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THE ECONOMICS OF THE INTERNATIONAL TRANSFER
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MYWISH K. MAREDIA

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Carl K. Eicher
Major professor

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THE ECONOMICS OF THE INTERNATIONAL TRANSFER OF WHEAT VARIETIES

By

Mywish K. Maredia

A DISSERTATION

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ABSTRACT

THE ECONOMICS OF THE INTERNATIONAL TRANSFER OF WHEAT VARIETIES

By

Mywish K. Maredia

It is widely believed that there is underinvestment in agricultural research in both industrial and developing countries. Increasing investment in agricultural research has been justified on the grounds of high returns, limited transferability of technology, and non-economic factors such as autarky, food security, and prestige. But with shrinking budgets, research administrators are being forced to rationalize their priorities. This study was undertaken to analyze the international transfer of wheat varieties and develop a model to guide decisions on the appropriate size and capability of wheat improvement programs.

Levels of research capability are broadly divided into the capability to conduct evaluation research (testing program) and creation research (breeding program). The level of research capability is considered as a function of research spillins (i.e. direct and indirect transfer of improved germplasm from other research programs). CIMMYT's international wheat yield trial data are used to assess the yield advantages of cultivars developed locally relative to those imported from other environments and from CIMMYT. These estimates of research spillins are incorporated into the cost-benefit model to estimate the threshold level of production to justify wheat evaluation and breeding programs. The model was also used to determine the profitability of 69 wheat improvement research programs in 31 developing countries.

Two major findings of this study deserve note. First, CIMMYT's wheat varieties were found to be widely transferable across different environments. This result reveals that spillovers of wheat breeding research are larger than previously reported and suggest the need for the CGIAR to rethink its recent 'downsizing' of CIMMYT's budget. Second, 36 out of 69 research programs were found to be 'overinvesting' in wheat improvement research by placing too much emphasis on wheat

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breeding and too little attention to developing an efficient capacity to borrow improved varieties from the global research system. Although these results are confined to wheat improvement research, they challenge the conventional wisdom of 'underinvestment' in agricultural research. These results also suggest the need to incorporate research spillins into the analysis of investments in research on a commodity by commodity basis.

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Like a tree, we all must find a place to grow. I would like to take this opportunity and convey my thanks and appreciation to all the people who 'gave me a place' and 'helped me to grow'. First and foremost, I would like to thank Prof. Carl Eicher, my major professor, and Dr. Derek Byerlee, my thesis advisor. Their support and guidance was vital to the successful completion of my graduate study.

Prof. Eicher has provided solid support throughout my graduate program. His prompt response to any requests and his guidance on all matters has been invaluable. His insightful discussion of the research findings served to improve the thesis' focus and organization. Prof. Eicher has been instrumental in arranging financial assistance necessary for my graduate studies and research. His scholarly achievements and commendable personal qualities has made me feel proud and privileged to be his student.

Dr. Byerlee, has been a constant source of professional guidance ever since I began working with him in 1987. He has helped me develop the dissertation topic and played a vital role throughout my research by his technical skills as an economist and focusing my attention on the policy-relevance of the results. His continuous guidance and rapid response in commenting on drafts, despite his busy schedule, has been commendable.

I would also like to thank other members of my thesis committee, Prof. Richard Bernsten, Prof. Jack Meyer, Prof. Lindon Robison, and Dr. Richard Ward for their support and guidance in various aspects of my research. I am particularly grateful to Dr. Richard Ward, wheat breeder, for his assistance with understanding the biological complexities of breeding process and helping me cross the disciplinary boundaries to explore the presumptuous world of economist.

I am also grateful to several people at the Michigan State University and CIMMYT for their important support and assistance. Notably, Dr. Michael Morris whose recommendation helped me start my career at the Michigan State University, Prof. Roy Black for his

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Most of all, I would like to record my thanks and appreciation to my family for bearing and sharing the laborious years of my graduate studies. Especially, I am thankful and grateful to my husband, Karim, for encouraging and supporting all my endeavors. With his encouragement I was able to make a greater contribution than would have otherwise been possible.

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CHAPTER ONE

INTRODUCTION

1.1 Background

1.1.1 Trends in Agricultural Research

The development and diffusion of improved technology is a proven means of increasing agricultural growth. This explains why global agricultural research expenditures are now running around nine billion dollars per year. Because of the closing of the land frontier and the high rates of return on research investments, developing countries have dramatically increased their investment in research and extension. For example, over the two decades from 1961-65, the average research expenditures per NARS (National Agricultural Research System) in developing countries (including China) increased from $8.4 million to $27.9 million[1] (Pardey et al. 1991c, p.289).

Increased research efforts are also reflected in the rapid growth in the numeric size of NARS in devéloping countries. In Nigeria, for example, the number of scientists in the NARS increased from 100 at independence in 1960 to 1,000 by 1985 (Eicher 1991b). In Mali the number of scientists in the NARS increased from an average of 9 in 1965-69 to 275 in 1983 (Pardey and Roseboom 1989). At an aggregate level, the average numeric size of developing country research systems (including China) quadrupled from 150 in 1961-65 to 600 in 1981-85 (Pardey et al. 1991b, p.205).

This increase in national research capacity has been both extensive (research effort on more commodities and problems) and intensive (increased effort on a given commodity and problem). The acceleration in the size of crop improvement research programs in many developing countries is a good example of the increase in the intensity of research efforts on a particular crop. To cite an example, Kenya began its maize research program in 1955 by hiring one full-time expatriate breeder, who directed the program for 15 years with the assistance of one agronomist. By 1990, the size of the maize research

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program had increased to 57 full-time equivalent (FTE) researchers (Eicher 1991a). In the case of wheat, the success of Green Revolution in Asia has triggered an expansion in wheat research programs to the extent that most countries now have a strong wheat improvement research program (CIMMYT forthcoming). Brazil, for example, has 15 different wheat improvement programs while India has 57 different wheat improvement programs employing about 200 FTE researchers.

1.1.2 Rationale for Increasing Research Investments

The increase in global agricultural research expenditures has been motivated by the high returns to research.[2] Studies on returns to agricultural research investments (both at the aggregate level and at commodity-specific project levels) have consistently shown that research investments in agriculture yield extraordinarily high returns.[3] One of the implications of these studies is that there is underinvestment in research.[4] Therefore, according to these studies optimum investment strategies require further expansion and strengthening of research systems.

One of the arguments often made in favor of increasing support for NARS is that, unlike industrial technology, agricultural technology is not easily transferable to different countries and regions (i.e. they are location-specific) because of agroclimatic diversity and socio-economic factors (Evenson 1984; 1991a; 1991b). Based on his study on international transferability of CIMMYT wheat technology, Englander

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[2] A number of studies on rate of returns to agricultural research have been undertaken since the pioneering attempts of Schultz (1953) and Griliches (1958) in the 1950s. The results of these studies have been summarized by Arndt et al. (1977); Evenson et al. (1979b); Ruttan (1982); Evenson (1984); Daniels et al. (1992).

[3] The rate of return studies have been criticized in the literature on a number of grounds. First, it is argued that the literature is replete with only success stories. Second, although ex post evidence of high returns to aggregate research investments is used to counter the above criticism, this evidence cannot be used to justify future investments in specific projects. Third, the conceptual framework and data used in calculating the rate of return are often questionable.

[4] See Fox (1985) for a brief survey of the underinvestment hypothesis made in the context of developed as well as developing countries.

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reports that "one striking result is that all countries but one showed positive domestic yield bonuses - that is, varieties virtually always yielded more at home than abroad...This suggests that varieties tend to be highly specialized to local conditions" (Englander 1991, p.307). Based on this evidence, it is suggested that countries and regions within countries should establish strong research programs to modify internationally available technologies to fit local needs (Englander 1991; Evenson 1991b). Another argument often made in favor of expanded national research systems is that it is too risky to rely on other countries and international institutes for commodity research, especially for commodities for national food security (Winkelmann 1991).

Although all of these arguments are reasonable, continual expansion and proliferation of research programs can be questioned on several grounds. First, many national and international agricultural research systems are under severe financial stress. For example, the average expenditure per agricultural scientist in developing countries declined from $55,400 in 1961-65 to $46,700 per researcher by 1981-85. Even the International Agricultural Research Centers (IARCs) under the CGIAR (Consultative Group on International Agricultural Research) system are facing funding constraints because of the world recession, recent cutbacks in foreign aid and the general levelling off of donor support for the CGIAR system (Eicher 1991b). It is therefore crucial that the available resources be used judiciously for agricultural research.

Second, recent evidence suggests that research spillovers from international and regional research, may be larger than previously anticipated, at least in the case of plant breeding (Byerlee and Moya 1993). Based on this evidence it can be argued that by not explicitly accounting for the potential direct and indirect research spillins[5]

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[5] Research spillins are the effects of research conducted by other programs on a home research program. The total spillin effects can be a result of the combined effects of different types of spillins - price spillins, technology spillins or spillins of scientific knowledge. The terms direct and indirect spillins used in this study refer to the technology spillins. Technology that can be directly transferable to a home research program from another research program are called direct spillins and technology generated by other research programs that needs further research by a home research program are called indirect spillins.

from an IARC or other NARS, some national research programs may be overinvesting in research (Winkelmann 1991).[6]

The combination of stringent budget constraints of the 1990s and significant spill-in benefits from international agricultural research efforts suggest that developing countries should qestion the World Bank's guidelines of allocating about two percent of a nation's agricultural GDP to agricultural research (World Bank 1981). In the 1980s, many countries used this guidelines to justify an expansion of the size of their NARS. But as Eicher has noted, "this dubious norm...derived from the expenditure norm in industrialized countries with a century or more of experience in mobilizing political and financial support from farm organizations, and commodity groups...contributed to an unbridled expansion of NARSs in Africa..." (Eicher 1991b, p.30).

Given that the response of research output to research input depends on the nature of the research production function, which essentially has a temporal dimension associated with it, the past expenditure norm of industrialized country may not be optimal for developing countries today.[7] Planning the stream of expenditures in a research effort requires a balancing of the increase in costs and gains which result from an expansion of a research program. Graves (1987) reports that research costs increase as development time is

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[6] This evidence contradicts the argument conventionally used in the literature to support the underinvestment hypothesis. According to the underinvestment hypothesis, the externality nature of agricultural research suggests that investment in research by an independent decision maker will be always too little from a national or international perspective. See for example Evenson et al. (1979b), White and Havlicek (1981), Ruttan (1982) and Schweikhardt and Bonnen (1991).

[7] This can be illustrated by the example of U.S. maize breeding research. Duvick (1991) notes that, "the cost of research per unit of advance will become increasingly large....Over the past 60 years, increase in maize yielding ability at a rate of approximately 1.5%/year have been accompanied by increases in number of U.S. maize breeders at a rate of about 4%/year....Thus, yield gains, although still possible, are increasingly expensive." (Duvick 1991, p.5).

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compressed.[8] Also, a rapid expansion of research programs often leads to problems of imbalances in supply and demand of human resources (Tweeten 1971).[9] Timing in expansion of funds for research, therefore, is important because "too rapid an expansion not only may give a disappointing increase in output in the short run but actually decrease long-run output of knowledge." (Tweeten 1971, p.48).

1.1.3 Problem Statement

Although the return on many agricultural research investments will remain high in the future, there is a lack of guidelines on the size of optimal research programs. The ex-post rates of returns have limited relevance in guiding decisions on how much to spend on a given commodity, region or project in the future. The returns to research literature fails to answer the micro-level questions faced by a research administrator about when, where and how much to increase the research effort. The drive to expand research capacity has led many developing countries to situations which can be best characterized as "elephantiasis of research systems and atrophy of productivity".

Today, because of severe constraints on financing agricultural research in industrial and developing nations, the issue of optimal number and size of agricultural research programs has become a major

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[8] According to Graves (1987, p.42), there are three reasons for this phenomenon. (1) Since research is a heuristic process, each step is based on information gained from previous steps. With a shorter time period, each task is begun with less and less information. This leads to costly mistakes and more rework. (2) Because of the stochastic nature of the research process, different approaches may be attempted in series until one ultimately proves successful. With time compression, more approaches must be attempted concurrently, thus leading to a higher expected cost for the project as a whole, since more total approaches will be attempted on an average before a successful one is found. (3) Conventional diminishing returns are observed as more technical people are assigned to the same task.

[9] Hrones, as quoted by Tweeten (1971, p.47), states the human resource problem faced by the U.S. research institutes as follow: "One of the evils which industry tends to perpetuate and now universities have joined in as a result of the large-scale government supported program, is essentially to convert good, creative scientists and engineers much too early into administrators and managers (Hrones 1963, p.186)." Most of the sub-Saharan African countries are facing this same problem as a result of rapid expansion in agricultural research programs.

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agricultural research policy issue. The size issue is being raised at both the CGIAR level as well as NARS and among commodities within a country. For many countries which have experienced a rapid expansion in the size of NARSs, it has been suggested that they pursue a decompression strategy to reduce the overall size of NARSs and concentrate instead on increasing operating budgets for a smaller research staff (Eicher 1991b). The question for these countries, however, is how and how much to reduce the size of NARS and what determines the optimal size of a productive NARS? At the commodity level, countries are seeking advice on how much effort they should devote to each crop, and given the agro-climatic diversity, what is the appropriate number of research programs for each commodity? India, for example, has more than fifty wheat research programs, but only eighteen of these have released new varieties in the past twenty years, and of these, only a handful have released successful varieties (Jain and Byerlee 1993). However, these issues are faced not only by developing countries but also by industrialized countries. Australia, for example has 18 wheat improvement research programs and there is current interest in consolidating these programs (J. Brennan, personal communication).

At a commodity level, the issue often surfaces in the form of the following questions: what research programs (in terms of commodities) to have? how much to invest on a given commodity? what should be the size of the research program? what should be the appropriate research capability? and, which environments should be targeted?

For larger developing countries and industrialized countries with established research systems, the issue is whether and how much to allocate research resources to small environments or specialty crops or crop types. For small developing countries that have many crops relative to their resources, the issue often is not how much to invest on each crop, but whether to invest or not.

The size issue is emerging not only at the national level but also at the international research system level. For IARCs these issues are important in determining the allocation of their resources between the different environments and establishment of regional programs. With the recent cutbacks in research funding, these issues have become

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particularly important for many commodity-based CGIAR centers. For example, CIMMYT's core-funded senior scientific staff declined by 22% from 95 in 1989 to 74 in 1993. A further reduction of 10 more senior scientific staff is planned in 1994. This 'downsizing' raises hard questions for CIMMYT, including the scope, strategy and priority of its international wheat and maize research programs. Thus, the size issue is important to decision makers at three levels: small countries, small environments within large countries and international research centers.

All these issues raise the question of how to determine the economic criteria for establishing, expanding and in some cases, downsizing, a research program. Without question, non-economic factors such as, autarky, food security, regional development, and prestige, can override economic considerations, in decisions on the size of a research effort (Douglas 1980). However, it is important that decision makers be aware of the economic costs of their decisions.

The issue of appropriate size of a research program, is however too complex to be addressed at the NARS level. According to Vernon Ruttan, the scale considerations must be disaggregated by commodity and discipline (Ruttan 1982). Investigation of what should be the appropriate number and size of research programs at the NARS level needs to start at the micro-level for each commodity and type of research.

This study will investigate international wheat research spillovers with emphasis on crop improvement programs.[10] Wheat improvement research is chosen because it presents an interesting case study of research success, evidence of research spillovers, and reduced budgets for global wheat research programs, including CIMMYT.

1.2 Objectives of the Study

The goal of this study is to analyze international wheat research spillovers and develop a framework to guide decision makers on the

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[10] Crop improvement research is defined to include plant breeding and complementary research on plant pathology, agronomy, entomology and cereal chemistry for the purpose of developing improved varieties.

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appropriate size and capability of wheat improvement research programs.[11] In the past, the size and capability of agricultural research systems in developing countries have been heavily influenced by scientific, financial and political factors while inadequate attention has been given to the economic costs associated with such decisions. A framework will be developed to identify the economic costs of such decisions, and the appropriate size and capability of wheat improvement research programs from an economic point of view.

The first objective of this study is to compile an overview of global wheat research efforts in developing countries. Cross-sectional survey data on wheat improvement research programs will be used to assess the current status of wheat research programs in developing countries in terms of size, expenditures, research capability, environmental diversity and number of varieties released. Survey data on the wheat research programs in industrialized countries will be used to compare the size and capability of wheat research programs in developing and industrialized countries. The empirical results of these analyses will provide a picture of the current status of global wheat research efforts and some empirical measures of model parameters.

The second objective is to assess the transferability of wheat varietal technology across environments. As mentioned above, the expansion in the size of many research programs in developing countries has been partially justified on the ground that technology transfers are impeded by environmental interactions. In other words, local research programs are needed to create technology adapted to that environment. CIMMYT's data on International Spring Wheat Yield Nursery (ISWYN) trials will be used to test this hypothesis of 'location specificity' of agricultural technology by generating comparative data on the yield of wheat varieties developed by national programs in a local environment and those developed by national programs in other environments and by CIMMYT. The estimated yield differences will provide a measure of

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[11] Research capability refers to type of a research program. In the case of crop improvement research, the capabilities are broadly grouped into the capability to conduct evaluation research (a testing program) and the capability to conduct creation research (a breeding program that includes crossing, selection and testing component).

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potential research spillins for a research program in a given environment. Since research spillins can substitute for local research (Evenson and daCruz 1992), these estimates will provide the opportunity costs of establishing a local wheat improvement program.

The third objective is to develop a cost-benefit model to determine the appropriate capability of a wheat improvement research program in a given environment. Based on the average parameter values of different variables estimated from empirical analysis and the economic investment criterion of net present value, the model will be applied to make generalizations about the size of wheat production needed to justify a technology evaluation program (testing program) and a technology creation program (breeding program) in a given environment. The benefit-cost model will be also applied to some of the wheat research programs in developing countries using program specific data on the size, expenditures, production and environmental complexity in the geographic mandate regions. The model will provide estimates of profitability of the research programs at their current levels of investments and research capability. Using the Net Present Value (NPV) decision criteria, the best alternative for a given research program in terms of size and level of capability will be assessed.

The fourth objective of this study is to discuss policy implications for research administrators and researchers in designing an efficient wheat improvement research program. Given the results of the transferability analysis and the cost-benefit analysis, the efficiency of current levels of investment in wheat improvement research in developing countries will be assessed.

1.3 Organization of the Study

This study comprises seven chapters. Chapter 2 provides a brief overview of the literature on the size and capability of agricultural research and of different methodologies used to evaluate agricultural research, research spillovers and transferability of technology.

Chapter 3 provides a general conceptual framework of crop improvement research programs. It discusses the underlying biological and economic complexities of a crop improvement research program and how

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they influence the resource allocation decisions on research. The conventional production function framework that is used to make decisions on resource allocations is modified to incorporate some of these complexities. The implications for resource allocations are drawn for three levels of decision making - individual environment, country with more than one environment and international research center.

Chapter 4 presents an empirical investigation of wheat improvement research programs in developing countries, including cross-sectional data of wheat environments, size, expenditures and capability of wheat research programs and varieties released in developing countries. This information will provide a current picture of global research efforts on wheat improvement in developing countries.

Chapter 5 provides empirical measurements of the transferability of wheat varieties across different environments. A statistical framework based on Englander's (1981a) study is used to quantify the yield advantages of varieties developed in local environments over the varieties developed in other environments and by CIMMYT.

In chapter 6 a cost-benefit analysis model based on the framework developed in chapter 3 is used to estimate the threshold levels of production and rate of production growth rate needed to justify a testing and/or breeding research program in a given environment. The model is then applied to wheat research programs in developing countries to estimate the profitability of their current level of research investments.

Finally, Chapter 7 summarizes the results of this study and draws policy implications for guiding resource allocation decisions for wheat improvement research.

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CHAPTER TWO

REVIEW OF LITERATURE

The objective of present research is to develop a conceptual framework to determine the appropriate size and capability of crop improvement research program that a country or an environmental zone within a country can economically afford, given the research spillovers from other sources. We are basically interested in the appropriate level of capability of a crop improvement research program. In this chapter we will present the propositions in the literature about the size and investment in agricultural research at aggregate as well as commodity and project levels.

2.1 Literature on the Size of Agricultural Research

How much should a country invest in agricultural research? How can a country decide on the appropriate size and sophistication of its research system? These are straightforward questions without standard answers. One approach is for the private sector to carry out agricultural research and let the market take care of the optimum size and investment levels. This is currently the case in the U.S. for hybrid maize and most of the mechanical research. However, this approach is inappropriate for some commodities (such as self-pollinated crops like wheat). Also, in many developing countries the lack of social, economic and political incentives constrain private sector involvement in agricultural research.

The problem of appropriate size and investment level thus arises because we are dealing with public sector enterprise.[1] In theory, given that research is an investment activity (and size and capability of research is a function of level of investment), the criteria should

[1] This does not imply that private firms are unconcerned with the issue of what should be the optimal size of the R&D budget. The engineering management literature is replete with studies evaluating and proposing different methods for determining the size and allocation of R&D budget by private firms (see for example, Freeman 1960; Rubenstein 1966; Naslund and Sellstedt 1974; Graves 1987). However, given the fact that the profit maximizing objective of private firms should eventually lead to an efficient allocation of resources to R&D, optimal size of the research budget by private companies is not a public policy issue.

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be oriented toward setting resources for research at the level where marginal benefits equal marginal costs and the rate of return to research expenditures equals those for alternative uses of funds. But due to conceptual and methodological difficulties (whose benefits should be considered? what is research output?, etc.) and empirical considerations (data and information requirements), such an analysis is not proposed for arriving at the country's optimal level of investment at the system level. However, at the commodity or research program level such an approach is used in the literature to conceptualize the problem.

Although there is no standard answer for the questions we are interested in, we can gain some insights about this issue from the literature. These can be divided into five types: (1) studies that provide general system-level rules of thumb; (2) studies that quantify size; (3) studies that look at the relationship between size and productivity of research program; (4) studies that compare returns and costs of research; and (5) studies that incorporate research spillovers.

2.1.1 Systems-Level Rules of Thumb

Some broadly defined rules of thumb exist that guide the level of research expenditures. For example, the World Bank argues that benefit-cost analysis indicates that the optimal level of expenditure on research should be 2% of agricultural GDP (World Bank 1981). At the commodity level, the 'congruence principle' has been proposed as a guiding tool for determining the level of research expenditure among different commodities. According to such rules of thumb, the research expenditures for a commodity is a function of the importance of that commodity in the economy (as measured by the value of production).

This approach of determining the level of expenditure, unfortunately, does not recognize the country differences in level of development, prior investment in a given commodity, and the complexities of their agricultural problems, all of which are important in determining the level of research expenditures. Also, these rules do not help research administrators to determine the size of research programs at different levels of organization and research sophisticat

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Javier (1987) introduced the notion of 'planned level of capability' in research as a decision rule for a research system. The capability in research can be divided into three levels of sophistication: 1) capability to monitor, introduce, test and adapt technologies; 2) capability to conduct applied research and generate new technology; and 3) capability to conduct basic and strategic (upstream) research. According to the concept of 'planned level of capability', a country determines in advance the desired level of research capability for a given commodity. Thus, the size of research effort for a commodity will depend on the predetermined target level of research capability. This is an interesting notion as it links the size (resource allocation) of research with the desired *level* of research. However, this concept does not indicate what determines the level of capability to be chosen and the appropriate size at each level.

2.1.2 The approach of quantifying size

Dagg (1988) made a useful attempt at quantifying the scientist-years required at each level of these capabilities for each commodity: monitoring, 0.2; introduction and testing, 0.4; adaptive research, 0.8; applied research, 3.0; and basic research, 10.0. This can be interpreted as the minimum size (or critical effort) of a research team at each level of research sophistication for a given commodity. Dagg (n.d.) has also made a speculative attempt to quantify the appropriate number of research groups at various levels of research organization. His list contains the following ranges of appropriate size: research testing site - 1 or 2 technicians (no permanent scientist); on-farm research team - 1 agronomist, 1 socio-economist, 1 animal husbander, and back-up from other disciplines and links with extension; research station - 12 to 30 scientists; national commodity station - 30 to 100 scientists (made up of research groups of about 15 to 20 each); regional research group - 80 to 250 scientists grouped into a main station and sub-stations; NARs - size compatible with 1% to 2% of agriculture GDP per annum. These ranges specified by Dagg reflect two different concepts of size - minimum size and optimum size. For example

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example, the minimum number of scientists needed to justify a research station, according to Dagg, is 12, and "if there are more than 30 scientists, there could conceivably be two stations." (Dagg n.d., p.3), thus 30 is the optimum size of a research station.

