Transitions in Agbiotech: Economics of Strategy and Policy

EDITED BY
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Proceedings of NE-165 Conference
June 24-25, 1999
Washington, D.C.

Including papers presented at the:

International Consortium on Agricultural Biotechnology
Research Conference
June 17-19, 1999
Rome Tor Vergata, Italy

PART FIVE: Developing Countries

25. Investment Strategies for Biotechnology in Emerging Research Systems

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Chapter 25

Investment Strategies for Biotechnology in Emerging Research Systems

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Introduction

After years of heavy investment, much of it by the private sector, biotechnological processes and products are becoming mainstream in some crops in industrialized countries, especially in the USA. A few large developing countries, such as India, China, Mexico, and Brazil, have also developed considerable capacity in biotechnology research and in some cases, these products and processes are being commercialized. However, most countries of the developing world have little research capacity in biotechnology, especially in molecular biology and genetic engineering, and in addition do not have a regulatory framework to be able to legally acquire and safely release products of biotechnology.

This chapter will discuss investment strategies for emerging research systems of small- and medium-sized developing countries in dealing with biotechnology. Most of these countries are struggling to develop sustainable research programs, against a background of a public funding crisis for research, fragile public research organizations, and growing demands on science to address problems of rural poverty, food security, and environmental conservation. For these countries, lack of an appropriate regulatory framework, small market size, and predominance of resource-poor farmers will severely limit private sector investment in research and development (R&D) for the foreseeable future.

An incomplete summary of the biotechnology and regulatory capacity for some developing countries is shown in Table 1. Most countries in this sample are relatively large (populations exceeding 50 million). Among the small- and medium-sized countries, with the exception of Kenya, capacity is very limited, and most have yet to formulate a coherent investment strategy for biotechnology research, nor do they have the capacity to evaluate even imported biotechnologies. Overall, we estimate that less than ten percent of developing countries have established mechanisms to evaluate risks and benefits of new biotechnologies and few have an intellectual property right's (IPR) framework that would allow them to acquire biotechnologies from abroad. Although many countries are moving toward establishing these regulatory mechanisms, as required by international treaties, progress has been slow.

Against this background, the objectives of this chapter are to: (i) develop a conceptual framework within which to analyze biotechnology research investment decisions by emerging national agricultural research systems (NARS), (ii) discuss investment

decisions and estimate approximate investment needs for different types of biotechnology capacity, including an appropriate regulatory framework, (iii) analyze investment decisions in biotechnology research capacity within the conceptual framework, and (iv) review strategies and priorities for enhancing cost effectiveness for biotechnology investment decisions. We build on our previous work on efficiency and investment decisions in crop improvement research in small- and medium-sized national research systems (Maredia and Byerlee 1999), and analyze how recent advances in molecular biology might affect research and investment strategies. A benefit-cost framework will be used to discuss options, in light of the limited human and financial resources that characterize emerging research systems. Special attention will be given to the role of regional and international collaboration and spill-ins in realizing economies of size in R&D and technology policy.

TABLE 1 Overview of Agricultural Biotechnology Research Capacity in Selected Developing Countries

Country	**No. of key public institutions with biotech research capacity**	**Research focus[a]**	**Total no. of researchers in public institutions[b]**	**Research Expd. (M $US)**	**Status of Biosafety framework**	**Status of IPR framework**
Mexico	65 labs across 10 key institutions	-TC -MB -GE	216	11.5	Institutional-ized in 1989	Comprehensive IPR policy is in place
Egypt	NA	-TC -MB -GE	NA	NA	Put in place in 1995	PVP law pending in parliament
Indonesia	31 labs across 5 key institutions	-TC -MB -GE	274	6.0	Put in place in 1997	Patent law revised in 1997 to include animals and crops. PVP not in place yet.
Kenya	13 labs across 4 key institutions	-TC -MB -GE	49	1.1	Approved in 1999	PVP office in place
Peru	15 labs across 3 key institutions	9 TC labs and 2 MB labs	10	NA	Approved in 1999	PVPs approved but not being implemented
Ethiopia	6 key institutions	All focus on TC	NA	NA	None in place	None in place
Ghana	3 key institutions	TC and one MB lab.	< 10	NA	None in place	None in place

Source: ISNAR studies (for Indonesia, Kenya, and Mexico). Other countries – personal communication with key researchers in a country.
NA = not available
[a]TC = Tissue culture; MB = Molecular biology; GE = Genetic engineering.
[b]Includes researchers with Ph.D. and/or M.S. degrees.

Setting the Context: Biotechnology and Crop Improvement Research

Biotechnology uses the disciplines of molecular biology, microbiology, genetics, biochemistry and plant breeding to translate basic biological knowledge into practical processes and products that have economic implications. It encompasses a range of techniques and technologies, that require differing levels of investment. Techniques for plant biotechnology, which is the focus of this chapter, range from simple and widely-used cell and tissue culture to sophisticated and more expensive tools of recombinant DNA and genetic engineering.

Investment requirements in research capacity building, product development and technology transfer, vary widely for different applications of biotechnology. For example, cell and tissue culture techniques have modest investment requirements (under $US 50,000) and can be used to achieve near-term goals in a plant breeding program like mass production of uniform and disease-free planting materials, facilitating difficult inter-specific and inter-generic crosses, and eliminating breeding cycles. These techniques are already fairly widely used in developing countries, especially for vegetatively-propogated and high value crops.

The discussion in this chapter focuses on the investment decisions and strategies for the higher end of biotechnology research grouped under the rubric of DNA technologies. The two main categories of DNA technologies that are relevant to crop improvement are molecular markers (including genetic mapping) and genetic transformation. *Molecular marker technology* uses various techniques[2] to aid in cultivar identification, assuring seed lot purity, conducting wide crosses, and in marker-assisted selection processes in plant breeding efforts. These techniques affect the *efficiency* of crop improvement by reducing the time required to screen and select individuals in breeding populations. *Genetic transformation technology* uses various recombinant DNA technology and tools to isolate, clone, recombinate and insert genetic materials to produce "transgenic" varieties, thus affecting the *final product* of crop improvement research.

The evidence of the growing role of molecular biotechnology (both as a complement and a substitute to conventional plant breeding) is given by the increasing range of applications being explored in plant research. Some estimates suggest that molecular marker technology can halve the time needed to produce new varieties with resistance to important crop diseases. The use of molecular markers is also accelerating progress in the development of genetic resistance to insects and of tolerances to drought, salinity, and heat.

Transgenic approaches considerably broaden the range of gene pools accessible for crop improvement purposes. Thus, for many pests, pathogens, and environmental stresses which seriously limit agricultural productivity, genetic transformation approaches may provide new options where current options are lacking in their efficacy or existence (e.g. nuclear male sterility, improved heterosis breeding, reduced food toxins, increased nutritional content, herbicide tolerance, and novel resistance genes for a range of pests). Genetic transformation may also speed up the breeding process as it may

allow the incorporation of resistance genes from wild relatives faster than by conventional breeding approaches.

Biotechnology can both complement and substitute conventional breeding research which will remain the major means of maintaining and improving crop yields in farmers' fields. Strong conventional plant breeding programs are needed to translate the results of genetic engineering into finished varieties. Some tools of modern biotechnology, such as molecular markers and tissue culture, may partially substitute for conventional breeding by making it possible to skip some intermediate steps in the selection or crossing procedures of crop improvement research through laboratory and green house procedures.

In order to take advantage of these biotechnologies a country will have to invest at a different order of magnitude than in conventional plant breeding research. To build biotechnology research capacity will require considerable investment in human and financial resources. It also requires a sound regulatory framework to guard against risks of damage to the environment and health, and to provide intellectual property protection. For many biotechnologies such as tissue culture, marker-assisted selection and genetic mapping, biosafety and food safety are not issues. However, the need for biosafety regulations arises from concerns related to the risks of deploying genetically modified organisms (GMOs) on genetic diversity, environment, and human and animal health. Establishing a national biosafety system and assuring the compliance with these regulations also facilitates faster public acceptance of the products of modern biotechnology.

