he or she wished to do so. One commentator noted that this technology could give rise to food security concerns, since it could make farmers susceptible to gene warfare (J. Jiggins, pers. comm.). The authors feel that this concern is unlikely to materialize, partly for logistical reasons (replacing a major part of the seed of a whole region is a highly visible activity) and partly because sowings that were not exposed to the compound would still produce the basic crop. Only the value-added trait would be lacking.

Compounds and inducible promoter systems produced by the private sector are proprietary and available to farmers and researchers only on a commercial basis. However, such systems could in theory also be developed by the public sector for non- or less commercial applications, such as those in basic research or those directed to meeting the needs of resource-poor farmers (Jefferson, 1993a, 1993b). Publicly funded systems would use non-proprietary inducer compounds which, ideally would be relatively abundant and inexpensive in rural areas. If made widely available, such systems could be useful in transgenic approaches to facilitating the process of farmer PPB. However, it remains an open question whether or not they will actually be developed.

Needs assessments with farmers will help identify the priority traits over which farmers might wish to have greater control. The following is a possible list:

- The ability to switch apomixis gene(s) on and off could have major empowering implications for resource poor breeding situations (see Tools for Selecting Germplasm, p. 47)

- The ability to control the timing of grain-filling could allow farmers greater control over the timing of their harvest (M. Gale, pers. comm.)
- The ability to induce flowering could be used to shorten generation times, especially in the early stages of breeding programs, and to avoid continuing or imminent stresses (Laurie, 1997)
- The ability to control the induction of biocontrol agents such as Bt toxin could allow farmers practising IPM to manage the use of these agents on their fields (Lewis et al, 1997)
- The ability to control or delay ripening or senescence could help farmers avoid post-harvest losses and get their produce to markets at the right time (C.S. Prakash, pers. comm.)
- The ability to control photosensitivity, which affects time to flowering and harvesting (T. Hodgkin, pers. comm.), could also help manipulate crop cycles in response to weather conditions and other factors
- The ability to switch male sterility on and off could allow PPB projects greater flexibility and facilitate their increased use of heterosis
- The ability to induce tolerance genes for sudden or continuing abiotic stresses such as drought, cold or heat could allow farmers to save more of their harvest in bad years.

There may be cases in which the additional labor implied by increased farmer control over biological processes and products may prove a disincentive. For example, in IPM, rather than continually monitoring a field of crops for the emergence of insect pests before manually inducing Bt expression in infested plants, some farmers may wish to rely on promoters induced by feeding insects, which would enable them to devote their labor to other activities.

Tools for Delivering Planting Materials

The shortage of high-quality, healthy seeds and other planting materials is among the most widely expressed concerns of resource-poor farmers. Shortages are both chronic, caused by a variety of factors including poorly developed systems for multiplication and dissemination, and acute, caused by natural and man-made disasters, such as droughts and war.

Farmers everywhere are almost invariably keen to try out new crop varieties. Their planting material wishes are nearly always expressed in terms of a specific variety or varieties of interest. This may be a variety seen in a formal breeder's demonstration plot, or a local selection, or a sample carried home from a trip to distant relatives. Farmers often find their opportunities to grow desirable new varieties limited by access to planting material, whether from formal or informal breeding programs. An example is cassava in Tanzania (Thro et al, 1994). In other cases, the performance of an already widely adopted variety may have

deteriorated due to the infestation of planting material with systemic pathogens. Other quality-related problems in planting materials include poor germination, slow maturation, and low yield potential. It is not uncommon to find all these constraints together.

The rapid propagation of desirable genotypes using in vitro culture of shoot tips or meristems (often referred to as tissue culture) is a relatively low-cost and hence 'appropriate' biotechnology which is already delivering tangible benefits to many farmers in both developed and developing countries (Bryan, 1988; Van Uyen and vander Zaag, 1993; Govil and Gupta, 1997; Sasson, 1998). Tissue culture can allow rapid response to demand for large quantities of high-quality planting material in vegetatively propagated crops. Through in vitro clonal thermotherapy, it can also be used to generate disease-free planting materials. Large yield gains have been reported from the use of tissue culture to eliminate diseases from existing farmers' cultivars, many of which have low yields due to the high disease load that has built up over the generations (Delgado and Rojas, 1993; Garcia et al, 1993; Zok, 1993; Mabanza et al, 1995). There are numerous examples of tissue culture projects that are proving highly successful in delivering disease-free planting materials to resource-poor farmers (Sasson, 1998).

Tissue culture techniques have now been developed for a wide range of crops. In many Latin American and Caribbean countries, large-scale tissue culture is used for crops such as coffee, banana, plantain, taro, cocoa, cocoyam, sweet potato, apple, blueberry, raspberry, pineapple, citrus, grapes, papaya, mango, guava, potato, kiwi, cherry, pear, ornamentals, and yams (Sasson, 1998). In Asia, China has now developed tissue culture for more than 100 crop species. In the country's Guangdong Province, 3-4 million micropropagated banana plantlets are produced annually, 1 million of which are exported. In 1994 it was estimated that farmers in Guangxi had earned an extra US$723,000 by adopting approximately 600,000 disease-free plantlets. Similarly, 10% of China's potato area was planted with virus-free tissue culture materials in the early 1990s, with yields that are reported to have increased by up to 200% (Sasson, 1998). Tissue culture capacity is less well developed in most African countries, where it has the potential to benefit farmers greatly if integrated with other efforts to boost the production and delivery of planting materials. A few successful projects have been launched in the 1990s, including one on bananas in Kenya (Box 9).

Although biotechnology is often not considered in cases of disaster relief (FAO, 1996), tissue culture has been used for the rapid supply of cassava varieties in post-war Angola and in post-flooding disaster aid in Ecuador (Boxes 10 and 11). Some of the world's poorest farmers and most marginal cropping areas could make use of tissue culture to propagate much-needed planting materials.

Box 9

Tissue culture and small-scale banana producers in Kenya

Tissue-cultured banana plants are free of the damaging weevils and nematodes that infest most bananas grown by resource-poor farmers throughout the world.

In 1996, the International Service for the Acquisition of Agrobiotechnology Applications (ISAAA) brokered a project involving a wide range of Kenyan institutions, including the Kenya Agricultural Research Institute (KARI), in the development of tissue culture to rejuvenate banana orchards in Kenya and Uganda. The project tapped the considerable experience in banana tissue culture and mass propagation obtained in South Africa, where the public and private sector had worked together to lay the basis for a profitable plantlet export industry.

Project scientists worked with 12 representative farmers (including women) in Kenya's main banana growing regions. These farmers grew demonstration plots of 120 in vitro plants of each of three varieties. They were trained in plot management by KARI officers and a visiting technical advisor from the Institute of Tropical and Subtropical Crops (ITSC), South Africa. Each farmer had a group of 50 other farmers using his or her plot as their focal point for learning. These 50 farmers each purchased between 10 and 500 in vitro plants for their own plots. They then disseminated information and clean planting material to other farmers in their areas. The original supply of plantlets is being met by a Kenyan private-sector biotechnology company, Genetic Technologies Limited (GTL).

The shorter time to maturity and the superior quality and quantity of bananas produced by the tissue-cultured trees have made this biotechnology popular everywhere it has been demonstrated. The 1-year-old trees produce bunches weighing about 40-60 kilograms, compared to 10-20 kilograms from traditional trees after 2 years. By mid-1999 it was clear that most farmers were prepared to pay for the plantlets because they were confident that they would be able to increase their incomes from them. Farmers do, however, need to nurture the plantlets carefully, providing them with adequate nutrients and water. Micro-credit schemes are being introduced to enable farmers to invest in the plantlets and the improved management they require.

The demonstration and diffusion strategy adopted by the project is ensuring that orchards in most banana growing regions of Kenya are now being, or will soon be, rejuvenated. The ultimate aim is to spread the technology to other African countries, starting with Uganda and Tanzania. A banana growers' association is being established to help provide marketing information. Socio-economic studies are in progress to help farmers identify and tailor their product to reliable market outlets.

SOURCES: F. Wambugu, S. Sharrock (pers. comms.).

The application of tissue culture to local varieties and landraces of root and tuber crops could not only increase yields also limit the genetic erosion caused by the loss of clonal varieties to systemic pathogens and other problems (F. Engelmann, pers. comm.). Links need to be developed between genetic resources conservation and tissue culture initiatives, so

Box 10

Market-linked restoration and conservation of cassava in Ecuador

Ecuador is one of five tropical American countries where per capita food supplies are dangerously low. Cassava and plantain are the main staple foods.

Coastal Ecuador was inundated with torrential El Niño rains for almost 12 months during 1997-98, when rainfall was 400%-450% more than normal. The rains wiped out all crops and left deep ravines and landslides where fields and roads had been. By early 1998, savings had been exhausted. Men and young people migrated from the countryside to nearby cities in search of work.