The concepts of minimum and optimum size as used in this context are defined as follows: minimum size refers to the size which equates research benefits with research costs, and optimum size is defined to mean the size when difference between research benefits and research costs are maximum, i.e. marginal benefits equal marginal costs. It should be noted, however, that Dagg did not use these definitions in deriving the ranges of the size of research teams. The size of research teams estimated by Dagg were not based on any formal analysis.

Another attempt to quantify the size of a research group was made by Trigo and Pineiro (1984). They estimated a *minimum*[2] research module for one commodity as consisting of 4 chief researchers (with M.S. or Ph.D.), 8 specialists (with B.S.), administrative staff, materials and equipments. Gamble and Trigo (1985) applied this concept of minimum research module proposed by Trigo and Pineiro to 7 prime crops in 38 small countries in Central America, the Caribbean, and Africa. Their analysis showed that only 14 out of 207 country-crop combinations had an economic base large enough to support a minimum research effort. Even if research allocations would be doubled, the authors conclude that the picture remains approximately the same. By relating the justifiability of research to the size of a country/region, this study well illustrated the problem faced by small countries and small environments for whom the question often is not how much to invest but whether to invest at all.

Based on these estimates of Trigo and Pineiro, Ruttan (1987) arrived at the *minimum* level of professional capacity (with training at M.S and Ph.D levels), of around 250 scientist at the national level

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[2] The concept of minimum size as used by Trigo and Pineiro (1984) differs from the concept introduced above (in the context of Dagg's study). Here minimum size refers to critical minimum effort needed to produce positive research results. There is no comparison of research costs with research benefits.

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(Ruttan 1987, p. 84)[3]. But these attempts to quatify a minimum or optimal size of a research program have limited analytical bases. First, the studies do not indicate how they arrive at the given numbers. This raises questions about the generalizability of the numbers. Second, the size of a research program can be viewed from three angles - aggregate commodity level, level of research capability (testing, adaptive etc.), and level of research organization (research site, research station, etc.). These studies have tried to quantify size from only one of these dimensions. For example, Dagg (1988) examined the level of research capability but ignored the differences among commodities and level of organization. Similarly, Trigo and Pineiro (1984) determined the minimum size of a commodity research program but ignored the differences in size at different levels of capability and organization. Ideally, the issue of appropriate size should be analyzed from all the three dimensions (which means dozens or even hundreds of estimates of sizes depending on the combination of these three levels). This makes these approaches inadequate and inappropriate as a generalizable method of determining the size.

Third, this approach provides the minimum size of research effort but does not indicate what size is economically efficient. For example, Dagg (1988) estimates the size at each level of research capability but does not indicate what level would be optimal.

Fourth, this approach does not consider factors like the diversity of environments, type of constraints, number of economically important crops and animals, and previous research. The size of a research program will undoubtedly be influenced by such factors.

Nevertheless, for the purposes of this research, this approach provides important parameters in determining the appropriate level of

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[3] Ruttan's estimate of 250 researchers as a generalization about the minimum size is suspicious on two grounds. First, it is based on the estimates of Trigo and Pineiro's table (1984) whose generalization across different countries and commodities is doubtful. Second, the arithmetic behind Ruttan's derivation of 250 is not clear either. With each commodity requiring 4 chief researchers (as per Trigo and Pineiro) and small countries having 6 to 10 major commodities (Ruttan, 1987, p.84), the minimum size of research capacity would be 24 to 40, which is far less than 250.

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capability of research at a commodity level. The size of crop improvement research system can be considered as a fixed number at each level of capability (testing, breeding, etc) and the optimal level can be determined by taking into account the research costs and research output at each level.

2.1.3 Relationship Between Size and Productivity

In order to determine appropriate size, some knowledge about the relationship between size and productivity of research (research production function) is needed. However, there is little empirical evidence available on this relationship (Ruttan 1982) and this is limited to the U.S. only. Moreover, the results are conflicting.

Evenson's study (1971) on the size of U.S. experiment stations, for example, indicates that the largest stations and stations with the largest graduate program yield a higher marginal product per dollar of research than the smaller stations. Schultz's analysis (1971) also supports the hypothesis of increasing returns to scale in agricultural research, especially the association of experiment stations with research-oriented universities. By contrast, studies by Pound and Waggoner (1972) and Salisbury (1980), as quoted by Ruttan (1982, p.167) suggest diminishing and constant returns to scale in research effort, respectively. Both these studies measure research output in terms of scientific publications. Evidence assembled by Kamien and Schwartz (1975) from the industrial sector overwhelmingly support diminishing returns to R&D (Research and Development) intensity as measured by number of patents per researcher, for a given firm size[4].

Branson and Foster (1987) used scientific publication as a measure of research output to show that decreasing economies of size exist for

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[4] In the context of industrial sector R & D efforts, conceptually there are two major "scales" that may affect efficiency and quality of innovation. First is the effect of firm size on the efficiency of a given size R & D facility. Second is the effect of scale of the R & D facility for a given firm size. These two questions are conceptually distinct. However, as Kamien and Schwartz (1975) point out there is more evidence on the first than the second question. But, as a comparison with agricultural research effort, the answer to the second question is more relevant and therefore reported here. It tells us the extent to which efficiency varies with the size of the R & D program itself, for a given firm size.

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the relatively small USDA (United States Department of Agriculture) agricultural experiment stations and increasing economies of size prevail for the larger stations. Fitting a U-shaped long-run average cost curve, the authors found that the lowest average cost was associated with research stations with approximately 35 scientist years.

These studies indirectly address the issue of appropriate size[5]. According to the evidence of increasing returns to scale, a large organization is more efficient, implying that an increase in size of research effort is a step towards the optimum. The study by Wallmark et al. (1973), for example show that there was a threefold increase in productivity per team member as the team is increased from 1 to 50 members. Improved research environment (better service and equipment) and personal factors (improved selection of productive members) were found to be the possible reasons for increased efficiency. On the other hand, diminishing returns to scale implies that as research organizations grow, they become increasingly difficult to administer and manage, thereby forfeiting some degree of efficiency and productivity. The implication is that there is an optimal size beyond which research will yield decreasing returns.

The approach used by these studies estimates the marginal product of research input. However, the marginal productivity by itself does not indicate what the optimal level should be. Theoretically, given that research involves costs, the optimal level will be determined by equating the value of marginal product with marginal cost. Thus, determining the relationship between size and productivity is inadequate as an approach to determine the optimal size of research systems.

2.1.4 Methodology Based on Costs and Returns to Research

As we saw above, studies estimating the relationship between size and productivity of research, help to show whether there are increasing or decreasing returns to scale. They do not however, indicate what the optimal or minimum scale would be.

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[5] It should be noted that the objective of these studies was not to determine the appropriate size of research system. Their main interest was in the relationship between research inputs and output. They were mainly interested in the question of returns to scale.

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In theory, to do so, we need to specify a maximizing objective function. Binswanger (1978) argues that the issue of optimal size should be analyzed from the perspective of the profitability of research investments. This means the objective function would be profitability of research, which involves calculating the benefits and costs of research based on functional relationship between research output and inputs, size of area affected, price of commodity, etc.. According to Binswanger, profitability is positively related with the area affected by new technology and the price of that commodity.

Binswanger's analysis shows that based on the relationship between research output and input, the returns and costs of research can be defined and a model can be built. Minimum size can then be defined as the size which equates research benefits with research costs (i.e. when profits are zero), and optimal size as the size when marginal benefits equal marginal costs of research (i.e. when profits are maximized).

Based on the returns and costs of research, Brennan (1992a) developed a model to determine the criteria for establishing a plant breeding program. Using the criterion of profitability and the size estimates of Dagg (1988), Brennan estimated the threshold levels of wheat production needed for establishing different levels of a wheat improvement program. According to his analysis, the critical environment size to economically justify a full wheat breeding program was 322,000 tons, somewhat larger than expected, given that many wheat research programs in both developing and industrialized countries are based on smaller wheat production environments. The wheat production level at which a breeding program (with crossing, selection and testing components) became more profitable than only a selection program (that includes testing component) was even larger, over 1.5 million tons. Brennan's approach provides a useful starting point for conceptualizing the decision making process in terms of alternative levels of research capability.

The studies of *ex-ante* research evaluation are also somewhat relevant to the types of questions this research is trying to address. These studies have used a number of different approaches to select an efficient allocation of resources among alternative research programs -

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scoring models, benefit-cost approach, simulation models, and mathematical programming models are some of the more common ones (Norton and Davis 1981; Ruttan 1982; Daniels et al. 1992). Among these, the benefit-cost approach as described, for example, by Fishel (1971) is very similar to the approach used by Brennan (1992a). This approach consists of estimating the benefits and costs of the proposed research, and ranking the research alternatives using any of the three criteria - benefit cost ratio (B/C ratio), maximum difference between benefits and costs (NPV), or Internal Rate of Return (IRR).

The *ex-post* returns to research studies also use a cost-benefit framework to estimate the economic surplus attributed to research. Since the pioneering studies by Shultz and Griliches in the 1950s, these studies have reported high rates of return to agricultural research and raised questions about the apparent underinvestment in agricultural research. The evidence of high rate of returns is used in the literature to increase the level of research expenditures.

The underinvestment hypothesis based on the rate of return studies is, however, criticized on the following grounds: 1) Shortcomings of the analytical framework and methodology used to estimate rate of returns (Wise 1975, Pasour and Johnson 1982, Lindner and Jarrett 1978). 2) Incorrect basis of comparison. Fox (1985) argues that the underinvestment hypothesis based on the comparison of social rate of return to public investments with private rate of private investments is misleading. 3) Underestimation of total public expenditures on agricultural research in deriving the rate of returns (Fox 1985). 4) Skepticism about the continued high rate of returns in future (Pasour and Johnson 1982). 5) The bias toward evaluation of only research successes.

2.2 Models Incorporating the Spillover Effects of Agricultural Research

Agricultural research impacts can spill over well beyond their target location, commodity or even market level. This pervasive nature of research complicates the allocation of resource funds (Latimer and Paarlberg 1965). The expenditure which might be considered as an optimal le

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optimal level by a state or province, whose decision makers account only for the benefits accruing within, would not be optimal from the country's viewpoint because of the presence of spillovers. This is well recognized in the literature. However, as shown by Garren and White (1981), failure to account for potential spillins of research benefits may also lead to non-optimal allocation of expenditures. Hence, both research spillovers and spillins need to be accounted for in resource allocation mechanisms. The studies reviewed above do not consider research spillovers.

The eventual total spillover effects of research can be a result of the combined effects of the following types of spillovers:[6]

1. Price effects from increased production due to reduced costs (price spillovers)[7]
2. Spillover of technology from one country to another with or without any research required on the part of the recipient country (technology spillovers).
3. Spillover of scientific knowledge which ultimately enhances research in other aspects of research on the same commodity or in other areas of research[8] (Davis, et al. 1987, p.17).

The third type of spillover effects is usually not quantified because of conceptual and measurement difficulties. In the context of agricultural research, the estimates encountered in the literature are usually those

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[6] There are many different ways of classifying the research spillovers. Evenson (1989), for example, classifies agricultural research spillovers as follows: (1) Interlocational spillovers consisting of direct or indirect transfer of technology across locations; (2) Interfoci spillovers consisting of transfer of knowledge among different specializations, namely, pretechnology science, technology invention and development, and technology development and subinvention; (3) Intercommodity spillover; and (4) Intersectoral spillover from private (and public) input supply sector to agriculture sector.

[7] A caveat is needed at this point. The price spillovers should not be confused with pecuniary externalities which are defined as the effects of a project on the prices paid and received by others outside the project (Gittinger 1982). Price spillovers as used here are the direct effects of a research project on the price of the commodity in question due to reduction in costs.

[8] A prime example of such spillovers is Dr. Barbara McClintoch's Nobel Prize in Medicine, for her work on the genetics of maize.

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of the price and technology spillovers. However, the study by Jaffe (1989) on research spillovers in industrial R&D and Pardey (1986) provide examples of estimating the third type of spillovers. Jaffe (1989) used a distance metric based on patent data to quantify the 'technological proximity' of firms doing R&D and showed that the productivity of a firm's R&D was affected by the R&D of its technological neighbors. Pardey (1986) used a similar distance metric based on citation index to measure the research spillovers across countries and regions.

There are at least three important reasons for understanding and measuring the spillover effects of agricultural research (Davis 1991). First, a better modelling of research spillovers is needed to enhance the research evaluation methodology; it can facilitate more realistic disaggregation of research evaluation analysis and also provide additional dimensions for understanding the adoption of technologies. Second, it can assist research managers in designing their research program; it can help them in better focussing their research efforts, in making choices about physical location of research infrastructure and the structure of human capital expertise. Last, better understanding of research spillovers can add to the research policy debate; the evidence of wide adaptability of research across many locations and environments can be used to make a case for governmental involvement and a continuum of national, regional and international centers (Davis 1991).

The few attempts to estimate research spillovers include econometric models that estimate spillover effects as one of the variables in the production function, economic surplus approach that uses a research spillover matrix in calculating gains in consumer and producer surplus due to agricultural research, and models analyzing the process of technology transfer. The studies using econometric models are concerned with evaluating agricultural research investments (for example, Evenson 1977, Evenson and Kislev 1975, Flores-Moya et al. 1978), determining optimal financing of research by state and federal government (for example, White and Havlicek 1981) and estimating the demand for research (for example, Khanna et al. 1991). The methodology used by these studies essentially consists of classifying the geo-

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political boundaries into agro-climatic zones, and estimating a function with the research done in the same agroclimatic region included as one of the independent variable. Research spillovers are then calculated differently by different studies. Total Factor Productivity analyses has also been used to measure research spillovers (Evenson 1989).

These econometric approaches of estimating the research spillovers are useful for evaluating aggregate research investments on a given commodity or in a given region. However, requirement for time series data makes the approach less practical. Also, it is based on an arbitrary definition of regional research variable. Evenson (1977), Evenson and Kislev (1975), and Flores-Moya et al. (1978), for example, use number of publications, and White and Havlicek (1981) use research expenditures as the measure of regional research. Moreover, the use of this approach for the purpose of assisting research management in designing a research program is very limited. It is difficult to estimate spillover coefficients for a specific type of research, viz., plant breeding research versus crop management research. Also, this method does not assist research managers in their decisions about which environments to target.

In this study our interest in spillovers is to assist research managers in designing their research programs (the second reason given by Davis 1991). The relevant studies are therefore those that use a research spillover matrix and those that analyze the process of technology transfer. These two approaches are therefore reviewed below.

2.2.1 Economic Surplus Approach and the Notion of Research Spillover Matrix

Under this group are the studies concerned with research evaluation for priority setting, for assessing the distribution of research benefits between the consumers and producers of a country undertaking the research and other countries affected by that research (see for example Edwards and Freebairn 1984, Davis et al. 1987).

These studies estimated the combined effect of price and technology spillovers and introduced the notion of a research spillover matrix. The spillover matrix is usually an m x m matrix (where m is the number of production environments) with spillover indexes or weights,

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s_{ij}. The elements, s_{ij} are defined as the value of cost-reducing (or yield increasing) effect of the research done in environment 'i' on the supply of the commodity in environment j. Because of location specificity, it is expected that the $s_{ij} < s_{ii}$, that is the cost reduction (or yield increments) are less in production environments for which the technology was not specifically designed for.

Edwards and Freebairn (1984) used a disaggregated commodity supply and demand model with separate sectors for the home country (Australia) and the rest of the world (ROW). They used tradeable commodities (wheat and wool), and assessed the benefits from research to producers, consumers, aggregate in home country, ROW, and the world (including Australia) under different assumptions about the spillover effects (measured by percent cost reductions). Along the lines of Edwards and Freebairn (1984), Brennan (1989a) estimated the shift in Australia's wheat supply curve as a result of spillover from CIMMYT wheat breeding programs. The reduction in costs were obtained from the change in the index of varietal improvement calculated by taking into account the percentage yield advantage of CIMMYT-based varieties in Australia and the proportion of the area sown to CIMMYT-based varieties. However, he did not estimate the benefits or distribution of benefits between producers and consumers.

Davis et al. (1987) extended Edward and Freebairn's (1984) two-country (home country and ROW) model to a multi-country model. This extension led to more detailed and comprehensive specification of spillover effects. They divided the world into agroclimatically homogenous regions, and determined the potential spillover effects from each region where research is undertaken to each other region where research can feasibly spillover. Subjective guesses of spillover effects (defined as the proportion of direct unit cost-savings) were used to construct this spillover matrix. The regional spillover effects were then aggregated by countries and used to calculate the research benefits accruing to consumers and producers.

The concept of a research spillover matrix introduced by these studies, makes the notion of spatial research spillovers more tractable. However as noted by Pardey and Wood (1991), two major issues need to be addressed

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addressed in constructing such a matrix. The first relates to the zonal classification system to be employed and second to the estimation of spillover coefficients. According to Pardey and Wood (1991), the zonal classification system should be flexible (i.e., different for each commodity and perhaps even within a country) and should not be highly disaggregated nor highly aggregated[9]. Another important issue is estimating the spillover coefficients (the elements of the matrix). Edwards and Freebairn (1984) used values that were arbitrarily chosen, and Davis et al. (1987) used subjective guesses based on information regarding the production environment and their distribution for each commodity. Given the large number of regions/countries involved and diversity of production environments within some of these, the subjective estimation process is often mentally taxing.

Both, Davis (1991) and Pardey and Wood (1991), therefore, discuss the need to expand the subjective estimation procedure used by Davis et al. (1987). Pardey and Wood suggest two alternative approaches to estimation namely quantitative assessment and expert elicitation. Among the quantitative methods are the analysis of the growth of industry and/or experimental yields in order to assess likely productivity increases attributable to research, and the assessment of land suitability to estimate the yield potential for each zone. The expert elicitation process could be implemented as a formal Delphi study. However, both these estimation procedure (quantitative and expert elicitation) have their advantages and disadvantages. The quantitative methods of estimating spillover coefficients, while providing objective estimates, require historical data and face conceptual and analytical difficulties. The expert elicitation process, on the other hand can be both practical and sufficiently precise, but the problem with this approach is to strike a balance between providing too little and too much information (that may potentially lead to ill-informed expert judgements or confuse the experts). Thus, a hybrid method is suggested

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[9] Most of the international studies use either Papadakis classification or regional studies of FAO on agroecological zones. See Pardey and Wood (1991) for a discussion on classification of agroecological zones.

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whereby quantitative estimates are used to condition expert opinion in a subsequent elicitation phase (Pardey and Wood 1991).

2.2.2 Technology Transfer Models

Ruttan and Hayami (1973) distinguish between three phases of international technology transfer: 1) material transfer, 2) design transfer, and 3) capacity transfer. The first phase is characterized by the simple transfer or import of new materials without any systematic research on local adaptation. In the second phase, the imported technology is subjected to orderly tests and are propagated through systematic multiplication. The capacity transfer phase is characterized by the transfer of scientific knowledge and capacity to produce locally adapted technology. These three phases correspond to the development of research capacity in a country and help explain the theory and history of international technology transfer.

Each of the three phases correspond to different emphasis on the type of technology transfer. As a research system moves from one phase to another, the technology spillins become more indirect in nature rather than direct.[10] However, the capacity to create new technology (as in the third phase) does not necessarily imply that direct spillins of foreign technology is no longer an option. Research systems in Phase 3 have to resolve the issue of how much to rely on direct transfers and how much on indirect transfers in creating new technologies. The solution to this issue will depend on the availability and transferability of technology from other sources.

The studies on the transferability of agricultural technology, therefore come closest to analyzing the micro-level questions this research is interested in. All the studies on spillover effects mentioned above, accept the fact that the transfer of agricultural technology is inhibited by environmental factors. This is reflected in their use of agroecological zones in assessing the spillover benefits. However, these studies do not measure this environment interaction and

[10] The concepts of direct and indirect transfer are used in the sense of Evenson (1991b). In the former, technology produced or generated in one region becomes directly implemented in another region, and in the case of indirect technology, it needs further research in order to be introduced in another region.

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the tradeoff between producing technology that perform well in many different environments and that which performs well in only one environment. Also, they do not differentiate between direct and indirect technology transfer.

Binswanger (1974) outlined an ex-ante cost-benefit analysis framework of research resource allocation by incorporating the alternative of technology transfer from other sources. Although, he did not suggest any methodology of estimating the technology transfers, he pointed out the importance of straight borrowing of technology or not doing any research on a particular commodity as a potentially profitable alternative if the expected present value of these alternatives is greater than the present value of research on creating new home technologies.

Englander and Evenson (1979) presented a model of optimal targeting of crop breeding activities. They used a net returns maximization model containing two regions, and computing the first order derivatives of maximization, derived the equations that established the optimal scale of research in one region, given the location and scale of research station in other region. However, as they themselves admit, the model was difficult to solve in real world situations. The data requirements were demanding and few of the models' relationships were estimated. As an attempt towards exploring some of the model relationships, they used the data on International Nursery Yield Trials conducted by CIMMYT to offer some empirical evidence regarding stability and adaptability in wheat genotypes.

Englander (1981a; 1991) described the tradeoff between foreign and home performance as the technology transfer frontier. Using a production function approach, and wheat yield trial data from CIMMYT, he estimated the varietal effects on yield when the variety is planted in different environments, and the technology transfer frontier. His results suggest that wheat varieties could be made much more adaptable to regions other than one in which they are bred, although varieties tend to yield more at home than abroad. Also, the results suggest that varieties that incorporated CIMMYT (foreign) technology and are bred locally outperform both traditional varieties and CIMMYT varieties.

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Although not free from limitations, this study has important implications for research system design. It also demonstrated the use of international yield trial data in the analysis of technology transfer.

Evenson (1991b) distinguishes between direct and indirect technology transfer and suggests different methods for analyzing them. Direct transfer can be measured by indicators such as the proportion of varieties developed in other locations (including IARCs) that are planted in a given local. Another method suggested and applied to rice research in India, is the measure of relative advantage (A_{ij}) index based on yield trial data, and defined as the ratio of the yield in region 'i' of the varieties that performed best in 'j' and yield of highest yielding varieties in region 'i'[11]. This can be useful for indirect transfer studies also.

No measures are available that directly analyze the indirect technology transfer. However, he suggests that indicators such as genealogy data and citation data can be used to show the importance of indirect transfers. Some studies that use the production function approach and spillover matrix measure the indirect transfer. But according to Evenson, these studies have not been able to separate direct from indirect transfer. He discusses several extensions of the A_{ij} indexes to make the actual research spill-in (both direct and indirect) estimation feasible.

Evenson (1991b) argues that for the purposes of research system design, it is important to know how much direct spill-in can be stimulated with only extension and screening activities, and how much adaptive research will be needed. The knowledge about who benefits from research and by how much (that the economic surplus approach tries to estimate), although necessary, is not sufficient for research management to efficiently design their research programs. For a research system design, the estimates of technology transfer are more important than the

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[11] This approach is similar to the spillover matrix used by Davis, et al. (1987). The difference, however, is the definition and method of estimating the research spillover coefficients (i.e., the elements of the matrix).

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price spillovers. In these respects, therefore, the third group of studies (that estimate the technology transfers) can be more useful in providing insights into analyzing the problem to be addressed by this research.

2.3 Conclusion

Although the issue of appropriate number, size and capability of agricultural research programs is of growing importance, it has not been adequately addressed in the literature. As Vernon Ruttan pointed out a decade ago, "...there has been very little analytical or empirical research on the relationship between size and productivity in agricultural research." (Ruttan 1982, p.167). Moreover, available studies lack in methodological and conceptual consistency and do not address the question of appropriate size and capability of a research program.

Global agricultural research is now a $9 billion annual activity (Eicher 1992). Because of the rapid expansion of agricultural research over the last two to three decades, research productivity and research resource allocation have become important issues for development planners, research managers, and researchers. These issues have spawned a series of studies on returns to research, productivity of national and international research systems, *ex-ante* priority setting models, the role of economic and social factors in research resource allocation, and organization and management of agricultural research systems. Today, because of budget constraints in industrial and developing countries and the IARCs, research is urgently needed on how best to allocate limited research funds; how to consolidate existing research programs or how to justify the continuation of existing programs and the establishment of new programs.