Similarly, for emerging countries to take advantage of molecular biotechnologies they will require a sound policy on IPR that includes comprehensive patent and plant variety protection laws. This is needed to facilitate cooperation and partnership between the public and private sectors. Many modern biotechnology innovations are intellectual properties that reside with the private sector in the industrialized world and a strong IPR framework is essential to access these technologies and build research capacity in molecular technologies. Although genetically modified organisms can be directly acquired from outside the country, this requires biosafety, IPR and food safety regulations to access the technologies, attract private sector investments, and facilitate commercialization and trade with the international community.

A Conceptual Framework for Analyzing Investments in Crop Improvement Research

Public Versus Private Roles

This chapter focuses on decision making for public investments in biotechnology research capacity. Since the private sector dominates biotechnology R&D in industrialized countries, the immediate question is why a model of public investment decision making is required. One might argue that the major role of the public sector should be to put an effective regulatory system in place for biosafety and IPRs, ensure that there are

no regulations negatively impacting private sector investments (e.g., varietal release procedures), and leave the introduction of biotechnology to the private sector.

However, we believe that for the foreseeable future, the public sector in emerging research systems will have to play a major role in developing crop varieties for many food crops, whether through conventional breeding or through biotechnology. First, direct spillovers from current biotechnology research in the private sector in temperate areas of industrialized countries are likely to be minimal due to differences in crops and type of problem in sub-tropical and tropical ecologies. However, many of the processes now used in industrialized countries could readily spillover to developing countries. Second, small market size and the dominance of resource-poor farmers act as a strong disincentive for private R&D in many countries with emerging research systems. Third, even with strengthening of IPRs in many countries, it will not be cost-effective to enforce them in small-farm situations. Except in some cases where hybrid-seed technology is available, it will be difficult for the private sector to recoup investments.[3]

In commercial agriculture and for commercial crops, like cotton, it is likely that the private sector will be able to assume a dominant role. For most self-pollinated crops in small-farm agriculture, the public sector, both international and national, will continue to play the lead role. For crops, like maize, where hybrids are already grown and the private sector is active, some public-private sector mix will prevail. The initial establishment of hybrid seed markets in small-farm agriculture has largely been through public sector efforts in breeding and extension (Byerlee and Lopez-Pereira 1994), and similar initial investments by the public sector will also likely facilitate eventual private sector entry with adapted biotechnology products into these hybrid seed markets.

A Decision Framework for Public Investments

Since the focus of this chapter is the public sector, investment decisions are analyzed based on the criterion of whether research generates social benefits large enough to justify investments in building biotechnology research capacity. A common method used in the economic's literature to determine the efficient level of investment is to estimate a production function relating investments to outputs. A research production function can be conceived as a meta-function made up of discrete research programs of increasing complexity and scope as the size of the research effort expands. Decisions typically involve an addition of sub-programs which will increase the number of researchers in a program, add research infrastructure and in turn affect the *research focus* and *capacity* of a research program. For a conventional crop improvement program, discrete steps can be categorized as follows:

1. Spontaneous diffusion of imported technologies without the benefit of local R&D.
2. Direct transfer of technologies after testing and screening by local R&D programs for adaptability to local environments.

3. "Adaptive" transfer of technologies whereby finished technologies from elsewhere are subject to local adaptation before local release (e.g., the use of imported varieties as parents in local breeding programs).
4. Comprehensive applied research where imported knowledge from basic research conducted elsewhere is utilized in local applied research programs to produce home-grown technologies.
5. Comprehensive basic and applied research which utilizes imported knowledge but also has the ability to conduct its own basic or pre-technology research.

These various types of research programs often result in discontinuities in the production function as each new step requires a minimum investment. For example in a crop improvement program, the transition from step 2 to step 3 involves the addition of a crossing program and early generation selection which is considerably more expensive than testing (step 2) (Brennan 1989).

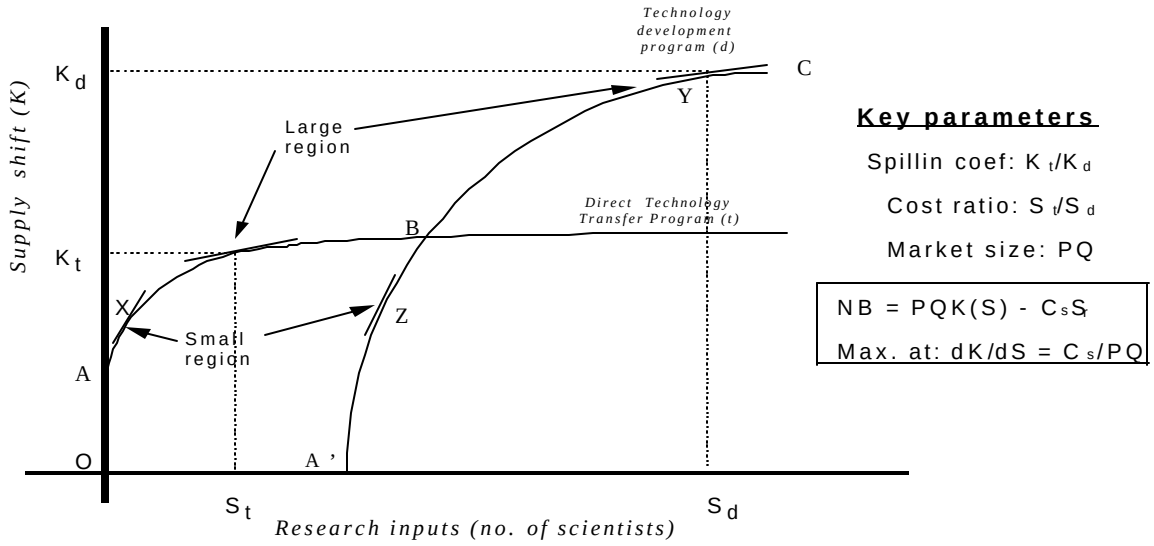
Figure 1 shows how research spillins (i.e. technologies resulting from research conducted elsewhere) and market size affect the choice of research program capacity for the cases of direct and adaptive spillovers of technology (steps 1 to 3 above). Without research, some spontaneous diffusion may take place, given by OA. With local capacity to seek out, screen and test technologies from elsewhere for direct transfer, a new stage of the production function is reached given by AB. The shift to adaptive transfer research requires the addition of specialized skills and facilities and a minimum threshold level of research effort, OA', is needed to produce research output. Further research inputs allow movement along the research production function from B to C. Abstracting from differences in timing of research costs and benefits, the net benefits (NB) of research investments are given by:

$$(1) \qquad NB = PQK_r(S) - C_sS_{r,}$$

where, $PQK_r(S)$ is the conventional measure of the change in the economic surplus (ΔES) assuming perfect elasticity of demand and perfectly inelastic supply. Variable P is the price of output Q affected by the research, $K_r(S)$ is the research production function of Figure 1 relating the shift in the supply curve, K, to research input, S, measured here in scientific person years with unit cost, C_s. The subscript, r = t, d represents research production functions for direct technology transfer (step 2), and adaptive transfer (step 3), respectively.

NB is maximized at $dK/dS = C_s/PQ$. That is, the optimal size and scope of the research program will depend on parameters of the research production function, and the cost of research inputs in relation to market size, PQ. Thus it may be profitable for a small region or country (implying higher C_s/PQ ratio) to operate at X with a direct transfer program, while a research program for a larger region or country (implying lower C_s/PQ ratio) would operate at Y on the adaptive transfer function (Figure 1).