CBN supported the participatory development of a relief proposal by the Unión de Asociaciones de Trabajadores Agrícolas, Productores y Procesadores de Yuca (UATAPPY), the Universidad Técnica de Manabí (UTM), the Instituto Nacional Autónomo de Investigación Agropecuaria (INIAP), and CIAT. Independent proposals from all the partners were synthesized by a representative group into an integrated project to restore small-scale cassava production and processing capacity and re-establish markets lost as a result of crop failure and the destruction of infrastructure. The proposal was funded by USAID's Office of Disaster Assistance.

The project is unique because it combines cassava germplasm testing, tissue culture, and new management skills to (i) reconstruct local food security and economic opportunity and (ii) establish a locally managed in situ genetic resources conservation effort. Restored and rescued local cassava germplasm and elite cassava clones are being used in combination with new concepts in micro-enterprise development to jump start a disaster-struck rural economy. Tissue culture is an essential tool for the project. It is being used to conserve cassava germplasm collected by the farmers and characterized using oral history and DNA fingerprinting. It is also being used to repatriate the Ecuadorian national cassava collection, which was destroyed by the floods, from the duplicate collection held at CIAT.

SOURCE: Thro et al (1999b).

as to bring about a rapid increase in the supply of planting materials of a wide range of genotypes, including those of endangered species. There is considerable potential for integrating the periodic supply of disease-free germplasm from genebanks with decentralized farmer-led tissue culture and dissemination efforts.

Tissue culture is well suited to practice by 'meticulous non-scientists' (D. Duvick, pers. comm.) and can therefore be conducted by farmers or village groups. Although the technology is a laborious one for working farmers, the low cost of labor in many areas, together with the potential for developing low-cost locally adapted in vitro propagation methods, could create significant commercial opportunities (G.G. Henshaw, pers. comm.). In most countries, several important

Box 11

Rehabilitation of cassava production in post-war Angola

A joint project between the International Institute of Tropical Agriculture (IITA) and World Vision (an NGO) used tissue-cultured cassava germplasm to rehabilitate cassava production in post-war Angola.

In 1996, over 14,000 in vitro cassava plantlets were produced at IITA, airlifted to Angola, transplanted and acclimatized before delivery to rapid multiplication centers. Of the 216 genotypes shipped, 16 had been selected by IITA for immediate distribution to farmers, while the rest were to be evaluated by Angolan cassava researchers. An IITA researcher based in Angola was responsible for transplanting the initially delicate plantlets from glass tubes to starter pots and training World Vision staff to care for and multiply them. High survival rates were achieved.

None of these cassava genotypes would have been as rapidly accessible to Angolan farmers or researchers if they had not arrived as in vitro plantlets, enabling them to be certified as disease-free.

SOURCES: IITA (1997); P. Ilona, S.Y.C. Ng (pers. comms.).

vegetatively propagated crops could benefit from the development of 'barefoot' tissue culture operations.

Tissue culture need not be expensive or require very sophisticated technologies. Kitchen-based micropropagation kits are sold to amateur horticulturalists in the USA (C. Stiff, pers. comm.). Basic designs for very simple aseptic culture hoods (involving plastic sheeting, bulldog clips, and file folder supports) that can be constructed and folded away in minutes have been developed (T.M. Horn, pers. comm.). There are many formulations for cheap growth mediums using table sugar, coconut milk, and so on. Recycled glass jars can be used as sterile containers.

To date, few technology development or transfer organizations have become involved in the promotion of 'low-tech' methodologies and materials for use by farmers or farmers' groups in developing countries. Some taro farmers in Samoa have become adept at basic tissue culture (M. Taylor, pers. comm.) as also have potato farmers in the Dalat province of Vietnam, cassava farmers in Colombia, and strawberry growers in the Dominican Republic. In some recent cases there have been efforts to involve farmers' organizations in the design and running of tissue culture schemes. CIAT's small-scale cassava micropropagation work with NGOs and farmers' organizations in Colombia is an example (Box 12). Much experience in adapting tissue culture to the village or district level has been gained in the ongoing work on potato initiated by the CIP and national program staff and now conducted independantly by farmers in Dalat province of Vietnam (Box 13). The farmer participatory FLASH system successfully developed for potato

Box 12

Low-cost rustic tissue culture for cassava and other indigenous root crops in Colombia

Cassava in Colombia's Cauca region is grown by resource-poor farmers for home consumption and sale to small-scale local starch extraction plants. The crop is a good source of future income and rural employment, provided local producers can compete with those of Brazil and Thailand.

In 1999 an NGO, the Fundación para la Investigación y Desarrollo Agrícola (FIDAR) and local farmers' organizations in Cauca, including the Asociación de Agricultores de Pital, the Asociación de Productores Agropecuarios de Pescador, and the Grupo Comunitario Mi Lucha, began working with CIAT under a project funded by the SWP-PRGA. Cauca's cassava farmers had already worked with CIAT and FIDAR for about a decade in participatory cassava varietal selection. But in the late 1990s it became clear that the limited supply of planting materials was preventing this work from having an impact.

Interest in other local root crops, such as achira (*Cana* spp.), aracacha (*Aracacha* spp.), and local varieties of batata or camote (*Ipomoea* spp.), is increasing, but for these crops too a shortage of planting materials is expected to constrain development. Remaining stocks are in very small plots, often diseased, and generally inadequate in quantity and quality to allow propagation to be scaled up adequately to develop new markets.

To meet the need for high-quality planting material, FIDAR, through CBN, invited CIAT researchers to join with Cauca farmers' associations to explore affordable tissue culture methods. The idea is to organize tissue culture as household micro-enterprises or as projects for farmers' associations. Farmers will provide knowledge of local materials and information on the social and economic context, in addition to their skills and labor. CIAT biotechnologists will provide technical information on cassava in vitro culture, and collaborate with the farmers in proposing and testing media and methods. FIDAR is to coordinate farmers' participation in technology and enterprise development, to monitor and evaluate the project, and to assess its impact.

Cassava plantlets will be used for the production vegetative planting materials (stakes). These will be distributed at a price yet to be determined, but which may be subsidized in the first year, when the value of the technology is not yet established. Production will be monitored to assess (i) the agronomic and socio-economic value of the technology and (ii) how frequently on-farm planting material should be replaced to maintain yield and quality levels.

Timely access to high-quality planting material will enable local farmers to use their own varieties more fully, to get access to new varieties from other sources, and to respond rapidly and flexibly to market signals and changes in the agro-economic environment.

If successful, this project will greatly enhance local control over planting material, increase the supply of improved materials, increase diversity and flexibility in the local farming system, stimulate interest in cassava R&D and enhance their impact, and serve as a model for other regions. The project will also create one of the first teams of biotechnologists trained to conduct participatory research with resource-poor farmers.

SOURCES: Thro et al (1999b); J. Restrepo (pers. comm.).

Box 13

Farmer-led micropropagation of potato in Dalat, Vietnam

One well documented and often cited example of successful biotechnology-assisted participatory research is that of farmers in Vietnam's Dalat province, who have used in vitro tissue culture methods for commercial potato production.

In the early 1980s, clean potato planting materials were virtually unobtainable in the major potato-producing region of the Dalat highlands. Researchers responded by introducing a system whereby farmers could maintain three newly selected cultivars as test tube potato plantlets and multiply them in vitro as well as by using cuttings. The in vitro propagation method used relatively simple materials, including a small steam autoclave, a home-made inoculum box, and a culture shelf with a fluorescent light and glass tubes. The cultivars were established in culture as mother plants, from which apical shoots were harvested continuously for up to 6 months. After cutting the apical shoots were rooted in potlets. Two weeks later they were sold to other interested farmers or used for transplanting by the farmer, who produced cuttings. In 1982, over 2.8 million cuttings were sold to commercial potato growers. After 4 years, all potatoes in the Dalat area were grown with this material. Growers keep the small tubers from the harvest for use as seed over two or three generations.

The advantages of this system are considerable. Farmers can produce high-qulity planting materials themselves, and no longer need to import tuber seed from elsewhere. The system is cheaper than conventional multiplication, with rooted cuttings selling for US$0.005 each. In addition, healthy stocks can be maintained indefinitely. It is thought that this system could be adapted to other locations around the world with similar environmental conditions.

A follow-up survey 5 years later suggested that farmers' interest in this project had waned and that there were difficulties in initiating similar projects in other areas of Vietnam. In 1993 it was noted that only 3 out of 10 farmer micropropagation units were still functioning. Nevertheless, the system continued to supply an adequate amount of clean planting material to commercial growers in the Dalat area. It has now been running for nearly 20 years. A 1998 update confirmed that most villagers found the tissue culture process too time-consuming, but that one 'expert' farmer had continued and was selling plants to neighbors. In other words, a rural micro-enterprise had developed.

SOURCES: Van Uyen and vander Zaag (1983, 1987); van Uyen (1984); Broerse and Visser (1996); G. Prain, L.T. Binh (pers. comms.).

micropropagation has been extended to other countries and crops (Sasson, 1998; Bryan, 1988; vander Zaag et al, 1990).

