Technology Adaptation and Adoption: The Experience of Seed-Fertiliser Technology and Beyond

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Technical change in agriculture is examined for two contrasting situations in the developing world: the largely irrigated wheat-based systems of South Asia, where improved seed-fertiliser technology has been widely used for more than two decades, and rainfed maize-based systems of sub-Saharan Africa, where adoption of this technology remains incomplete. Zones of medium to high production potential and relative land scarcity are the primary focus of the analysis. Experience with the adoption of seed-fertiliser technology in these areas helps to identify the key changes in institutions and policies needed to foster continuing growth in food grain production by small-scale farmers, especially changes in research and extension strategies and in input supply policies.

1. Introduction

Undoubtedly one of the most important sources of growth in agricultural productivity during this century has been the widespread adoption of high-yielding, input-responsive varieties of cereals (or so-called modern varieties—MVs), accompanied by applications of increasing levels of nitrogenous fertiliser. This growth strategy was first exemplified in the 1930s by hybrid maize technology in the United States (Griliches 1957). A more recent instance has been the Green Revolution in rice and wheat in Asia, where improved semi-dwarf varieties of rice and wheat, together with increased water and nutrient supplies, accounted for over three-quarters of the very rapid growth in Asia's food grain production over the past 25 years (Vyas 1983). Seed-fertiliser technology has been widely adopted in much of Asia, Latin America, and parts of Africa, even in many rainfed areas.

The widespread adoption of seed-fertiliser technology follows the Hayami-Ruttan model of induced innovation, in which investment in research (i.e. new knowledge) has enabled the substitution of fertiliser (whose real price has declined in the post-war period) for increasingly scarce supplies of land in many developing countries (Hayami and Ruttan 1985). Elsewhere I have suggested that this substitution process can be divided into three phases (Byerlee 1992b):

1. A Green Revolution phase, where input-responsive varieties are developed and adopted with modest levels of fertiliser.

2. A first post-Green Revolution or input intensification phase, where farmers improve allocative efficiency by using higher levels of inputs.

3. A second post-Green Revolution or input efficiency phase, where farmers improve technical efficiency by substituting improved management and skills for higher levels of inputs.

Today in the developing world, regions and farmers can be found at each of these three stages of transition in the technological continuum. The purpose of this paper is to review experiences with this general strategy of technical change in order to identify the key elements of institutional and policy change that are required to foster rapid and sustainable growth along this continuum. My emphasis throughout is on food grain production by small-scale farmers in agro-climatic zones characterised by medium to high production potential and relative land scarcity. I recognise at the outset that, outside these areas, the promotion of seed-fertiliser technology is often not an appropriate development strategy, especially in drought-stressed environments where improvements in crop and resource management (e.g. to conserve moisture) will often precede adoption of MVs (the experience of cereal farming in Australia is a good example).

The paper is built around two inter-related sections. In the first section, the general path of technical

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change is traced in two contrasting situations—the wheat-based systems of South Asia that experienced a Green Revolution beginning in 1966, and the maize-based systems of sub-Saharan Africa where the adoption of seed-fertiliser technology has been slower and is still very incomplete. The second section then distills lessons from these and other experiences to address common debates on the appropriate institutional and policy changes needed to support rapid and widespread adaptation and adoption of technology. Among the issues considered are international vs. national research; adaptive research, especially farming systems research; research vs. extension; technology vs. policy; and equity issues in technology adoption.

2. Overview of Issues in Technology Adaptation and Adoption in Two Contrasting Settings

2.1 Wheat in Asia[1]

The path of technical change in wheat in Asia over the past 25 years follows the general model of technical change in land-intensive agriculture presented above. Beginning in 1966, high-yielding semi-dwarf varieties of wheat were introduced from Mexico into the irrigated systems of South Asia; within five years the new MVs covered over half the irrigated wheat area. At the same time, farmers adopted modest levels of fertiliser and both farmers and governments invested heavily in irrigation infrastructure (Figure 1). Together, these three factors accounted for the very rapid growth of wheat production in the region, which averaged 7 per cent annually from 1965 to 1980.

This Green Revolution in wheat production has been exhaustively documented (see Lipton with Longhurst 1989, Dalrymple 1986, Hanson, Borlaug, and Anderson 1982). Less attention has been given to the experience of the post-Green Revolution period, when production growth rates have generally been more modest. The following brief review of more recent changes identifies some of the issues emerging in the post-Green Revolution period.

Development of Local Research Systems. Although the early MVs were largely imported, national research systems quickly developed the capacity to breed and adapt varieties to local conditions. Over the past 25 years, wheat breeders in South Asia have released nearly 300 varieties increasingly tailored to specific niches defined by agro-climatic characteristics, moisture status, and cropping system. Not only have national research systems matured, but in large countries such as India and Pakistan, sub-national programs have been established at the state level. Wheat breeders have continued to achieve modest gains in yield potential (although no further spectacular breakthroughs of the Green Revolution type have been or are likely to be achieved). More importantly, breeders have also maintained genetic resistance to rust diseases, which are a major threat to wheat in the region.

A major challenge to South Asia's wheat breeders has been to meet the needs of the region's rapidly evolving cropping systems. Partly in response to the adoption of MVs, which matured earlier than the older varieties they replaced, the incidence of double cropping, especially rice-wheat and cotton-wheat, has increased rapidly and led to delayed planting of wheat (Figure 2). Although this conflict might be resolved either by developing rice and cotton varieties which mature earlier and can be harvested earlier, or by developing wheat varieties suited to late planting, simple economic calculations suggest that the tradeoff should be made in the wheat crop (Byerlee, Akhtar and Hobbs 1987). However, wheat breeders who are part of the commodity research teams developed in the wake of the Green Revolution have been slow to recognise the need for varieties to fit specific cropping systems, and only in the 1980s have such varieties become widely available.

Beyond the issue of adapting technology to fit evolving cropping systems lies another issue: the slow adoption of newer wheat varieties. The first MVs were generally adopted within five to seven years, whereas newer varieties with much more modest yield advantages have often required 10 years or more for widespread diffusion. Although the new varieties appear to be acceptable to farmers, appropriate institutions for seed multiplication and marketing and stronger extension efforts are

[1] This section is abbreviated from Byerlee (1992b).