FIGURE 1 Research Production Function for Direct Technology Transfer and Adaptive Transfer Programs



Source: Byerlee and Traxler (1996).

Adding fixed costs, the production functions in Figure 1 allow for both economies and diseconomies of size as the size of the program expands. The shape of the cost function will be determined by three key parameters in Figure 1.

1. K_t/K_d, representing the value added from adaptation of imported technologies. This ratio is directly related to the common definition of the spillover coefficient k_t/k_d, where $K = \alpha k$, k is the relative decline in production cost per unit area, and α is the adoption level,
2. S_t/S_d, representing the additional cost of moving from direct transfer to adaptive transfer research. This ratio as well as fixed costs, determine economies of size in research, and
3. PQ, the market size targeted by the research program.

An additional dimension not included above is the differences in research lags for various types of research. Generally research lags become longer in moving through the various stages of research complexity given above, but the use of some biotechnologies may reduce lags.

Options for Biotechnology

The above model can be conceptually expanded to include biotechnology processes and products. To reflect the practical decision-making problem of research managers, discrete investment decisions in plant biotechnology can be analyzed in terms

of research capacity or type of biotechnology research program. Thus, the basic decision variable in our model is specific research capacity, rather than research expenditures *per se*. Investment decisions can then be based on the criterion of whether research generates economic surplus large enough to justify investments in building research capacity.

For investment decisions at the higher end of modern biotechnology, a country has several options to phase-in the development of capacity. These options are:

1. Import biotechnology products (such as transgenic varieties) from other sources and incorporate them into the conventional crop improvement program, either by back crossing with local germplasm or including them immediately in a local testing program. This will improve the *product* of crop improvement research to the extent that the transgenics include traits which are appropriate to the local situation, and therefore affect research benefits.
2. Import tools of biotechnology, such as molecular markers, and utilize them to facilitate selection in the local breeding program. This will improve the *efficiency* of crop improvement research, and therefore affect research costs and research lags.
3. Establish a full research program to develop *new* tools and products of biotechnology by conducting basic, comprehensive and applied research to improve both the *efficiency* and *product* of crop improvement research (e.g., develop molecular markers and undertake genetic transformations). This will affect research costs, benefits and lags.

These options are not mutually exclusive so that the use of molecular markers in a breeding program, for example, may be combined with importation and testing of GMOs.

The basic formula for estimating the net benefits (NB_t) associated with these options is as given in equation 2:

(2) $NB_t = \Delta ES_t - C_t$

where, change in economic surplus ΔES_t , is defined as:

(3) $\Delta ES_t = K_t P_t Q_t$

and research cost C_t , is defined as:

(4) $C_t = C_{pt} - \mu C_{it} - \nu C_{nt}$

Thus, total research costs, C_t represent various types of costs. Some costs, C_p, occur at the program level, and can be treated as for a conventional breeding program. However, other research costs at the institute level, $C_{i,,}$ and regulatory costs at the national level, C_n are shared across programs. These are represented above by the parameters, μ, $\nu < 1$, so that institute and national level costs are pro-rated across programs according to some criteria such as size.

The appropriate yardstick for judging whether a research option is acceptable is the investment's net present value of ΣNB_t over time for each research investment option. To be acceptable on economic grounds, an investment option must meet two conditions: (a) the expected net present value of the investment in a given option must not be negative, and (b) the expected net present value of the investment must be higher than or equal to the expected net present value of investment alternatives. The main parameter estimates to operationalize this framework are K, $C_{it,}$ and μ and ν.

In the following section, we examine the investment needs of emerging research systems in building capacity in both the areas—biotechnology research and the regulatory framework—with the aim of making a preliminary assessment of the magnitude of their costs. Throughout we emphasize investment in the high-end biotechnology processes—molecular markers and genetic transformations.

Investment Needs to Conduct Biotechnology Research

Investment in Research Capacity

Building research capacity to conduct advanced biotechnology research is a resource-intensive endeavor. Table 2 provides estimates of the cost in human and financial resources to establish one moderate-size research facility to conduct research in molecular marker and genetic transformation technologies in two countries. The cost of establishing a laboratory for molecular marker technology is about $US 150,000 to $200,000 with an annual operating costs (including personnel and overhead costs) of $US 100,000. The costs of establishing and operating an advanced genetic transformation laboratory is almost double that of a molecular marker laboratory. However, the costs of establishing a molecular marker or a genetic transformation laboratories, is changing rapidly both in the industrialized and developing countries with the decline in the cost of laboratory equipments (e.g., gene gun). These cost estimates, therefore need to be periodically revised to reflect the changing costs of major equipments.

The human resource costs to a country are not only those related to the annual compensation costs (salaries and benefits) but also training costs that are not reflected in Table 2. A country will have to incur significant investments in training researchers (mostly at Ph.D level) in basic sciences, and in research and organizational skills to operate and maintain a research laboratory. In addition, technicians will need to be trained in the skills of day-to-day maintenance, quality control and operation of a biotechnology research laboratory. These training costs based on external degrees are likely to double the total investment requirements (about $150,000 per Ph.D).

Thus, investment needs in building research capacity in biotechnology (beyond tissue culture) are substantial. To put this in perspective, a conventional wheat improvement research program (defined in terms of a specific mandate region) in developing countries typically requires 2 to 5 full-time equivalent researchers with a total annual cost estimates in the range of $US 40,000 to $US 100,000.[4] The investment needs for other

conventional crop improvement research programs are likely to be of the same order of magnitude.

TABLE 2 Cost of Establishing Molecular Marker and Transformation Technology Laboratories: Estimates from Selected Countries

	Molecular Marker Technology		Genetic Transformation Technology	
	South Africa	**Egypt**	**South Africa**	**Egypt**
Capital costs				
Establishment costs of facilities and equipment ($US)	140,000	200,000	120,000	250,000
Establishment of biocontainment facilities ($US)	NR[a]	NR	115,000	200,000
TOTAL Capital costs	***140,000***	***200,000***	***235,000***	***450,000***
Annual operating costs				
a. Laboratory ($US)	20,000	50,000	25,000	70,000
b. Biocontainment facilities ($US)	NR	NR	5,000	8,000
c. Utilities ($US)	20,000	25,000	40,000	35,000
Annual personnel costs ($US)	65,000	60,000	140,000	115,000
TOTAL Annual costs	***105,000***	***135,000***	***210,000***	***228,000***
Human Resources (critical mass)				
a. Number of researchers per year	2	2	5	4
b. Number of technicians per year	1	2	2	3
c. Number of assistants per year	2	2	3	3

Source: South Africa (Dr. Johan Brink, personal communications); Egypt (Dr. Magdy Madkoor, personal communications).

[a]NR = Not required

However, compared to conventional crop breeding, investments in higher-end of biotechnology research are characterized by considerable economies of scope since costs are likely to be shared across several research programs. For example, investment in a molecular marker and genetic transformation laboratory leads to research infrastructure and techniques that are not commodity-specific and that can be shared across crop research programs and even with livestock research. In some cases, however, physical isolation of specialized national commodity research institutes may make it difficult to realize these economies of scope.

Another distinguishing (and encouraging) feature of biotechnology research capacity is the continuing trend in the reduction of costs of doing biotechnology research. For example, the cost of gene sequencing needed for effective use of molecular markers is reported to be less than 10% of what it was five years ago.