Because of their relative simplicity, tissue culture services launched by formal researchers can probably be transferred successfully to innovative farmers over time, perhaps as a form of micro-enterprise development. Some farmers' organizations, especially those organized

around commodities, may be able to establish and sustain tissue culture micro-enterprises which provide planting materials not only to their members but also to a wider circle in the local farming community. In any event, increased farmer involvement in some or all of the tissue culture process seems likely in the future.

There will, of course, also be constraints to farmer participation in tissue culture. These include the need to provide training in technical and business skills, together with small amounts of capital to finance start-ups. However, the amount of external support needed is small compared to other biotechnologies. The FIDAR project in Colombia is experimenting with the effectiveness of such support.

Many factors, both environmental and socio-economic, affect the success of tissue culture operations in different areas. For instance, low-technology operations have temperature needs that can be met less expensively in a place like Dalat, in Vietnam, where the climate is mild, without extremes of heat or cold. Farmers in highland areas with cooler climates may have a comparative advantage in providing virus-free planting materials of vegetatively-propagated crops to farmers in other areas. On the socio-economic side, labor requirements, and especially the seasonal availability of labor, could prove critical. No comprehensive studies to define the conditions that favor the establishment of farmer-led tissue culture enterprises have yet been carried out. GIS could be used to identify possible areas where low-cost tissue culture may be possible.

Given its evident popularity, low-technology tissue culture could probably be integrated with PPB relatively easily in many developing countries. It could prove a valuable tool in speeding the delivery of the products of PPB to farmers, thereby overcoming one of the severest and most universal constraints to the increased productivity of resource-poor farming systems.

5. Relevant Products from Biotechnology Research

Biotechnology is now developing a wide range of products which, if they can be incorporated into appropriate crops and varieties, are likely to be useful to resource-poor farmers. Table 3 gives some examples.

Access to these technologies depends on the stage of the research, the terms under which they might be made available, whether resources are provided for technology transfer, whether the technology is durable enough for field use, and whether IPR or biosafety restrictions apply.

Resistance to Pests and Diseases

Farmers expend considerable financial and labor resources in trying to counter the crop losses associated with diseases, insect pests, and weeds. The management practices and chemical control of insects alone are estimated to cost around US$10 billion annually, yet the losses caused by insects still account for 20%-30% of global crop production (Oerke and Dehne, 1997).

Much research effort has gone into developing crops with increased tolerance or resistance to pests and diseases. New resistance options emerging from biotechnology research may be able to supplement the products developed through conventional breeding and the practices developed through IPM, leading to reduced pesticide and agrochemical use. For example, a recent survey of the adoption of insect resistant-cotton in four states of the USA found that insecticide use had decreased significantly while yields and profits had increased (Smith and Heimlich, 1999, www.ers.usda.gov/whatsnew/issues/gmo/). The potential of 'integrated transgenic crop management' to further reduce insecticide use has scarcely been explored.

Two biotechnology routes are generally used to enhance germplasm with increased resistance to biotic stresses: marker-assisted QTL selection, and transgenesis. Marker-assisted QTL selection generates resistance using loci within the accessible primary to tertiary genepools. Over the past decade, increasing numbers of resistance genes have been isolated and analyzed (Michelmore, 1996). Different genes are often clustered on particular regions of chromosomes

Table 3. Some biotechnology products useful for resource-poor farmers

Need	Example	References
Resistance to biotic stresses		
Insect resistance	Resistance to brown plant hopper, yellow stem borer, and the striped stem borer in rice	Wunn et al, 1996; Estruch et al, 1997; Nayak et al, 1997; Rao et al, 1998; Tang et al, 1999
Nematode resistance	Resistance to root-knot nematodes	Bridge et al, 1990; Vos et al, 1998
Fungal resistance	Rice blast resistance; powdery mildew resistance in barley	Wang et al, 1999; Simons et al, 1997
Bacterial resistance	Resistance against bacterial blight in rice	Ronald, 1997; Salmeron and Vernooij, 1998; Tang et al, 1999
Viral resistance	Rice yellow mottle virus (RYMV) in African rice varieties	Pinto et al, 1999; Beachy, 1999
Disease-free planting materials	Many different crops, especially those vegetatively propagated	Sasson, 1998
Tolerance to abiotic stresses		
Drought tolerance	Maize	Hoisington et al, 1996; Kasuga et al, 1999
Flood tolerance	Flood tolerance Name crops?	Weretilnyk and Hanson, 1990; Claes et al, 1990; Hoisington et al, 1996; Kasuga et al, 1999
Salinity tolerance	Rice, alfalfa	Roxas et al, 1997; Hayashi et al, 1997; Kasuga et al, 1999; Winicov and Bastola, 1999
Aluminium tolerance	Tobacco, papaya	de la Fuente et al, 1997; Herrera-Estrella, 1999

(Continued)

Table 3. (Continued.)

Need	Example	References
Cold tolerance	Rice, *Arabidopsis*	Hayashi et al, 1997; Jaglo-Ottosen et al, 1998; Sakamoto et al, 1998; Kasuga et al, 1999
Improved varietal qualities		
Higher yield	Rice, tomato	Tanksley and McCouch, 1997; Li et al, 1997; Peng et al, 1999; Xiao et al, 1998
Improved harvest index	Tobacco	Robson et al, 1996
Improved source-sink relationships	Increased tuber size of potato tubers	Sonnewald et al, 1997; Herbers and Sonnewald, 1998
Higher levels of desirable compounds	High laurate in rapeseed; new starch compositions in potato	Gibson et al, 1994; Voelker et al, 1996; Lloyd et al, 1999; Poirier, 1999
Increased nutritional value	Better amino acid profile in legumes	Bright and Shewry, 1983; Gilbert, 1995; Karchi et al, 1993; Molvig et al, 1997
Increased nutritional value	Higher vitamin A or E levels in rice and *Arabidopsis*	Sommer, 1988; Humphrey et al, 1992; Burkhardt et al, 1997; Shintani and DellaPenna, 1998
Improved digestibility	Reduced or altered lignin content in maize	Cherney et al, 1990; Halpin et al, 1994
Improved processing or cooking qualities	Improvement of the functional properties of wheat	Barro et al, 1997
Reduced post-harvest deterioration	Prevention of cold-induced sweetening of potato tubers	Greiner et al, 1999
Reduced labor requirement	Herbicide resistance in maize and other crops	Gressel et al, 1996

(Kanazin et al, 1996; Ghesquière et al, 1997). It is becoming increasingly feasible to use markers to select for these regions. Alternatively, the use of markers can be combined with that of transgenesis to isolate and transfer the functional genes from the clusters between species (Michelmore, 1995; Paterson, 1995; Hamilton, 1997). Some transgenic approaches are generating useful traits that were previously not available or accessible.

Recent progress in understanding the genetics of plant disease resistance has opened up a number of new avenues towards genetically engineered solutions. Genes controlling race-specific and broad-spectrum resistance responses have been cloned (van der Biezen and Jones, 1998), allowing new induced resistance pathways to be identified (Hunt et al, 1996). Advances continue to be made in the identification of antifungal proteins, which inhibit either pathogen development or the accumulation of mycotoxins. PPB programs facing continuing problems with specific pests or diseases may be able to make good use of these new biotechnology approaches to control.

Breeding for insect resistance and the use of biocontrol measures are attractive alternatives to insecticides, and both can be enhanced by genetic engineering. A wide range of transgenic approaches to combatting insect pests are now under development (Estruch et al, 1997). These include the transgenic use of insecticidal proteins such as *Bacillus thuringiensis* toxins, polyphenol oxidases, proteinase inhibitors, chitinases, lectins, vegetative insecticidal proteins (VIPs), and alpha-amylase inhibitors.

Nematodes, especially root knot nematodes (*Meloidogyne* spp.), cause annual losses of US$100 billion to world agriculture. In developing countries, root knot nematodes account for losses of 11%-25%, with peaks of 70% (Bridge et al, 1990). Current chemical control using nematicides (e.g., Aldicarb) is considered environmentally hazardous, as well as costly. Crop rotations can be used to limit nematode infestation, but are ineffective on their own. In a few crops, nematode-resistant varieties have been developed through conventional breeding, but many crops lack sources of nematode resistance (Roberts, 1992). Several transgenic approaches to the development of nematode-resistant crops are now emerging. These complement the use of transgenes from the crop genepool with those from other sources (Atkinson et al, 1995).