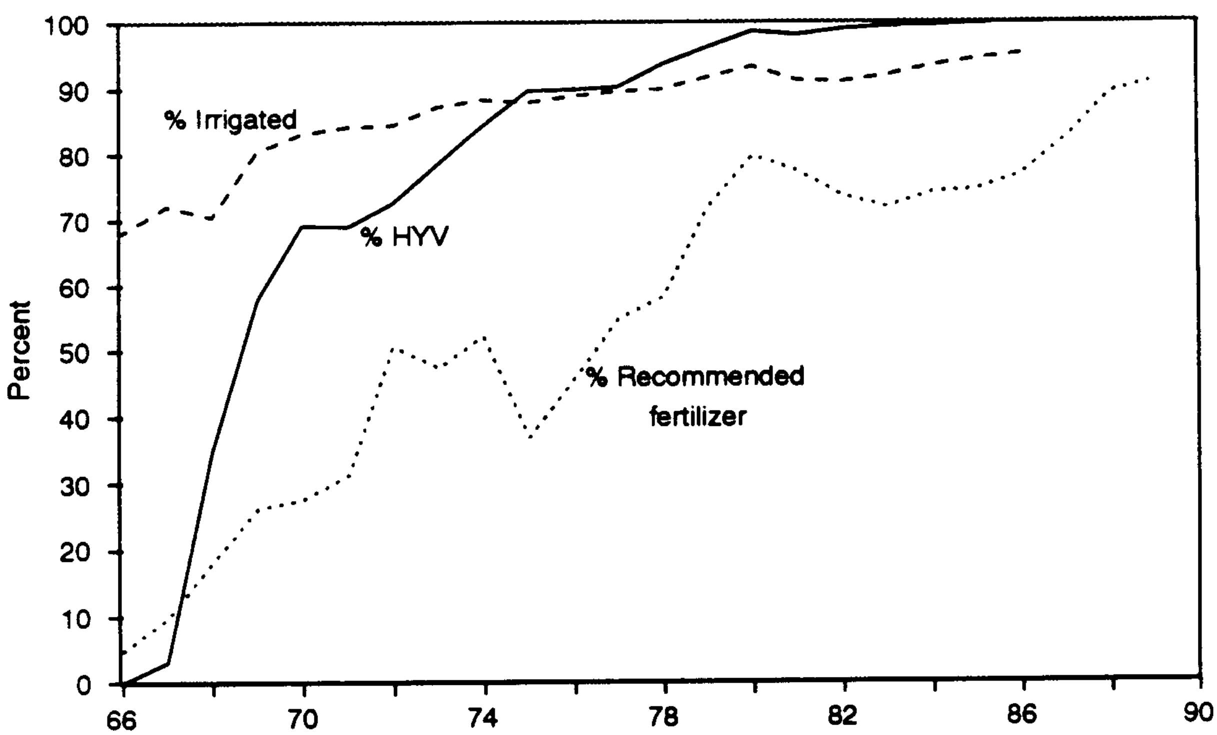

Figure 1: Trends in Input Use in Wheat, Indian Punjab

required to facilitate more rapid adoption in this post-Green Revolution period (Heisey 1990).

Crop Management to Improve Input Efficiency. Even though the first round of inputs—MVs, fertiliser, and water—has been widely adopted, much of South Asia has been slow to move into the next phase of post-Green Revolution agriculture, in which productivity gains depend more on increasing input efficiency than on increasing input levels. This phase of technical change requires greater emphasis on cultural practices such as the timing and method of input use, integrated pest management, reduced tillage, and improved planting methods and spacing. These practices, aimed at enhancing efficiency of input use, are often managerially intensive since they depend largely on improved information and skills. These improvements in information and skills require greater efforts at location-specific adaptive research to tailor crop recommendations to local needs, an effective extension service, and increased schooling and literacy of farmers. Commodity research programs that are breeding- and experiment-station-based have not proven effective in this type of adaptive research. Although investment in adaptive research and extension (some of it based on the farming systems approach) has increased in Asia, it is still grossly inadequate to meet the needs of this new stage of technical change.

Longer Term Sustainability Issues. It is now increasingly recognised that the resource base supporting South Asia's intensive irrigation systems may be undergoing a serious decline in productive capacity. Some of this decline is associated with the highly visible 'macro-level' problems of water logging, salinity, and ground water depletion.

However, there is growing evidence that a host of 'micro-level' problems, such as soil-nutrient depletion, declining organic matter, secondary salinity and sodicity from poor quality tubewell water,