Investment in Regulatory Frameworks

Biosafety. An efficient biosafety system is one of the prerequisite for realizing the potential benefits of advanced biotechnologies, especially transgenic technologies. Establishment of a biosafety system, however, adds costs. A specific aspect of national capacity building relates to the capacity to review and manage the environmental and human safety aspects of genetically engineered plants, animals, and vaccines. A comprehensive biosafety regulatory framework has many facets, including the formulation and adoption of safety guidelines, establishing national and institutional biosafety committees, and constructing additional infrastructure for small-scale, contained trials and large-scale field testing (Table 3). It entails administrative and staff costs in the form of hiring inspectors, conducting risk assessment tests, and carrying out the day-to-day administration of applications, approvals and complaints. In addition to physical and organizational infrastructure, a country will need human resource capacity to assess risks of a range of products from transgenic plants to recombinant livestock vaccines. Human resources knowledgeable in various fields of agricultural, health and environmental sciences will thus be needed to assess these risks appropriately.

TABLE 3 Summary of National-, Institute- and Program-Level Costs of Establishing a Biosafety System

Cost Components	**National**	**Institute**	**Program**
Development of biosafety policy (guidelines, regulations)	■	■	
Maintenance of national biosafety committee	■		
Human resource development and awareness creation	■	■	
Administration and review of biosafety permit applications	■		
Institutional biosafety committee/biosafety officer		■	
Monitoring costs (risk/benefit assessments)	■	■	■
Establishment and maintenance of biocontainment facilities		■	■
Time investment by researchers to generate data for permits			■
Conducting field trials as per biosafety guidelines			■

All countries establishing a biosafety regulatory framework, will incur costs at the national level. There will also be costs for those research institutes and programs that engage in biotechnology research with potential risks (Table 3). Table 4 summarizes approximate investment and resource costs in two countries to implement biosafety system at the national- and institute-level. Clearly the major costs are in additional human resources (e.g., biosafety officers) and in training.

In most countries where a biosafety system has been established, most of the costs have been paid by governments. International donor agencies have contributed significantly in terms of building capacity to develop biosafety guidelines, train researchers and policy makers, and conduct needed reviews.

TABLE 4 Cost Implications of a Biosafety System at the National- and Institute-Levels in Selected Countries

	Egypt	Indonesia
National-level		
Time required to develop the biosafety system	4 years	3 years
Human resources:		
• Number of researchers/ and policy makers trained	8	12
• Number of members in the National Biosafety Committee	31	11[b]
• Size of National Biosafety Committee in terms of number of FTE members	2	2
Institute-level[a]		
Human resources:		
• Size of the Biosafety Program/Office (FTE)	4	1.4
Research costs:		
• Additional time needed to get biosafety approvals	3 months	9 months
• Annual opearing costs of biocontainment facilities	$8,000	$3,000
• Biosafety permit application fees	none	$1000-$1400 for pvt company $250 -$500 for public institutes

Source: Information for Egypt was provided by Dr. Magdy Madkoor and for Indonesia by Dr. Muhammad Herman.

[a]Insititute-level estimates correspond to the following institutes: Egypt -- Agricultural Genetic Engineering Research Institute; Indonesia -- Research Institute for Food Crops Biotechnology.

[b]In addition to a National Biosafety Committee, Indonesia has a 11 member Technical Advisory Committee that works closely with the Biosafety Committee.

Intellectual Property Protection. Accessing molecular technologies and generating new technologies by building local capacity will incur costs of acquiring biotechnology processes and products (in the form of license fees and royalty payments) and costs of protecting intellectual properties (i.e., establishing an in-country IPR system and protecting locally-developed products and processes both in-country and in other countries).

Developing countries who are members of the World Trade Organization (WTO) are obliged to establish an IPR system for agricultural and biotechnology processes and products (by the year 2000 for some countries, and by 2005 for the least-developed countries).[5] The costs and impacts of these changes are not dear. In theory IPRs should stimulate innovation and economic growth by mobilizing private sector investments in local biotechnology research and development (R&D). However, IPRs may have social costs due to the granting of temporary monopolies which allow firms to charge above the marginal cost of diffusing an innovation (e.g., Perrin 1995). To minimize these social costs in emerging countries, the public sector may have to play an important role in biotechnology research capacity building.

Cost implications of IPRs at the national-, institute- and program-level are summarized in Table 5. The investment implications of the WTO agreement are that countries will have to introduce much stricter intellectual property protection regulations, establish technology transfer offices at the national-level, and develop appropriate policies and infrastructure for IPR enforcement. National level costs will also include training and education in IPR issues for policy makers, legislators, patent examiners, members of the judicial system, and administrators.

TABLE 5 Summary of National-, Institute- and Program-Level Costs of Establishing an IPR System for Agricultural Biotechnology

IPR Cost Components	**National**	**Institute (as needed)**	**Program (as needed)**
Developing national IPR policies (patent laws, PVP laws, legislative approvals)			
Enforcement/implementation costs (e.g., national PVP office)			
Training and education (policy makers, administrators, patent examiners)			
Developing insitutional IPR policies/guidelines/handbooks			
Establishing and operating IPR management office/Focal point			
Negotiation for research and license agreements, material transfer agreements			
Cost of database searches and legal fees for patent/PVP application preparation			
Cost of filing and maintening patents, PVP and other forms of IP protection			
Cost of accessing proprietary technology (royalties, technology fees)			

At the institute level, IPR costs may include development and operation of an IPR management and technology transfer office responsible for day-to-day handling and management of intellectual properties. The office would play an active role in the development of institutional IPR policies, protection and licensing of intellectual properties and education of researchers on IPR management issues. Some costs, such as patent filing fees, database searches, legal fees for preparation of applications for plant varietal protection, patents, and negotiation costs may also be incurred at the research program level. An institution or individual research program may also incur costs related to accessing a specific piece of proprietary technology.

Since the establishment of an IPR office can be quite costly, emerging NARS may initially need only a small office with legal and business management expertise contracted on a short-term basis. This office can then expand as IPR management activities increase.

Food Safety. Modern biotechnology also raises a host of food safety concerns related to the production of toxins and allergens in food products derived from GMOs and other biotechnological processes. Food safety standards, guidelines, and other recommendations of the Codex Alimentarias Commission (CAC)[6] are explicitly recognized under the WTO Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement).

Developing the national food safety policies, adhering to the CAC food safety standards and guidelines, and meeting the SPS and TBT Agreements thus pose additional costs to emerging systems of developing countries. These costs will include (a) updating or developing national food safety standards, (b) conducting food safety research and experiments to assess the potential allergenicity or toxicity of foods, testing possible gene transfer from GMOs, testing for pathogenecity deriving from the organisms used, and analyzing nutritional content, (c) time costs in getting food safety approvals, (d) product labeling costs, and (e) monitoring costs.

Many of these costs will be borne by governments and incorporated into the existing national food administration system. However, costs of conducting food safety research and costs associated with obtaining food safety approvals may have a direct impact on research insitute- and program-level costs for biotechnology research.