Most crop genepools lack sources of durable resistance to serious viruses. Potato leaf roll, cassava mosaic, and rice tungro viruses are examples. A range of pathogen-derived resistance (PDR) strategies emerged in the 1980s (Kavanagh and Spillane, 1995), using transgenes derived from the pathogen itself to trigger resistance against it. The mechanisms underlying different PDR strategies, such

as coat protein genes, movement proteins, RdRp, antisense, gene silencing, co-suppression, VIGs, DIs, and satellite RNAs, are highly diverse, as also are their effects (Dempsey et al, 1998; Baulcombe, 1999; Beachy, 1999). As a result they have been used to generate a far wider range of transgenic options for controlling viral diseases than was available a decade ago (e.g., Pang et al, 1997).

Tolerance to Abiotic Stresses

Arable land, which comprises about 3% of the earth's surface, is deteriorating and decreasing as a result of soil erosion, salinization, over-cultivation, and acidification. As demand for food grows, many of these abiotic stresses are increasing in effect and magnitude. It is estimated that these factors, combined with rising population, will reduce the global per capita availability of arable land from the current level of 0.28 to 0.17 hectare by the year 2017 (Dyson, 1996).

Unlike biotic stresses, abiotic stresses do not evolve. Hence, qualitative or single genes may prove effective solutions. A considerable amount of biotechnology research is now devoted to the development of transgenes to improve crop tolerance to abiotic stresses such as drought, salt, and aluminium. As many resource-poor farmers use marginal land where these stresses are high, the incorporation of these transgenes into their crops may provide significant benefits (Herrera-Estrella, 1999). Besides protection against the stress itself, the benefits might extend to earlier sowing, longer growing seasons or minimizing soil erosion.

None of the prototype technologies developed so far have yet been subject to large-scale field testing for their durability and sustainability under actual farming conditions. Much therefore remains to be done before the benefits of this research are realized on farmers' fields.

Yield Per Se

Yield is at once the most widely desired and the most complex of all crop traits. Private companies are investing in the identification of QTLs that will enable them to breed for yield advances using MAS. The work of companies such as Pioneer Hi Bred and Novartis shows that it is now possible to manipulate several QTLs simultaneously, allowing performance to be fine-tuned in closely defined environments (M. Gale, W. Beversdorf, pers. comms.). Combinations of specific quality or resistance traits with high yield, elusive in the past, are expected to become possible. Molecular and tissue culture technologies will also make it feasible to handle larger populations for selection, permitting increases in selection intensity and thus in genetic gain for quantitative traits, including yield.

These new options could be extremely important to resource-poor farmers, who often require high yields with specific environmental adaptation and quality traits. The initial development of markers for a set of genetic materials and environments requires from 2 to 4 years, with results that may or may not transfer across sites. Adding this time-frame to PPB will require a dedicated and understanding funding agency and great care not to raise farmers' expectations too high. However, the ultimate benefits to resource-poor farmers from research to increase yields may be among the highest obtainable from agricultural research (Lipton, 1999) (see Employment and Enterprise Development, p. 95).

Post-Harvest Losses

Reducing post-harvest crop losses among resource-poor farmers has remained a major challenge despite progress through conventional breeding. Significant proportions of the harvest are lost in developing countries as a result of crop physiological processes such as rapid ripening, senescence of the produce, or defective wound healing (as in rapid cassava spoilage), in addition to damage by storage pests.

Prolongation of, or delay in, the ripening or sensescence of the fruits or flowers of some crops could benefit resource-poor farmers, especially those farthest from markets. Transgenic manipulation of hormones (ethylene) and enzymes (e.g., polygalacuronase) has resulted in the development of a range of transgenic plants with delayed ripening and senescence (Newbigin et al, 1995). In addition, the use of inducible promoters and repressors is being explored. Work on delayed deterioration of cassava is under way at the University of Bath, UK (Li et al, 1998).

Nutritional Quality and Processing Characteristics

Much genetic engineering research is under way on the manipulation of biosynthetic pathways so that plants produce higher levels of compounds or new phenotypes useful to humans. Genes from the biosynthetic pathways of one species (a bacterium or a plant) can often be successfully used as transgenes in another to increase the levels of desirable compounds such as lipids (Gibson et al, 1994).

It can be argued that resource-poor farmers have as much interest in the functional properties of crops as industrial food processors do. Both groups are interested in manipulating the proteins and carbohydrates in foods, which affect traits such as cooking time, texture, dough elasticity, digestibility, gelling, foaming, and emulsification (Altpeter et al, 1996; Barro et al, 1997). For instance, it might be possible to develop varieties that require less fuel for cooking or that provide dough with greater elasticity. Farmer preferences for the functional characteristics of landraces are often considered a major

reason for non-adoption of high-yielding varieties (FAO, 1996). While knowledge of how to modify functional properties is rapidly growing in the food processing sector (e.g., Barro et al, 1997; Mazur et al, 1999), little or none of this knowledge has been transferred to those who could use it to broaden the range of options available to resource-poor farmers.

The nutritional value of plant protein is often limited by the lack of essential amino acids, especially lysine, threonine, and methionine (Bright and Shewry, 1983). Most plants are deficient in one or more of these critical protein components, whereas milk, meat, and eggs tend to contain them in adequate amounts. In some crops this nutritional deficiency applies irrespective of whether the variety is a landrace or a modern variety. Among the cereals, maize is low in the amino acid lysine. Grain legumes such as soybean and peanut, which serve as valuable sources of protein in the diets of human beings and livestock, are especially deficient in the sulfur-containing amino acids methionine and cysteine.

Conventional plant breeding has had little success in altering the essential amino acid composition of plants. Major efforts have been devoted to increasing the quantity and quality of maize protein through the breeding of high-lysine varieties, but this has led to a trade-off between yield and protein quality/quantity (Gilbert, 1995). Transgenic approaches may offer routes round such trade-offs, and a range of such approaches has now been developed. These improve the amino acid profile of crop protein either by transferring genes encoding more nutritious proteins from other species (e.g., Molvig et al, 1997) or by manipulating crop biosynthetic pathways to increase the nutritional profile of endogenous proteins (Karchi et al, 1993). The use of artificial genes has also been attempted (J. Jaynes, pers. comm.). Where transformation protocols have been developed, important legumes such as peanut and phaseolus beans can now be improved nutritionally through the transfer of methionine-rich protein genes from species such as sunflower (Molvig et al, 1997).

Micronutrient deficiency is a major problem amongst the poor worldwide and is often referred to as 'hidden hunger'. Lack of micronutrients such as vitamin A and iron not only causes suffering and death but also has adverse affects on labor productivity. Poor nutrition, especially during peak labor periods, can lead to low output, triggering a spiral of decline in which poverty, ill health, and hunger reinforce one another. The knock-on effects of micronutrient deficiency are immense. For instance, the correct levels of zinc in diets can reduce the incidence of malaria in children by 40% (Graham et al, 1999).

The International Food Policy Research Institute (IFPRI) and the International Development Research Centre (IDRC) of Canada are

implementing a project to select germplasm which is high in micronutrients from genebanks (see http://www.idrc.ca/). This germplasm could be fed directly into PPB or PVS projects in areas where micronutrient deficiency is a problem. It may also be possible to unravel the genetics of high- and low-micronutrient phenotypes using molecular markers and QTL analysis (DellaPenna, 1999) and hence to develop populations of germplasm 'enriched' with micronutrients. Transgenic approaches to increasing nutritional value could have a very great impact by adding micronutrients such as vitamin A to inexpensive staple foods such as rice (Ye et al, 2000) and cassava (Iglesias et al, 1997).

Many crop species contain high levels of anti-nutritional factors. These include compounds such as tannins, erucic acid, allergens, cyanogens, and nitrates. Increased processing and cooking are typically necessary to reduce the active levels of these compounds so that the resulting food is safe for consumption. The reduction of anti-nutritional factors has long been an objective of conventional breeding, with variable success. Often selections having low levels of the anti-nutritional factor are unproductive, suggesting an ecological role for the compound or compounds involved. MAS can reduce the levels of anti-nutrients more efficiently than the methods used previously. Rapeseed low in erucic acid is one product of research using MAS. Transgenic approaches are now being used to develop plants in which the anti-nutrient is not synthesized at all. Besides improving human nutrition, this research will allow the roles of these compounds to be studied—an avenue of research that could lead to the identification of alternative plant protection strategies that are less damaging to human nutrition.

Labor-Saving Biotechnologies

Many resource-poor farmers are interested in saving labor, particularly during peak periods, rather than solely in increasing returns to land (Gilbert, 1995). Hence, yield per hectare may not be the most appropriate criterion for assessing the impact of research on farmers (Chambers, 1983). Resource-poor farmers assess technologies in terms of the extent to which they may enable them to reallocate existing land and labor to other productive activities, while maintaining current levels of production. The other activity may be agricultural (e.g., shifting good-quality land out of maize into a more valuable crop) or off-farm (e.g., sending children to school) (Gilbert, 1995).

Affordable biotechnologies that reduce the labor and other resources devoted to crop management are likely to benefit many resource-poor farmers. Examples include herbicide- and pest- or disease-resistant cultivars, early-maturing cultivars, and cultivars that require less post-harvest processing. Conversely, technologies that increase the labor burden may not prove popular, even if they raise yields. Some farm-level inducible promoters may fall into this category.