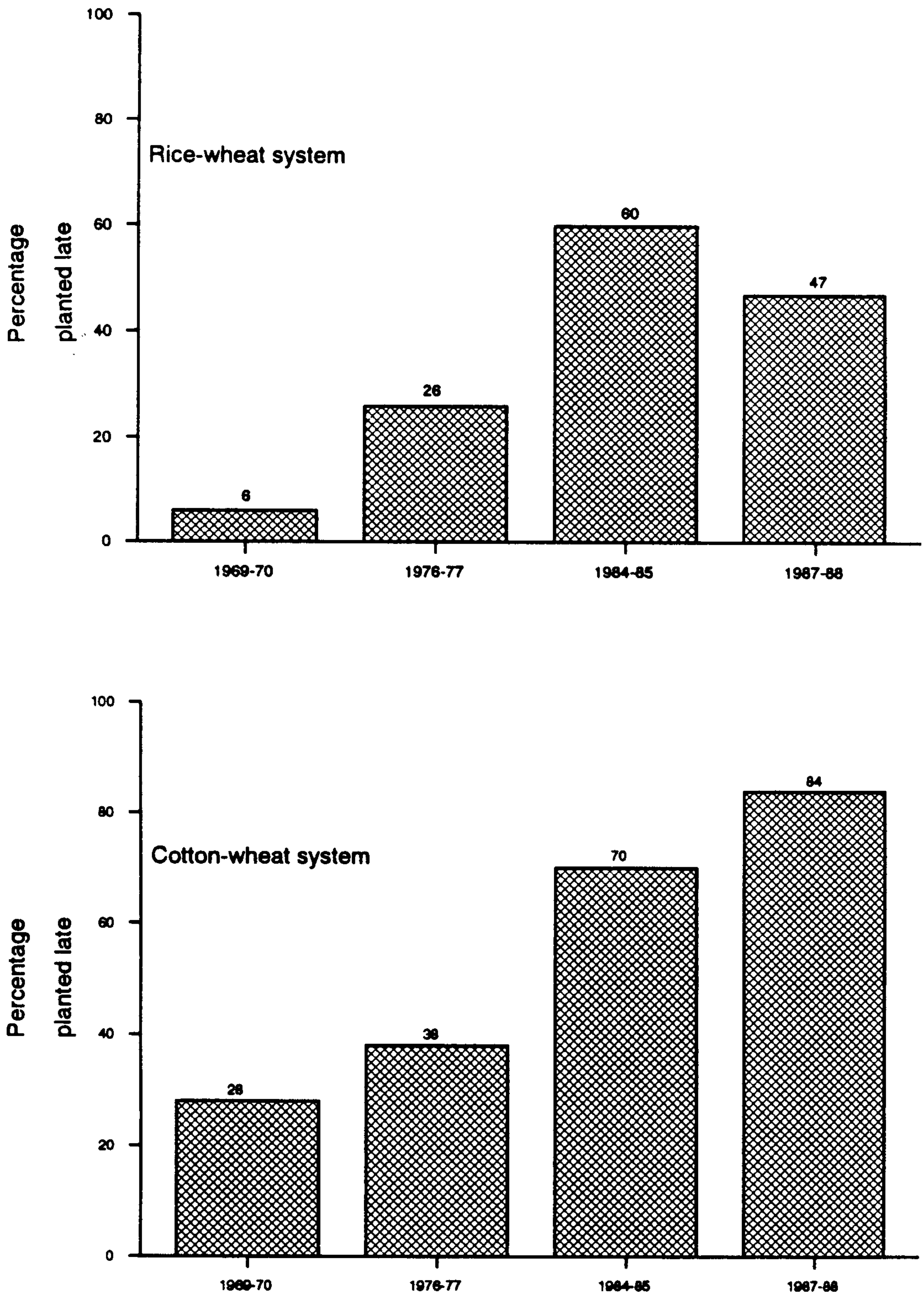

Figure 2: Percentage of Wheat Planted Late (after 1 December), the Punjab, Pakistan

and soil health problems are also responsible for the decline in productivity that has gradually become apparent in many systems (Byerlee 1992b, Pingali 1991). Research on these issues requires a multi-disciplinary and multi-commodity, problem-oriented approach which is not part of the tradition of commodity- and disciplinary-oriented research systems of the region.

Extending the Gains to Marginal Areas. Beginning in the mid-1970s, the seed-fertilizer technology slowly diffused to the more marginal rainfed areas of South Asia. Diffusion is still incomplete, but most farmers in marginal areas now use improved wheat varieties and modest levels of fertiliser (Ahmad *et al.* 1992, Hobbs *et al.* 1991, Byerlee 1992a). However, the experience of technology adoption in marginal areas has differed somewhat from the adoption process in more favoured locations. In many cases, the adoption of fertiliser has preceded the adoption of improved varieties. Farmers in marginal areas tend to give greater weight to grain and straw quality, since price premiums for grain quality and higher straw yields for local varieties often outweigh the yield gains from MVs until fertiliser is adopted. Also, the impact of seed-fertiliser technology has been much smaller, whether measured in terms of yield gains or profitability. Finally, crop-livestock interactions, in the form of straw quantity or quality, intercropping of a fodder crop in wheat, or management of farm yard manure, have often been critical factors in technology adoption (Byerlee and Husain 1992). These experiences all underline the need for improved crop and resource management (e.g. tillage methods to conserve moisture or production of a fodder crop) rather than seed-fertiliser technology as the basis for widespread technical change in marginal areas.

2.2 Maize in Sub-Saharan Africa[2]

The adoption of seed-fertiliser technology is at an early stage in sub-Saharan Africa, partly because low population densities and land-extensive agricultural systems are still prevalent. Nonetheless, a large and increasing area in Africa can be classified as land scarce. In much of this area, especially the mid-altitude and highland zones of eastern and southern Africa, maize is the basic crop in the system. Over the next two decades, when much of the land frontier in Africa will be exhausted, researchers will need to focus increasingly on land-saving technologies (Binswanger and Pingali 1988).

At present, only about one-third of the maize area in Africa is sown to MVs, and even where MVs are grown, fertiliser levels tend to be low (Byerlee and Heisey 1993). The notable success stories are the adoption of hybrid maize in Kenya beginning in the 1960s (Gerhart 1975) and in Zimbabwe, Swaziland, and to a lesser extent Zambia in the 1970s (e.g. Rohrbach 1989). The 1980s also saw widespread adoption of maize seed-fertiliser technology in the West African savannah (Smith *et al.* forthcoming, Ghana Grains Development Project 1991). Despite these successes, large parts of the land-intensive maize-based systems have yet to adopt seed-fertiliser technology, and even in areas where the technology is used, there is some uncertainty about the sustainability of the gains that have been made.[3]

Is the Technology Available? There is little doubt that the lack of appropriate MVs has slowed the diffusion of maize seed-fertiliser technology in Africa. The early successes in Kenya and Zimbabwe were both characterised by the existence of large-scale commercial sectors for which the hybrids were initially developed. Over time, small-scale farmers in the same agro-climatic zones also successfully adopted these hybrids, especially as newer hybrids with varietal characteristics more suited to small-scale farmers became available (e.g. early maturing hybrids to fit farmers' needs for late planting brought about by a labour constraint) (Low and Waddington 1991, Blackie 1990). In other cases, such as Malawi, hybrids have been adopted only on a limited area because the grain type of available hybrids is not suited to local processing and storage methods employed by small-scale farmers (Kydd 1989). During the 1980s, international and national research programs greatly expanded their breeding efforts and now suitable varieties with improved disease resistance are becoming available for much of the region. Hence

[2] This section is based on Byerlee and Heisey (1993).
[3] For example, in 1990 only half of the farmers in Ghana who had adopted MVs applied fertilizer (Ghana Grains Development Project 1991). Fertilizer use declined sharply in 1991 with the withdrawal of the subsidy.

lack of appropriate MVs is no longer the major constraint to technology adoption in maize-based systems in much of sub-Saharan Africa.