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CHAPTER THREE

CROP IMPROVEMENT RESEARCH: A CONCEPTUAL FRAMEWORK FOR RESEARCH RESOURCE ALLOCATION

Economists have conventionally applied marginal principles on research production function to determine the efficient levels of research expenditures. The objective of this chapter is to develop a conceptual framework using this conventional approach to guide the resource allocation decisions specifically for crop breeding research. The chapter discusses the underlying biological and economic complexities of plant breeding and how they affect the costs and returns to crop improvemetn research. These biological and economic factors are brought together in a simple net returns maximizing model. The distinctive feature of this framework is the comprehensiveness in the definitions of costs and benefits, which are a function of not only the research expenditures but also the research capability. The conceptual framework is then used to analyze the decision making process of a research program in a given environment. The results of the marginal analysis are used to draw implications for research programs at the country level and at the international level.

3.1 The Production Function Framework for the Efficient Allocation of Agricultural Research Expenditures

The most common method used in the economic literature to determine the efficient level of research expenditures is to estimate a production function that includes research expenditures as a variable. Since, research done in other regions affects the agricultural production in a given region, the appropriate specification of the production function includes research expenditures within the region and outside the region (research spillovers)[1]. Thus, the quantity of a particular commodity produced within a region (Q_i) can be viewed as a function of conventional inputs (X_i), regional research expenditures (R_i) and sum of research expenditures in other regions (R_k).

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[1] The term 'region' as used here denotes a politically bounded jurisdiction. Thus, it could be interpreted as a state, province or country, depending on the level of aggregation one is looking at.

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$$Q_{it} = f(X_{it}, R_{it-m}, R_{kt-m})$$
$$\frac{\partial Q_{it}}{\partial R_{kt-m}} \geq 0 \tag{3.1}$$

where, t-m captures the research lag.

The problem facing research administrators is to determine the optimum amount of research expenditures, R_{it-m} subject to the production constraint. The procedure suggested is to increase research expenditures up to the point where its marginal rate of return is just equal to returns from alternative social investments (r_i). Making the simplifying assumption that research expenditures in period t yields one time benefits after a lag of m years, this condition can be written as,

$$\left[\frac{P_{it+m}\, MP_{it+m}}{(1+r_i)^{t+m}}\right] - 1 = 0 \tag{3.2}$$

where, MP_i is the marginal product of research in region i.
P_i is the price of the output in region i.
m is the research lag.

This condition can also be interpreted as selecting the level of research expenditures, R_{it} such that the marginal benefits discounted at the social rate of return is just equal to its marginal cost. Thus, on the margin each dollar of expenditures will generate benefits equal to one dollar in present value.

The MP_i is the partial derivative of the production function with respect to research in the ith region. For a region making independent decisions, this is equal to

$$MP_{it+m} = \frac{\partial Q_{it+m}}{\partial R_{it}} \tag{3.3}$$

On the other hand, for a region that accounts for the spillover benefits of its research expenditures to other regions (externalities), the MP will be equal to equation 3.4.

$$MP_{it+m} = \frac{\partial Q_{it+m}}{\partial R_{it}} + \sum_{\substack{k=1 \\ k\neq i}}^{K} \frac{\partial Q_{kt+m}}{\partial R_{it}} \tag{3.4}$$

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The calculation of the marginal product of research as given in equation 3.3 represents the classic situation of a region operating in its own best interest, while ignoring social benefits generated by its research that accrue to other regions. The expression in equation 3.4, represents the situation which is socially optimum since the calculation of the MP includes not only the benefits to the region itself but also benefits to other regions (research spillovers).

Since the research done in region i benefits to other regions (i.e. the second term in equation 3.4. is positive), research allocation decisions based on the MP as calculated in equation 3.3 are likely to be small relative to the interest of the whole society. This situation is depicted in Figure 3.1 by the region's selection of R_1 as the appropriate level of research expenditures. This choice is based on equating the present value of marginal benefits accruing to region i (MB_i) to the present value of marginal costs (which is = 1). This decision-making process ignores the marginal efficiency of research investment from the social perspective (MB_s) which indicates that the socially optimum level of research expenditures is R_2 and not R_1. The literature on research spillovers, thus argues that regions that make decisions based on it's benefits alone, may be underinvesting (level R_1 instead of R_2) when viewed from a national or international perspective (see for e.g., Davis, et al. 1987; White and Havlicek 1981).

The production function approach illustrated above provides a good theoretical and analytical framework for the allocation of agricultural research expenditures at a regional and intra-regional level. Difficulties occur, however, in empirically determining such continuous research production functions. Moreover, research resource

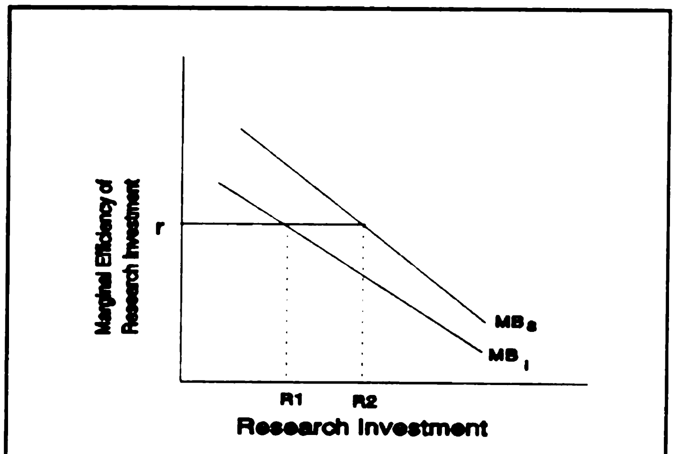

Figure 3.1: Marginal Efficiency of Research Investment: Adjustment for Research Spillovers

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allocation decisions in practice, are not made continuously for each dollar. The decisions are made discrete in time and involve an addition or subtraction of sub-programs which will either increase or decrease the number of researchers and in turn affect the research focus (in terms of adaptive, applied, basic and strategic research) (Brennan 1992b). Since, a given amount of dollars can be expended on a research program composed of one breeder and fifteen research technicians or two breeders, one entomologist, one cereal chemist and two technicians, each implying a different research capability, the problem facing research administrators is more in terms of 'what type of research program to have' rather than how much to invest.

If in practice, the research resource allocation decisions are made in terms of research focus or what Javier (1987) refers to as the 'planned level of research capability', then the analytical framework needs to be modified to take this in to account. Moreover, the research spillins conventionally measured by research expenditures (R_k as in equation 3.1) assumes that each dollar expended on research will have an equal opportunity to spillout. However, in reality there is an asymmetry in the transfer of technology (Evenson 1991b), as it is a function not only of research effort as measured by dollars expended, but also a function of level of research capability and 'environmental distance' between the originating and receiving research programs.

The conventional dollar specification also fails to account for the differential effects of different types of research spillins (direct and indirect) on the decisions of appropriate research capability which is particularly important for crop improvement research. The spillover specifications in the analytical framework discussed above assumes that all research spillins enhance or complement local research productivity. In fact, as shown by Evenson and daCruz (1992), research spillins may substitute for local research. For example, research spillins in the form of crop varieties that can be directly introduced to farmers may eliminate the need for a local breeding program; adaptive research in the form of local testing would suffice. Or, the availability of improved germplasm, resistant to a given insect, may eliminate the need for large investments in mass insect rearing laboratories and artificial infest

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infestations in the fields to detect the resistant germplasm. The available resistant germplasm, in such a situation, can be directly used in the breeding program as a parent material. Thus, the direct or indirect research spillins will affect the decisions on what the local research program should focus on without being redundant.

Englander and Evenson (1979) contend that the design of an efficient crop breeding research program incorporates a number of complex factors. Thus, in order to guide the research resource allocation decisions, particularly for crop breeding research, the analytical framework needs to be modified to account for the underlying biological complexities in the decision making process. However, before we do that, we need to better understand these underlying complexities and how they affect plant breeding research decisions.

3.2 Underlying Complexities in Designing a Crop Improvement Program

Crop improvement research basically aims at improving genotypes for a given environment. Thus, there are two explicit components that define a crop improvement research program - the genotypes and the environments. The genotypes define the sources (raw materials) of genetic improvement and the environment defines the size, scope and objectives of the program. There is, however, a third implicit component in an improvement program - the genotype by environment (G x E) interactions that determines the type of research spillovers, the targeting strategies, and ultimately the rate of genetic gains.

3.2.1 Understanding the Three Components of Plant Breeding

Genotypes:

The genotype refers to the genetic constitution of a plant. It is this component that a breeder aims to improve. Since different genes condition different traits of a plant, genotypes differ from each other in their abilities to react to a given circumstance. The genetic diversity in a plant population stems from these differences among genotypes in their responses to different circumstances. The success of a plant breeding program, in part, will depend on the genotypes available to a breeder and their genetic diversity.

Since the breeder does not know why the plant performs the way it does, there is no predictable way of improving the genetic constitution. In practice, the breeder alters the genetic composition of crop populations by selection mechanism. Genotype improvement is therefore, rightly referred to as a numbers game, because the chance of selecting a superior cultivar is improved by increasing the number of genotypes tested each year. However, increasing the number of testings may not necessarily lead to the selection of a genotype with the right combination of traits. This is because, some traits are easier to alter genetically than others; and some may be impossible to alter. For example, deploying a disease resistance gene may be in general easier than deploying the gene for maturity. Also, the number and combination of traits that needs to be altered poses different degree of difficulty to the breeder. For example, developing a variety that is tolerant to soil toxicity and also drought resistant may be more difficult than developing a variety tolerant to soil toxicity alone. At the extreme, some traits may be impossible to alter genetically if it requires the plant to exist in two mutually exclusive states. For example, a breeder cannot alter the habitat of spring wheats into winter wheats, or alter a white dent maize into a yellow flint maize.

Thus, the complexity in the G component arises from three sources: (1) lack of knowledge about the causal relationship between the genetic constitution of the plant and its performance; (2) different levels of difficulty associated in deploying the genes for different traits; and (3) incompatibility of some traits with a given state of a plant.

Environment:

The 'Environment' as one of the component of a breeding program determines the problem statement and objectives of research and provides a spatial and temporal dimension to a research program. However, to better understand the conceptual framework, we have to distinguish the concepts associated with this component of a breeding program.

The first is the research program domain. The definition of a research domain for which improved cultivars are to be developed is fundamental to any breeding program. In practice, a research program domain is generally defined either in terms of geographically bounded

locations or politically bounded jurisdictions. The classification based on political boundaries reflects the financial system of research investments and includes a state, province or a country as a whole. The geographical classification system would include locations that can be characterized by fixed environmental factors such as the geographic, edaphic and some socio-economic factors (latitude, elevation, soil type, cropping pattern, etc.) or by ranges of variable factors such as climatic and biotic factors (high, low or very low rainfall, different degrees of disease stress, etc.) that increases the predictability of the circumstances in a given research domain. This type of research domain classification is most common in international research centers and in large countries with diverse production environments. Thus, a research domain could be wheat in Michigan (defined in terms of political boundaries) or it could be white dent maize in the lowland tropics (defined in terms of socio-economic and geographical factors) or it could be sorghum in the low-rainfall areas in a given country (defined in terms of climatic factors).

Irrespective of the way a research domain is defined, it is unlikely that it will be homogenous because of the random and dynamic nature of environmental factors. We can think of the research domain as consisting of many (or a continuum of) 'plant environments' (in short, environments). The plant environment can be defined as the sum of all external forces and substances that affect the growth, structure and reproduction of that plant (Billings 1952). It is made up of environmental factors that can be grouped as climatic, edaphic, geographic, and biotic[2]. These factors interact with the plant by

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[2] The biological factors listed here are not the only factors that cause G x E interactions. There are also socio-economic and management factors that influence the plant environment. However, unlike the biological factors which cause G x E interactions in the performance indicator, yield, these factors cause G x E interactions in other traits of the plant that ultimately affect the adoptability of a crop technology by farmers. Factors such as cropping pattern and consumer preferences, for example, determine the level of crop maturity and grain quality desired by farmers in a crop. Traditionally, G x E studies have ignored interactions in traits other than yields. However, in target domains characterized by heterogenous non-biological factors, these factors should be taken into consideration in not only defining the objectives of a breeding program but also in assessing G x E interactions.

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affecting the adaptability of the plant to the environment. They could be either limiting or triggering to the growth and distribution of the plant. Moreover, one biological factor may compensate for another and allow a plant to perform beyond its apparent tolerance range. The adaptability and performance of a plant will thus depend on the combination and pattern of occurrence of different environmental factors occurring at a given place and growing season of a plant.

The large number of environmental factors influencing the plant environment not only makes it very complex but also very dynamic. This is because these factors vary both in space and time. If we define a 'circumstance' as the combination and pattern of all the different environmental factors occurring at a given place and growing season of a plant, then, no two locations will have the same circumstance at a given time, and no location will have the same circumstance at different time periods. Understanding these biological complexities of plant breeding research is important because they determine the genotype by environment interactions, which in turn influence the resource allocation decisions.

Genotype x Environment Interactions:

G x E interactions denote the differential response of genotypes to different plant environments. There are basically two types of interactions - crossover and non-crossover. The former refers to the significant alterations in the ranking of the genotypes in different environments and the latter refers to the situation where only relative yields of different genotypes change in different environments. In terms of implications for breeding strategy, crossover interactions are more important to a plant breeder because they complicate selection and identification of superior genotypes (Romagosa and Fox 1993).

The presence of G x E in a research program domain implies the following: (1) variability in the traits of the genotypes tested, (2) variability in the combination of the limiting and triggering factors at the testing sites (i.e. more than one plant environment in the domain), and (3) differential response of the genotypes to the plant environments. Note that G x E interactions cannot be defined independently of the genotypes and the testing sites. The G and the E are the basic ingredients of the G x E interactions. Any alteration in the G and/or E component can change the significance of the interactions. And any change in the significance of the interaction can change the breeders reaction to it (in terms of either exploiting or ignoring the interactions) which in turn affects resource allocation decisions. Herein lies the challenge of plant breeding and the crux of the research resource allocation problem (Hill 1975).

3.2.2 Implications of the G x E Interactions on Plant Breeding Research Design

Plant breeding research would be immensely simplified were it not for the G x E interactions. There are several implications of the G x E interactions on the research resource deployment decisions that need to be accounted for in designing an efficient crop breeding research program.

Implications for the Number of Breeding Programs in a Region

The presence of G x E interactions imply that there is more than one plant environments and different genotypes with differential response to each environment in the target research domain. The implication of significant crossover G x E interaction is that there can be no one variety which will excel everywhere and in all years. Hence, there are potential gains from ensuring that breeding research is tailored to each environmental niche (Simmonds 1991). In other words, environmental diversity as revealed by G x E interactions creates a potential need for separate breeding programs within a given region.

Thus, one of the implication of G x E interaction is on the decisions about the number of breeding programs, if any, a region should have. If a plant breeding program already exists, then the implication is on whether to further expand or maintain the existing crop breeding research program in the target domain.

Implications on the Level of Research Capability

We have pointed out that the presence of significant crossover G x E interactions hinders technology transfers and creates the need for separate breeding programs. Similarly, the detection of insignificant non-crossover G x E interactions between different regions create technology spillovers which affect the decision on the appropriate level of research capability. The different levels of researc

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research capability for a region can be broadly grouped as - technology evaluation and technology creation. Technology evaluation research in crop improvement refers to testing and selecting germplasm developed by other research programs and releasing the best adapted variety. Technology creation research, on the other hand involves a crossing program in addition to local testing and selection. There could be different levels of sophistication within technology evaluation and technology creation research depending on the emphasis given to direct versus indirect transfers. For example, technology creation research may range from a simple breeding program to conducting large scale screening trials for insect and disease resistance to molecular biology.

As noted earlier, the type and magnitude of technology spillins (direct versus indirect) will affect the decisions on the level of research capability a region should opt for. For example, the absence of significant crossover interactions would imply the possibility of direct technology spillins from other regions which in turn may eliminate the need for a local breeding program; a testing program would suffice. Alternatively, if the technology cannot be directly transferred, a region may opt for a local selection program to make the technology more adaptable to a local environment or use the available germplasm in local crosses and create a new technology. This decision is important in designing a crop improvement program because of its implication on the number and composition of researchers in the program.

Implications on the Targeting Strategy

Since plant breeders can, through genetic manipulation, alter the degree of G x E interaction, this phenomenon has important implications on the targeting strategy in designing a breeding program[3]. Targeting refers to the selection of a specific environment or set of environments toward which a breeding program is directed. Thus, a breeder is confronted with the problem of deciding between different targeting strategies - whether he/she should aim at developing cultivars that can be commercially released in all the environments in

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[3] The degree to which this interaction can be manipulated, however, varies with the crop. In some crops such as maize, there is little scope for wide adaptability, in others the scope is considerable.

the target domain (widely adapted) or develop cultivars that meet the specific needs of each environment in the domain (specifically adapted).[4] Note that the concepts of wide and specific adaptability are defined in relation to a given set of genotypes and a given set of environments in a target research domain. A genotype that is considered to be widely adapted in Michigan, may be only specifically adapted if the research domain is defined as the midwest plains that includes other states of the U.S..[5]

The different strategic decisions that a breeder needs to make are in terms of early versus late generation testing and selection in different environments within the domain. These decisions will affect the range of adaptability of selected germplasm and in turn will affect the rate of genetic gains in the region.

3.2.3 Resource Allocation Implications of Different Decision Alternatives

Each of the implications of the G x E interactions discussed above have resource allocation implications in designing plant breeding programs. Basically, the challenge posed by the G x E interactions is in terms of deciding on the extent to which a region should exploit or suppress the interactions. The decisions to have separate breeding programs, a full-fledged crossing and selection program or to target

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[4] Some prefer the term 'adaptation' in the context of spatial variation and use the term 'stability' for performance at a given site across years (see for example, Evenson et al. 1979a). Here, we use adaptation to refer to both spatial and temporal dimensions, as environment is defined in general terms that covers *conditions under which plants grow* and involves both site and year. The use of the term 'wide' and 'specific' for the adaptation phenomenon is to differentiate the range of circumstances in the domain in which a genotype is adapted.

[5] Different methods have been used by breeders for the assessment of adaptation of genotypes (Westcott 1986). Among these the regression analysis of individual variety yields at each location on the mean yield of all varieties at the same locations, has been extensively used to account for the G x E interactions, and yield 'stability' and adaptability. According to this method, the regression coefficient and mean yield of a given variety are used as measures of 'stability' and adaptability, respectively. A variety has average 'stability' if the coefficient is 1. Coefficient value less than one, signifies above average 'stability' and value more than one signifies below average 'stability'. A variety has general adaptability if it produced above-average yields in all environments. On the other hand, if a variety produced below-average yields, it is considered to be poorly adapted to all environments (Finlay and Wilkinson 1963).

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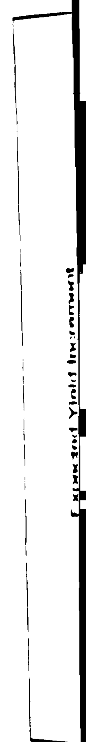
specifically each plant environment in the domain, illustrate the case of exploitation of interactions. It is a challenge because each alternative has different implications for the costs and benefits generated by plant breeding research.

The decision to exploit the G x E interactions by establishing a separate breeding program in each sub-regions or expand the level of capability from technology evaluation to technology creation requires more resources in terms of research scientists, support staff, technicians, and physical infrastructure. On the other hand, the decision to suppress the G x E interactions by maintaining current research programs, by importing technology from other regions or by targeting a wide range of environments within the region in one research program, saves research resources. However, each decision embodies associated differential costs and benefits which increases the complexity of deciding how much to allocate to plant breeding research. For example, the rate of genetic gains from selection will be higher when interactions are exploited than if they are suppressed. However, this alternative will have a smaller impact in terms of size of crop area in the target domain since the developed varieties will be specifically adapted to a limited range of environments.

Evenson et al. (1979a) illustrate this dilemma faced by a crop breeding program (Figure 3.2). Suppose a region consists of five environments, E1,E2,...,E5. If there are five research programs and each targeted towards a single environment, the expected yield increments are represented by 11′, 22′,...,55′. These technologies have high G x E interactions and, thus, are highly tailored to particular environments (to minimize G x E effects). As against this, the curve AA′ reflects the performance of a material developed by a research program that selects for low G x E interactions, i.e. wider adaptability. Each of the highly tailored programs has a higher expected yield increment for its local environment (but the total research costs are higher because there are five research programs) while AA′ has a higher yield increment over a broad range of environments (but total costs are less since only one large research program is needed).



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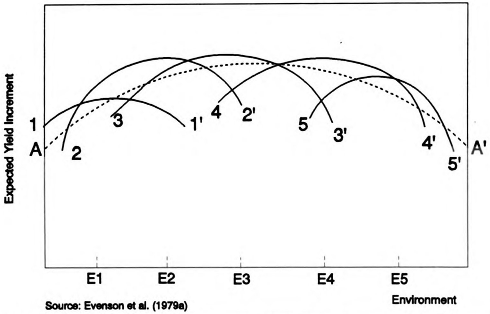

Figure 3.2: Expected Yield Increments from Research Programs Targeted to Specific Environments

The decision about the appropriate level of research capability has implications not only for the financial costs of breeding research but also the indirect costs of delayed benefits. As the level of capability in crop breeding research increases, so does the time needed to produce the research results. This time gap between the initiation of research and the realization of benefits by releasing varieties is called the research lag. For a country that is maximizing the present worth of a research program the choice between different levels of capability will also depend on the research lag involved and the opportunity cost of capital (discount factor). Since the present worth of distant benefits is reduced by discounting, the longer it takes for a research program to produce benefits, the lower will be its present value after discounting. Also, the higher the opportunity cost of capital, the lower will be the present worth of distant benefits. In other words, there are implicit costs (in terms of foregone early benefits), as the research program gets involved in local crossing in terms of

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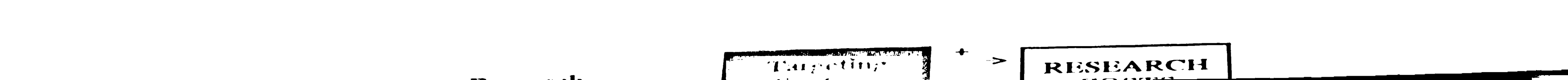
terms of increased research lag. Thus, an efficient research program has to balance the tradeoffs between low returns but small research lag (if it opted for only evaluation of foreign materials), and high returns but long time lag (if it opted for breeding its own varieties instead).

The decisions on whether and to what extent the interactions should be exploited or suppressed are important not only to the breeder but also to research administrators since these decisions determine the evolution and growth of a research system. If we imagine the whole world as a target research domain, then the establishment and evolution of plant breeding programs in different countries, regions and states represent an exploitation of G x E interactions. Increasing the research efforts of an existing breeding program by targeting more environments or establishing a new breeding program, both imply exploitation of G x E interactions. They also imply deployment of more resources for plant breeding research. Thus, the G x E interactions and the reaction to these interactions by the breeder and research administrators necessarily have clear implications on research resource allocation.

However, the decisions on whether to exploit or suppress the G x E interactions by breeders and administration should not be based only on the magnitude and type of G x E interactions or mere pride of having a highly capable breeding program. The problem of research resource allocation arises from the fact that increasing the level of capability of a research program leads to increases in both costs and returns to research. Planning an efficient crop breeding research program requires a balancing of these increases in costs and returns. Moreover, there are factors other than own research effort (that is research spillins) that influence the productivity increments and research costs. Thus all these underlying factors need to be accounted for if the resource allocation decisions in plant breeding research are to be economically justified.