Participatory research often reveals that women or children bear the brunt of labor-intensive activities such as weeding and post-harvest processing. It may also reveal the periods when labor intensity is at its highest and lowest. Such information could be factored into the setting of biotechnology and breeding research priorities. The subsequent research could have a major impact if it led to products that reduced the drudgery of underprivileged household members or community groups at peak labor periods.

Post-harvest processing is an area in which labor-saving technologies might prove especially beneficial. Many plant-derived foods require a great deal of processing, such as shelling, pealing, cooking, and fermentation, before consumption. The biological basis of many traditional food processing practices is well known (e.g., NAS, 1992). Genetic engineering to improve the functional properties of crops for specific industrial or domestic processing purposes could help reduce gender-specific labor constraints in many environments (e.g., Barro et al, 1997).

Labor-saving technologies may not always be beneficial. While positive impacts may be felt in one social context it is possible that the same technology could have negative impacts in another. For instance, herbicide-tolerant plants (especially if the seed is treated) can be expected to be very valuable to maize farmers threatened by striga in western Kenya, but could displace labor if deployed in the Kenyan maize belt in Trans Nzoia (J. Lynam, pers. comm.). Herbicide-tolerant crops in general tend to displace labor, especially where they also allow no-till farming (Naylor, 1994). However, this technology also has highly positive implications, especially for women and children, who often provide the bulk of labor for weeding (Box 14).

Participatory needs assessments with farmers may be necessary to clarify the full impact of changes in labor use. The situation can be extremely complex and difficult for 'outsiders' to understand. In the case of cassava, for example, women farmers in unstable parts of Africa feel that eliminating toxic compounds from the plant—to reduce the heavy demands on their labor for removing the toxin after harvest—could put food security at risk by making the growing or stored crop more liable to theft (Chiwona-Karltun et al, 1997) (see Box 5).

Conservation

Many of the biotechnologies that can be used to enhance plant production and productivity can also be used to meet conservation objectives. One example is tissue culture, whose use in rapidly propagating materials threatened by genetic erosion has already been discussed. Another is the use of the techniques of molecular analysis to understand the diversity of plant populations. These techniques can

Box 14

Herbicide-resistant crop varieties for weed control

Weed control is a major problem for nearly all resource-poor farmers. The introduction of herbicide-resistant crop varieties would release much of the labor spent on weeding for other, more productive and profitable activities. Farmers in Brazil and Thailand have actually requested the development and introduction of such varieties because they recognize their advantages.

Some commentators express concern that the use of herbicide-resistant crops in developing countries will unwisely add to the 'chemical armoury' of agriculture. The technology makes the use of herbicides more attractive where, up to now, no herbicides at all have been used. Although overall herbicide use is low in developing countries, some chemicals have been over-used or used without proper safety precautions in some regions.

Few data exist to assess the validity of this concern. However, a recent survey found that the adoption of herbicide-resistant soybean in 19 states of the USA had led to significant decreases in total herbicide use, while the cultivation of herbicide-resistant cotton was associated with no change in total herbicide use. As rates of use are higher in the developed than in the developing world, these results suggest that trends in developing countries adopting herbicide-resistant crops might at first continue upward, then level off at a lower usage level than would have occurred if they had gone on using non-herbicide resistant crops. A more diverse range of herbicides available to farmers could, in conjunction with the development of herbicide-resistant crops, form the basis of an integrated approach to weed control.

Among the barriers to the use of transgenic herbicide-resistant varieties in developing countries is access to the genes for herbicide tolerance. As patents on widely used herbicides such as glyphosate (Round-up) expire, reducing the cost of the herbicide, so the value of the genes conferring herbicide resistance increases. Discussion on this issue is under way between public-sector researchers and some of the companies concerned. The chemical industry is interested in developing herbicides for major world crops such as maize, soybean, wheat, rice, and cotton. But there are many minor crops and non-commercial market situations in which it has little interest. Some companies might be willing to facilitate access to herbicide resistance transgenes for introduction into crops or varieties in which they have no commercial stake, particularly in situations where they are the manufacturer of the herbicide.

Two further problems deserve a mention. Given the current difficulties with regard to biosafety regulations, it is unlikely that clearance would be given to use herbicide-resistant transgenic varieties in some developing countries. And the use of this technology would also require measures to ensure that resistance to the herbicide would not evolve in weeds. This is less likely to happen when the genes for resistance are derived from bacteria rather than plants.

Farmers in developing countries face many weed problems for which no effective control measures have yet been developed. These include the parasitic broomrapes and witchweeds (*Striga* spp.). The areas infested with such weeds are

(Continued)

Box 14. (Continued.)

vast and expanding. For example, a survey in Nigeria found that 70% of fields were infested with witchweed seeds. Witchweeds infest the grain crops of more than 100 million people in sub-Saharan Africa and Asia, reducing yields by 50% and more in drought years. Labor-intensive weeding is largely ineffective against such weeds.

Recent research has shown that it is possible to control *Striga* spp. using imadizoline-resistant maize. Herbicide-resistant seed is treated with a systemic imadizoline, resulting in excellent control. Because of the small amounts of herbicide required, this weed control technology is likely to be accessible to resource-poor farmers.

Under a Rockefeller Foundation project, the Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT) is collaborating with Pioneer Hi-Bred to provide a non-transgenic herbicide-resistant strain of yellow maize to serve as the source of the herbicide resistance trait. This has been crossed into the preferred African white maize varieties. Tests on the new materials obtained are currently being conducted in farmers' fields.

SOURCES: M.J. Sampaio (pers. comm.); Goldburg et al (1989); Hindmarsh (1991); Rissler and Mellon (1996); Gressel et al (1996); Gressel (pers. comm.); J. Jiggins (pers. comm.); Smith and Heimlich (1999); Hartman and Tanimonure (1991); Abayo et al (1996); Coghlan (1996).

be particularly useful as a basis for making decisions about where to collect accessions of threatened species.

The International Centre for Research in Agroforestry (ICRAF) is combining molecular analysis with the use of participatory plant collection missions and on-farm research to domesticate and hence save valuable tree species that are threatened with extinction in the wild (Box 15).

Biotechnology Products and New Management Knowledge

Some commentators believe that biotechnology for resource-poor farmers should not demand the absorption of too much new information and too many new skills by farmers. They argue that the main reason why many resource-poor farmers do not adopt new technologies, or adopt them late, is the dearth of information about them, rather than risk aversion or mere conservatism (R. Gerster, B. Stockli, pers. comms.). The lack of information is considered to be generally related to weak extension services—a shortcoming which some participatory research approaches aim to rectify.

It is often stated that one advantage of biotechnology is that its innovations are contained in seed and can therefore be delivered in a form that is already familiar to farmers and readily adapted to existing

Box 15

Saving *Prunus africanus*

Prunus africanus is a slow-growing hardwood tree species found in the cool moist forests of highland Africa. Its bark is a valuable remedy against prostate disorders. To increase their profits, collectors often harvest the bark unsustainably, killing the tree, which is now threatened with extinction.

ICRAF and its partners are working to save the tree by domesticating it. In collaboration with the Kenya Forestry Research Institute (KEFRI) and Cameroon's Institut de recherche agronomique pour le développement (IRAD), they have participated in collection missions in Kenya and Cameroon. The accessions are being grown in a range of research sites in the two countries. Once the best accessions have been identified, the stands will serve as selection gardens and seed orchards, from which small-scale farmers will be invited to choose materials for growing on their farms.

Studying all the populations of prunus by collecting seed and growing it under observation in the field would take up far too much space and time, especially as the species is slow growing. To make the process of conservation more efficient, the scientists are using RAPD to analyze the diversity of populations from Ethiopia, Kenya, Cameroon, Uganda, and Madagascar. The techniques do not cut out the need to collect and grow material, but they greatly reduce it by pinpointing the sources of genetic diversity in advance.

The results obtained so far show that Ethiopian and Kenyan materials are closely related, while those from Cameroon and Uganda form another distinct group. Populations from Madagascar are quite unlike any other group, suggesting they may be particularly worth conserving and evaluating. Overall, the level of variation between countries is greater than between populations within the same country, implying that evaluation should be carried out across the whole range of the species, not just within local populations.

The molecular studies are being combined with research to improve vegetative propagation, so as to increase the supply of high-quality planting materials. These materials are being tested through on-farm research designed to find out whether farmers are willing to grow the tree as a long-term investment.

SOURCE: ICRAF (1999).

dissemination systems (C. Ives, pers. comm.). However, some useful biotechnologies, although low-cost, are highly knowledge-intensive. This poses additional questions about whether they are practical for resource-poor farmers and can be adopted by them (E. Friis-Hansen, pers. comm.).