Hybrids versus Open-Pollinated Varieties (OPVs). A further issue is the appropriate breeding strategy for small-scale farmers—hybrids, which require farmers to replace their seed every season, or open-pollinated varieties, which make it possible for farmers to retain seed from season to season. In eastern and southern Africa, most countries have emphasised hybrids. Seed companies in Kenya and Zimbabwe have successfully produced and marketed hybrid seed for small-scale farmers. The emphasis in West Africa has been on OPVs, with seed distributed through area development projects. While this effort has led to short-term success in terms of the adoption of MVs, no viable seed system has developed to allow farmers to replace seed periodically or adopt still newer varieties. This is partly because it is not profitable for the private sector to invest in producing seed of OPVs. In the long run, hybrids—despite the higher seed costs—may be a more appropriate strategy to reach even the small-scale farmers of the region.

Lack of an Appropriate Policy Environment. Even where technology is available, its adoption in Africa has often been slowed by inappropriate policies and poor infrastructure. Poor access to inputs and lack of stable price incentives have often been greater constraints in sub-Saharan Africa than in Asia—even compared to conditions in Asia 25 years ago when MVs were first rapidly adopted. For example, fertiliser prices are generally higher and less stable in Africa because of high transport costs and because many input subsidies were phased out in the global climate of policy reform that prevailed during the 1980s (Figure 3a and Table 1). Also, especially in West Africa, maize markets are characterised by high year-to-year and seasonal price instability, which adds considerably to the risks of adopting fertiliser under rainfed conditions (Figure 3b). In the long run these problems are best resolved through increased investment in infrastructure, especially rural roads, but in the short to medium term governments still have a role in price stabilisation, input supply, and even input subsidies, as essential elements of technology adoption in sub-Saharan Africa (see below).

Table 1: Nitrogen fertiliser price in relation to maize grain price, 1989

Country	Farm-level nitrogen price (US$/t)	Farm-level maize grain price (US$/t)	Ratio of price of nitrogen to maize
Cameroon	732	100	7.3
Kenya	1,016	112	9.1
Malawi	720	64	11.3
Zambia	353	125	2.8
Zimbabwe	711	98	7.2
India	334	163	2.1
Pakistan	321	125	2.6
Philippines	469	164	2.9
Thailand	722	92	7.9
Mexico	250	158	1.6

Source: CIMMYT (1990).

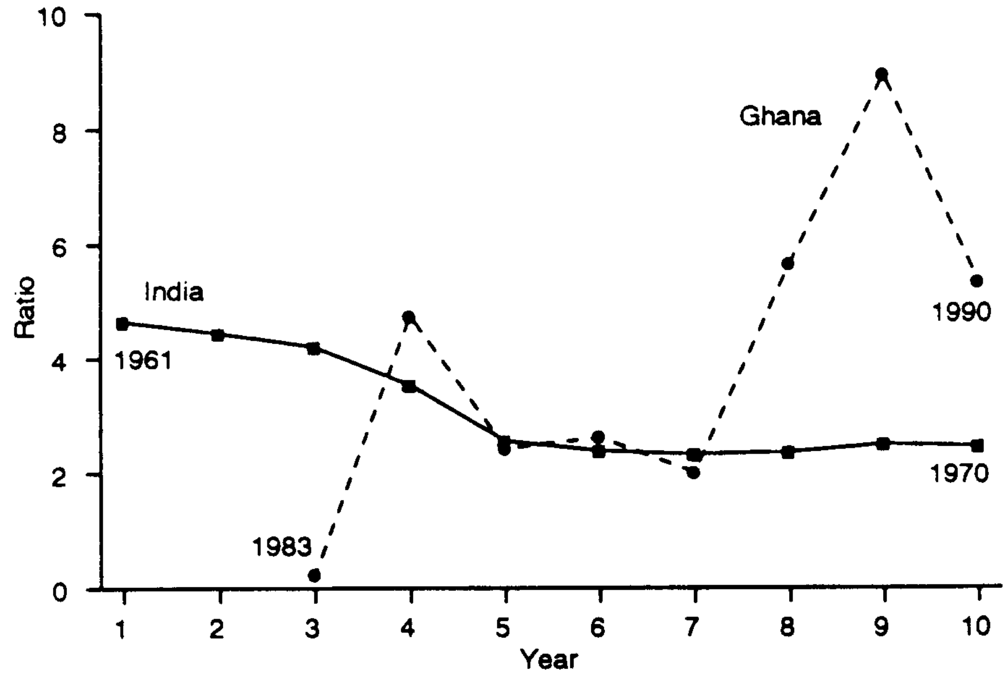

Figure 3a: Ratio of Price of Nitrogen to Price of Grain, India (1961-1970), and Ghana (1983-1990)