Analyzing Investment Options for Biotechnology

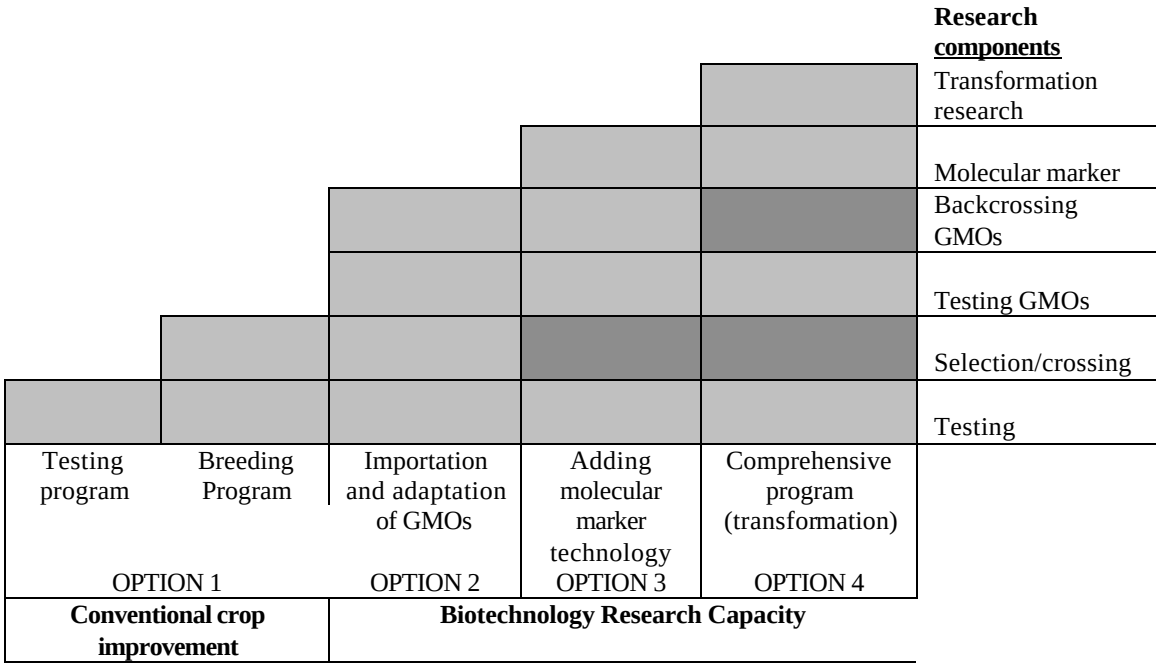
The above review indicates that the development of biotechnological research capacity will require potentially large investments in physical, human, institutional and organizational infrastructure. Emerging research systems need to position themselves to take advantage of the evolving potential of biotechnological research but the amounts to be invested must be defined within the context of the limited finances, the opportunity costs of these investments in other high priority research, and the existing organizational structures of these national systems. It is within this constrained funding environment that agricultural research institutions will have to make decisions on potential applications of, and level of investments in biotechnology research capacity.

Defining Investment Options

For the analytical purposes of this paper, four investment options are considered in increasing order of investment costs: (1) continue to invest in conventional crop improvement research program (either at a testing capacity or a full-fledged breeding program capacity) using non-biotechnology mechanisms for solving a problem (e.g., conventional breeding for pest resistance), (2) invest in a regulatory framework to enable importation and evaluation of biotechnology products (e.g. direct introduction and testing of transgenic varieties or back crossing of transgenic varieties in a conventional breeding program) or (3) invest in research capacity to import biotechnology tools (e.g., molecular marker techniques) to improve the efficiency of plant breeding research and shift back-

crossing research from field to greenhouse facilities, and (4) invest in building comprehensive research capacity (e.g., genetic transformation technology) to create tools (e.g., gene constructs, gene maps) and products (e.g., transgenic varieties) of biotechnology. Options 2 and 3 may be classified as adaptive biotechnology programs, while option 4 is a comprehensive program.

FIGURE 2 Research Components Associated with Different Levels of Conventional and Biotechnology Crop Improvement Research Capacity



As a research program shifts from conventional crop improvement research to adaptive biotechnology to comprehensive biotechnology research, we assume it adds new components of research capability in a sequential manner according to investment costs (Figure 2). A program to import GMOs (option 2), for example, will include conventional testing and crossing components in addition to back crossing and testing GMOs. Similarly, a biotechnology research program that uses molecular marker technology (option 3) will include the GMO-back crossing and GMO-testing components of Option 2.[7] A comprehensive biotechnology research program with transformation capability (option 4) will similarly include all the components of an importation and adaptation program, a molecular marker technology program, and the capacity to generate new tools and products.

As a research system adds new components of biotechnology, these may either complement or substitute previous research components. For example, adding the molecular-marker technology component in option 3 and option 4 may in some case substitute conventional crossing and selection processes. This is represented in Figure 2

by the dark shading to indicate potential reductions in activity. Similarly, adding the transformation capability in option 4, may substitute the GMO back-crossing step for certain traits and commodities (Figure 2).

The efficient choice among alternative investment options of continuing with non-biotechnology research (option 1) or importing and creating biotechnologies (options 2 to 4) will differ greatly across commodities and countries, depending on the size of the commodity sector, physical environment, resource costs, productivity impacts of research, research lags, economies of size and scope in research, and the potential for research spill-ins (i.e., the availability of appropriate biotechnology tools and products for a given crop or constraint from other sources). The first step towards this analysis is identifying and estimating the costs and benefits of investing in different options for biotechnology research capacity within the local situation.

Costs and Benefits of Investment Options

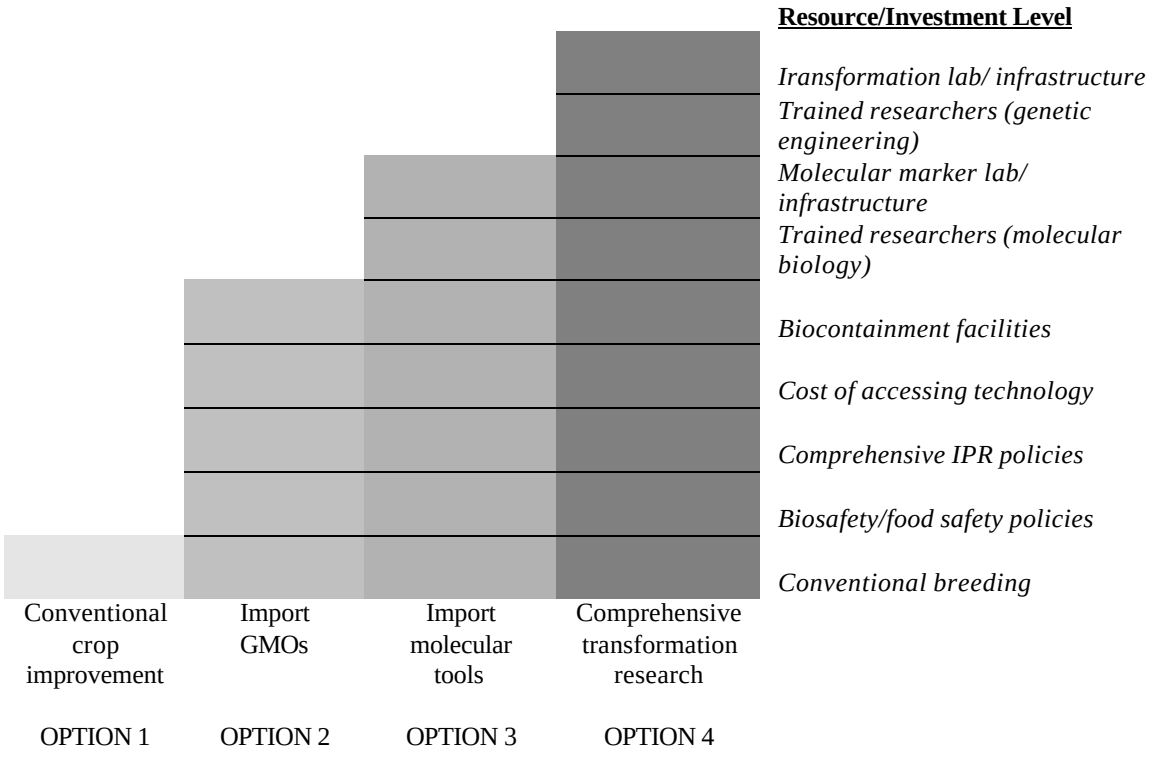
The additional components of investment under different options of biotech-nology research capacity identified above are illustrated in Figure 3 as mix of regulatory and research costs. Whatever the level of investment and research capacity in biotech-nology, a country must have a good plant breeding research capacity (crossing, selection and testing) in order to make biotechnology a useful investment. Hence research capacity in conventional crop improvement research (with at least a testing component) is included for all biotechnology research options.[8] The biotechnology research options require added investments in both regulatory capacity (indicated in italics in Figure 3) as well as research capacity.