Transgenic, insect-resistant crop varieties are one example of a biotechnology product that would require relatively high levels of farmer management. A farmer growing transgenic insect-resistant maize must understand how to manage the crop in a new way if the benefits of the resistance trait are to be preserved (McGaughey et al, 1998). The same

will apply to the Colombian farmers who requested insect-resistant cassava as a result of the DGIS priority-setting exercise. Other products that can be developed using biotechnology, such as varieties with gene expression 'switches' to turn traits on or off in specific situations or new products for managing recombination and selection on-farm, would similarly require special management practices.

PPB projects may be highly compatible with the development of such products, since farmers would be involved from the start in developing the new management techniques and evaluating their practicality. The Colombian farmers, for example, are looking forward to being involved in developing their management package (L.E. Herazo, pers. comm.).

6. Implementation Issues

In this chapter we take a brief look at some of the factors that may affect the implementation of biotechnology-asssisted PPB: society's vision of its future, enterprise development, intellectual property, biosafety, and planning and providing resources.

Biotechnology and Society

By 2025, world food demand is predicted to rise by about 60% (McCalla, 1994). Expectations of higher living standards, including better health care and education as well as better diets and greater consumption of consumer goods, are widespread. Local increases in the yields of food staples will be vital in the struggle to eradicate poverty and hunger in the rural areas of developing countries (Lipton, 1999). People hold diverse and often conflicting views on the role of small-scale agriculture in a world that must meet these demands, on the suitability of biotechnology or of participatory research as tools for bringing about the required changes in an effective and socially desirable way, and on the need to retain traditional cultural values and practices while meeting the rising expectations of individuals.

One commentator said that it is 'disingenous to divorce considerations of a technology's potential from the context (i.e., human and social factors) in which it might be used' (J. Jiggins, pers. comm.). The authors point out that the context includes not only the local farming system and the natural resource base but also the market, the policy environment, and other influences from the outside world to which even the most remote rural areas are increasing connected. And, most important, the context also includes the aspirations of both those who will use a technology and those who will feel its impact in other ways.

Obtaining a shared vision of a community's future is an important part of project planning for biotechnology-assisted PPB, increasing the chances of designing a successful project. This is particularly the case given the long time-frame of biotechnology research. It would be unrealistic to expect all the protagonists in a PPB project to share an identical vision, so taking minority viewpoints into account is also important.

In the developed countries, lobby groups that are both pro- and anti-'biotechnology in agriculture' have formed in recent years. These groups often represent quite small sections of society, yet have acquired a disproportionate influence over public opinion and, in some cases, a disproportionate amount of control over the direction of public-sector research. Giving a voice in the technology and agriculture debate to resource-poor farmers and other poor social groups in food-deficit countries is essential if the current imbalance is to be righted (Spillane, 2000). This could even attract more laboratories in developed countries to work on problems relevant to such farmers, since they would realize that by doing so they could improve their public image at home.

Stakeholder analyses, which outline the main threats and opportunities perceived by each group potentially affected by a new project or technology, can provide useful inputs to biotechnology research planning. They may be especially useful in helping the biotechnology community realize who its clients are and where shared interests lie. This would help anchor discussion of the possibilities for collaboration and participation and of the obstacles and incentives facing different stakeholder groups (A. Sutherland, pers. comm.). Given the diversity of stakeholder groups, it may be necessary to move beyond the farmer participatory research framework to use a broader client-oriented framework such as that developed by Merrill-Sands et al (1991) in the 1980s.

There is a tremendous need to shift the biotechnology debate from unproductive confrontation between devotees and critics to the development of the necessary policies, mechanisms, and institutions that will ensure that resource-poor farmers in developing countries share in the benefits of biotechnology.

Employment and Enterprise Development

Agriculture remains the principal source of employment for over 75% of the developing world's rural people and over 8% of its urban people. Over half the world's poor depend on farming for their livelihoods. In the debate about increasing crop yields, it is often forgotten that the production, processing, and marketing of food staples will continue to be the most prolific source of work and income in developing countries for the forseeable future. Job creation and income generation for rural people should be key objectives of agricultural research for developing countries (Lipton, 1999). Whether this will require technology that increases yields per se or other yield-increasing innovations, plant biotechnologies are likely to be part of the answer.

Increases in the incomes of poor rural people can stimulate the establishment of non-farm enterprises, further contributing to poverty eradication. Some commentators feel that the prospects for technology

adoption may be poor where there is no link to rural enterprise development (C. Juma, pers. comm.). The development of rural enterprises is one way of ensuring that research continues to have an impact once a publically funded project ends (see Box 12).

Arguably, a marriage between contract farming and farmer cooperatives could increase farmers' access to new technologies and market opportunities. Farmer cooperatives have a stronger negotiating position than individual farmers in their interaction with agri-business, which is rapidly developing new models of contract farming. Coulter et al (1999) review a range of initiatives that could empower farmers going in for contract farming.

Just as tissue culture can serve as an 'entry-level biotechnology' (G. Henshaw, pers. comm.), so tissue culture micro-enterprises may provide a model that will stimulate the formation of other small-scale, local businesses, appropriate for disseminating other biotechnology tools and products. Cooperatives or family-level seed enterprises could disseminate biotechnologies developed through PPB, as they already do in the case of at least some of the technology developed through conventional plant breeding. Local enterprises could also serve as the intermediary between farmer customers and professional breeders and biotechnology laboratories, interpreting the needs of farmers and making the necessary connections to obtain what is needed (D. Duvick, pers. comm.). Perhaps such businesses could, in the longer term, also serve as economically sustainable successors to the multidisciplinary public fora proposed to meet today's immediate needs (see Background, p. 1, and How Can Resource-Poor Farmers..., p. 31).

Certain conditions must be met if local biotechnology suppliers are to emerge as a functioning part of the rural economy in developing countries. These conditions include not only a supply of useful technologies, but also political stability, fair traders, honest agricultural institutions (including banks and courts), affordable technology licensing arrangements, reliable markets and prices, and a reasonable transport and communications infrastructure (D. Duvick, pers. comm.). In some developing countries, for example in Latin America, many of these requirements can already be found or are developing; in others, such as many African countries, they remain elusive.

Intellectual Property Issues

The issues associated with IPR relevant to biotechnology-assisted PPB will vary according to the jurisdiction obtaining in different countries, as well as the biotechnology being developed and disseminated. They will require transparent discussion and understanding among participating farmers, researchers, national program scientists and

their international partners, the relevant regulatory authorities, and the suppliers of any proprietary germplasm or other technology used (Spillane, 1999).

Farmers involved in projects that may use proprietary biotechnologies have a right as well as a responsibility to understand the issues and participate in discussions and negotiations. Another paper in this series will examine IPR issues in PPB in more detail.

Biosafety and Risk Assessment

Not all biotechnologies raise the issue of biosafety. MAS and tissue culture, for example, do not. At present this issue refers mainly to the development and use of transgenic organisms.

The involvement of farmers in biosafety risk assessment may help identify and balance the risks and opportunities inherent in transgenic products. The opportunity costs of participation in such assessments by individual farmers may be high—especially if attempts are made to involve women, who typically have many other tasks to perform. This is an area where farmers' organizations may have a role to play (Spillane, 1999).

The Cartagena Protocol on Biosafety, finalized in Montreal in January 2000, includes provisions for public participation in decision making regarding the use of transgenic crops (Article 23) and for review of their socio-economic implications (Article 26). The Conference of the Parties to the Convention on Biological Diversity, in its draft decision to adopt the protocol (UNEP/CBD/ExCOP/1/L.6, 28 Jan 2000), proposes a 'roster of experts' in fields relevant to risk assessment and management as one review mechanism. Implementation of these articles and decisions should provide opportunities for the participation of farmers' organizations.

It would seem axiomatic that biosafety and risk assessment standards in developing countries should not be lower than standards in the developed world. But the reality is that a very stringent biosafety review system, or the absence of a functioning system, can delay or prevent farmers' access to biotechnology innovations (Nuffield Council on Bioethics, 1999; Spillane, 2000).

The costs and time required for regulatory clearance are likely to limit the amount of research invested in transgenic tools or products for resource-poor farmers in developing countries. Funding for biotechnology-assisted PPB research on transgenics targetted at the needs of resource-poor farmers, already difficult to obtain, will become even more so. Wealthier research institutions and projects in developed countries are more likely to be able to ride out the costs imposed by the present regulatory structure than are the under-resourced

public-sector institutions of developing countries. In the long term, as more experience is gained and regulations become more streamlined, it may become possible to move faster.

Older projects to develop transgenic crops for small-scale farmers in developing countries—those that started in the 1980s—had no budget for the regulatory process. Thanks to dedicated researchers and/or understanding donors, several of these projects have survived through several funding cycles and have recently achieved technical success (e.g., Thro et al, 1999a). The resulting transgenic prototypes remain in containment greenhouses until means are found of entering them into the regulatory process (C. Fauquet, pers. comm.) (Box 16).