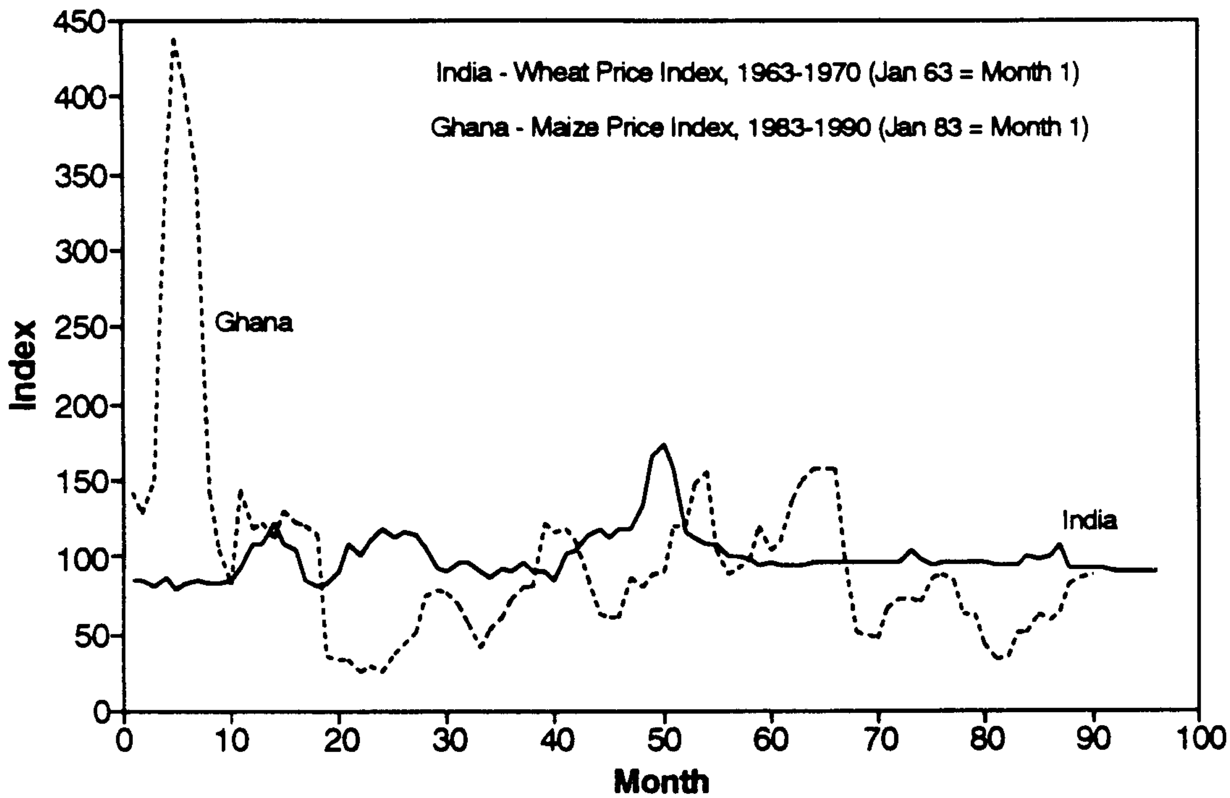

Figure 3b: Indices of Real Monthly Wholesale Prices for Wheat in Indian Punjab, 1963-1970, and Maize in Ghana, 1983-1990 (Average for Period = 100)

3. Institutional and Policy Issues in Adaptation and Adoption of Seed-Fertiliser Technology

Technology adaptation and adoption occur in a complex institutional and policy environment (see Figure 4 for the case of crop management technologies). The importance of each component of this environment changes at different stages in the sequence of technical change. In this section some of the lessons of the past two decades in developing and transferring seed-fertiliser technology are described, drawing on the experiences mentioned above for maize in sub-Saharan Africa (at an early stage in adoption of improved technology) and wheat in Asia (at a much later stage in the technology transition).

3.1 Sources of New Technology: International vs. National Research

In a world of ever tighter research budgets, it is imperative to work out an appropriate division of labour between international and national research efforts. Much of the development of MVs shifted toward international research after the international agricultural research centres (IARCs) were established in the 1960s (Figure 5). However, over time large national agricultural research systems (NARSs) have come to use germplasm from the IARCs as an intermediate product—that is, as a parent in local crosses—while smaller programs depend more on using IARC germplasm as finished products (Table 2). In general, varieties developed at IARCs have proven to be broadly adaptable and acceptable to farmers in a wide range of agro-climatic and socio-economic situations, so that the 'value added' by national program breeding efforts is often not very large. There are, of course, important exceptions. For example, until recently the limited adoption of hybrid maize in Malawi largely reflected the unavailability (both at the international and national levels) of flinty (hard) maize types suitable for local food processing requirements.

In the foreseeable future, international centres will remain a major source of germplasm for developing country programs to use, either directly as finished varieties or indirectly as parents in local crosses. This reflects considerable economies of scale in breeding germplasm for similar agro-climatic environments across countries, and also reflects the fact that local socio-economic conditions are not usually decisive in farmers' varietal choice decisions, at least for wheat (Winkelmann 1993). For example, Brennan (1992) calculates that approximately 800,000 ha of reasonably homogeneous crop area are needed to justify a fully developed crop breeding program. This suggests that many countries, especially many small countries of Africa, over-invest in crop breeding, given the materials available from international breeding efforts.

Table 2: Distribution of NARSs by extent of wheat varieties released from their own crosses, 1965-90

	Percent own crosses		
	< 25%	25-50%	50-75%
Number of NARSs	10	8	6
Average production of wheat in country, 1987-90 (million t)	1.3	5.5	10.6

Source: Byerlee and Moya (1993).