The factors influencing the costs and returns, discussed above, define the structure of the conceptual model to be developed in the next section. These are outlined in Figure 3.3. The arrows in the Figure indicate the direction of influence and the signs indicate the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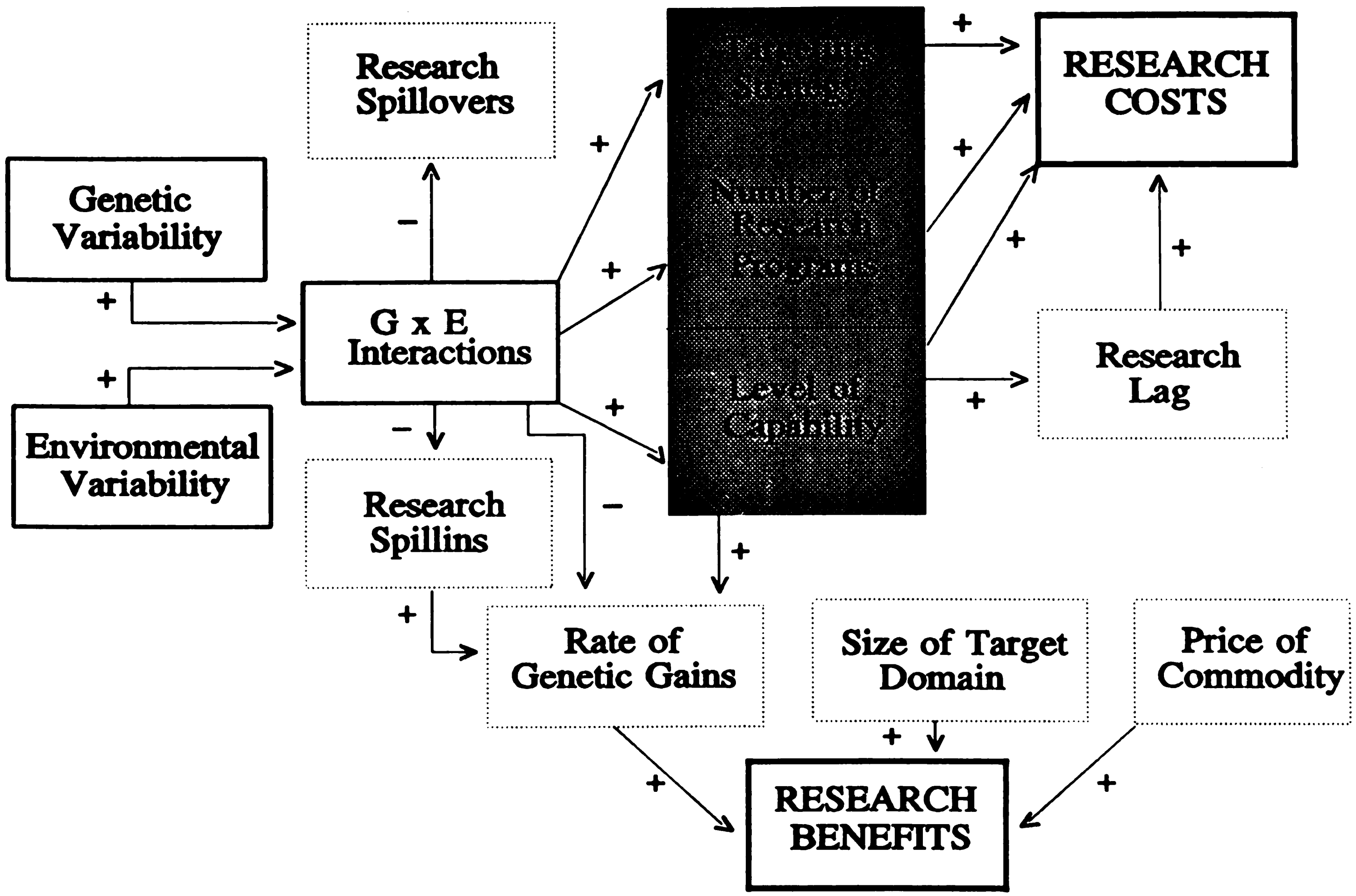

Figure 3.3: Factors Influencing the Costs and Benefits of Crop Improvement Research Program

relationship between two variables. For example, where a program simply selects materials targeted for other environments, the research expenditures as well as research lag will be much less than if the materials are used as parents in a breeding program. The latter option will reap greater benefits in terms of increasing productivity, but due to increased expenditures and long research lag, it will be more costly. Thus, the level of research capability is positively related to both benefits and costs. Similarly, if the region was served by many breeding programs, each following the strategy of specific adaptability to sub-regional environment, crop productivity will increase more than if the whole region was served by only one research program. Viewed from the region's perspective, technology spillins (direct and indirect) are positively related to research productivity, but negatively with the decision on level of research capability.

3.2.4 Economies of Scale and Economies of Scope in Crop Breeding Research Design

There are two other factors, not explicitly depicted in Figure 3.3, which affect the efficiency of a crop breeding research program. These are economies of scale and "economies of scope" in crop research. Clearly, economies of scale are determined by the area affected by new technology. Large countries and large homogenous environments within countries are therefore better positioned to benefit from economies of scale in crop research[6]. There may also be "economies of scope" due to multiproduct nature of research (Pardey et al. 1991c). For example, there are likely to be strong and positive economies of scope across some product lines (e.g., rainfed and irrigated rice technologies, bread and durum wheats, etc.), which means the research program can produce a given bundle of products more cheaply than a combination of separate operations, each producing a single product at the same general level. These economies of scope arise from the sharing or joint utilization of indivisible assets, the economies of networking within a research operation, the reuse of an input, and the

[6] In this respect, the IARCs have a strong argument for its support. See Winkelmann 1991 for this and other arguments made in favor of continuing support for the IARCs.

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sharing of intangible assets or knowhow (Pardey et al. 1991c). The gains from economies of scope depends on the organization of research activities. They can be realized with the development of crop breeding research program from one level of capability to another, and with the development of other research programs in a given environment.

The unit costs of crop breeding research will depend on how much a region is able to take advantage of economies of scale and economies of scope in research. Thus, the efficiency of crop breeding research will depend not only on the size of the crop industry but also on how the research is organized, including the number and location of research sites, number and type of crops researched, etc.. Therefore, the design of an efficient crop research program must incorporate issues such as the appropriate number of crop types to include in a research program (e.g. irrigated, rainfed, deepwater-rice) and the level of research capability for each crop type.

3.3 Determining the Level of Capability of Crop Breeding Research: A Modified Production Function Framework

In this section we will bring together the different factors, discussed above, in defining the costs and returns to crop breeding research program and analyze the design of crop breeding systems from a more theoretical aspect. The conceptual framework is then applied at a single environment (or region with a homogenous production environment) and implication are drawn for decision making by a country with more than one environment and an international research center.

The conceptual framework presented below builds on the early models and discussions on incorporating the externality nature of agricultural research in determining the efficiency of resource allocation (for e.g., Englander and Evenson (1979), Englander (1981a;1981b;1991), Evenson and Binswanger (1978), White and Havlicek (1981), Garren and White (1981), and Brennan (1992a)). It shares some common elements with these models. But it goes further in several crucial respects. First, like Brennan's (1992a) model, it addresses the question of whether and what type of breeding research program a region/country should have based on the costs and benefits of research.

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But unlike Brennan's model, it incorporates the technology spillins and environmental variability in the decision process. Second, it develops and incorporates the concept of environmental sensitivity measure discussed by Evenson and Binswanger (1978). Third, similar to the model of Englander and Evenson (1979) it allows a program to chose a targeting strategy, but it extends their model by including different levels of research capability as decision variables.

The last extension is important in two respects. First, previous models express the continuum of research effort in terms of research expenditures. However, as noted in previous section, expenditures per se do not affect research productivity; a given amount of money can be expended in many different ways by a research program. It is the research capability that determines research productivity. Thus, the basic decision variable is research capability, rather than research expenditures. Second, by incorporating the level of research capability in the model, we recognize the fact that technology transfers may be " asymmetric" or "one way" (Evenson 1991b) (from higher levels of research to lower levels). In other words, research spillovers depend on the level of research capability rather than the level of research expenditures per se. For example, a research program operating at the level of screening and testing imported germplasm will create no or very little direct and indirect spillovers to other programs. But a research program developing new materials can potentially be a source of direct and indirect technology transfers to other research programs. By allowing for different levels of research capability, we can make research spillins a function of research capability.

The model presented, is a net benefits maximizing model. The influencing factors discussed in previous section are considered in defining the costs and benefit functions[7]. The following assumptions underlie the conceptual framework.

(1) The objective of a research program is to maximize net monetary returns. No other social objectives are considered. In other words the

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[7] Except economies of scope. This is an important factor but it is excluded from this study for reasons of simplicity.

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framework will determine the economic criteria for appropriate investments in plant breeding research.

(2) The assumptions of neoclassical model - certainty and factor mobility - are maintained.

(3) Technology is freely transferable from one region to another (i.e. no political or institutional barriers to technology transfer exist).

(4) Although, breeding research is undertaken with the aim of improving the overall performance of a genotype, only one performance indicator is considered in the model - namely, yields.

3.3.1 The Production Function

Following Melton and Ladd (1979), an 'interdisciplinary production function' is defined as follows.

$$g_d = g_d(X_j,\ E_d,\ G) \qquad j = 1,2,\ldots,m$$
$$\frac{\partial g}{\partial X_j} > 0;\ \frac{\partial g}{\partial G} > 0;\ \frac{\partial^2 g}{\partial X^2} < 0;\ \frac{\partial^2 g}{\partial G^2} < 0 \tag{3.5}$$

where,
- g_d = Increments in crop yields in region d.
- X_j = j-th variable input (like fertilizer, management, etc.); the controllable part of the plant environment.
- E_d = an environmental index of region d representing other factors of plant environment (viz. climate, soils, temperature, etc.).
- G = the genetic constitution of the plant.

The arguments of this function are the customary economic variables X_j's and non-customary variables, E_d and G's, that economists usually treat as parameters, but breeders treat as variables. The plant environment, E_d is a 'fixed' variable in the production function which a research program considers as given. This is an important factor of production as it determines the potential increments in crop productivity and differentiates one environment from another. It also determines the potential technology spillovers and spillins of research done by other research programs. The variable G represent the genetic component of breeding research which the breeder aims to improve. It is defined as:

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$$G = G(S, R, T)$$
$$\frac{\partial G}{\partial S}, \frac{\partial G}{\partial R}, \frac{\partial G}{\partial T} > 0 \qquad (3.6)$$

where,
S = potential technology transfer (spillin) pool.
R = local research effort.
T = targeting strategy of local research program. T is an index ranging from t_w (representing the strategy of testing and selecting genotypes such that the varieties are released commercially in the whole domain - widely adapted) to t_s (representing the strategy of testing and selecting genotypes such that different varieties are released for specific areas in the whole domain - specific adaptability). $t_w < t_s$

Thus, the research productivity as measured by the changes in the genetic component such that it increases the crop yield are determined by three factors: 1) own research expenditures (R); 2) research spillins (S); and 3) the targeting strategy (T) followed by the local research program.

3.3.2 Defining the Technology Transfer Pool

The technology transfer pool (S), is an important variable in crop breeding research as we discussed in a previous section. In the literature most studies define this variable as the sum of research expenditures by other programs in similar agro-climatic zone (see for example, White and Havlicek 1981; Garren and White 1981). This definition, although accounts for the importance of environmental factor in facilitating or hindering technology transfer, gives the same weight to each dollar spent by other programs. In this study, we define S as the sum of research expenditures by other programs (R_k), weighted by two factors - (1) b_k: level of research capability (or research focus) in other regions k = 1,2...K. (2) $f(E_{kd})$: an index of environmental distance between the domestic (local) region d, and other regions, k (equation 3.7).

$$S_d = \sum_{\substack{k=1 \\ k \neq d}}^{K} [b_k \; f(E_{kd}) \; R_k] \qquad (3.7)$$
$$f' < 0$$

Where R_k = research expenditures in region k and the prime on function f indicates differentiation of the function with respect to

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E_{kd}. The value of the potential technology transfer pool, as indicated by equation 3.7., is determined negatively by the environmental distance and positively by the research focus and research expenditures of other research programs.

However, it is not only the magnitude/availability but also the type of research spillins which are important in designing a crop breeding program. In the definition of S (equation 3.7), the variables b_k and E_{kd} will determine the type of research spillins. Conceptually, S can be considered as a sum of S_1 (direct transfer pool) and S_2 (indirect transfer pool). If the technology transfer pool contains a large number of research programs with highly capable research programs (i.e. research programs engaged in technology creation research) and sharing a similar agroclimatic environment (i.e. less environmental distance) then S_1 (direct spillins) will be higher for the domestic environment. Similarly, a large number of research programs with low values of either f will increase the size of S_2 (indirect transfers) to domestic research program. In other words, the closer the domestic environment is to other environments where research programs are engaged in technology creation research, the higher will be the proportion of direct transfers in the potential technology transfer pool.

3.3.3 Defining the Levels of Research Capability

The distinctive feature of this model is that it allows for different levels of research capability as decision variable. In reality there is a continuum of levels of research capability. For simplicity, however, the following decision variables, corresponding to technology evaluation and technology creation research are defined:

1. Variable 'a' determines whether a region should have a crop improvement program or not.

$$a = \begin{cases} 0 \textit{ if there is no research program (level } 0) \\ 1 \textit{ otherwise (i.e. if there is a research program)} \end{cases} \tag{3.8}$$

2. Variable 'b' determines the level of research capability when a = 1.

$$b = \begin{cases} 0 \textit{ if there is only a testing program (level } 1) \\ 1 \textit{ if there is a breeding program (level } 2) \end{cases} \tag{3.9}$$

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To recollect, the variable b defined here as the indicator of the research capability is the same as defined in equation 3.7. Thus, a research program will have a potential to create spillovers to other regions only if b = 1 (i.e. if it is engaged in technology creation research). Following Evenson (1991), we can say that research programs operating at level 1 are the dependent programs representing 'end of the chain' in technology transfer.[8]

3.3.4 Defining the Research Benefit Function

Following the pioneering studies by Griliches (1958) and others (Ayer and Schuh, 1972; Peterson, 1967; Akino and Hayami, 1975;) the Marshallian concepts of producer and consumer surplus have been widely used as a measure for evaluating research benefits. According to this method, gains from research are determined by estimating changes in annual surpluses (consumer plus producer surplus) as a result of research-induced shifts in supply curves. Thus, in order to calculate the social benefits of research, the demand and supply curves need to be defined and price elasticities need to be estimated.

The literature is full of controversies about the appropriate definitions of supply and demand curves, type of supply shifts, and the estimates of the price elasticities.[9] Depending on the data available and type of research evaluated, a number of different ways of defining the supply and demand curves have been used in empirical research analysis. To keep the theoretical framework simple and to facilitate the marginal analysis, this study will follow Brennan (1989b; 1992) and Byerlee (1993) in defining research benefits as the change in total value of production. Thus, the benefits from research (B) to the society in a given time period are defined as:

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[8] It should be noted that technology transfers are defined as the origin of a variety in terms of where it was crossed rather than where it was selected and released. Thus, even though a testing program may facilitate the identification of a potential variety it is not considered as the source of technology spillovers.

[9] See for example Lindner and Jarrett (1978), Rose (1980).

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$$B = P\,Q\,g^{f}\,\alpha \qquad (3.10)$$

where,

P	=	per unit price/value of the crop.
Q	=	total crop production in the research domain without a local research program.
g	=	annual average rate of yield gains due to research (defined in equation 3.5). superscript f = research capability (evaluation or breeding)
α	=	level of adoption (% of Q that can be attributed to the adoption of new varieties).

This simplified approach has a number of underlying restrictive assumptions for empirical analysis. These assumptions are not critical for the results of the theoretical analysis of this chapter; but since this basic framework is used in one of the later chapters for empirical analysis, the implications of these assumptions are worth mentioning here. First, it assumes a perfectly elastic demand curve so that changes in wheat production due to research will not affect world wheat prices. While this is obviously a simplification, it seems to be a reasonable assumption in this study, where individual research programs are analyzed and also since the model is applied to developing countries which are mostly importers of wheat. This assumption also implies that all the benefits are appropriated by producers[10]. Second, it assumes that outward shifts in the supply curve are due to increasing yields rather than area. To the extent that new technology leads to an increase in the area planted to the researched crop, research benefits are underestimated. Third, it involves the assumption of parallel shifts in the supply curve. Thus, it will provide an over estimate of the benefits if the true shifts are pivotal or divergent rather than parallel. The approach used has the advantage however, in the sense that the benefits are the same whether the result of research is seen as a fixed percentage cost reduction or a fixed yield increase in the form

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[10] Although the relative magnitudes of the changes in consumers' and producers' surpluses are critically dependent on the values of the price elasticities of the demand and supply curves, total benefits defined as the change in total economic surplus (consumers' plus producers' surplus) is not so sensitive to the assumption about the price elasticities. According to Akino and Hayami (1975, p.5) "...any possible error in the estimate of social benefit would be within 10% for both positive and negative directions."

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To explore the theoretical implications on resource allocation decisions, the research benefit function given in equation 3.10 can be written as:

$$B = P\,Q^{*}[\;(1-a)\;g^{0}(X_j^{0},E,G^{0}) \\ +\;a\left[(1-b)\;g^{1}(X_j^{1},E,G^{1})\;+\;b\;g^{2}(X_j^{2},E,G^{2})\right]] \tag{3.11}$$

where, Superscripts 0,1,2 indicate levels of research capability.
0 = no research program
1 = only testing (evaluation) program
2 = breeding program[11]
a,b = indicator variables (0,1) defined in equations 3.8 and 3.9.
Q^* = $Q * \alpha$ (total crop production in the adoption region without research).

Note that the definition of Q^*, implicitly assumes that the level of adoption (α) is independent of g, but in reality it is probably a function of g. The superscripts on variable g indicates that the rate of yield increments varies with the level of research capability. In fact, it is assumed that $g^0 < g^1 < g^2$. Similarly, the improvement in the genetic component, G_i's are also different at levels 0, 1 and 2. For a specific level of research capability, the G_i function given in equation 3.6 is defined as,

$$G^{0} = G^{0}(S_1) \tag{3.12}$$

$$G^{1} = G^{1}(S_1,\; R_s,\; T) \tag{3.13}$$

$$G^{2} = G^{2}(S_1+S_2,\; R_s+R_c,\; T) \tag{3.14}$$

where, R_s and R_c = research costs of testing/selection and crossing component of a research program, respectively. $R_c > R_s$

There are a few things to note about the G functions.

1. $G^0 < G^1 < G^2$. In other words, genetic gains increase with the level of research capability.

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[11] Note that breeding program includes the selection and testing capabilities.

2. The genetic improvement without a research program, G^0 represents the case of genetic gains due to natural selection by the farmers or it may be due to technology spillins in the form of direct farmer to farmer exchanges of varieties from a region where there is an active research program to the region where there is no research program[12].

3. The genetic improvement due to evaluation research, G^1 is a function only of direct technology spillins, S_1, defined as the cultivars developed by foreign programs that can be transferred directly with some adaptive research in the form of local testing and selection.

4. It is assumed that $\partial G^0/\partial S_1 \leq \partial G^1/\partial S_1$. That is the genetic gains from local testing and selection of foreign cultivars will be more than if the foreign cultivars were directly planted by farmers without undergoing any further research in the form of local testing and selections.

5. The genetic improvement due to breeding research, on the other hand is a function, both of direct and indirect technology spillins, S_1+S_2. The indirect spillins, S_2, as defined as the use of foreign germplasm in the local crosses to create a new variety.

6. It is assumed that $\partial G^2/\partial S_1 \leq \partial G^1/\partial S_1$. In other words, given the fact that varieties released from testing and selection of foreign cultivars will be only a part of the total varieties released from a breeding program, the effect of direct spillins on the genetic gains realized will be more for a research program operating at level 1 rather than level 2.

3.3.5 Defining the Research Cost Function

The costs (C) to the society of a research program are defined as the direct costs in the form of research expenditures on the research personnel and research infrastructure (buildings, laboratories,

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[12] This types of direct transfers are common in small countries located near countries with strong research programs. The examples of farmer to farmer exchange of semidwarf wheat varieties in Nepal in the sixties and improved varieties of maize in Swaziland, illustrate such a case.

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equipments, library, etc.). These are represented as R_s and R_s+R_c for the evaluation and breeding programs, respectively. Note that the yield gains realized are a function not only of the genetic gains due to crop improvement research but also due to increases in other conventional inputs X_j (such as fertilizers, irrigation, management) and the efforts of extension agents in technology diffusion. Thus, there are also indirect costs to the society in the form of increased use of other inputs and extension service. However, assuming that these costs are the same for technologies resulting either from an evaluation program or a breeding program, they do not affect the decisions on which type of research program a region should have. These are therefore not included in the analysis.

The total costs of a crop improvement research program in a given time period can be represented as,

$$C = a\left[(1-b)\ R_s + b\ (R_s+R_c)\right] \tag{3.15}$$

where a and b are the variables defined in equations 3.8 and 3.9.

3.3.6 <u>Defining the Net Returns to Research</u>

The research benefits and costs as defined by equations 3.11 and 3.15, are benefits and costs for a given period in time. However, crop breeding research is a continuous process, characterized by a flow of costs and returns. The research program will therefore be interested in maximizing the present value of discounted net returns which will be a function of not only the benefits and costs in each period, but also a function of research lag and the discount factor. Most studies, use the static framework (equations 3.11 and 3.15) and analyze the problem of optimizing net returns. Such an approach simplifies the analysis, but it does not capture the tradeoffs arising from increasing research lags as research capability increases. This is an important factor since the level of research capability is a decision variable, not a parameter.

To capture these tradeoffs, the framework is presented as a present value model. However, in order to keep the theoretical analysis simple, the research expenditures in current time are related with the research benefits of the peak adoption period N. The expenditures are assu

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assumed to yield benefits after a lag of n_1 years for an evaluation program and n_2 years for a breeding program, where $n_1 < n_2 < N$.

The net present value (NPV) of the research project is defined as:

$$NPV = \left[\frac{B_N}{(1+r)^N}\right] - C$$
$$= Q_o^* \left[(1-a)\ \frac{P_N\ g_N^0}{(1+r)^N} + a\left((1-b)\ \frac{P_N\ g_N^1}{(1+r)^N} + b\ \frac{P_N\ g_N^2}{(1+r)^N}\right)\right] - \quad (3.16)$$
$$a\ \left[(1-b)\ R_s + b\ (R_s + R_c\ )\right]$$

where, r = the discount rate
Q_o^* = total production in period 0 without a research program
g_N = yield increments in period N.

The PV_B is negatively related to both the discount factor and the research lag. Whereas, the PV_C is positively related to research lag and negatively with discount factor.

Equation 3.16 defines the conceptual framework for determining the level of research capability of a crop improvement research program. It has two important and unique features that need to be reiterated.

(1) It considers most of the complex factors in designing a crop breeding research program, particularly the environmental variability, technology spillins and research lag. Thus, the definitions of costs and benefits are more comprehensive than earlier models.

(2) It takes into consideration the problems faced by decision makers - whether to have a research program or not; if yes, what should be the research capability.

These features will become apparent in the following section as it is applied at an individual environment level making decisions - 1) independently and 2) based on research spillovers to other programs.

3.4 Application of the model

3.4.1 Crop breeding research design at an individual environment level making independent decisions

In this case, the application of the conceptual framework is based on the assumption that each environment conducts its crop breeding

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research independently, taking the research products of other programs as given and assuming that its own research will not affect research decisions in other programs. Thus, this represents the classic case where a research program considers the research spillins (implicitly built in the production function) from other regions in resource allocation decisions, but does not account for spillover effects.

The environment is defined as a homogenous unit of geographic mandate with no significant crossover interactions. The environment is faced with the problem of maximizing the NPV of crop improvement research, given the research spillins from other regions, expected production in the target domain, price of the commodity, and research lag. The decision variables are a and b[13]. The problem is given as:

$$\max \ NPV = Q_o^* \left[(1-a) \ \frac{P_N \ g_N^0}{(1+r)^N} + a \left((1-b) \ \frac{P_N \ g_N^1}{(1+r)^N} + b \ \frac{P_N \ g_N^2}{(1+r)^N} \right) \right] - a \left[(1-b) \ R_s + b \ (R_s + R_c \ ) \right] \tag{3.17}$$

The conditions of maximization are as follows:

(1) b = 1, if the change in the NPV due to addition of crossing component (ΔNPV_b) $\geq$ 0 (equation 3.18).

$$\begin{aligned} &b = 1 \ \ if \ \ \Delta \, NPV_b = a \ Q_o^* \left[\frac{P_N \ (g_N^2 - g_N^1 \ )}{(1+r)^N} \right] - a \ R_c \ \geq \ 0 \\ &b = 0 \ \ otherwise \end{aligned} \tag{3.18}$$

(2) a = 1, if the change in the NPV due to a research program (either evaluation or breeding program) (ΔNPV_a) $\geq$ 0 (equation 3.19).

$$\begin{aligned} &a = 1 \ \ if \Delta \, NPV_a = \ Q_o^* \left[\frac{P_N \left((1-b) \ g_N^1 + b \ g_N^2 - g_N^0 \right)}{(1+r)^N} \right] - \left[(1-b) \ R_s + b \ (R_s + R_c \ ) \right] \geq \ 0 \\ &a = 0 \ \ otherwise \end{aligned} \tag{3.19}$$

Equations 3.18 and 3.19 can be regarded as a two stage decision process.