Figure 4 illustrates the additional benefits (positive and negative) of different biotechnology research options in relation to a conventional crop improvement program. Biotechnology can increase the efficiency of crop improvement programs by reducing research lags, improving the precision of selection and reducing the number of lines in field testing, and making breeding programs more deterministic (i.e., increase the probability of research success). The benefits of biotechnology research may also be reflected in price premiums for enhanced product quality and desired commercial characteristics. These impacts, obviously increase with the level of research capacity. Although not reflected in Figure 4, the magnitude of the increase in the productivity of the final product will be larger for comprehensive research targeted on local problems and opportunities (Option 4) than for Options 2 and 3 using imported technologies.

Biotechnology research may also negatively impact research benefits (compared with conventional crop improvement research) through possibly reduced adoption rates by producers and perhaps a price discount on consumer products due to negative public reaction to GMOs. GMOs may also initially increase research and product development lags by increasing the time period needed to conduct laboratory tests to generate data, to get approvals from biosafety regulatory agencies, and to conduct field tests before making a biotechnology product available in the market. However, as a country gains

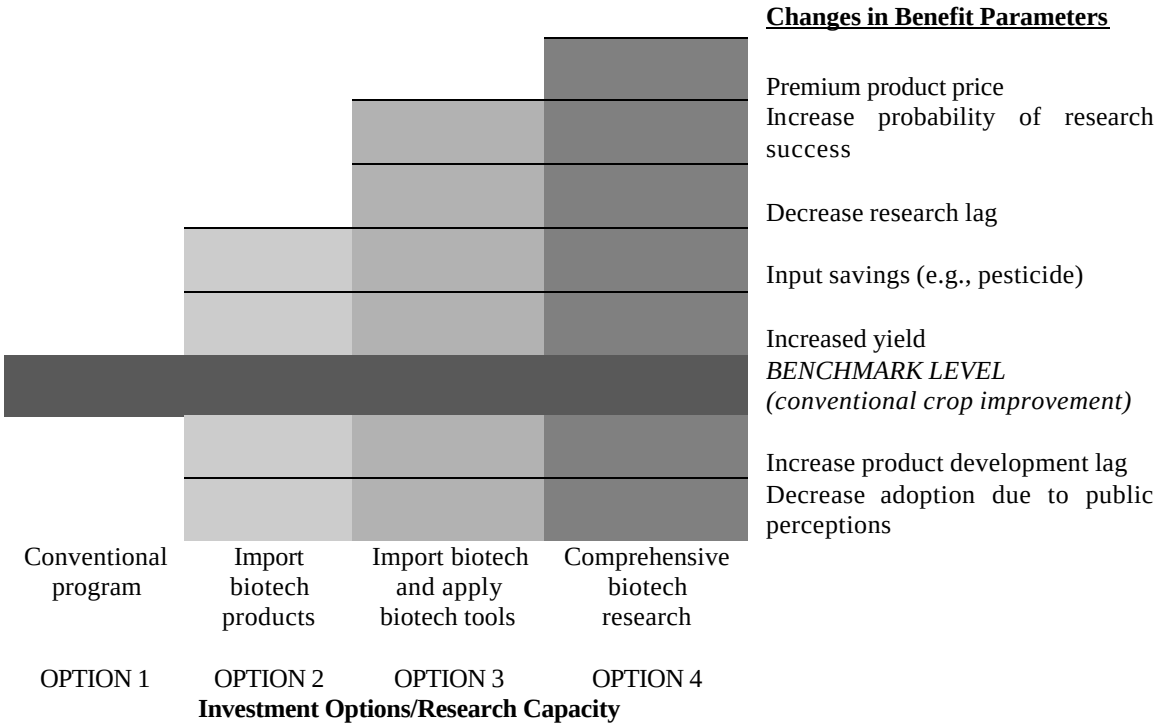
experience in dealing with biosafety applications and the review process becomes routine, the approval lags may eventually shorten (as in the case of U.S) and may not significantly delay product development.

FIGURE 3 Investment Levels and Resource Needs for Different Levels of Biotechnology Research Capacity



The magnitude of cost differences (illustrated in Figure 3) and changes in benefit parameters (illustrated in Figure 4) for the different options of biotechnology research capacity are empirical questions. Introducing biotechnology in crop improvement research increases substantially the data requirements for investment decision making, both on the benefit and cost sides (Lynam 1996). For example, overcoming streak virus in maize can be pursued through a number of routes, including existing sources of resistance in conventional breeding programs, vector control or through biotechnology options 2 to 4. The resulting benefits in the form of productivity improvement may be the same, independent of what strategy is chosen but costs may vary widely. Effective investment decisions in biotechnology, therefore, rests on good estimates of research costs and benefits for a range of options, an area in which there has been very little empirical work.

FIGURE 4 Changes in Research Benefits for Different Levels of Biotechnology Research Capacity Compared with the Benchmark Level of Benefits from Conventional Plant Breeding Research



Because of economies of scope, many of the cost components identified in Figure 3 are national or institute-level costs, whereas the benefits in Figure 4 and equation 2 are realized at a commodity-level and are thus research-program specific. Investment decision making in biotechnology research is therefore complicated by requiring some biotechnology costs to be apportioned across research programs. These include investments in institutions (IPR and biosafety system establishment and implementation costs), human resources (training costs) and infrastructure (laboratory and research facilities) to build biotechnology research capacity.

However, adding a biotechnology component to an ongoing conventional crop improvement program will also entail some *program-specific costs* that will be reflected in their annual budget allocations (e.g., costs of accessing proprietary technologies, linking and coordinating laboratory research with field research, conducting field and laboratory tests to meet biosafety guidelines, etc.). Thus investment decisions need to be made at a program-level including program-specific costs and some share of non-program-specific biotechnology costs. In the following section, we describe a typical crop improvement research program for wheat. Using the general economic and conceptual framework discussed above, we analyze the impacts of biotechnology on investment decisions at a program-level.

An Example for Wheat

The resource allocation problem facing small countries for conventional crop improvement research is whether to invest in a testing program (which relies on spillins, i.e., varieties developed elsewhere and released by national program after testing and screening them for local adaptation) or a full-fledged breeding program (with both crossing and testing component to develop new varieties locally).[9] Results of a survey of of over 70 wheat research programs conducted by CIMMYT in the early 1990s indicate that the average developing country wheat improvement program employs five full-time equivalent (FTE) scientists in a fully-fledged wheat breeding program (including crossing and testing components) and two FTE scientist in a testing program (without local crossing) (Bohn et al. 1999). The average (median) cost per researcher (including overhead costs) in wheat improvement research in developing countries was estimated at US$20,000 (in 1992 $ converted at the official exchange rate [OER]). Thus the average annual cost of a conventional wheat breeding program (which includes both testing and crossing components of crop improvement research) in developing countries was estimated at about US $100,000 (in 1992 $OER).

Maredia and Byerlee (1999) used the economic framework discussed above (equation 1) to analyze investment decisions of a typical wheat improvement program in developing countries for two options—a testing program and a breeding program. These options were analyzed using data from the wheat program survey and international yield testing. If research spillins were minimal (the case where variety yields from a testing program increased at a rate of 0.6% per year compared with 1% per year of varieties developed by a local breeding program), and the research and development lags were 5 and 12 years, respectively for a testing and breeding program, the threshold size of wheat production in conventional wheat breeding program was estimated to be around 100,000 tons.

However, if research spillins realized in the recent past were assumed to continue in the future, such that yields of varieties from a testing program would increase at an annual rate of 0.86% compared with 1% for locally bred varieties, the threshold size of wheat production in the mandate region to justify a conventional breeding program (as against a simple testing program) increased to 275,000 tons. Overall, a surprising result was the finding of overinvestment in many programs. Twenty eight of the 69 wheat research programs analyzed appear to be overinvesting in wheat improvement research either because of the small size of the mandate region relative to the size of the research effort or because of the overemphasis on adaptive research instead of importing and testing varieties from international sources (Maredia and Byerlee 1999).