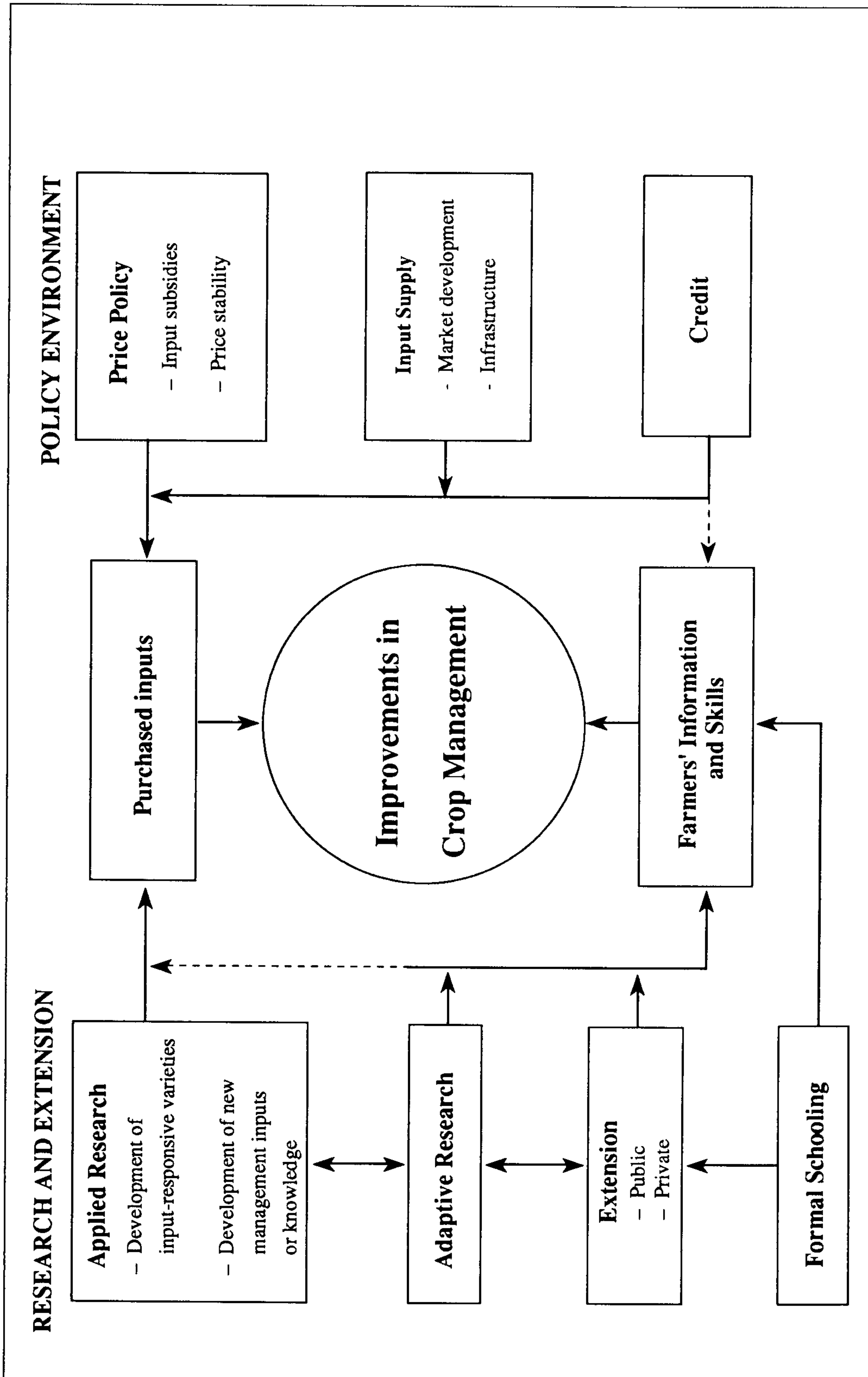

Figure 4: Schematic Representation of Factors Influencing Improvements in Crop Management.

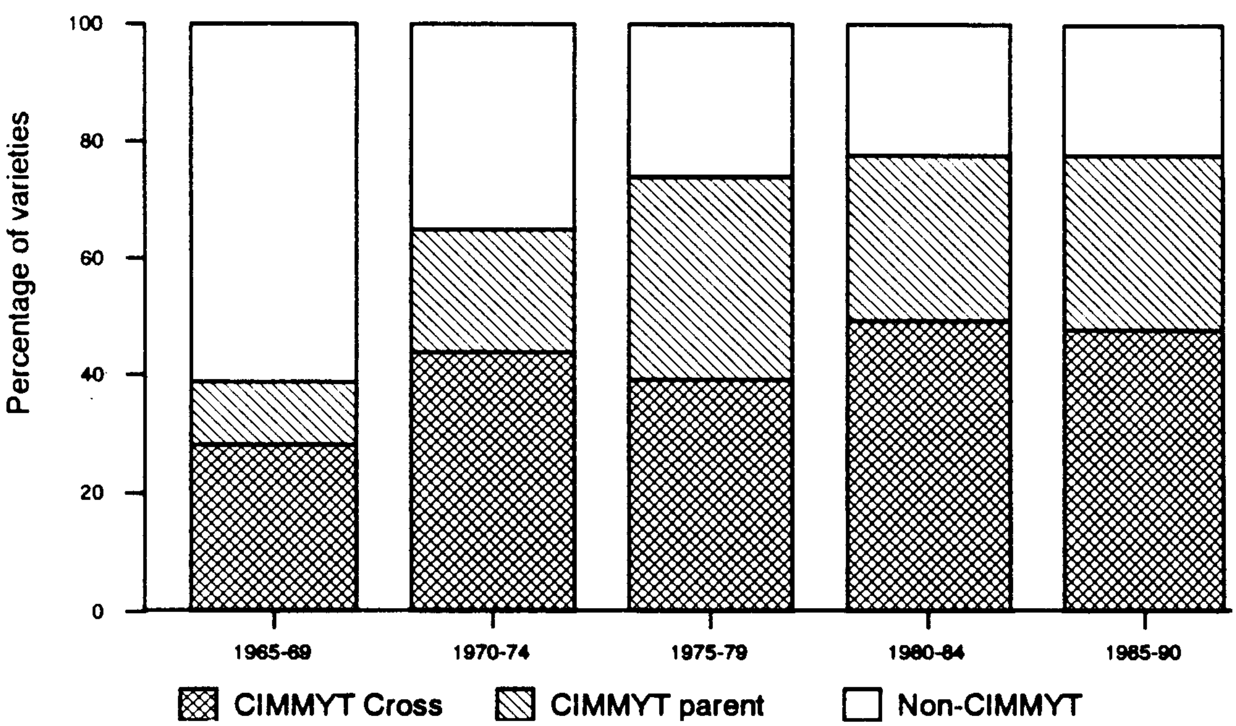

Figure 5: Trends in the Origin of Spring Bread Wheat Varieties Released in Developing Countries, 1965-1990

3.2 Technology Adaptation: The Farming Systems Approach

At the local level, various approaches have been used to adapt technologies suited for particular groups of farmers. During the early phase of the Green Revolution, the 'technological package' was extensively employed to exploit positive interactions between several technological components, especially between MVs and improved crop management practices, and in demonstrating the potential of the new technology. While the package approach had some merit in the homogeneous environments of Asia where the new technology first spread, it was less appropriate to the more heterogeneous conditions of rainfed agriculture. This led to the rediscovery in the 1970s of farming systems research (FSR), which became a major 'development fad' in international and national research systems in the 1980s. Much of FSR consisted of an effort to increase farmers' participation in adaptive research and develop more location-specific technological recommendations suited for both the agro-climatic and socio-economic situations of farmers. FSR also legitimised the role of social science in both IARCs and NARSs, a role which previously had been tenuous, at best.

We at CIMMYT were intimately involved in developing and popularising the methods of FSR, as well as in institutionalising those methods in national programs. FSR occupied most of the resources of our social scientists for a decade or more. Given this heavy commitment, we have recently begun to evaluate the results of our efforts (Tripp *et al.* 1990, Tripp 1991). The experiences accumulated in over 20 countries suggest that FSR has not lived up to early expectations (admittedly too high), especially when measured by the rate of adoption of improved technology in areas where FSR has been implemented. However, we have found that FSR contributed substantially to improved research methods (e.g. diagnostic surveys based on rapid rural appraisal methods) and to researchers' understanding and appreciation of small-scale farming systems, especially the role of crop-livestock interactions, intercropping, risk and household food security, and seasonal cash and labour constraints in technology adoption.