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[13] Since the environment is assumed to be homogenous, the targeting strategy of wide versus specific adaptability has no meaning as a decision variable.

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Equation 3.18 establishes the optimal level of research capability (whether to have an evaluation or a breeding program) assuming that a = 1. The decision to have a breeding program (b = 1), as required by the condition in 3.19, will depend on whether the present value of net benefits of a breeding program exceeds that of an evaluation program.

Using the optimal research capability from equation 3.18, equation 3.19 determines whether to have a research program in the environment or not. The decision to have a research program (a = 1) requires that the present value of net benefits from having a research program at the optimal level of research capability should exceed the present value of net benefits without a research program in the region. These conditions thus establish the economic criterion for decisions about whether and at what level an environment should establish a crop breeding research program. The criterion is that the NPV of the research program should be maximized (rather than merely being greater than zero).[14]

The important factor that will influence the decision about a breeding program is the difference in the cumulative yield gains ($g_N^2 - g_N^1$) from a creation program (as against an evaluation program). Similarly, the decision about an evaluation program will be determined by the difference in the cumulative yield gains ($g_N^1 - g_N^0$) from a local evaluation program (as against no research program).

Following Brennan's (1992a) approach, these conditions can be used to determine the threshold size of base period production needed in the given environment, to justify different levels of research capability.

[14] If investment decisions are not mutually exclusive, then adopting individual projects with positive NPVs or IRRs above the opportunity cost of capital would lead to the optimal choice of research investments as long as the six principles (the cash flow principle, the homogeneity of measurements principle, the consistency in timing principle, the life of the asset principle, the total costs and returns principle, and the geometric mean principle) that ensure the consistency in the construction of present value models are adhered (Robison and Barry, forthcoming). However, the three decisions that we are interested here, namely, the decision to have no research program, an evaluation program or a breeding program, are mutually exclusive. In such a case the optimal choice is the investment with the largest positive NPV (Robison and Barry, forthcoming).

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Threshold level of production when the NPV of evaluation program is maximized (a=1, b=0):

$$Q_s^* \geq \frac{R_s}{\left[\dfrac{P_N\ (g_N^1 - g_N^0\ )}{(1+r)^N}\right]} \qquad (3.20)$$

Threshold level of production when the NPV of breeding program is maximized (a=1, b=1):

$$Q_c^* \geq \frac{R_c}{\left[\dfrac{P_N\ (g_N^2 - g_N^1\ )}{(1+r)^N}\right]} \qquad (3.21)$$

Given the assumption that $R_c > R_s$ and $g_N^2 - g_N^1$ *is greater than* $g_N^1 - g_N^0$ (due to decreasing returns), it follows that $Q_s^* < Q_c^*$. In other words, *ceteris paribus*, the threshold size of crop production in the geographic mandate to economically justify a research program increases at higher levels of research capability. Thus, it is more likely that an environment with larger size of the expected crop production will have more sophisticated levels of research than a smaller environment. In other words, the optimal level of research focus for a given crop is directly related with the size of crop production. Equations, 3.20 and 3.21 can be used to see the effect of changes in research spillins on the threshold level of production.

1. Effect of changes in direct research spillins, $\partial Q^*/\partial S_1$:

Given the definition of G functions in equations 3.12 - 3.14, an increase or decrease in the direct research spillins from other research programs will affect the cumulative yield gains at all the levels. In terms of equations 3.20 and 3.21, the direct research spillins will affect the cumulative yield gains. Given the assumptions about the relative influence of direct research spillins on the genetic gains at level 0, 1 and 2 (that $\partial G^1/\partial S_1$ is greater than both $\partial G^0/\partial S_1$ and $\partial G^2/\partial S_1$) an increase in direct spillins will increase the difference in the cumulative yield gains of an evaluation program as against no research program (i.e. it will increase the denominator of equation 3.20), and decrease the difference in the cumulative yield gains of a breeding

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program as against an evaluation program (i.e it will decrease the denominator of equation 3.21). The net effect being that $\partial Q_s^*/\partial S_1 < 0$ and $\partial Q_c^*/\partial S_1 > 0$.

The implication of this result is that, for an environment making independent decisions, increase in direct technology spillins will decrease the need for local research capability. It will require larger level of production to justify a breeding program that can earn maximum NPV. On the other hand, an increase in direct spillins will decrease the threshold level of production for a testing program, implying that a sufficient increase in direct spillins may make evaluation research affordable for smaller environments who were not able to afford otherwise.

2. Effects of changes in indirect research spillins, $\partial Q^*/\partial S_2$:

Given the definition of indirect spillins, changes in S_2 will have impact only on the yield gains of a breeding program. An increase in indirect transfers will increase the cumulative yield advantage of a breeding program (as against a selection program), thus, increasing the denominator in equation 3.21. The net result being that $\partial Q_c^*/\partial S_2 < 0$.

The implication of this result is that, for an environment making independent decisions an increase in indirect technology spillins to the region will make a breeding program more justifiable at smaller production levels in the geographic mandate.

To summarize the results, an increase in direct technology transfers will encourage smaller environments for whom level 0 (no research program) was the most optimal, to have at least an evaluation research program (testing/selection). But a large increase in direct transfers will also discourage local breeding efforts. Thus, an increase in direct transfers expands the range between Q_s^* and Q_c^*, making evaluation program more likely to be optimal. Similarly, an increase in indirect transfers will encourage smaller environments for whom level 1 (evaluation) was the most optimal, to have its own breeding program.

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3.4.2 Implications for Country Level Decision Making

In the previous section we examined the decision making process of a research program that make decisions independently of its effect on other programs. This assumption is perhaps true for a country as a whole that typically does not take in to account the spillover effects to other countries. However, countries comprise of more than one environment need to account for the spillover effects within the country in designing crop research programs, so as to maximize total national benefits.

It is argued that given the positive externality nature of research, research programs making decisions based on their own benefits alone are underinvesting in research from the whole society's perspective. For example, if a research program takes into account the spillover benefits to other environments, then the maximization condition given by equation 3.18 will have another positive term in the form of the marginal benefits of local research to the cumulative yield gains in other environments. These marginal benefits will be:

$$\sum_{\substack{k=1 \\ k \neq d}}^{K} Q_k^{*} \, P_N \;\; f(E_{kd}) \; R_d \;\; \Delta S_d \;\; \Delta B_k \tag{3.22}$$

$$where \;, \quad \Delta B_k = (1-a_k) \frac{\partial g^0}{\partial S} + a_k \left[(1-b) \frac{\partial g^1}{\partial S} + b_k \frac{\partial g^2}{\partial S} \right]$$

and ΔS_d = change in research spillovers due to change in the research capability of local research program, d.
g = is the discounted cumulative yield gains
R_d = research expenditures of the domestic program for breeding research
subscript d = local/domestic research program

Note that the maximization condition corresponding to the decision about whether to have a research program or not will be the same, since research spillovers are only generated by a breeding program. The underinvestment hypothesis argues that consideration of spillover benefits (as given in equation 3.22) should increase the research effort (White and Havlicek (1981); Davis et al. (1979); Ruttan (1982); Bonnen and Schweikhardt (1991)). However, it can be shown that consideration of spillover effects may not necessarily increase research efforts of all the research programs within the country.

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Clearly, the difference in the decisions made by an independent region in the previous case and in this case depends on the magnitude of the spillover benefits (Equation 3.22). The spillover benefits to other regions are defined as the sum of marginal benefits due to change in the technology transfer pool in each of the other K-1 environments, weighted by the environmental distance and the research expenditures of domestic breeding program. The net spillover benefits could be more, less or zero depending on the combination of these factors. *Ceteris paribus*, the greater the distance between the domestic environment and other environments in the country, less will be the spillover benefits from domestic program to other environments. Similarly, the higher the level of research effort in the domestic region the higher will be the net spillover effects to other regions. Moreover, the marginal benefits will also depend on the type of research spillovers generated and the level of research capability in other environments. A combination of generation of indirect spillovers and no research programs in receiving regions will create zero spillover effects and thus will not increase the research effort in the domestic region.

From a national point of view, the net effect of increasing spillovers may not necessarily be that of increasing research levels in all the environments. For example, if the country comprise of similar environments (i.e., less environmental distance between environments), the spillover effects will be more. But there is also other side of the spillover effects - research spillins. If the environments are too close in distance the effect of research spillins on research productivity in the receiving region may outweigh the effect of spillover effects in the source region. This may result in evaluation research as being more profitable than technology creation research. Thus, from a national point of view, the increased spillins may lead to overall decline in research investments (since for the spillin receiving region evaluation is now more profitable) rather than an increment in research efforts. Also, another factor that may influence the decision is the size of the international technology transfer pool. If the regions are already getting benefits from research outside the country, any effort to increase the research spillins by increasing research eff

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effort within the country will be redundant.

If the spillover effects are positive it may encourage an environment already operating at level 1, to expand its research program into a breeding program. The decision, however will be based on whether the spillover benefits exceed the marginal costs (direct plus indirect) due to increased level of research capability. Thus, a local strategy of wide adaptability, less environmental distance, low level of international transfers and low research costs in the country will increase the transferability of technology within the country, thus leading to an expansion of research effort in the domestic environment.

To conclude, the implication on the design of an efficient crop improvement research program is that for a country comprising of many environments, the decisions about the size and capability of research programs must take in to account the research spillovers. But the consideration of research spillovers does not necessarily imply an increase in overall research effort. Other factors, such as environmental distance, type of research spillins, current level of research capability in different environments, international technology spillins, research costs, are as important as research spillovers. Consideration of all these factors in designing a crop breeding research program may or may not imply a further increase in research effort as an optimal solution.

3.4.3 Implications for Decision Making by an International Research Center

Since, international agricultural research centers (IARCs) are sources of technology transfer, the marginal analysis has important implications on how an IARC should design its crop improvement research program. In making resource allocation decisions, an IARC is faced with two basic problems. First, how much to allocate to different global environments and second, what should be the targeting strategy in each environment, given the independent decision making by the countries comprising these environments. The solution to the first problem will determine the extent of global research spillovers and that of the second will determine the type of spillovers (direct versus indirect).

According to the model specification, research spillovers

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generated by an IARC will influence the rate of yield increments in different research programs of a given environment. *Ceteris paribus*, spillovers will positively affect the NPV of individual research programs. Assuming that the objective of an IARC is to maximize the change in the total profitability of global crop improvement research, the following implications can be drawn about the relative importance of different environments and type of spillovers to be generated.

There are two important factors that will determine the relative size of resources allocated across different environments - (1) the global size of the environment. Since the profitability of crop improvement research is directly related to the size of crop production, *ceteris paribus*, a large global environment will receive relatively more importance than a small environment. It also follows, that because of the economies of scale, an IARC can devote resources on environments which is composed of small countries unable to justify a research program. (2) the environmental complexity. Environments with greater marginal productivity in yield gains will receive greater attention than environments with low yield gain potential.

There is however, another important factor which will influence the resource allocation decisions at an international level - namely, the level of research capability of the individual research programs in a given environment. Research spillovers generated by an IARC will influence the yield gains only if there are research programs operating at levels 1 and 2. However, the targeting strategy to be followed for a given environment will depend on the general level of research capability of individual research programs. For an environment composed of research programs with the capability of testing and selection, the optimal strategy for an IARC would be to generate directly transferable crop technology. Thus, such environments will receive greater importance in terms of resource allocations. On the other hand, it would be redundant if an IARC tried to devote research resources to generate directly transferable technologies for an environment with highly capable research programs. In such cases, its strategy should be to provide the research programs with improved germplasm that can be used as parent materials in the breeding program.

3.5 Conclusions

Research resource allocation decisions for crop improvement research are influenced by the biological, environmental and economic factors. The biological phenomenon of G x E interactions have implications for three components of a crop improvement research design - number of research programs, level of research capability, and the targeting strategy. These three decision variables together define a continuum of research efforts (in terms of human and physical resource mix) of a crop improvement research program. For example, a country with two distinctive production environments could have only one research program doing technology creation research and targeted for both the environments, or two technology creation programs each targeted for a given environment, or a combination of technology evaluation and creation research programs for different environments. The complexity in designing a research program arises from the fact that increasing levels of capability have increasing levels of costs and benefits associated with them. An efficient design of a crop improvement program needs to balance the increasing costs and benefits of breeding research.

The NPV model developed in this chapter tries to address this complexity by making productivity a function of research focus rather than research expenditures. Each level of research capability is associated with a given level of costs and benefits. The benefits are defined in terms of yield gains which are a function of research spillins, target strategy and research expenditures. The costs associated with increasing research lag for different levels of research capability are accounted for in the NPV model in terms of the time period between the initiation of research costs and realization of benefits. The unique features of this conceptual framework is that it makes levels of research capability (research focus) a decision variable and allows for differential effects of direct and indirect technology spillins on the productivity associated with different levels of research capability.

The conditions of maximization yielded the NPV decision criterion according to which investments in crop improvement research must be such that the NPV of that investment is greater than any other alternatives (de

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(defined in terms of different levels of research capability). Given that research spillins affect the productivity potential of alternative investments differently than the current investments, this condition indicates that an increase in research spillovers will have positive effect on productivity but depending on the type of research spillins, it may or may not have a positive effect on the decision to increase research investments.

The implication of this result for a country comprising more than one environment is that the research decisions must take in to consideration the spillover effects generated by one program to another. However, depending on the environmental distance, international spillins, size of each environment and level of research, spillover considerations may not imply an increase in overall investments.

The implications for an IARC which is generating technology spillovers is that it should allocate its resources to different environments based on the type of spillovers to be generated. For environments comprising countries with research programs capable of generating their own technology, the optimal choice would be to generate indirect spillovers in the form of improved germplasm that can be used as parents in the local crosses. For environments comprise of small countries and research programs with limited capability, the IARC should devote more resources to generate directly transferable technology.

CHAPTER FOUR

EAT RESEARCH PROGRAMS IN DEVELOPING COUNTRIES: DESCRIPTIVE PROFILE

This chapter describes the global research efforts on wheat ovement in developing countries. Descriptive and tabular analyses g cross-sectional data of wheat improvement research programs are ented with the objective of analyzing the relationships between erent variables discussed in the previous chapter.

General Aspects of Wheat and Wheat Improvement Research

4.1.1 Some Basic Biological Characteristics of Wheat

Wheat is commonly classified according to commercial type growth habit. Although many species of wheat are commonly gnized, only two species, *Triticum aestivum* (bread wheat) and *icum durum* (pasta wheat) are commercially important. Each wheat has distinct characteristics that make it suitable for special : the bread wheats are used for making leavened and unleavened bread the durum wheats are used for pasta and other products.

In terms of growth habit, wheats are classified into three basic s: spring, winter and facultative. Spring wheats have a continuous to six months growth cycle and generally cannot survive an extended od of freezing temperatures. Winter wheats, however, are sown in mn and harvested after a total growing period of nine to eleven hs. Winter habit wheats pass through an inactive stage during the weather, before they change to a reproductive phase. Facultative ts have attributes of both spring and winter wheats and have evolved it fairly specific environmental niches.

In terms of the relative importance of different types of wheats, spring habit bread wheats dominate the wheat area in developing tries (66.3% of total area, mid 1980s) followed by winter bread ts (13.6%), spring durum wheats (9.3%), facultative bread wheat %) and winter durum wheat (1.4%) (CIMMYT 1989). Developing :ries that grow mainly spring bread wheat include Argentina, ladesh, Brazil, Egypt, India, Iraq, Kenya, Mexico, Nepal, Pakistan, , Sudan, and Uruguay. Countries producing primarily winter bread

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wheat include Iran, South Korea, and Turkey. In Algeria, Ethiopia, Jordan, Morocco, Tunisia, and Syria, at least half of the wheat area is sown to durums.

4.1.2 Trends in Wheat Production and Major Factors Influencing Wheat Yields

Since World War II, wheat has been the most dynamic sector in world cereal production. During the post-war period, wheat production has experienced the fastest growth rate (3.5% per year) of all cereals. The rate of change has been especially marked in developing countries (Table 4.1). Third World wheat production grew at the rate of 4.1% a year, quadrupling from less than 50 million tons in 1948-52 to 220 million tons in 1986-90. During the same period, the share of developing countries in world wheat production increased from 27% to 41%. The increasing supplies of wheat due to increased production, and demand factors such as population growth, rising incomes, urbanization, price policies and food aid have all contributed to the increasing importance of wheat in Third World cereal economies.

The most striking change in wheat production has been the dramatic switch from area increases to yield increases as the main source of growth in production (Table 4.1). Wheat yields have grown far more rapidly than area, accounting for 78% of the increase in world wheat production and 68% of production increases in developing countries.

According to Hanson et al. (1982) at least three major factors contributed to rising wheat yields in developing countries in the post-war period - 1) the spread of high-yielding semi-dwarf wheat varieties, 2) expansion of irrigation and rapid increase in the use of chemical fertilizers, and 3) development of suitable agronomic practices for the new varieties. These three factors together provided the basis for what is popularly called the Green Revolution.

Among all the factors, the development and spread of high-yielding semi-dwarf wheat varieties was undoubtedly the most important in triggering the Green Revolution. The initial introduction of semi-dwarf wheat varieties into irrigated areas of Mexico, Pakistan and India in the late sixties, and the subsequent spread of these varieties to other countries and environments in 1970s and 1980s made a spectacular

Table 4.1: Wheat Area, Production and Yield: Regional Shares, 1948-52 to 1986-90

Region	Area			Production			Yield		
	1948-1952	1986-1990	Growth rate[a]	1948-1952	1986-1990	Growth rate[a]	1948-1952	1986-1990	Growth rate[a]
	million ha		(%/yr)	million tons		(%/yr)	tons/ha		(%/yr)
sub-Saharan Africa	1.1	1.2	0.4	0.7	1.8	2.4	0.6	1.5	2.7
West Asia and North Africa	16.3	25.5	1.2	13.9	42.0	1.8	0.9	1.7	3.0
South, East and Southeast Asia	37.3	62.2	1.4	26.8	154	3.4	0.7	2.5	4.9
Latin America	7.5	10.8	1.0	7.9	21.7	1.8	1.0	2.0	2.8
Developing countries	62.1	99.6	1.3	49.2	219.7	2.8	0.8	2.2	4.1
Developed countries	114.3	125.1	0.2	130.0	318.0	2.2	1.1	2.5	2.5
World	176.4	218.8	0.7	179.2	537.7	2.3	1.0	2.4	3.0

Source: FAO Production Yearbooks

[a] Growth rate from 1948-52 to 1986-90

contribution to wheat production.[1] The area planted to semi-dwarf varieties in all developing countries (excluding China) has steadily increased from 8.4 million ha (15% of wheat area) in 1969 to about 50 million ha (75% of wheat area) in 1990 (Byerlee and Moya 1993).

The development of short-strawed (semi-dwarf) wheat varieties constitutes one of the most significant accomplishments in the history of plant breeding. It was made possible by the successful introgression of genes for reduced height (Rht genes) into taller wheat varieties that dominated wheat production before the Green Revolution. Although the history of semi-dwarf wheat development and cultivation can be traced back to as early as the mid-nineteenth century in Japan, the ancestry of most of the semi-dwarf wheat varieties in developing countries can be traced to varieties developed in Mexico by Norman Borlaug and associates (subsequently known as the International Maize and Wheat Improvement Center [CIMMYT][2]). The Japanese short-strawed variety, Norin 10 crossed with a U.S. variety, Brevor, formed the basis for the development of improved Mexican varieties, and subsequently for most of the semi-dwarf breeding materials throughout the developing world (Dalrymple 1986).

The development of short-strawed high-yielding and rust resistant varieties has been an important objective of many breeding programs since the introduction of intensive husbandry using large applications of artificial fertilizer. Given the fact that wheat is pre-eminently a crop of developed countries (due to its adaptation to cultivation in temperate regions), wheat breeding research has historically been concentrated in the developed countries of Europe, North America and Australia (Lupton 1987). However, the success of Mexican wheat breeding research in the fifties and sixties gave an impetus to wheat research in

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[1] Data on the area planted with high-yielding semi-dwarf wheat varieties in developing countries can be found in Dalrymple (1986). For a more recent analysis on the spread of semi-dwarf wheat varieties in developing countries see Byerlee and Moya (1993).

[2] CIMMYT is the spanish acronym for Centro Internacional de Mejoramiento de Maiz y Trigo

many developing countries as well[3]. Today, the total researchers working on wheat improvement research in developing countries (not including China) stand at about 1,000 FTE researchers with a total expenditure of about $70 million (at 1980 constant prices). In addition to this, CIMMYT in Mexico and its associated collaborative program at International Center for Agricultural Research in Dryland Areas (ICARDA) in Syria, with a total wheat research staff of about 50 FTE scientists and wheat research expenditures of about $13 million - continue to work towards development of improved wheats for developing countries.[4]

4.2 Analysis of Wheat Environments in Developing Countries

Environment forms the basis for defining and differentiating one crop improvement program from another. It is not only the major element in shaping breeding priorities but also the major determinant of the extent and opportunity of technology spillins. This explains why an assessment of the implications of international technology transfers on the size of research effort requires an understanding of the diverse environments under which wheat is grown in different countries.

However, grouping wheat producing regions of the developing world into few homogenous environments is not an easy task. As noted earlier, environments differ both in space and time and in biological as well as non-biological dimensions. If all these factors are taken into account, each farmers' field at a given period of time, would fall under a distinct micro-environment. Of course, limited resources do not permit research programs to target each and every micro-environment in a region. In reality, for designing a crop improvement program, these

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[3] Among developing countries, India, Kenya and Argentina are perhaps exceptions with a long history of wheat improvement research (Hanson et.al. 1982).

[4] The research mandate of CIMMYT's wheat program is to develop high-yielding, widely adapted, semidwarf wheat varieties for developing countries. However, many developed countries sharing the same agro-climatic environment as developing countries have also benefitted from CIMMYT's wheat research. The spread of CIMMYT-based varieties in Australia is a prime example of such spillover effects of CIMMYT's wheat research to developed countries. Between 1973 and 1984, 78% of total wheat varieties released in Australia were CIMMYT based (i.e. they had a CIMMYT line in their parentage) varieties (Brennan 1989a).

diverse micro-environments are grouped into a few major environments based on some common underlying factors. In wheat, some of the common factors that form the basis for defining an environment are - soil conditions, ecology, climatic conditions, growing season, wheat type, whether the crop is grown under irrigated or rainfed conditions, etc..

Previous studies of international research spillovers have either used the Papadakis (1966) classifications of world agricultural environments or the FAO classifications. The wide use of these classification systems proves that they are good proxies of diverse agricultural environments across the world. However, these classifications are not crop specific, and therefore tend to be too aggregated from a crop's point of view. Also, they do not consider factors such as irrigation which are important in determining the performance of a crop such as wheat.

Ideally, an environmental classification system should be based on each country's zoning system for a crop. However, if the zoning system of every country is accounted in defining environments at a global level, it will be too disaggregated, making the task of assessing international transfers beyond the resources of this project.

As an alternative, the approach used by CIMMYT, is employed here to define major wheat producing environments (megaenvironments) in developing countries. CIMMYT's strategic plan defines megaenvironments (ME) as a broad, not necessarily contiguous area, usually international and frequently transcontinental. It is defined in terms of similar biotic and abiotic stresses, cropping system requirements, and consumer preferences for types of wheat (Fischer and Rajaram 1990).