The option of providing a 'basic set of transgenic donor parents', suggested by some commentators (M.J. Sampaio, D. Duvick, pers. comms.) (see Chapter 4), would be one way of addressing these problems, at least partially. The disadvantage of having to work through such a set would be the slowness of the process, which would involve identifying an important new transgenic trait, creating the donors, submitting them to regulatory testing in each country, and clearing the regulatory procedure—all of which would have to be done before backcrossing to a locally preferred variety so that research on farmers' fields could begin. The speed and flexibility with which transgenic technology can respond to farmers' needs is lost in such a process. Moreover, only a very limited number of transgenic traits could be handled, owing to the costs involved. The advantage lies in the fact that at least some transgenic innovations would eventually reach resource-poor farmers, rather than none at all. Resources would be focussed on a smaller, more manageable task—that of establishing the environmental and food safety effects of a small set of genotypes—rather than on the myriad regulatory protocols that would be required if primary transgenics were crossed with local varieties before the regulatory process.

A broader regulatory issue is that current risk assessment models from developed countries (e.g., the EU and the USA) are costly in human, financial, and other resources. In some developing countries, regulations are even more stringent and thus still more costly. Recent biosafety cost estimates from Brazil, for example, are as high as US$4-5 million for a single transgenic event (Sampaio, pers. comm.). It is often not clear how biosafety regulatory processes can be paid for. Their high costs may continue to bias transgenic research towards larger markets or farmers (Spillane, 1999; Nuffield Council on Bioethics, 1999).

Anyone proposing work with transgenic plants in a PPB project will have to factor in from the outset the uncertainty over whether the plants will reach farmers' fields in a given country, and whether the farmers will be able to sell the produce in their target markets.

Box 16

Biosafety and the introduction of transgenic materials

Three examples illustrate the conflict that can arise between the need for effective biosafety regulatory process and the need to deliver technology to resource-poor farmers:

- Transgenic cassava lines are being developed in several public-sector laboratories. Some lines will contain genes to protect the crop against cassava mosaic disease, while others will carry genes to increase vitamin A content or to prolong leaf retention during drought. All these traits are critical to small-scale farmers in Africa and South America. When the projects were initiated in the early 1990s, it was planned to field-test the transgenic plants in these regions, choosing countries where cassava is a staple crop and a national priority. National breeding programs in those countries would be able to take up promising experimental materials rapidly and put them to good use in local PPB. But delays occurred in the implementation of biosafety regulations in these countries. It now appears possible that the first field tests of transgenic cassava will take place in collaboration with research institutes in Southeast China, where the target traits are not high priority. At best, the field tests will enable the researchers to get a first impression of the probable suitability of the new materials. The absence of biosafety regulations in the target countries—or their high cost, in countries where they do exist—will create a delay, possibly of many years, in testing the research products and getting them into the hands of the resource-poor farmers who need them.

- Biotechnology tools for altering the cyanogen metabolism in cassava have been under development for over a decade. Transgenic plants with a range of variation in the cyanogen metabolic pathway can now be produced. Participatory research has shown that the role of cyanogens in cassava is complex and that farmers' selection criteria are not fully understood, so a broad range of variants needs to be explored with farmers. But can this be done? In transgenic research, the number of gene insertion events, the chromosomal location of an insertion, and several other factors influence the phenotype and performance of transformed plants. Biosafety regulations require precise molecular information about the transformant and a separate review process for each transformation event. Requesting permits for multiple variants is extremely costly.

- In collaboration with WARDA, scientists at the John Innes Institute and the Gatsby Foundation have developed a transgenic rice variety resistant to rice yellow mottle virus (RYMV). Occurring in devastating epidemics, RYMV can cause a yield gap as high as 330,000 tons of rice in a single year in West Africa. PVS may be the ideal way to evaluate the new varieties with farmers. However, in the current biosafety regulatory climate it is unlikely that a PVS project involving resource-poor farmer evaluation of transgenic varieties will meet with approval.

SOURCES: C. Iglesias, J. Pounti Kaerlas, I. Ekanayake (pers. comms.); Pinto et al (1999); Witcombe (2000b).

Planning and Providing Resources

If biotechnologies are to be added to the PPB tool-box, who will initiate and plan the projects? How will the projects be funded? How will the partners access trained human resources and facilities for biotechnology research? And how can they ensure effective communication with each other?

To date, the biotechnology projects in which resource-poor farmers have been involved have usually been initiated by researchers or donors, and only rarely by NGOs (J. Restrepo, pers. comm.). NGOs and participatory researchers who consider biotechnology as an option in PPB often run the risk of being more or less ostracized by the rest of the NGO community, where for the most part an anti-biotechnology dogma reigns. Farmer-initiated biotechnology-assisted projects are extremely rare, but may increase as farmers gain experience and see what has happened elsewhere, particularly with low-technology tools such as tissue culture.

Funding has come mainly from international donors but also from national sources, and in a very few cases from the private sector, which, for example under the auspices of ISAAA, has made occasional charitable donations to sectors that do not threaten its commercial interests. The costs of biotechnology-assisted research may decrease in the future, but 'upstream' research of this kind is always likely to cost more than the resources of small-scale farmers can support on their own. What, if any, demand pull will small-scale farmers exert on the research community in the coming years (Spillane, 1999)?

Early experience suggests that farmers' participation in project planning for biotechnology-assisted PPB will lead to projects that integrate biological and economic activities and criteria more closely than researcher-developed project models (Thro et al, 1999b). Such projects are already in progress with 'on-the-shelf' biotechnologies such as tissue culture. However, when a project requires the development of new biotechnology tools, such as specific molecular markers or inducible promoters, farmer participation breaks down because projects become too long-term to interest them. If upstream research were develop a repertoire of ready-made tools relevant to farmers' priorities, this would permit the design of participatory biotechnology-assisted projects to move beyond tissue culture yet stay within farmers' time-horizons. This will become more likely if farmer-participatory research practitioners develop strategic alliances with leading public-sector research institutions with the capacity to develop such tools, and if public funding agencies consider such research a priority.

Access to facilities, human resources, and interdisciplinary training for both biotechnology and farmer participatory research may

be created through links between national organizations, farmers' groups, leading research institutes in developed countries, and international centers such as those of the CGIAR. Project proposals should specify the resources needed to maintain links, facilitate communications, and develop research agendas collaboratively.

The level of investment and its continuity will both be critical. However, dependence on donors in the past has more often led to discontinuity: loss of support for long-term projects and networks and reliance on short-term 'impact-oriented' projects, with few or no sustaining mechanisms in place, are problems that are all too familiar to most researchers. Consequently, broad dialogue between local and national representatives, agricultural researchers, and donor-country constituencies is urgently needed, to secure long-term support. And, more than that, it will be vital to inform public opinion in the developed world, as well as the developing countries, about the importance of biotechnology options for resource-poor farmers. Informed, pro-developing country public opinion could do much to right the imbalances in the biotechnology research agenda that so many perceive today.

Dialogue and collaborative research between biotechnologists and farmer participatory researchers is unlikely to happen unless it is actively promoted. Incentive mechanisms such as new funding criteria, new fora of communication, and peer recognition of the value of participatory research are needed. The CGIAR centers and other interdisciplinary research institutions could play a major role in promoting such dialogue. Unless the dialogue is initiated, both biotechnology and farmer participatory research will continue on divergent trajectories and the potential of biotechnology-assisted PPB will be lost.

7. Conclusions

There is a real but as yet unrealized potential for synergy between the plant biotechnology and farmer participatory research communities. Little biotechnology research is explicitly targetted to the needs of resource-poor farmers (Spillane, 1999). Biotechnology-assisted PPB does not yet exist in any real sense or on any meaningful scale, anywhere. Yet, with vision and support, it could.

Biotechnology can strengthen the process of PPB with resource-poor farmers, for example, by generating 'enabling tools' that would greatly increase the efficiency of their breeding efforts at field level. Similarly, farmer participatory needs assessments could strengthen biotechnology research, providing it with an essential 'reality check' with which to sharpen its focus on the needs of resource-poor farmers.

In spite of this potential, biotechnologists and the practitioners of farmer participatory research currently have no fora for exchanging information or interacting with one another. They speak different professional languages and in most cases are unaware of how each other's work could be relevant to their own or to society as a whole.

Although the authors contacted hundreds of researchers, in both biotechnology and farmer participatory research, only a handful of biotechnology-assisted PPB projects were identified. Almost all involved tissue culture—a mature, low-cost biotechnology that can give good results quickly. This situation stands in marked contrast to that of 3-5 years ago, when it seemed that more projects covering a broader range of technologies would soon be implemented.

Many of the traits currently being developed through biotechnology research correspond to farmers' expressed needs. PPB offers opportunities to incorporate these traits into varieties in demand by farmers. For example, biotechnology could be used to reduce the labor requirement of key on-farm processes, as well as to increase yields and protect against pests and diseases. Whether small-scale farmers will have access to these traits will vary according to the technology that embodies them and to a range of other factors.