A number of reasons appear to explain the limited impact of FSR. First, FSR was often implemented in a 'project mode' and did not become an integral part of the total research system. This often prevented the active feedback of information from farmers to persons responsible for setting overall research priorities—for example, the need discussed above for breeders in South Asia to adapt varieties to evolving cropping systems. Second, farming systems adaptive research has sometimes been implemented where there is no technology to adapt (Low and Waddington 1991). In this case, the major value of FSR is to diagnose farmers' demands for technology to guide technology development. Again, the maize hybrid story in Malawi represents a situation where the impact of FSR was limited by the unavailability of technology, especially appropriate varieties, yet weak linkages between the FSR teams and maize breeders meant that information on varietal requirements of local farmers was slow to influence the priorities of the maize breeding program (Kydd 1989). Finally, FSR has often not been well linked to extension, and useful results from FSR have failed to reach farmers. Given that a major objective of FSR is to develop site-specific crop management information or recommendations, the link with extension is critical. For example, most FSR programs devote a significant share of on-farm experimentation to testing different input levels—e.g. to develop economically optimum fertiliser doses for specific conditions, defined in terms of either agro-climatic variables (e.g. soil type), or socio-economic variables (e.g. land tenure arrangements or access to credit). While much of this information is potentially useful, very few programs have found effective ways to transmit it to farmers.

These weaknesses in implementing FSR also suggest what needs to be done to improve the payoffs to FSR in the future. The perspective and methods of FSR are undoubtedly an important and even critical addition to successful agricultural research, and ways and means must be found to integrate those perspectives and methods at all levels of the research system. This means less emphasis on FSR as a separate and distinct activity and more emphasis on training scientists at all levels in the perspectives and methods of FSR, and on incentive systems to promote the FSR approach throughout the research system.

In addition, FSR will need to develop closer links with extension. This is particularly true in the later stages of the technological sequence, when improved information and skills play an increasingly important role in enhancing productivity. On-farm research programs in which both researchers and extensionists assume responsibility for managing on-farm experiments and verification trials offer one way to enhance integration (e.g. Ghana Grains Development Project 1991). However, in many cases extension systems themselves are insufficiently developed to play an effective role in information transfer (see below).

Finally, the balance between on-farm diagnostic and experimental activities and applied research (such as varietal development usually undertaken on the experiment station) needs to be reconsidered. In the early stages of the agricultural transition, the key role of FSR is to diagnose farmers' 'demand' for new technologies and to verify simple technological recommendations (e.g., an improved variety and fertiliser dose) over a wide range of farmers' conditions. At later stages in the transition, when the need for more complex location- and season-specific information increases, FSR (with extension) has a major role in on-farm experimentation to develop the necessary information base to make more specific recommendations, including recommendations conditional on site and seasonal variables.

Ironically, at present FSR is now best institutionalised in sub-Saharan Africa, where there may have been over-investment in on-farm experiments at the expense of applied research to develop new technologies (although on-farm diagnosis is critical to defining the requirements for new technology). In contrast, at the current stage of development in Asia there is a need to greatly strengthen on-farm adaptive research to develop more site-specific recommendations. As sustainability concerns assume more importance in these intensive systems, FSR will also need to develop better methods for improved diagnosis and monitoring of longer-term changes in the quality of the resource base. However, it is important that 'research with a sustainability perspective', which is becoming so fashionable in the 1990s, builds upon the rich base of methods and experiences developed through the farming systems perspective of the 1980s, rather than devises an entirely new research agenda.

3.3 The Role of Extension

In the early stages of the agricultural transition, the key element in technology adoption is to have a good technology that is generally appropriate to a large number of farmers. Such a technology is usually based on one or two inputs which provide a high payoff over a wide array of conditions and which are often fairly simple to manage (that is, not very dependent on the timing and method of application of inputs). Extension can play an important catalytic role in initiating adoption, especially through on-farm demonstration programs. This was the strategy successfully employed for seed-fertiliser technology in South Asia in the 1960s and more recently in Ghana in the 1980s (Dowswell and Borlaug 1991). Once adoption has been initiated, the technology, if appropriate, will diffuse rapidly from farmer to farmer.

At later stages in the agricultural transition, the amount of information and skills that farmers require to effectively use a managerially more complex technology increases. Since this type of information travels less well from farmer to farmer, extension must establish more direct contact with a larger number of farmers and employ a wider range of communications media. In general, extension systems, especially in South Asia, have been slow to adapt to this new situation, and extension remains a weak link in technology transfer. Some efforts have been made in the 1980s to improve extension performance, notably through the Training and Visit System, but this system is still closely tied to extension in a communications role—i.e. delivering simple messages—rather than in a broader educational and farm management role which would enable a wider array of information and skills to be transmitted. Indeed, given the complexity of modern scientific agriculture, the knowledge and skills of extension workers themselves will require considerable upgrading before they can be expected to adequately serve the needs of farmers.

3.4 The Role of Policy vs. Technology

Another important debate in technology adoption is the relative importance given to getting policies right versus getting the technology right. It is probable that those of us who work in the research system have a 'technology-first' bias, when in fact the constraining element in many cases is the lack of an appropriate policy environment, whether measured in terms of input-supply systems or price incentives.

Certainly, the disappointing performance of seed-fertiliser technology in Africa is partly due to the lack of a conducive policy environment. Even in the wake of widespread policy reforms of the 1980s, the policy environment in Africa is still less favourable than that at an equivalent stage of development in Asia. High transport costs depress price incentives and, together with high storage costs, contribute to price instability (in large part by creating a wide margin between import- and export-parity prices). Also, input supply systems in Africa are often poorly developed, increasing the difficulty of farmers in obtaining access to required inputs, especially fertiliser. In fact, problems of input supply explain the lack of impact of FSR in many African situations (Low and Waddington 1991).[4] Finally, uncertain prices and input supplies add considerably to the risk of employing new technology.