This megaenvironment classification system is based on the estimates of not only of CIMMYT staff, but also NARS scientists. Thus, they reflect the actual geographical location and area devoted to wheat in each environment in each country and the biological and non-biological dimensions that are particularly important for wheat. Therefore, they better represent wheat growing environments of the developing world and make the assessment of spillovers more accurate.

4.2.1 Description of Mega-environment Data Base

The mega-environment data base compiled by CIMMYT comprises 26 developing countries that each have a wheat area of at least 100,000 hectares (ha). No data are available for countries with less than 100,000 ha under wheat cultivation. The variables available in the data set include wheat area, production, type of wheat, megaenvironment class, maturity, moisture code, and disease/insect stress. For each country, these data are given by zone, which are then grouped into megaenvironments. The data are based on the surveys of national programs and CIMMYT staff, and may not, therefore, correspond to FAO estimates on total wheat area and production. Moreover, the CIMMYT data base has not been updated in recent years. The data used in the analysis of this section, correspond to about 1980. However, given the fact that the data are disaggregated by environments within countries, they are the best source for comparative analysis of different wheat growing environments in the developing world.

4.2.2 Major Characteristics of Wheat Megaenvironments

According to CIMMYT estimates, the wheat area in 26 major wheat producing developing countries falls under 13 distinct megaenvironments (ME) (Table 4.2). The definition of the environments are based on the soil conditions, level and distribution of rainfall, temperature, growth habitat and whether the crop is grown under irrigated or rainfed conditions. All of these factors are important in determining the performance of a wheat cultivar.

Using crop production as the indicator of size, it can be seen that the size of the wheat megaenvironments on a global basis, varies from as small as 2.4 million tons in the environment characterized by acid soils, high rainfall and temperate climate (ME3) to as large as 82.8 million tons in irrigated, low rainfall, temperate environment (ME1). Clearly, ME1 dominates on both the cropped area and production basis with almost a third of the total wheat area and 40% of total wheat production in the developing world.

As we saw in the preceding chapter, the size of an environment greatly influences net returns to research. Global research, such as that by an IARC, would thus favor large environments to take advantage

Table 4.2: Wheat Megaenvironment Classification for Developing Countries

Megaenvironment Code	characteristics	Major Diseases[a]	Representative Locations	Wheat Area[b] (000 ha)	Wheat Prod.[b] (000 t)	Wheat Yield[b] (t/ha)
	SPRING TYPE					
ME1	irrigated, low rainfall, temperate[c]	Lr, Yr, Pm, Sr	Yaqui Valley, Mexico; Indus Valley, Pakistan; Gangetic Valley, India; Nile Valley, Egypt	32,251 (32.7%)	82,773 (40.3%)	2.57
ME2	high rainfall, temperate	Lr, St, Yr, Pm Sr, BYD, Bact Scab	Meditarranian Basin; Southern Cone; Andean Highlands; East African Highlands	9,846 (10.0%)	24,511 (11.9%)	2.49
ME3	acid soil, high rainfall, temperate	Lr, St, Sr, Pm BYD, Bact, Scab	Brazil, Andean; Highlands, Central Africa; Himalayas	1,680 (1.7%)	2,394 (1.2%)	1.43
ME4A	low rainfall, temperate, winter rains	St, Yr, Lr,	Alepo, Syria; Settat, Morocco	10,107 (10.3%)	8,902 (4.3%)	0.88
ME4B	low rainfall, temperate, winter drought	St, Yr, Lr	Marcos Juarez, Argentina	3,145 (3.2%)	3,998 (1.9%)	1.27
ME4C	Low rainfall, temperate, mostly stored moisture	Sr	Indore, India	5,840 (5.9%)	5,950 (2.9%)	1.02

Table 4.2 (Cont'd)

Megaenvironment Code	characteristics	Major Diseases[a]	Representative Locations	Wheat Area[b] (000 ha)	Wheat Prod.[b] (000 t)	Wheat Yield[b] (t/ha)
ME5A	high temperature, high relative, humidity	Lr,Helm, Scab	Poza Rica, Mexico; Joydebpur, Bangladesh; Encarnacion, Paraguay	3,890 (3.9%)	9,394 (4.6%)	2.41
ME5B	high temperature, low relative humidity	Sr	Gezira, Sudan; Kano, Nigeria	3,170 (3.2%)	2,843 (1.4%)	2.49
ME7	severe winter, spring sown, high latitude	Lr,Scab, Helm	Harbin, China	4,830 (4.9%)	12,939 (6.3%)	2.68
	SUBTOTAL (Spring type)			74,759 (75.9%)	153,704 (74.9)	2.06
	FACULTATIVE/ WINTER TYPE					
ME6A	moderate cold, high rainfall	Scab,Yr, Pm	Temuco, Chile; Zhengzhou, China	5,485 (5.6%)	18,745 (9.1%)	3.42
ME6B	moderate cold, low rainfall	Bunt	Diyarbakir, Turkey	4,475 (4.5%)	3,921 (1.9%)	0.88

Table 4.2 (Cont'd)

Megaenvironment Code	characteristics	Major Diseases[a]	Representative Locations	Wheat Area[b] (000 ha)	Wheat Prod.[b] (000 t)	Wheat Yield[b] (t/ha)
ME6C	severe cold, high rainfall	Yr,Lr,Pm	Beijing, China	6,705 (6.8%)	18,368 (9.0%)	2.74
ME6D	severe cold, low rainfall	Bunt	Ankara, Turkey	7,115 (7.2%)	10,420 (5.1%)	1.46
	SUBTOTAL (Facultative/ Winter type)			23,780 (24.1%)	51,453 (25.1%)	2.16
	TOTAL			98,539 (100%)	205,157 (100%)	2.08

Source: CIMMYT wheat megaenvironment data files

[a] Yr-Yellow (stripe) rust; Lr-Leaf rust; Sr-Stem rust; Pm-Powdery mildew; St-Septoria tritici; Helm-Helminthosporum Sativum; Scab-Fusarium spp.; Bunt-Tilletia Indica; BYDV-Barley Yellow Drarf Virus

[b] Figures correspond to 1980

[c] Rainfall just before and during the wheat crop cycle: high-500 mm; low-less than 500 mm

of economies of scale. The irrigated low rainfall (ME1) and high rainfall temperate (ME2) environments, for example, are better positioned in terms of taking advantage of economies of scale. Not surprisingly, these were one of the earliest targeted environments in CIMMYT's wheat breeding program (Fischer and Rajaram 1990). However, there are factors other than size of environment which will influence net returns to research, and hence, the research priorities of an IARC. These are the research productivity potential of a given environment and the level of research capability in each environment at a country level. These factors determine the rate of change in potential genetic improvements from an additional research effort at international level.

Research productivity potential depends on two factors. (1) the production potential of an environment, and (2) the research production function for a given environment. *Ceteris paribus*, environments with favorable environmental conditions will have higher research productivity potential than environments with unfavorable conditions[5]. And, environments with a low level of prior research will have higher research productivity potential than environments where research efforts have already reached their potential maximum. Among the 13 wheat megaenvironments, the environments characterized by high rainfall or irrigated conditions and low heat or other type of stress thus, have higher research productivity potential due to favorable environmental conditions (ME1, ME2, ME5A, ME6A, ME6C and ME7). The above average yields per hectare in these environments reflect these effects of favorable environmental conditions. In terms of level of prior research efforts, winter wheats (ME6A to ME6D) have been less researched in developing countries (at least, outside of China) and thus possess higher research productivity potential than spring wheats.

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[5] This is perhaps the reason why agricultural research efforts at the international as well as at national levels have focussed more on developing technologies for favorable environments. This factor is also the source of criticism of the Green Revolution technology, which mainly increased productivity in favorable environments. However, relative to the share of the value of wheat produced, Byerlee and Morris (1993) show that the proportion of research resources invested in marginal environments has been high both at the international level and in their case study country, India.

Table 4.3: Percent Area and Production Under Bread and Durum Wheat in Each Megaenvironment in Developing Countries, 1980

Megaenvironment	Area (%)		Production (%)	
	Bread	Durum	Bread	Durum
SPRING TYPE				
ME1 irrigated	99	1	99	1
ME2 high rainfall	76	24	81	19
ME3 acid soil	100	0	100	0
ME4A low rainfall,winter rain	53	47	51	49
ME4B low rainfall,winter drought	100	0	100	0
ME4C low rainfall,stored moisture	74	26	80	20
ME5A high temperature,high humidity	100	0	100	0
ME5B high temperature,low humidity	100	0	100	0
ME7 severe winter,high latitude	100	0	100	0
SUBTOTAL	88	12	93	7
FACULTATIVE/WINTER TYPE				
ME6A moderate cold,high rainfall	100	0	100	0
ME6B moderate cold,low rainfall	100	0	100	0
ME6C severe cold, high rainfall	98	2	96	4
ME6D severe cold,low rainfall	83	17	84	16
SUBTOTAL	94	6	95	5
TOTAL	90	10	93	7

Source: CIMMYT wheat megaenvironment data files

The 13 megaenvironments defined in Table 4.2 are not based on the commercial types of wheat grown in the environment. Since research programs are targeted by type of wheat (although one research program can handle both bread and durum wheats), it is important that we distinguish environments in terms of types of wheat also (Table 4.3). Durum wheats are less extensive and are encountered in only 6 megaenvironments. In terms of relative importance about two-thirds of the durum wheats are produced in the spring-habit environments - ME2 (high rainfall temperate) and ME4A (low rainfall temperate, winter rain). Bread wheats are grown in all the environments. But megaenvironments characterized by good water supply in terms of either irrigation or high rainfall (ME 1,2,6A,6C) clearly dominate in bread wheat production. These megaenvironments claim about three-quarters of the total wheat production in the developing countries.

4.2.3 <u>Distribution of Megaenvironments Across Different Countries and Regions</u>

The information on the distribution and density of megaenvironments by geographical regions can be used to make a case for regional or international cooperation in wheat research. As indicated in Table 4.4, ME1 (irrigated), ME2 (high rainfall temperate), ME4A (low rainfall, winter rains) are highly concentrated in a few regions. ME4A for example is concentrated in only one region - West Asia and North Africa. Such high concentration of a megaenvironment in geographically neighboring regions could be conducive to regional cooperation in wheat research. Some megaenvironments, such as ME6A (moderate cold, high rainfall), ME6B (moderate cold, low rainfall) and ME6D (sever cold, low rainfall) are very sparsely and widely distributed among different developing regions. For such environments, a strong case for international research support could be made.

Table 4.4: Distribution and Density of Wheat Megaenvironments by Regions

Region	Megaenvironment													
	1	2	3	4A	4B	4C	5A	5B	6A	6B	6C	6D	7	Total
	(Number of Countries)													
sub-Saharan Africa		2												1
West Asia and North Africa	8	8		10			2	2	1	2	3	1		10
South Asia	3					3	2		1					4
East Asia	1	1				1	1		1	1	1	1	1	9
Latin America	2	6	1		2		2	2	1	1	1	1		10
Developing Countries	14	17	1	10	2	4	7	4	4	4	5	3	1	13

Source: CIMMYT wheat megaenvironment data files

Table 4.4 also provides information about the diversity of environments at a regional level. Latin America, West Asia and North Africa, and East Asia are highly diverse regions, each comprising of 10, 9 and 9 megaenvironments, respectively. On the other hand, sub-Saharan Africa and South Asia are less diverse in terms of environmental distribution. The diversity of the environment in a given region is an indicator of the size of research effort needed in that region. *Ceteris* *paribus*, regions with high environmental diversity will require relatively more research efforts than regions with less diversity.

4.2.4 Size Composition of Global Wheat Megaenvironments

Since, the productivity of international research depends on the size of research effort at the country level, and the size of research effort at the country level is related to its size, from an international perspective, the size composition of the megaenvironments is also as important as the composition of countries (Table 4.5). The size of the environments at country level (referred to as CLE - country level environments) are grouped into following 4 classes: (1) less than 100,000 tons. (2) 100,000 to 500,000 tons (3) 500,000 to 1,500,000 tons (4) more than 1,500,000 tons. As can be seen, about 40% of the CLEs produce less than 500,000 tons of wheat each. As can be seen there are many extremely large CLE that make the mean size of the CLE around 2.7 million tons (which falls under the fourth size group).

Table 4.5: Size Composition of Wheat Megaenvironments in Developing Countries, 1980

	Size (000 tons)				
	(< 100)	(100-500)	(500-1500)	(> 1500)	Mean Size (000 tons)
	(Number of Country Level Environments)				
ME1	1	5	3	5	5,912
ME2	3	7	3	4	1,442
ME3	0	0	0	1	2,394
ME4A	1	1	7	1	890
ME4B	0	1	0	1	1,999
ME4C	0	1	2	1	1,488
ME5A	1	1	3	2	1,342
ME5B	1	2	0	1	711
ME6A	1	1	1	1	4,686
ME6B	1	0	2	1	980
ME6C	0	2	0	3	3,674
ME6D	1	0	0	2	3,473
ME7	0	0	0	1	12,939
TOTAL	10	21	21	24	2,699

Source: CIMMYT wheat megaenvironment data files

The distribution of a megaenvironment across different size CLEs will also determine the opportunity for research spillovers. A wide distribution implies potentially greater source of research spillins and greater distribution of research benefits. However, the opportunity for spillovers within the megaenvironment will also depend on the level of concentration of megaenvironments by different countries. Assuming that research effort in a given CLE is proportional to its size, a high concentration of production in a few large CLEs or an even distribution among large CLEs would suggest a greater capability of research in these countries and greater opportunity of research spillovers from these CLEs. On the other hand, an even distribution of megaenvironments across small CLEs would suggest low level of research capability and therefore less creation of research spillovers. This would make a case for international research support to supplement these CLEs' research.

The level of concentration of each megaenvironment by different CLE is given in Table 4.6. The concentration ratio represents the skewness in distribution of total production of a megaenvironment by different size CLE. Figure 4.1 presents an example of such a distribution curve (similar to a Lorenz curve) across all developing countries (77 CLEs). The curve indicates the percentage share in total production by a given percentage of CLEs. The further the curve is from the 45° line, greater is the skewness of distribution, indicating a high level of concentration of total production in a few large CLEs. For example, in ME1 (irrigated) which has one of the higher concentration ratios, the largest 25% of CLEs produce more than 80% of total wheat production in the developing countries in that megaenvironment.

The concentration ratios were measured by Gini coefficient. The closer the ratio is to 1, the higher is the concentration ratio and vice versa. Megaenvironments with a high concentration ratio are generally found in a large wheat producing country. For example, in ME1 (irrigated, low rainfall) about 90% of wheat production is concentrated in the three largest (about 21%) CLEs - China, India and Pakistan. Since these large countries with strong NARS are more likely to generate spillovers, the research spillovers in this megaenvironment will likely be more than in other megaenvironments.

Table 4.6: Distribution of Total Production of Wheat Megaenvironments in Developing Countries by Size of CLE, 1980

Mega-Environment	No. of CLE	Number of CLE (cumulative %) 25%	50%	75%	100%	Concen-tration Ratio[b]
		Cumulative % of total production				
ME1	14	0.5[a]	2.3	8.3[a]	100	0.77
ME2	17	1.4[a]	5.5[a]	17.0[a]	100	0.70
ME3	1	---	---	---	100	1.00
ME4A	10	7.0[a]	25.2	52.5[a]	100	0.35
ME4B	2	---	3.0	---	100	0.47
ME4C	4	5.7	18.3	42.5	100	0.71
ME5A	7	2.0[a]	16.0[a]	41.0[a]	100	0.49
ME5B	4	3.4	13.0	22.6	100	0.55
ME6A	4	0.1	1.7	4.4	100	0.72
ME6B	4	1.7	15.3	53.2	100	0.40
ME6C	5	1.8[a]	8.0[a]	25.0[a]	100	0.60
ME6D	3	0.4[a]	---	40.0[a]	100	0.67
ME7	1	---	---	---	100	1.00
ALL ME	76	1.15[a]	6.0[a]	23.0[a]	100	0.74

Source: CIMMYT wheat megaenvironment data files

[a] Depending on the number of country level environments (CLE), cumulative percentage of total production for exactly 25, 50 and 75 percent of cases were not available. For example, ME6C has 5 cases which mean the cumulative percentages available are for 20, 40, 60, 80, and 100 percentage of cases. In such cases the figures are approximate percentage calculated as the mean of upper and lower cumulative percentage production for that range.

[b] Concentration ratio is the Gini coefficient that measures the concentration of wheat production by size of CLE. A ratio close to 1 implies high concentration of wheat production in few largest CLEs. A ratio close to 0 implies equal distribution across CLEs.

4.2.5 Size, Distribution and Diversity of Megaenvironments at Country Level

The size and distribution of environments at the country level is important in determining the overall size of research effort. For a given country, production in each environment indicates the size of the environment and the number of environments indicates diversity.

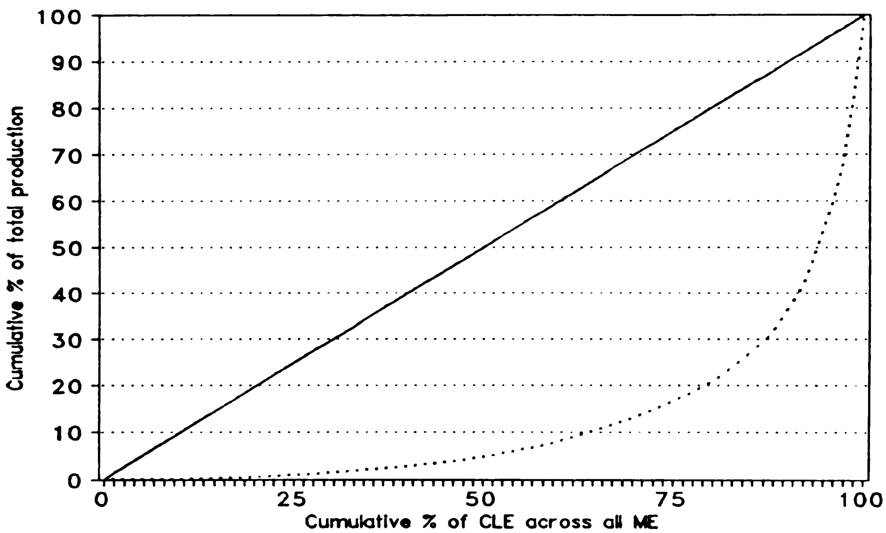

Figure 4.1: Cumulative Distribution of Wheat Production by Size of CLE

At the country level, the size of an environment is an important factor in the decision on whether and how much to spend on agricultural research. This question is particularly trivial for small countries. For example, the size of ME1 (irrigated, low rainfall) varies from as little as 9,000 tons in Jordan to as large as 34 million tons in India (Appendix A). Given the large size of this megaenvironment, India has a clear advantage in terms of economies of scale in research on irrigated wheat. Jordan, on the other hand is unlikely to able to justify a wheat research program targeted to this environment. It may have to rely on borrowing technologies for this environment.

In terms of environmental diversity, there is a wide variation among countries. For example, Kenya, Sudan and Uruguay, comprise one homogenous wheat environment, whereas, countries like Turkey, China, Chile and Iran comprise of 10, 9, 7 and 6 environments respectively (including durum wheats) (Appendix A). Ceteris paribus, a country with diverse environments will require greater research efforts than countries with less environmental diversity.

Table 4.7: E
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Count
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Jordan
Chile
Paraguay
Highly Dive
Nepal
Egypt
Mexico
Libya
Moderately
Syria
Ethiopia
Iraq
Morocco
Tunisia
Banglade
Algeria
Average Di
Afghanis
Brazil
Turkey
Iran
Below Aver
Argentin
China
Pakistan
India
Uniform
Kenya
Sudan
Uruguay

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Table 4.7: Environmental Diversity Index for Major Wheat Producing Developing Countries

Country	Wheat Area (000 ha)	No. of mega-environments[a]	Environmental Diversity Index[b]
Extremely Diverse			
Peru	100	2	27.1
Jordan	155	3	26.2
Chile	615	7	15.4
Paraguay	190	2	14.2
Highly Diverse			
Nepal	475	3	8.5
Egypt	555	3	7.3
Mexico	750	4	7.2
Libya	790	4	6.9
Moderately Diverse			
Syria	1525	6	5.3
Ethiopia	545	2	5.0
Iraq	1864	6	4.4
Morocco	1950	6	4.2
Tunisia	1310	4	4.1
Bangladesh	695	2	3.9
Algeria	2150	4	2.3
Average Diversity			
Afghanistan	2300	3	1.8
Brazil	1700	2	1.6
Turkey	9160	10	1.5
Iran	6120	6	1.3
Below Average			
Argentina	5930	4	0.9
China	28970	9	0.4
Pakistan	7500	2	0.4
India	22700	6	0.4
Uniform			
Kenya	110	1	0.0
Sudan	170	1	0.0
Uruguay	210	1	0.0

[a] Includes durum wheat as separate megaenvironment

[b] The diversity index measures the diversity of wheat environments in a relation to the population mean ratio of 1,353 thousand hectares per country level environment.

The environmental diversity, however, has no correlation with the size of the country. For instance, a large country like Argentina consists of 3 megaenvironments, which is the same for a small country like Jordan or Nepal. Thus, considering the small size of Jordan and Nepal, they can be considered to be relatively more environmentally diverse than Argentina.

An index of environmental diversity tries to capture these size differences (Table 4.7). The index, D_i, is based on the number of CLEs (considering durum wheats as separate environment), M, in the country, weighted inversely by its size weight, w_i.

$$D_i = \frac{M}{w_i}$$

$$\text{where,} \quad w_i = \frac{A_i}{\sum_{i=1}^{N}\sum_{j=1}^{M}\left(\frac{E_{ij}}{NM}\right)}$$

A_i is the size of total wheat area in country i and E_{ij} is the size of the CLE in country i for environment j. Thus, it tries to factor out the effect of size on the number of CLEs a country would have. The mean ratio of 1.35 million ha per CLE was taken as the base for constructing the size weights and diversity index. There seems to be no correlation between the number of CLEs and environmental diversity. For example, Peru, Jordan, Chile and Paraguay, although they have varying numbers of environments, are the most diverse in the group. Other countries with the same or more number of CLEs are relatively less diverse. This is due to the size factor. Environmental diversity seems to decline with the size of total wheat area at the country level. Thus, some of the largest wheat producing countries are the least diverse.

To sum up, the megaenvironment classification system presented in this section provides an informative tool for analyzing the economics of environmental complexities in wheat improvement research. The information on the size and distribution of these megaenvironments across different countries and within a country can be used to explain the opportunities for international technology spillovers, justification for wheat research, and for creating support for regional and international cooperation in wheat improvement research. In the next chapter, this megaenvironment classification system is adopted to analyze the international transferability of wheat technology.

4.3 Wheat Improvement Research Efforts in Developing Countries

The increase in wheat production in the developing countries in the 1960s and thereafter was attributed to the agricultural research efforts that led to the development and spread of high-yielding semi-dwarf varieties. In this section we will describe the current status of wheat research programs in developing countries.

4.3.1 Data Sources and Methods

The data used for the analysis in this section are based the global impact study survey conducted by CIMMYT in 1990-92, mainly for building an inventory of varieties released by national programs (these data are used for the analyses in Section 4.5). However, the survey also included a section on the size and composition of national wheat improvement research programs. The data on wheat improvement efforts collected by this survey include the following variables: number of FTE scientists (aggregated for the whole country) working on wheat improvement in the public sector by degree status and discipline, national wheat research budget by discipline and type of costs.

The impact data represent national level research efforts and are used for regional and country level comparisons to get an idea about the current levels of global wheat research efforts. The data on wheat research expenditures collected by this survey, however, suffer from the following limitation. There was no consistency in the definition of research budget among different countries. Even if the research expenditures data reported in the survey were correct, there still remained the problem of conversion (from local currency to a common currency unit) to make the figures comparable. They were therefore not used in the comparative analysis. As an alternative, the following procedure was used to estimate research expenditures for each country:

1. Data on total agricultural research expenditures and total number of agricultural researchers provided in Pardey et al. (1991a, Appendix Table) were used to calculate expenditures per researcher for each country for the period 1981-85. The expenditure data available were in 1980 PPP (Purchasing Power Parity) dollars[6] to facilitate a comparison

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[6] PPPs represent a synthetic exchange rate that seeks to compare the relative cost in local currencies of a specific basket of (traded and nontraded) goods and services. It is defined as the price of a commodity bundle in local currency divided by the dollar price of the same bundle. See Pardey and Roseboom (1989) and Pardey et al. (1991) for a detailed discussion on the construction of this index and for

of the research expenditures of each country in a comparable numeraire currency.