Adding the biotechnology research option 2 (i.e., importing transgenic wheat varieties from either public or private sources with desired characteristics and incorporating it in the back-crossing and testing programs) to the baseline scenario of an "average" conventional wheat breeding program (option 1) affects several model parameters and thus the threshold size of wheat production to justify research investments. Similarly, adding research capacities needed to use molecular marker

technology (option 3) and genetic transformation technology (option 4) in wheat improvement research will further affect the threshold size of mandate region to justify additional investments in biotechnology research capacity.

TABLE 6. Changes in the Model Parameter Values with the Addition of Different Levels of Biotechnology Research Capacity in Wheat Improvement Research Program

	INVESTMENT OPTIONS			
Economic analysis (model) parameters	**OPTION 1 (Baseline) Conventional breeding program [a]**	**OPTION 2 Import GMOs and backcross with local varieties**	**OPTION 3 Add molecular marker technology**	**OPTION 4 Add genetic transformation research**
RESEARCH BENEFIT PARAMETERS (Average values)				
K (annual supply shift due to genetic gains)	1%	increase depending on the traits targeted		increase substantially
Research lag (years)	10	no impact	decrease dramatically	same as option 3
Development lag (years)	2	Initially longer than in option 1(for GMOs)		
Adoption (% of target region)	100%	May be lower than 100%		
Price	average market price	Higher than average or no change depending on traits		
RESEARCH COST PARAMETERS (Average values)				
Number of researchers (FTE)	5	may increase	may increase by more than 1 FTE	may increase by more than 2 FTE
Cost per researcher	US$20,000	no change	increase substantially	increase even more
Technology access cost (licensing)	0	Positive change	may increase depending on the source of technology	increase substantially
Biosafety/food safety costs	0	Positive change		increase even more
Technology protection costs (IPR)	0	no change	may increase	Increase even more

[a]Source: Maredia and Byerlee (1999). Breeding program includes crossing, selection and testing components.

The decision criteria for research investment options will ultimately depend on the actual changes in the parameter values affected by biotechnology research. Table 6 illustrates how investments in different biotechnology research options will affect the parameter values of the baseline conventional wheat breeding research program (option 1). The actual result will greatly depend on research spillins—either from public or

private sources—available to developing countries in the form of biotechnology tools (molecular markers) and products (germplasm, gene constructs, gene mapping) for crops and traits relevant to developing countries environments. Empirical research to estimate these model parameters based on the actual spillins for different investment options in a developing country setting is still lacking. Estimating program specific costs of biotechnology research for components such as biosafety, IPR, and laboratory infrastructure, which are shared across programs, also poses a challenge and requires more empirical research.

According to the cost estimates given in Table 2, the addition of molecular marker technology (Option 3) and genetic transformation research (Option 4) will require additional operating costs of $120,000 for option 3 and $220,000 for option 4. The affect of these costs will depend on how many programs share the biotechnology laboratory. To provide an example of the potential impact of including biotechnology costs in the Maredia and Byerlee (1999) model, we assumed that the costs given in Table 2 are spread equally across five commodity research programs, and added a 20% overhead for regulatory costs. Under these assumptions, annual costs for an individual research program would increase by $30,000 for adding a molecular biology laboratory and an additional $50,000 for a transformation laboratory. Also pro-rating the average capital costs to a specific research program based on the assumption of 5 commodity programs sharing the infrastructure and spreading these costs over 4 years gives an annual capital costs (for the first 4 years) of $8,500 for a molecular marker laboratory and $17,000 for a transformation laboratory.

Table 7 gives the results of extending the model to options 3 and 4 for a wheat improvement program for differerent sized mandate regions for the program. Assuming that the research lag in options 3 and 4 is reduced by 3 years (almost half of the crossing and selection lag in option 1) and all the other parameters (i.e., adoption rate, product price, and discount rate) remain the same as in option 1, the yield gains (k parameter) needed to justify investments in options 3 and 4 at 100,000 t of wheat production (adoption size) is 3.2% and 6.3% per year compared with 1.2% per year estimated for conventional breeding research. These rates of gain are unrealistic, but as expected, with the increase in the adoption size of the mandate region, the threshold level of yield gains needed to justify investments in a given investment option decreases (Table 7). At a mandate size of one million tons of production, the rates of gain required to cover the biotechnology costs are 1.0% and 1.4% for options 3 and 4, respectively, compared to the conventional program gains of 0.9%.

Options 3 and 4 only make sense for countries that already have crossing and selection programs. To the extent, that research lags are reduced and traits can be targeted more precisely for local conditions, research efficiency is increased both in options 3 and 4. However, under what circumstances the relatively high investment at this stage would cause some of the 28 inefficient programs identified in Maredia and Byerlee (1999) to become efficient is not known. If cost trends for molecular markers continue their downward trend this will certainly enhance the wider use of these techniques.

TABLE 7 Yield Gains Needed to Justify Investments in Biotechnology Options 3 and 4 Compared with Option 1: Results of the Model Analysis by (Adoption) Size of the Mandate Region

Adoption Size (tons of wheat production)	**OPTION 1 Conventional breeding program**	**OPTION 3 Import biotech tools and test/backcross GMOs**	**OPTION 4 Comprehensive (add transformation)**
	Genetic gains in wheat yields to justify investments (%/year)[a]		
100,000	1.2	3.2	6.3
275,000	1.0	1.7	2.8
500,000	0.9	1.4	2.0
1,000,000	0.9	1.0	1.4

Source: Authors' calculations

[a]Assumes research spillins of 0.86%/year yield gains from a conventional testing program.

It is clear that for most emerging research systems, costs are very substantial and benefits would have to be high, or the costs have to be shared widely over many research programs, to justify local research capacity in higher-end biotechnology. The estimates given in Table 7 are necessarily notional and underscore the urgency of undertaking some detailed benefit-cost case studies of investments in biotechnology. Recent studies on the economic evaluation of investments in tissue culture and DNA technologies is a positive step towards generating empirical estimates for some key parameters affected by biotechnology research (e.g., Qaim 1998, Qaim 1999, Falck-Zepeda et al. 1998).

Strategies to Enhance Cost-Effectiveness

It is clear from the estimates presented to date, that small and emerging NARS will only be able to benefit from higher-end biotechnology processes and products, if ways can be found to reduce costs of acquiring and using these techniques. Cost-effectiveness can be pursued in building both research capacity and the regulatory framework.

Cost-Effectiveness in Research

Maximizing spillins will be key to cost-effectiveness of biotechnology research and testing. Thus the short-term strategy for small- and medium-sized emerging countries should be to access the intermediate or final products of biotechnology and adapt them to the local environments and needs. This suggests that initial investments in capacity should emphasize crops economically important to industrialized world (such as maize, wheat, potatoes, horticultural crops), since many transformation, regeneration and gene constructs have already been developed. Initial experience suggests that private firms are willing to provide proprietary technologies to some developing countries at low

costs, in part as "loss leaders" to encourage the implementation of appropriate regulatory frameworks, and in part, due to segmented markets, in which returns to direct private investment in some parts of the market are low. Therefore, investment in the regulatory framework to enable technology importation would be a higher priority than investment in biotechnology research capacity.

On the other hand, the development costs of the transformation, regeneration, molecular maps and gene constructs for many crops important to emerging country economies but not necessarily important for industrialized countries (e.g., millet, sorghum, cassava, plantains, etc.) are likely to be high as a result of lack of spillins. Moreover, small countries will have difficulty in recovering the investment costs in tool and product development for these crops.