This brief overview suggests that improvements in the policy environment may be a prerequisite to more widespread adoption of improved technology in sub-Saharan Africa. Clearly a major priority is investment in infrastructure to reduce transport and marketing costs. I also believe that, beyond this important and long-term role, the public sector has a key catalytic role to play through price stabilisation schemes, subsidies on transport and distribution of

[4] For example, Low and Waddington found that 44 per cent of the recommendations developed by FSR in Zambia were not adopted because of input supply problems.

inputs (at least in the short term), and even in input promotion and marketing, until infrastructure and input volume are sufficiently well developed for the private sector to take over (Byerlee 1993). These comments are perhaps at odds with the current worldwide emphasis on privatisation and free markets, but experience from elsewhere, especially Asia, supports the assertion that the public sector has a critical role to play in initiating the adoption of new technologies in the early stages of technology transition in small-farm agriculture.

At the other extreme, in South Asia public sector intervention has lingered on well beyond the initial stage of technology adoption. Privatisation of input markets has been slow (although most inputs are now distributed through the private sector), fertiliser subsidies have become unsustainable given the relatively high dosages of fertilizers now used, and price stabilisation, while effective, has been very costly. These experiences illustrate the dilemma of judicious public sector intervention to promote the initiation of adoption, followed by phased withdrawal of the public sector from input supply systems and subsidies as adoption becomes more widely established.

3.5 The Equity Question

Much of the debate on seed-fertiliser technology has focussed on equity issues related to differential adoption by small- and large-scale farmers and by different regions (especially between favoured and marginal agro-climatic zones). More recently, the debate has focussed on the tradeoffs between short-term gains in productivity versus long-term preservation of the resource base (i.e. inter-generational equity).

The early concern that adoption of seed-fertiliser technology benefitted large farmers has largely been dispelled as small-scale farmers have been consistently found to adopt the same technology, often after only a short lag (see Lipton with Longhurst 1989, for a review). Only where the input-supply system is functioning very poorly have small-scale farmers (i.e. those with less political influence) been denied the benefits of the new technology.

A more difficult dilemma has been the fact that some regions, especially the more marginal ones, have been left behind as new technology has spread through favoured areas. As we have seen, seed-fertiliser technology has slowly spread into more marginal areas, but adoption is still incomplete and the impacts have been smaller even where adoption has occurred. This raises the question of whether more research resources should now be shifted to more marginal areas.

Economic logic and experience suggest caution in making such a shift. In the first place, there is evidence that the number of poor people who live in favoured environments is as large as those who live in marginal areas (Leonard 1989). Second, most poor people are net consumers of food grains, including many small-scale farmers in marginal areas who are not self-sufficient in cereals. Recent evidence suggests that 60-70 per cent of all households in Pakistan and Malawi are net food grain purchasers (Renkow 1991, Smale *et al* 1991), and these data probably hold for other countries and regions. Because increased agricultural productivity is often translated into lower food prices, the poor, whether in favoured or marginal areas, stand to benefit (assuming markets are functioning reasonably well).

The payoffs to research are also probably lower in marginal areas. In the driest areas, off-farm work and labour migration may be the most remunerative activity in the long run (Renkow 1991, Otsuka, Cordova and David 1990). Certainly more empirical analysis of these questions is required as a basis for decisions on reallocation of research resources toward more marginal areas.

Finally, recent interest in environmental issues has stimulated research, much of it of a long-term nature, on development of sustainable production systems. In the case of Africa, it is even suggested that it may be possible to by-pass the seed-fertiliser stage of the sequence of technological change by developing more integrated systems based on alley crops, crop residue management, organic manures, etc., for maintaining or enhancing soil fertility with low levels of external inputs (e.g. Lal 1987). While this is certainly a worthy long-term goal, I believe it is dangerous to assume that seed-fertiliser technology is environmentally harmful and inappropriate in Africa. Seed-fertiliser technology offers the opportunity for short-term payoffs, which in themselves are environmentally beneficial if they relieve the continued migration to marginal areas resulting from population pressure and technological stagnation in high potential areas. Second, the 'sustainable systems' being considered are often managerially complex and will require large investments in research, extension and perhaps even other types of institutional support, such as credit programs, to ensure widespread farmer adoption. Hence there is a need for a balanced approach in Africa, in which seed-fertiliser technology has an important place.

In Asia, which is now at a much more advanced stage in the technological transition, there is clearly a need to shift away from an exclusive emphasis on short-term production increases through input intensification, toward longer-term sustainability issues, especially given the evidence noted above on the decline in the quality of the resource base. This will require considerable institutional change to meet this challenge, especially in research systems where there is a need to greatly strengthen linkages between commodity and disciplinary programs to address problems in managing the resource base over the longer term.

4. Concluding Comments

The widespread adaptation and adoption of seed-fertiliser technology has made a major contribution to increased food production in the developing world over the past 25 years. This is particularly so in the intensive irrigated systems of Asia, where institutions and policies have generally been conducive to technology adaptation and adoption. Nonetheless, institutions and policies often have not evolved sufficiently rapidly to meet the challenges of a post-Green Revolution agriculture. The need to adapt technology to evolving cropping systems, the need to promote greater input efficiency (rather than intensification), and the need to emphasise longer-term system sustainability all have important implications for research and extension systems and supporting policies. In particular, it is imperative to generate and transmit both more and better quality information to meet the needs of farmers at this stage of development.

In contrast to irrigated areas, rainfed areas are at an earlier stage of adoption of seed-fertiliser technology, as exemplified in this paper by the case of maize in land-intensive systems of sub-Saharan Africa. Modest success has already been achieved with seed-fertiliser technology adaptation and adoption in these areas. It appears that in most cases appropriate technology is now available in the form of MVs, but the policy environment, especially input supply, remains a major constraint to wider adoption of the technology. Given the precarious state of food supplies in much of the region, efforts to extend the technology more widely must be accelerated.

The experiences of the past 25 years have greatly enhanced our understanding of the process of technology adaptation and adoption in small-farm agriculture. Nonetheless, there are still important gaps in our knowledge, especially in our current understanding of institutional behaviour, such as appropriate incentive systems to help make local research and extension systems and agricultural policies more responsive to small farmers' changing demands for improved technology. Social science research must begin to address these important issues in order to meet the needs for technological change in food production in small-scale farming systems that goes beyond the stage of seed-fertiliser technology.

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