2. The expenditure per researcher for 1990-92 (measured in 1980 PPP US $) were assumed to be the same in US dollars as those in 1980-85. This assumption is based on the fact that research budgets in many developing countries have stagnated in the last decade (CIMMYT forthcoming). It may lead to an upward or downward bias in the estimates for countries which have not followed this general pattern in real expenditures. For example, it will underestimate the expenditures for those countries that have experienced an increase in the real expenditures per researcher in the 1980s and overestimate the expenditures for countries that have experienced a decline in real expenditures per researcher in the last decade.

3. The 1990-92 estimates of total expenditures per researchers were then multiplied by the number of wheat researchers in 1990-92 to obtain the total wheat research expenditures (expressed in 1980 PPP US dollars) for each country.

There is an implicit assumption underlying this estimation procedure that wheat research expenditures per researcher are the same as the average expenditures per researcher for all agricultural research. To the extent that there are systematic differences across broad commodity classes in the expenditures per researcher, it is possible that using this assumption biases the expenditures estimates. According to Pardey et al. (1991a) ratios of spending per scientist are likely to be lower on average for crop programs than for livestock research. This implies that these estimates may be biased upward. However, they also argue that ratios for research oriented towards breeding are likely to be higher than crop management and protection research. In this respect, the estimates may not be too biased upward.

The analyses done in this section include all developing countries producing over 100,000 tons of wheat, with the following exceptions:

1. Data were collected for only 3 provinces of China that produces spring wheats. These provinces make up for only about 15% of

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further references.

China's wheat area and are not included in the analysis.

2. Iraq and Afghanistan are not included.

3. Countries with less than 100,000 tons of wheat production, but which have active wheat research programs were included: Burundi, Ecuador, Guatemala, Jordan, Lebanon, Nigeria, Tanzania, Uganda and Zambia.

Also, given the complexity of wheat research organization in India and Pakistan, the total number of wheat researchers for these countries was estimated based on a combination of published sources [Tandon and Sethi (n.d.) for India and Wheat Research Institute (1990) report for Pakistan] and other program specific CIMMYT survey (discussed in Section 4.4).

4.3.2 Regional Perspectives on Wheat Research Programs in the Developing World

In the early nineties the number of agricultural researchers working on wheat improvement research (i.e. it excludes agronomic and crop management research) in developing countries (excluding China) totaled 967 FTE researchers with a total expenditures of about $70 million per year (measured in 1980 PPP dollars) (Table 4.8).[7] If the wheat research efforts of CIMMYT are added to this global efforts, the number of researchers working on wheat improvement is about 1,017 and total research expenditures (excluding China) are estimated at $82 million per year (in 1980 PPP dollars).

In terms of the percentage share in total number of wheat researchers, India alone has a fifth of total researchers in the developing world (Figure 4.2 and Figure 4.3). The share of West Asia and North Africa in total number of researchers and expenditures exceeds that of any other region. In general there seems some congruence between the shares in total research personnel and total research expenditures. The discrepancy in the shares for CIMMYT is, however, worth mentioning. The large difference can be explained by the

[7] According to CIMMYT (forthcoming), the total expenditures on wheat improvement by national programs in developing countries (including China) in the early 1990s is estimated to be more than US$100 million in projected 1990 PPP dollars.

Table 4.8: Wheat Improvement Research Personnel and Expenditures in the Developing Countries, Early 1990s

Country	Total Researchers (FTE)	Research Expenditures ('000 1980 PPP $)	Expenditures per Researcher ('000 1980 PPP $)
sub-Saharan Africa	**90**	**6,582**	**73.1**
Burundi	2.0	157	78.57
Ethiopia	18.0	1,562	86.76
Kenya	11.0	645	58.66
Lesotho	2.7	191	70.88[a]
Nigeria	24.0	1,917	79.86
Sudan	9.3	546	58.74
Tanzania	9.0	642	71.38
Uganda	3.0	203	67.57
Zambia	6.0	218	36.36
Zimbabwe	5.0	500	100.00
W.Asia & N.Africa	**300**	**28,100**	**93.67**
Algeria	11.0	786	69.84
Egypt	41.0	432	10.53
Iran	80.0	13,355	166.94
Jordan	19.0	500	26.32
Lebanon	22.0	952	43.28
Libya	14.0	2,216	158.27
Morocco	18.0	2,090	116.13
Saudi Arabia	15.0	2,053	136.84
Syria	7.0	213	30.41
Tunisia	14.0	1,701	121.49
Turkey	56.0	3,731	66.63
Yemen, A.R.	3.0	90	29.87
South Asia (excl. India)	**140**	**5,074**	**36.2**
Bangladesh	29.0	2,140	73.79
Myanmar	9.0	404	44.94
Nepal	20.0	480	23.99
Pakistan	82.0	2,050	25.00
India	**200**	**10,728**	**53.6**
Latin America	**237**	**18,066**	**76.2**
Argentina	40.0	2,324	58.10
Bolivia	26.0	575	22.12
Brazil	47.0	3,620	77.04
Chile	20.4	2,025	99.26
Colombia	14.0	1,474	105.29
Ecuador	8.0	504	63.03
Guatemala	10.0	456	45.63
Mexico	24.0	2,926	121.93
Paraguay	15.6	1,850	118.6
Peru	25.0	1,937	77.48
Uruguay	7.0	373	53.25
National Programs	**967**	**68,550**	**70.9[b]** **57.5[c]**
CIMMYT	**50**	**13,000**	**260.0**
TOTAL	**1,017**	**81,550**	--

Source: CIMMYT Wheat Impact Survey

[a] The 1981-85 cost per researcher of US$333,000 was considered too high. The given figure is the average of the region.

[b] weighted by total number of wheat researchers.

[c] Weighted by total number of agriculture researchers in the country.

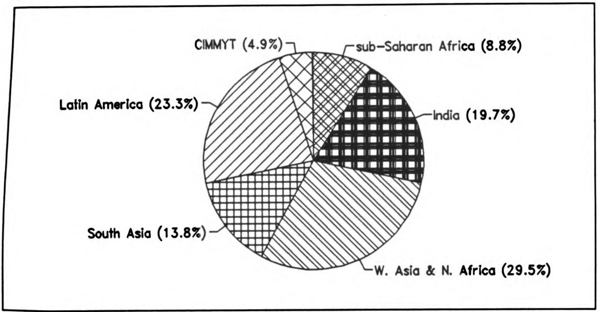

Figure 4.2: Wheat Improvement Researchers in Developing Countries, Regional Shares, Early 1990s

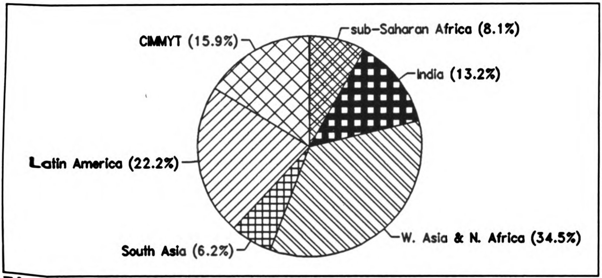

Figure 4.3: Wheat Improvement Research Expenditures in Developing Countries, Regional Shares, Early 1990s

differences in the per researcher expenditures, which are very high for an international research center (about $260,000) (Table 4.8).

There are wide variations between different countries in terms of the size and expenditures on wheat research. In general the research efforts in a given region are congruent with the importance of the crop in that region. Thus, sub-Saharan Africa has both the lowest mean number of wheat researchers and research expenditures per country. Considering that Nigeria is not an important wheat producer, the large size of the Nigerian wheat research program reflects the expansion of the Nigerian Agricultural Research System in general in the last two decades (which grew at an annual rate of 9.2% from 172 researchers in 1961-65 to about 1000 in 1981-85 [Pardey et al. 1991b]). On the other hand, the size of wheat research programs in Argentina and Brazil, large wheat producers, is strikingly small compared to other countries with similar size of wheat production. This can be attributed to the active private sector involvement in wheat research in these countries.

In terms of expenditures per researcher, the variation is highest in the West Asia and North African region. The research expenditures per researcher in South Asia are in general lower than in other parts of the world. However, in the past two decades, unlike in other regions, it has experienced a steady increase in this indicator, perhaps reflecting the fact that this region has relatively mature research systems (Pardey et al. 1991b).

The figures on expenditures per researcher reflect the costliness of research in these countries. In general, countries where human resources are scarce but state (or other source) revenues are ample will have higher spending per researcher than in countries where there is a rapid expansion in the number of researchers with no corresponding increase in research budgets. This explains the generally higher spending per researcher in many countries in West Asia and North Africa and the generally lower ratios in countries like Egypt and Nigeria.

The comparative analyses of degree status and qualification ratio of wheat research teams is given in Table 4.9. The composition of researchers with B.Sc., M.Sc. and Ph.D degrees in the overall total for all developing countries is almost a third for each type of degree qualification. Among the countries, India has the highest proportion of Ph.Ds in their wheat research program, followed by sub-Saharan Africa. Surprisingly, some of the countries in Africa have high qualification ratios. This may be due to the dependence on expatriate researchers (which is particularly high in some of these countries) who are likely to hold at least M.Sc. degree. However, data to distinguish expatriate

Table 4.9: Degree Status and Disciplinary Composition of Wheat Improvement Programs in Developing Countries, Early 1990s

Country	Researchers (%) B.S	M.S	Ph.D	Total	Percent with postgraduate degree	Percent Breeder
sub-Saharan Africa						
Burundi	100	0	0	100	0.0	25.0
Ethiopia	39	39	22	100	61.1	55.6
Kenya	55	46	0	100	45.5	54.5
Nigeria	0	54	46	100	100	12.5
Sudan	3	5	91	100	96.8	24.7
Tanzania	44	33	22	100	55.6	44.4
Uganda	100	0	0	100	0.0	66.7
Zambia	17	83	0	100	83.3	50.0
Zimbabwe	20	80	0	100	80.0	40.0
W. Asia & N.Africa						
Algeria	55	46	0	100	45.5	72.7
Egypt	10	32	59	100	90.2	51.2
Iran	65	31	4	100	35.0	93.8
Jordan	47	26	26	100	52.6	68.4
Lebanon	73	18	9	100	27.3	45.5
Libya	75	8	17	100	25.0	50.0
Morocco	0	33	67	100	100	33.3
Saudi Arabia	67	27	7	100	33.3	66.7
Syria	72	0	29	100	28.6	85.7
Tunisia	29	50	21	100	71.4	21.4
Turkey	57	27	16	100	42.9	50.0
Yemen, A.R.	100	0	0	100	0.0	66.7
South Asia						
Bangladesh	0	72	28	100	100	55.2
India	17	32	51	100	82.9	57.8
Myanmar	100	0	0	100	0.0	50.0
Nepal	70	25	5	100	30.0	25.0
Pakistan	7	71	23	100	93.3	50.7
Latin America						
Argentina	51	38	11	100	48.8	45.0
Bolivia	85	15	0	100	15.4	61.5
Brazil	16	57	27	100	84.6	29.1
Chile	40	41	20	100	60.3	44.1
Colombia	46	36	15	100	53.9	23.1
Ecuador	50	50	0	100	50.0	37.5
Guatemala	50	50	0	100	50.0	60.0
Mexico	33	42	25	100	66.7	62.5
Paraguay	46	55	0	100	54.5	36.4
Peru	84	16	0	100	16.0	36.0
Uruguay	29	72	0	100	71.4	28.6
National Programs	33	35	32	100	67	55

Source: CIMMYT Wheat Impact Survey

wheat researchers were not available to validate this observation.

The percentage of breeders range between 40% and 60% in the majority of developing countries (Table 4.9). The composition of a research team may reflect the complexity of the problem (*ceteris paribus*, more problems mean more involvement of specialists such as pathologist, soil scientist, entomologist, etc.) and the level of research capability (*ceteris paribus*, the higher the level of research sophistication, the more involvement of support disciplinary teams).

4.3.3 Analysis of National Wheat Research Programs in Terms of Size Groups

In the previous section we analyzed wheat research programs in developing countries from a regional perspective. Such analyses do not, however, capture the differences in research programs of different sizes in terms of research personnel. We therefore, present the situation in terms of differences in the size of wheat research programs. The national wheat improvement programs are classified into following 5 size groups: small (less than 10 FTE), medium (10 to 25 FTE), medium-large (25 to 50 FTE), large (50 to 100 FTE) and super large (more than 100 FTE). More than 70% of wheat improvement programs in the developing world employ less than 25 researchers per system, and about 30% employ less than 10 researchers (Table 4.10).

Table 4.10: Classification of Developing Countries' National Wheat Improvement Programs by their Size, Early 1990s

	Number of Researchers (FTE)				
	(< 10)	(10-25)	(25-50)	(50-100)	(> 100)
	Burundi	Algeria	Argentina	Iran	India
	Ecuador	Chile	Bangladesh	Pakistan	
	Lesotho	Colombia	Bolivia	Turkey	
	Myanmar	Ethiopia	Brazil		
	Sudan	Guatemala	Egypt		
	Syria	Jordan	Peru		
	Tanzania	Kenya			
	Uganda	Lebanon			
	Uruguay	Libya			
	Yemen, A.R	Mexico			
	Zambia	Morocco			
	Zimbabwe	Nepal			
		Nigeria			
		Paraguay			
		Saudi Arabia			
		Tunisia			
Total	12	16	6	3	1

Source: CIMMYT Wheat Impact Survey

Different measures of research intensities by size groups are given in Table 4.11. In general research intensity diminishes with increasing size of the research program.

Table 4.11: The Link Between Research Intensities and Size of Wheat Improvement Programs in Developing Countries, Early 1990s

Size No. of Researchers	Research expenditures: As % of value of wheat production	Research expenditures: Per ton of wheat produced	Wheat researchers: Per million dollars of wheat prod.	Wheat researchers: Per million tons of wheat produced
	(%)	(1980 PPP $)	(# of researchers)	
< 10 (11)[a]	1.12	1.10	0.20	19
10-25 (16)	1.25	1.22	0.14	14
25-50 (6)	0.60	0.59	0.11	11
50-100 (4)	0.45	0.44	0.05	5
>100 (1)	0.21	0.21	0.04	4
Developing countries(38)	0.51 6.14[b]	0.50 6.00[b]	0.07 1.02[b]	7 100[b]

Source: CIMMYT Wheat Impact Survey

[a] Numbers in the parentheses indicate the number of countries included

[b] Unweighted average of all national programs

Table 4.12: Variations in the Measures of Research Intensities by the Size of Wheat Improvement Programs in Developing Countries, Early 1990s

Intensity measures	Size of the research programs (number of researchers): < 10	10-25	25-50	50-100	> 100
1. Research expenditures as percent of gross value of wheat production			(percent)		
a. Smallest	1.0	0.5	0.1	0.1	0.2
b. Largest	25.8	22.3	17.5	1.6	0.2
2. Research expenditures per ton of wheat produced			(1980 PPP US $)		
a. Smallest	0.1	0.49	0.1	0.1	0.2
b. Largest	25.3	21.9	17.1	1.6	0.2

Source: CIMMYT Wheat Impact Survey

The variations in the intensity measures of research expenditures, given in Table 4.12, indicate this progressiveness in the declining intensities with the increase in size of research programs. The largest ratio of the two intensity measures within a size group declined with the increasing size in research programs. The high research intensities in small countries make them superficially appear like more-developed countries. However, as explained by Pardey et al. (1991c) the reasons for such high research-spending intensities are the expatriate dominance in small NARSs and the inability to exploit size economies.

These results for wheat are in accordance with the results obtained by Pardey et al. (1991c) that showed that most measures of research intensities (for total agricultural research expenditures) diminish progressively with increasing size as measured by the size of NARS. In order to capture the effects of size on total agricultural research intensity, Pardey et al. (1991c) also classified NARS according to population size. According to this classification, the research intensity measured in terms of total research expenditures as percentage of Agricultural GDP diminished progressively from 1.74% in countries with less than 1 million population to 0.37% in countries with population more than 40 million.

Parallel to this approach, the research intensities for wheat were estimated based on the size of wheat production. Wheat research intensity measured by research expenditures as a percentage of gross value of wheat is as high as 12.0% in small countries producing less than 100 thousand tons of wheat and progressively declined to 0.25% in countries producing more than 10 million tons (Table 4.13).

Table 4.13: The link Between Research Intensities in Wheat Improvement and Size of Wheat Production in Developing Countries, Early 1990s

	Research expenditures		Wheat researchers	
Wheat Production (000 tons) (1990-91)	As % of value of wheat production	Per ton of wheat	Per million dollars of wheat prod.	Per million tons of wheat
	(%)	(1980 PPP $)	(# of researchers)	
< 100 (13)[a]	11.9	11.7	2.3	222
100-500 (7)	5.1	5.0	0.6	55
500-1000 (4)	1.5	1.5	0.2	24
1000-10000(10)	0.9	0.8	0.1	8
>10000 (4)	0.2	0.2	0.04	4
All (38)	0.51	0.5	0.07	7
	6.14[b]	6.0[b]	1.02[b]	100[b]

Source: CIMMYT Wheat Impact Survey and FAO Production Yearbooks

[a] Numbers in the parentheses indicate the number of countries included

[b] Unweighted Average

The average wheat improvement research intensity for the 38 developing countries (excluding China) was found to be 0.51% of gross value of wheat production in 1990-91[8]. On a average, developing countries employ 7 researchers per million tons of wheat produced and spend about US$0.50 per ton of wheat produced on wheat improvement. As a comparison, Australia and the US employ 5.3 and 4.6 FTE researchers and spend about US$0.43 and US$0.73 per ton of wheat produced (CIMMYT forthcoming). The average data for the developing countries disguise the fact that developing country data are dominated by few large countries, especially India, with relatively low expenditures. In other 24 countries with less than one million tons of wheat production, research expenditures are very high as indicated by the research intensities (Table 4.13). Thus, the overall picture that emerges is that wheat research expenditures in developing countries on average are comparable or higher than levels in industrialized countries.

The corresponding figure for the period 1972-79 for research expenditures as a percentage of value of wheat production as estimated by Judd et al. (1991) for all wheat research in 25 developing countries (excluding China) was 0.51%. Given that our estimate of research intensity only includes wheat improvement research, this comparison (despite methodological differences in the present study and that of Judd et al. 1991) suggests that intensity in wheat research has increased since mid-1970s. Partially this can be explained by the increased total expenditures for wheat research[9] and partially by the fact that wheat prices have steadily declined in real terms over the

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[8] The wheat production for each country was valued at the import price (cif, Rotterdam) of wheat (deflated by 1980 US CPI).

[9] This can be substantiated by the estimates of wheat research expenditures of Judd et al. (1991). The average annual expenditures in 1972-79 period in developing countries excluding China for all wheat research was estimated to be 67 million in 1980 US$. Our estimate of $68.5 million (in 1980 PPP$) only for wheat improvement research in early 1990s suggests that the comparable figures of total research expenditures on all wheat research is much higher thus indicating that total wheat research expenditures have increased in real terms since mid-1970s. However, given the stagnated research budgets since mid-1980s, this increment is a reflection of increased expenditures in late 1970s and early 1980s.

past one a half to two decades.

A recent comparison can be made on the basis of research intensity of total agricultural expenditures in developing countries. According to Roe and Pardey (1991), the average research intensity measured by total agricultural research expenditures as a percentage of Agricultural GDP in the period 1981-85 for all developing countries was 0.41%. There are no corresponding figures of research intensities for other commodities available for more recent years to make a comparison between wheat research intensity and intensity of research in other crops. The figures given by Judd et al. (1991) for the years 1972-79 for other crops are: rice 0.25%, maize 0.23%, cotton 0.21%, sugar 0.27%, soybeans 1.06%, cassava 0.11%, field beans 0.32%, citrus 0.52%, cocoa 1.69% and potatoes 0.29%. These figures indicate that with the exception of export crops, research efforts on wheat (0.51%) have been more intense than other important crops in the developing countries.

4.3.4 Relationship Between Size of National Wheat Research Programs and Other Variables

In the preceding chapters and the preceding sections of this chapter, several hypotheses were put forward about the relationship between different variables. For example, it has been mentioned at several places that the size of research effort is positively related with the size of the crop production. Similarly, while discussing the wheat megaenvironments it was hypothesized that the size of research efforts are positively related with the environmental diversity and negatively with the opportunities for research spillins.

Regressions models, such as postulated by Pardey et al. (1991c) to study the economies of size and scope of NARS organizations can be used to study the relationship between size of wheat research program and other variables.

(4.1) $$S = F(Q, E, S_p, A, P, R)$$

where, S = Size of wheat research program
Q = Size of wheat industry (production)
E = Environmental diversity for wheat production
S_p = Opportunities for research spillins
A = Availability of scientific manpower
P = Complexity of production problems facing a country
R = Research costliness

However, due to lack of adequate number of observations and conceptual and empirical difficulties in measuring the variables, such an approach to estimate the model parameters is not undertaken here. The results of tabular analysis presented in Table 4.14, however provided a partial quantitative insight in to the postulated relationship.

Table 4.14: Mean Number of Wheat Researchers, Research Expenditures Per Researcher, Number of Varieties Released and Number of CLE, According to the Size of National Wheat Improvement Programs, Early 1990s

Size (FTE)	Mean wheat Researchers (FTE)	Mean Research expenditures	Expenditure per researcher	% of Varieties Released from Local Crosses (1965-90)	Mean Number of CLE	Wheat Production (1990-91)
		(Thousand 1980 PPP $)				(000 tons)
< 10(11)[a]	5.9	337	56.9	18	nc	305
10-25(16)	16.9	1,476	87.5	26	3.6	1,210
25-50 (6)	34.6	1,838	53.0	32	2.8	3,101
50-100(4)	54.5	4,784	87.8	49	5.2	14,390
>100 (1)	200.0	10,728	53.6	73	6.0	52,186
All (38)	25.0	1,804	70.9 57.5[b]	38	nc	3,605

Source: CIMMYT Wheat Impact Survey; FAO Production Yearbooks; CIMMYT wheat megaenvironment data files
Note: nc = not calculated because of inadequate data
[a] Numbers in the parenthesis indicate the number of countries included
[b] Weighted by total agricultural research personnel

As hypothesized, the size of wheat research programs are positively correlated with the size of wheat industry as measured by the annual production and with the number of megaenvironments encountered in a country. Although, the percentage of varieties released in the past from local crosses is a crude measure of opportunities of research spillins, it does show a positive relationship between size of wheat research efforts and reliance on locally created technology. Alternatively, these results suggest a positive relationship between the size of a research program and level of research capability (in terms of technology evaluation and technology creation). Data on the wheat varieties released in developing countries is presented in detail in Section 4.5. Expenditure per researcher can be considered as a measure of research cost, although in this analysis, it does not show the hypothesized negative relationship between size and costliness of wheat research programs, indicating that non-economic factors may be important in determining the size of a national research system.

4.4 Wheat Improvement Research Programs

The data collected for the analysis of the previous section represent national level efforts on wheat research in terms of total number of researchers, degree status and disciplinary composition. Given the fact that crop breeding programs are organized for specific environments and the decisions about the size and capability of research programs are made (or should be made) at the individual program level, these data were not adequate to explore the relationship between level of research capability and size of research program, size of geographic mandate region and environmental complexity; all of which are important to consider in designing a crop research program. In order to estimate empirical association of these different aspects of a research program data was collected for individual wheat breeding programs around the world.

4.4.1 Data Sources and Method

The data are based on the global survey undertaken by CIMMYT in 1992-93, following the impact study survey described in the previous section. Unlike CIMMYT's global 1990-92 impact study survey which focused on the national wheat research programs, the 1992 survey was conducted for individual wheat breeding programs in developing countries (for e.g., research institutes, universities and research stations doing wheat breeding research specifically for a region within a country).