In the longer run, in order to access proprietary technologies from the private sector in the industrialized world, NARS in developing countries will have to position themselves with some "bargaining chips". Seeking international protection of one's inventions is one option but is expensive. For example, in the US, patenting biotechnology inventions costs from $US 20,000 to $30,000 (including filing fees and legal costs). Costs of similar magnitude will also be required in Europe and Japan to provide comprehensive patent protection. NARS of small- and medium-sized countries may not be able to afford these high costs of international IPRs.

Since many developing countries are rich in genetic resources, these resources are increasingly seen as a potential bargaining chip for access to biotechnologies. Several countries now restrict the export of genetic resources, to enhance their bargaining position. Creating partnerships with private sector may allow them to integrate new tools of biotechnology to help improve the germplasm and commercialize it on a national or international scale. However, restrictions on germplasm exchange may have high social costs internationally, since free exchange of germplasm has been a central element in the international success of public research systems.

In any event, efforts by NARS and donor agencies will be essential to develop international public goods related to biotechnology that can improve efficiency of NARS investments. Collective action by NARS in a region or globally may be used to pool resources and to jointly negotiate access to technologies or to develop centralized regional research capacity that can capture economies of size. The CGIAR will also be critical as an intermediary in biotechnology research for many crops, especially crops that are largely grown in the developing world (e.g., cassava). However, their total effort is still modest, with only 7% of their budget invested in biotechnology and with efforts scattered across 15 centers. International research centers are just developing skills in negotiating with the private sector, and many of their biotechnology processes and products are based on proprietary technologies that are being used without clear agreements on commercialization of final products. Until clear IPRs are established even the biotechnology products of the CGIAR centers may not be readily available to NARS or developing-country farmers.

Cost-Effectiveness in Establishing Regulatory Frameworks

One strategy to enhance cost-effectiveness is to integrate biosafety, food safety and IPR frameworks within the existing legal and regulatory systems, rather than create new agencies and programs. Establishment of new regulatory systems must be based on the principle of flexibility to allow changes in the rules and regulations with the accumulation of experience. Many countries start out with a rigid system and relax it as they gain experience. This is an effective strategy if the strict standards do not deter private sector research and investment in biotechnology.

Both the biosafety and IPR regulatory frameworks present opportunities for cost-recovery and cost reduction. In designing the biosafety system, a country can explore the following mechanisms for enhancing cost effectiveness:

a. Charge an application fee for the permits for biosafety field testing, especially to the private sector and use these fund to support the national biosafety committee, risk-benefit analysis. This policy has been adopted by Indonesia, where the biosafety permit application fees are charged to both public and private sector institutions (Table 4).

b. Harmonize biosafety guidelines among countries in a region or establish a regional body, so that with a single application, GMOs can be tested and approved in all countries in a region. This is especially relevant to small countries sharing similar crop growing environments that have traditionally taken advantage of research spillovers from neighboring countries.

c. Integrate the biosafety system with the existing plant quarantine system so that costs of operation and implementation could be reduced by using the existing human and physical resources.

d. As experience and research results are accumulated, relax the permit application procedures. For example, in the U.S., for some crops and traits, only notification is now required, instead of full review.

Some of the cost-recovery and cost-reduction mechanisms that a country may consider for IPR are:

a. Charge application fees for plant variety protection, patents and other forms of IP protection.

b. Generate revenues from royalties by licensing or selling technologies. These funds may help support IPR management system or technology transfer offices at the institute-level. Also, these funds may help support further research and development.

c. For technologies that are commercially attractive, negotiations may be made with an appropriate private sector partner(s) prior to obtaining a patent or other forms of IPR protection in order to pay the costs of IPR protection up-front. The technology can then be licensed to the private partner.

A major issue with several of these mechanisms is to ensure that the public sector, small private companies and large multinationals have equal opportunity to introduce, test and protect new products. High fees may aid cost recovery but at the same time limit participation of small local companies and public organizations.

Conclusions

Emerging countries wanting to take advantage of the potential of biotechnology are faced with the strategic questions of how much to invest and what to invest in. The decision on the size of the investment is further compounded by the array of problems facing emerging nations' agriculture and the availability of a number of possible ways to solve these problems. In the case of crop improvement research, biotechnology is one of the many routes a country can take to address a specific problem (the others include, conventional breeding and various crop management practices). The decision on a particular approach to solving problems will primarily depend on the relative research costs and benefits involved in the different strategy choices. Given the relatively high costs of biotechnology research capacity shown in this paper, NARS must explore conventional means to solve agricultural constraints before making large and long-term investments in higher-end biotechnology.

In this chapter, we reviewed the types and levels of investments needed to establish different levels of research capacity and the associated regulatory system with particular reference to crop improvement research. We also developed a benefit-cost analysis framework within which to analyze biotechnology research investment decisions by emerging NARS. Introducing biotechnology to conventional crop improvement, increases substantially the specificity and data requirements of investment decision-making process, both on the benefit and cost sides. Effective biotechnology investment decisions by the public sector in emerging countries must rest on good estimates of research costs and benefits, an area that needs much empirical research. While we provide some empirical estimates for some costs of biotechnology research and technology transfer, much more information is needed to guide decision making.

The indicative numbers we have provided suggest that it will be difficult for small countries to justify the investment in research capacity. Careful cost-benefit analysis should be a pre-requisite to guide investment decisions. Initially, investments should focus on developing a sound regulatory framework to import, test and adapt as needed, products of biotechnology research. Whether investments focus on research or regulatory capacity, there are many opportunities to reduce costs through regional collaboration, use of bargaining chips, and cost recovery. For most emerging NARS, the development of

international public goods in the CGIAR and elsewhere can greatly enhance the efficiency of NARS investments.

Endnotes

[1]Mywish Maredia is Adjunct Assistant Professor, Department of Agricultural Economics, Michigan State University, Derek Byerlee is Principal Economist, Rural Development Department, The World Bank, and Karim Maredia is Associate Professor, Institute of International Agriculture, Michigan State University.

[2]Common molecular marker tecniques include Restriction Fragment Length Polymorphism (RFLP), Amplified Fragment Length Polymorphism (AFLP), Randomly Amplified Polymorphic DNA (RAPD), Polymerase Chain Reaction (PCR), Simple Sequence Repeats (SSR), Isozymes, etc.

[3]Biologically-based technology protection systems under development through genetic engineering (so called "terminator technology"), might change this situation if costs of seed can be kept to reasonable levels for small producers and the current high level of controversy abates. The same technology might also be used to induce male sterility and facilitate the development of hybrids in crops where hybrids are not now currently feasible.

[4]These estimates are based on a survey of wheat improvement research programs in developing countries discussed in the later section of this paper.

[5]WTO bounds all members to abide by the Agreement on Trade Related Aspects of Intellectual Property Rights (TRIPS) which requires member countries to grant patents for inventions in all fields of technology and it obliges them to protect plant varieties either by patents, by "an effective *sui generis*," or by a combination of both.

[6]CAC was formed in 1962 to implement the Joint FAO/World Health Organization Food Standards Programme. Its purpose is "to protect the health of consumers and ensure fair practices in the food trade."

[7]It is possible for a country to develop research capacity in molecular marker technology without the GMO-testing or back-crossing components. Ideally, this option (not considered in this paper) would come before the GMO importation option 2.

[8]In addition to investments in these resources and an appropriate regulatory framework, several other interrelated factors are necessary pre-conditions for successful payoffs to research, whether conventional or biotechnology research. These include: a portfolio of projects carefully selected to match the social, cultural, economic and environmental constraints on the agricultural sector; adequate information on scientific discoveries and new technologies developed elsewhere; and agricultural extension and seed distribution system to disseminate and utilize new technologies.

[9]These two options correspond to the first two columns (from left) in Figure 2 under conventional crop improvement.

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