The future of biotechnology-assisted PPB will depend on whether or not a number of conditions can be met. Among others, these conditions include:

- Mechanisms for contact and sustained communication between biotechnologists, plant breeders, participatory research practitioners, and farmers
- Short-term benefits to farmers, to compensate for the risks and costs of experimentation, and to address their most pressing needs—without sacrificing opportunities for long-term benefits
- Translation of farmers' needs into research action through effective 'problem transfer', incentives and accountability; or greater control for farmers' groups over research funds and objectives
- Transparent discussion and understanding among participating farmers, national programs, international centers, regulatory authorities, and suppliers of proprietary germplasm and other technology, concerning the regulatory, biosafety, and relevant social issues associated with each project
- Modes of access to biotechnologies from proprietary sources, a public biotechnology tool-box, and strategic alliances with leading research institutions
- Public support for sustained public-sector funding: successful biotechnology-assisted PPB cannot be achieved without investment.

Because of its capacity for multidisciplinary research, its focus on poverty eradication, and its experience in animating and sustaining long-term partnerships, the CGIAR is in a unique position to integrate biotechnology and farmer participatory research.

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NARC, Kenya; A. B. Molina, Philippines; A. Muimba-Kankolongo, Zambia; S. Y. C. Ng, IITA; G. W. Otim-Nape, NARO, Uganda; Y. Nishikawa, Japan; G. M. Paz, Universidad Industrial de Santander, Colombia; C. A. Pérez, CARE, USA; M. I. Plata, INTA-EEA Concordia, Argentina; S. Poats, FLACSO, Ecuador; I. Potrykus, ETH-Z, Switzerland; C. S. Prakash, Tuskeegee Univ., USA; J. Pretty, IIED, UK; D. Pagliano, INIA Las Brujas, Uruguay; A. Pereira, Univ. of Wageningen, Netherlands; C. Qualset, Univ. California Davis, USA; C. Quiroz, VERSIK, Venezuela; B. M. Reed, USDA, USA; J. M. Ribaut, CIMMYT; P. Richards, TAO, TCT, Agric. Univ. Wageningen, Netherlands; Ray Riley, Pioneer Hi-Bred International; W. Roca, CIAT; D. Rocheleau, Clarke Univ., USA; S. Rodriguez, INIVIT, Min. of Agriculture, Cuba; N. Roling, Agric. Univ. Wageningen, Netherlands; H. Rosling, Karolinska Inst., Sweden; M. J. Sampaio, EMBRAPA, Brazil; L. Sanint, CIAT; K. Schmidt, Novartis Foundation; G. Second, ORSTOM, France; S. Sharrock, INIBAP; U. J. Siregar, CGIAR, Indonesia; M. Smith, Cornell Univ., USA; R. Smith, USA; S. Smith, Pioneer Hi-Bred International; L. Sperling, SWP/PRGA (CIAT); S. Sriwatanapongse, BIOTEC, Thailand; M. Stanton, USDA, USA; M. A. Subroto, Centre for Biotechnology, Indonesia; J. Sumberg, U. of East Anglia, UK; A. Sutherland, NRI, UK; K. Tamminga, DGIS, Netherlands; M. Taylor, Univ. of Western Samoa, Samoa; P. Tennant, University of the West Indies, Jamaica; G. Thiele, GTZ (Bolivia); J. Tohme, CIAT; S. Torres, Universidad de Costa Rica, Costa Rica; R. Tripp, ODI, UK; G. Tzotzos, UNIDO, Austria; N. Uyen, Inst. Tropical Biology, Vietnam; B. Visser, CPRO, DLO, Netherlands; R. Visser, Agric. Univ. Wageningen, Netherlands; F. Wambugu, ISAAA Africenter; J. Wekundah, ETC, Kenya; E. Weltzien, ICARDA; B. Weiskopf, GTZ, Germany; L. Withers, IPGRI, Italy; D. Wood, Consultant, UK; T. Ximenes, Federal University of Para-Brazil, Brazil; R. Zimmerman, USDA, USA; M. J. Zimmermann, FAO.

A special thanks is also extended to readers of the first draft, including Donald Duvick, Iowa, USA; Esbern Friis-Hansen, CDR, Copenhagen, Denmark; Masa Iwanaga, IPGRI, Rome, Italy; Janice Jiggins, Swedish University of Agricultural Sciences; Calestous Juma, CID, Harvard University, USA; Maria Jose Sampaio, EMPRAPA, Brazil; Louise Sperling, SWP-PRGA, CGIAR; Alistair Sutherland, NRI, UK; Louk de la Rive Box, ECPDM, Netherlands, and John Witcombe, University of Bangor, Wales. Their thoughtful comments greatly improved the first draft. Their inputs reminded us that this paper is still a preliminary attempt at understanding the issues raised by the concept of small-scale, farmer-friendly biotechnology.

The authors also wish to thank Simon Chater of Green Ink Ltd., UK, for taking a difficult paper in hand on a tight schedule. If the finished work is at all readable, this is due to the discipline imposed by an editor well versed in agricultural development issues and expert in his craft. The authors, however, retain full responsibility for any omissions or errors in the text.

List of Acronyms and Abbreviations Used in the Text

AFLPs	Amplified Fragment Length Polymorphisms
ASSINSEL	Association Internationale des Sélectionneurs pour la Protection des Obtentions Végétales (Switzerland)
BMZ	Bundesministerium für Zusammenarbeit (Germany)
CAMBIA	Center for the Application of Molecular Biology to International Agriculture (Australia)
CBB	Cassava bacterial blight
CBN	Cassava Biotechnology Network
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
CPRO	Center for Plant Breeding and Reproduction Research (The Netherlands)
CSHL	Cold Spring Harbor Laboratory (New York, USA)
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
CSSA	Crop Science Society of America
DFID	Department for International Development (UK)
DGIS	Ministry for Development Cooperation (Netherlands)
DH	Doubled Haploid
ETC	Education Training Consultants (The Netherlands)
FAO	Food and Agriculture Organization of the United Nations
FFS	Farmer field schools
FIDAR	Fundación para la Investigación y Desarrollo Agrícola (Colombia)
FSRE	Farming Systems Research and Extension
GFP	Green Fluorescent Protein
GIS	geographic information system
GTL	Genetic Technologies Limited (Kenya)
GTZ	Gesellschaft für Technische Zusammenarbeit (Germany)
GUS	Beta-Glucuronidase
HI	harvest index
IARCs	international agricultural research centers
ICRAF	International Centre for Research in Agroforestry
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics

IDRC (Canada)	International Development Research Centre
IFAD	International Fund for Agricultural Development
IFOAM	International Federation of Organic Agriculture Movements
IFPRI	International Food Policy Research Institute
ILEIA	Information Service for Low-external-input Agriculture
ILTAB	International Laboratory for Tropical Agricultura Biotechnology (La Jolla, USA)
INIAP	Instituto Nacional Autónomo de Investigación Agropecuaria (Ecuador)
INIBAP	International Network for the Improvement of Banana and Plantain
IPGRI	International Plant Genetic Resources Institute
IPM	integrated pest management
IPRs	intellectual property rights
IRAD	Institut de Recherche Agronomique pour le Développement (Cameroon)
IRRI	International Rice Research Institute
ISAAA	International Service for the Acquisition of Agrobiotechnology Applications
ITSC	Institute of Tropical and Subtropical Crops (South Africa)
KARI	Kenya Agricultural Research Institute
KEFRI	Kenya Forestry Research Institute
LEISA	low-external input agriculture
MAS	marker-assisted selection
NAS	National Academy of Sciences (USA)
NGO	non-government organization
NMS	nuclear male-sterile
ODI	Overseas Development Institute (UK)
PDR	pathogen-derived resistance
PLRV	potato leaf roll virus
PPB	participatory plant breeding
PRA	participatory rural appraisal
PTD	participatory technology development
PVS	participatory varietal selection
QTL	quantitative trait locus
R&D	research and development
RAFI	Rural Advancement Foundation International
RAPDs	random amplified polymorphic DNA
RRA	rapid rural appraisal
RYMV	rice yellow mottle virus
SCARs	sequence characterized amplified repeats
SEARICE	Southeast Asia Regional Institute for Community Education
SIDA	Swedish International Development Agency
SLS-MAS	single large-scale marker-assisted selection
SLU	Swedish Agricultural University
SWP-PRGA	Systemwide Program on Participatory Research and Gender Analysis

UATAPPY	Unión de Asociaciones de Trabajadores Agrícolas, Productores y Procesadores de Yuca (Ecuador)
UNEP/CBD/ExCOP	United National Environmental Program, Convention on Biological Diversity, Convention of Parties
UNIDO	United Nations Industrial Development Organization
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
UTM	Universidad Técnica de Manabí (Ecuador)
VIPs	Vegetative insecticidal proteins
WARDA	West Africa Rice Development Association