The survey questionnaires were sent to individual wheat breeding programs in all the countries analyzed in the previous sections, plus some in the Peoples Republic of China. The data used for the descriptive analysis are based on sixty six wheat improvement programs across thirty one developing countries that responded to the survey.[10]

Since the data on the mandate area, level of research capability, number of crosses and number of FTE researchers were collected by wheat type, the research programs that worked on more than one wheat type were sub-divided in to different research programs (each for the reported wheat type in the geographic mandate area) for the purpose of the

[10] Except for Egypt, Iran and Syria who filled out the questionnaire forms for all the breeding programs in the country. These countries are excluded from the analysis of this section.

analysis[11]. For example, the wheat breeding program in San Benito, Bolivia, reported wheat research on spring bread and spring durum. In the analysis, this observation is subdivided into two breeding programs - wheat breeding program for spring bread and wheat breeding program for spring durum. The reason for doing this is that it makes the research efforts comparable across different programs. Given that environmental complexity is an important factor influencing the size and focus of a breeding program, defining a research program in terms of one wheat type eliminates at least one environmental complexity.

In addition to the above mentioned survey, CIMMYT had also sent short questionnaires to several public/private sector wheat breeding programs in various industrialized countries. These data are used to make comparisons of the size of wheat breeding programs in developing and industrialized countries.

4.4.2 Some Empirical Observations on the Size and Capability of Wheat Breeding Programs

As discussed in chapter 3, the decision on the appropriate research capability will depend on many factors including the size of crop industry and environmental complexity. Larger regions and highly diverse research domains are likely to opt for technology creation research and small environments are likely to opt for technology evaluation research. The means of different components of wheat improvement programs (size, area, production, environmental complexity and research intensity) for these two levels of research capability indicate a systematic trend in these variables as the level of capability of a research program increases from technology evaluation research (testing program) to technology creation research (breeding program) (Table 4.15).

In general the mean wheat area and production in the geographic mandate region of a testing program is significantly lower than that of a crossing program. Even within a breeding program the area and production systematically increase (although not linearly) with the number of crosses made per year (the breeding programs are grouped by

[11] The exception to this rule is triticale which was not included in the analysis.

Table 4.15: Number of Researchers, Research Intensity, Mean Area, Production and Envrionments in the Geographic Mandate Region of Wheat Improvement Programs in Developing Countries Grouped by Type of Improvement Program and Number of Crosses Per Year

Type of Wheat Improvement Program[a]	Number of Crosses per year	Mean Size of Research Programs (FTE)	Mean No. of Scientists on wheat improvement (FTE)[b]	Mean Area (000 ha)	Mean Production (000 tons)	Mean No. of Environ-ments[c]	Research Intensity[d]
Testing (13)	0	2.7	1.4	119	287	2.9	0.53
Breeding (19)	(1-149)	3.9	2.2	326	609	2.7	0.55
(9)	(150-299)	5.9	3.2	1,202	2,473	4.1	0.14
(21)	(300-599)	9.2	4.7	956	2,454	2.8	0.26
(8)	(600-999)	7.8	4.4	862	2,397	2.9	0.16
(9)	(> 1000)	11.3	7.7	2,133	5,613	3.4	0.09
(66)	All	7.4	4.2	957	2,349	3.0	0.19
Total (79)		6.6	3.8	819	2,010	3.0	0.20

Source: CIMMYT survey on wheat improvement research pograms, 1992-93

[a] Numbers in the parenthesis indicate number of research programs analyzed

[b] Researchers working on crop improvement component only (i.e does not include researchers working on crop management and seed production research)

[c] Research programs are defined for a specific wheat type (viz., spring bread, spring durum, winter bread and winter durum). The number of environments therefore, represent factors other than wheat type.

[d] Measures total expenditures on wheat research as a percentage of total value of wheat.

the number of crosses to capture the different levels of research capability within the broad group of technology creation research). The mean number of production environments in the geographic mandate region of a testing program was not found to be significantly different from that of a breeding program. On average, research programs in developing countries target their research towards three distinct production environments.

In terms of human resources devoted on research, there is a clear pattern in the relationship between the size and capability of a wheat improvement program. The overall size of a research program[12] increased from 2.7 FTE for testing to an average of 7.4 FTE for a breeding program. Even within the category of breeding programs, the mean size of research programs increased progressively from 3.9 to 11.3 FTE depending on the number of crosses made per year. The corresponding figures for the number of researchers working only on the crop improvement component (testing, selection, crossing and other disciplinary research directly related to improving genetic gains) also show a similar increasing pattern of relationship between size and focus. In terms of relative size of a testing and crossing program, these figures indicate that the number of researchers working in a testing program in developing countries is approximately one-third of those required by a crossing program (2.7/7.4 = 0.36 and 1.4/4.2 = 0.33). This is an important empirical observation and is used in a later chapter to estimate the relative costs of a testing and breeding program.

In general, small research programs conducting technology evaluation tend to invest more in research as measured by the percentage value of wheat crop. This declining research intensity measure is in accordance with the earlier observations given in Table 4.11 for the

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[12] The overall size includes researchers working on all the components of wheat research - crop improvement, crop management, seed production and administration.

different size of national wheat research programs[13].

So far the focus of the descriptive analysis has been on the wheat research programs in the developing countries. In order to compare the size of research programs in developing and industrialized countries, the data collected on the privately and publicly funded wheat breeding programs in industrialized countries are summarized in Table 4.16.

Privately funded programs seem to employ significantly less FTE researchers than the publicly funded programs in developed countries. This difference can be explained partly by the corresponding difference in the number of environments in the geographic mandate region and partly by the difference in the research focus. Public research programs generally do more strategic/basic research and provide germplasm for the private sector, thus requiring more number of researchers. This difference in the research strategy of private and public programs can be seen in the difference in the composition of the research programs. The proportion of researchers from other disciplines is more in public programs than in private programs.

In terms of the size of the geographic mandate region, private programs tend to work in regions with larger wheat area and less number of wheat environments than the public programs. Given that the private sector is in the research business with a profit motive, these results are not surprising. Also, the private sector is likely to have overlapping mandates with other private sector programs in a given mandate area.

The average size of breeding programs in developing countries (7.4 FTE) is significantly higher than the mean size of wheat breeding programs - public funded (3.9 FTE), private funded (2.6 FTE) and overall average (3.1 FTE) - reported in Table 4.16. Even the mean number of

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[13] The overall intensity measure reported in Table 4.16 is lower than that reported in Table 4.11. The probable reasons for this discrepancy are worth mentioning: (1) The analysis done in Table 4.11 excludes China, whereas that of Table 4.17 includes some of the Chinese wheat breeding programs. (2) The results of Table 4.17 are based on only those programs that responded to the survey. No effort was made to correct the size figures by including the researchers working in other organizations and universities for the same geographic mandate. Thus it may not represent an exhaustive effort on wheat breeding research in the given mandate region.

Table 4.16: Number of Researchers, Mean Area and Number of Environments in the Private and Public Wheat Improvement Research Programs in Industrialized Countries, 1992-93

Country of a Given Research Program[a]	Number of Researchers (FTE)			Area (000 ha)	Prod. (000 tons)	No. of Environ -ments
	Breeders	Support Disciplines	Total			
Private Programs						
Denmark	2.0	0.0	2.0	600	4,349	2
Finland	1.0	1.0	2.0	90	320	1
France	2.0	1.0	3.0	4,690	30,865	2
Germany	2.0	0.0	2.0	5,000	34,420	2
Italy	2.0	0.0	2.0	NR	NR	4
Spain	2.0	0.0	2.0	2,300	5,398	4
Sweden	2.0	2.0	4.0	350	2,186	5
U.K.	2.0	2.0	4.0	2,000	14,172	4
Average	1.9	0.8	2.6	2,147	13,101	3.0
Public Programs						
Australia	4.0	4.0	8.0	3,000	4,380	8
Australia	2.0	4.0	6.0	3,000	4,380	3
Australia	1.0	5.0	6.0	1,500	2,190	4
Germany	2.0	0.0	2.0	2,300	15,833	3
U.S.A.	0.5	0.5	1.0	800	1,999	2
U.S.A.	1.0	0.0	1.0	300	750	1
U.S.A.	1.0	3.0	4.0	1,400	3,499	3
U.S.A.	3.0	0.5	3.5	600	1,499	9
Average	1.8	2.1	3.9	1,613	4,316	4.0
Overall Average	1.9	1.2	3.1	2,118	7,929	3.6

Source: CIMMYT Survey on Wheat Improvement Research Programs, 1992-93
NR = Not reported
[a] To maintain confidentiality the name of the research programs are not reported.

researchers working only on crop improvement component in the crossing program of developing countries (4.2 FTE) is higher than the overall average of public and private funded programs. This does suggest that research programs in developing countries are significantly larger relative to their counterparts in developed countries.

However, to make any statement about size inefficiency based only on the size of research programs would not be appropriate. The size of geographic mandate region and number of environments also need to be accounted for (Table 4.17)

Table 4.17: Wheat Improvement Research Intensity in Developing and Industrialized Countries

Wheat improvement programs	Number of researchers per million tons		# of researchers per million tons per production environment	
	(weighted)	(unweighted)	(weighted)	(unweighted)
Developing Countries	2.74	19.6	0.014	8.8
Industrialized Countries	0.40	1.4	0.007	0.7

Source: CIMMYT survey on wheat improvement research programs, 1992-93

As can be seen the research intensity measured by the number of researchers per million tons and per production environment in developing countries' wheat improvement programs is significantly higher than that of industrialized countries' programs. Overall, compared to industrialized countries, wheat improvement programs in developing countries (excluding China) are employing at least two times more researchers per million tons for a single environment. Considering the fact that the weighted averages overrepresent large countries' research programs, the unweighted research intensities are also reported to indicate the extent of differences in the research intensities of developing and industrialized countries. These results do point to the fact that the size of wheat research programs in developing countries in general is greater relative to their counterparts in industrialized countries.

4.4.3 Disciplinary Composition of Wheat Breeding Programs

The difference between a testing and crossing program is not only in terms of the size but also in terms of disciplinary composition. Table 4.18 summarizes the composition of wheat research programs by different disciplines for testing and crossing programs.

The number of different disciplinary researchers tend to increase with the level of research capability. For example, the testing programs mainly comprise of breeders, pathologists and agronomists. However, a breeding program includes a cereal technologist (for programs doing less than 100 crosses per year) in the research team. With the subsequent increments in the level of capability as measured by the

Table 4.18: Disciplinary Composition of Wheat Improvement Research Programs in Developing Countries, Grouped by Type of Research Program and Number of Crosses per Year

Type of Program # of Crosses	(% of Total Researchers Working on Crop Improvement Component of Wheat Research)										
	Bree-ders	Patho-logist	Agro-nomist	Cereal Techno-logist	Entomo-logist	Physio-logist	Agric. Engi-neer	Soil Scie-ntist	Admi-nistr-ator	Other[a]	Total
Testing	67.7	9.5	20.9	0.0	0.0	1.9	0.0	0.0	0.0	0.0	100
Breeding:											
1-99	72.7	19.8	1.9	5.7	0.0	0.0	0.0	0.0	0.0	0.0	100
100-299	52.6	17.2	5.9	3.9	2.6	4.2	3.9	0.0	1.3	8.5	100
300-599	72.5	11.7	5.6	5.1	1.8	0.4	0.1	0.1	0.0	2.8	100
600-999	84.6	8.6	3.8	1.1	0.3	0.0	0.7	0.1	0.0	0.9	100
1000-2500	74.6	10.8	0.1	2.7	2.3	4.0	0.7	3.4	0.8	0.6	100
> 2500	61.2	11.7	8.0	7.6	5.2	1.6	0.0	0.2	0.3	4.2	100
All	74.5	11.3	4.0	3.4	1.6	1.3	0.7	0.6	0.3	2.1	100
Total	74.2	11.2	4.7	3.2	1.5	1.4	0.8	0.7	0.3	2.2	100

Source: CIMMYT survey on wheat improvement research programs, 1992-93

[a] Other Disciplines include - Weed scientists, Nematologist, Seed production specialist, Irrigation specialist, Computer/Statistician.

number of crossed done per year adds researchers from other specialized disciplines such as entomologists, physiologists, agricultural engineers, soil scientists, administrators and others. The pathologists, agronomists and cereal technologists are the most important among all the support disciplines. In general however, the importance of agronomists tend to decline with the increasing levels of research capability and that of other disciplines tend to increase.

4.5 Analysis of Wheat Varietal Technology in Developing Countries

The analysis presented in this section is on two aspects of wheat varietal technology: (1) the quantitative aspect in terms of trend and number of varieties released, types and environmental niche, and the success rate of these technologies. (2) the technology transfer aspect that uses the pedigree information of each variety to analyze the origin and source of released varieties in developing countries.

4.5.1 Data Sources and Method

The data used for the analyses were collected by CIMMYT as part of the global impact study survey on wheat. The survey of all major national wheat research programs in developing countries was undertaken by CIMMYT to construct an inventory of all varieties released by NARSs until 1990, along with the size and composition of wheat research programs. The database contains over 1,350 varieties, 1,300 of which were released in the period 1965-90 which is the focus of this analysis. The major wheat producing countries (excluding China) included in the impact study survey are the same as in Section 4.3. A detailed analysis of this survey data is reported in Byerlee and Moya (1993). Only the relevant results are summarized here.

4.5.2 Overall Trends in the Number of Varieties Released

Figure 4.4 shows the number of wheat varieties released per year from 1965-69 to 1985-90 in different regions and in all developing countries. As can be seen, the number of varieties released has steadily increased over the 25 years indicating the increasing strength of wheat research programs in developing countries. The number of varieties released per year in all the developing countries increased rapidly during the period 1965-69 to 1970-74 following the successful development of semi-dwarf wheat varieties and the establishment of CIMMYT in 1966 in Mexico. The number of wheat varieties released per year in developing countries has more than doubled from about 28 per year in 1965-69 to about 60 in 1985-90. In terms of regional trends, surprisingly, the Latin American countries have experienced the largest increments in the number of varietal releases in the past 25 years and sub-Saharan Africa has experienced a more or less steady trend of 5 to 6 releases per year in this period.

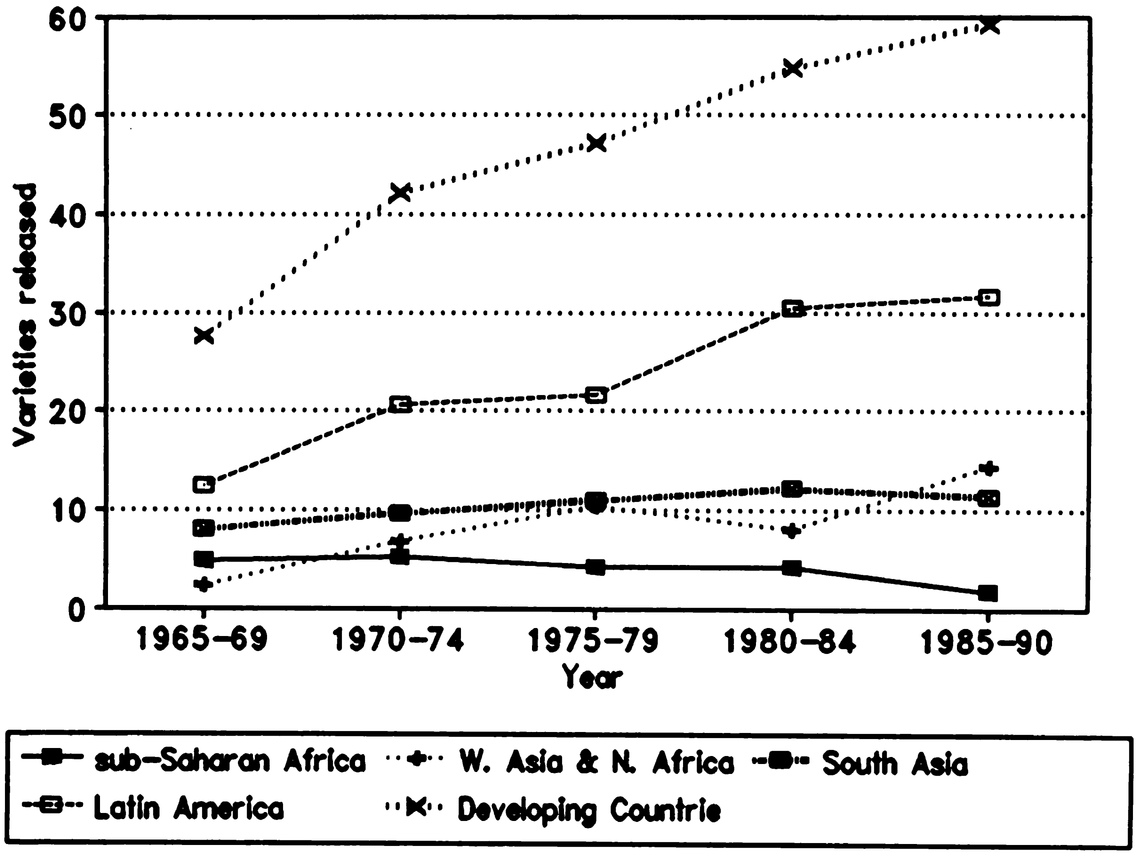

Figure 4.4: Trends in Number of Varieties Released in Developing Countries, by Region, 1965-69 to 1985-90

On a country basis, two patterns are worth noting. 1) As expected, large wheat producers have released large number of wheat varieties (Table 4.19). The number of wheat varieties released by Brazil (191) and India (180) is highest among developing countries. 2) As noted by Byerlee and Moya (1993) there seems very little congruence between the size of wheat area and number of varieties released. This

Table 4.19: Total Number of Varieties Released per Million Hectares of Wheat, 1965-90

Country	Number of varieties (1965-90)	Varieties/million ha/year 1965 to 1974	1975 to 1984	1985 to 1990	1965 to 1990
sub-Saharan Africa					
Burundi	6	0.0	22.7	62.9	24
Ethiopia	35	2.1	2.9	0.5	2
Kenya	34	11.7	12.5	7.0	11
Nigeria	8	35.5	8.9	16.2	20
Sudan	8	2.9	1.9	1.1	2
Tanzania	16	4.0	11.5	25.0	12
Zambia	14	2239	256	114	204
Zimbabwe	26	123	20.6	7.5	35
West Asia and North Africa					
Algeria	25	0.5	0.6	0.5	1
Egypt	18	0.9	1.2	1.6	1
Libya	24	1.8	7.2	2.7	4
Morocco	29	0.2	0.4	1.3	1
Tunisia	14	0.9	0.4	0.5	1
Iran	16	0.1	0.1	0.1	0
Jordan	13	1.0	3.5	16.9	4
Lebanon	10	7.0	3.3	35.7	10
Saudi Arabia	9	1.6	5.5	0.3	2
Syria	11	0.3	0.2	0.6	0
Turkey	78	0.1	0.3	0.8	0
Yemen, A. R.	12	13.6	4.8	67.6	12
South Asia					
Bangladesh	16	7.1	1.7	0.8	2
Burma	10	3.7	5.3	2.8	4
India	180	0.4	0.3	0.3	0
Nepal	14	1.0	1.2	1.2	2
Pakistan	52	0.3	0.3	0.3	0
Latin America					
Argentina	104	0.6	0.8	1.0	1
Bolivia	26	4.5	12.4	21.7	12
Brazil	191	2.8	3.1	3.2	3
Chile	110	3.3	9.6	10.4	7
Ecuador	12	7.1	15.3	4.7	9
Guatemala	18	18.5	16.6	29.5	20
Mexico	85	3.9	4.1	3.3	4
Paraguay	20	1.6	1.3	8.3	3
Peru	26	8.5	5.0	15.1	9
Uruguay	20	1.6	1.3	8.3	3

Source: CIMMYT Wheat Impact Survey

is reflected in the rate of varieties released as measured by the ratio of total varieties released per million hectares of wheat (Table 4.19 and Table 4.20). The ratios for small wheat producing countries like Zambia, Zimbabwe, Nigeria, Burundi, Guatemala, Tanzania and Bolivia, are among the highest in the group, thus illustrating the point.

On a regional basis, the rate of release in sub-Saharan African countries and Latin American countries for the period 1965-90 is over five times the rate in Asia and West Asia and North Africa (Table 4.20). As we discussed in previous chapters, crop area alone does not determine the size and output of research effort. Other factors such as environmental diversity, number of research programs, plus variety releasing procedures and the stage of development of the seed industry influence the size and output of research effort. These may be the reasons for this incongruence observed between number of varieties released and size of total wheat area.

Table 4.20: Total Number of Varieties Released per Million Hectares of Wheat (1965-90), Regional Perspectives.

Region	Total number of varieties released				Total varieties per million ha per year				Success rate (1965-90)
	1965 to 1974	1975 to 1984	1985 to 1990	1965 to 1990	1965 to 1974	1975 to 1984	1985 to 1990	1965 to 1990	
sub-Saharan Africa(8)[a]	59	57	31	147	5.5	5.6	4.6	5.3	63
West Asia & North Africa(12)	57	100	102	259	0.3	0.5	0.7	0.5	41
South Asia(5)	88	116	116	272	0.4	0.4	0.4	0.4	46
Latin America(11)	168	262	194	624	2.0	2.5	3.0	2.5	41
Developing countries(36)[b]	372	535	395	1302	0.7	0.8	1.0	0.8	44

Source: CIMMYT Wheat Impact Survey

[a] Numbers in the parentheses indicate countries included.

[b] Excluding China.

It is also interesting to note the declining or stable trend in the rate of varietal release in the last decade. For most developing countries, the total varieties released per million hectare of wheat area was highest in the 1960s and 1970s, the so-called Green Revolution phase. However, the total number of varieties released is one thing and the adoption of these varieties is another. As shown in Table 4.20, the overall success rate of commercial release of varieties was only 44 percent. In the data base, a variety was considered commercially successful if it covered at least 5% of the country's wheat area or 25,000 ha, which ever was least. Comparing the success rate of different regions with the number and rate of varieties released, it is clear that the success rate is inversely related to the other two indicators of research effort.

4.5.3 Analysis of Technology Transfer and Origin of Wheat Varieties Released in Developing Countries

As discussed in the previous chapter, direct and indirect technology transfers plays an important role in influencing the productivity of crop improvement research programs. In this section we will analyze the varietal release data to examine the extent of wheat technology transfers in the developing world. Since its establishment in the mid-sixties, CIMMYT has played an important role as a source of improved wheat technology. The semi-dwarf wheat germplasm developed by CIMMYT has proved to be an extremely adaptable instrument for change. By 1990, the percentage of wheat area planted to semidwarfs had reached 70 percent in the developing countries (CIMMYT 1992).

The national programs have a range of options in using the wheat germplasm developed by CIMMYT (or any other foreign program). They could directly release a CIMMYT line selected from yield trial nurseries (giving a local name) or make further selections under local environmental conditions and release the best line, or it could use it as a parent material in local crosses. As discussed in the previous chapter, these options correspond to different types of technology transfer. In order to examine the type of technology transfer embodied in the wheat technology in developing countries, all the varieties released were divided into following categories.

1. Varieties resulting from crosses made by national programs using
    a. no CIMMYT germplasm as one of the immediate parents[14] or,
    b. CIMMYT germplasm as at least one of the parents.
2. Varieties resulting from crosses made by
    a. CIMMYT staff in Mexico, or
    b. national programs of another country[15].

The two categories correspond to indirect and direct transfers, respectively, with different degree of utilization of CIMMYT germplasm.

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[14] Note that CIMMYT materials may however, occupy a more distant place in the genealogy of these varieties.

[15] These varieties may be either of type 1a or 1b described above.

Table 4.21: Percentage of Wheat Varieties Released in Developing Countries and the Success Rate by Origin of Cross, 1965-90

Origin	Percentage of all releases	Success rate (%)
1. Local cross (technology creation research)	*45*	*42*
a. Using no immediate CIMMYT parent	23.8	35.5
b. Using CIMMYT material as a parent	21.4	47.7
2. Foreign Cross (technology evaluation research)	*55*	*47*
a. Cross made by CIMMYT staff in Mexico	45.3	46.2
b. Cross made by other country	9.6	48.8
Total	*100*	*42*

Source: CIMMYT Wheat Impact Survey

Table 4.21 gives the percentage of all releases classified by the origin of cross. The option of directly borrowing varieties developed by a foreign program seems to be the most popular one among developing countries. Almost 55% of all varieties released in the period 1965-90 were directly introduced from either CIMMYT or another country. The role of CIMMYT in technology transfer is clearly demonstrated by these figures. CIMMYT has been the source of direct technology transfer in 45 percent of the cases. Its role as a direct source of indirect transfers (i.e. as a source of parent materials for NARS crosses) is also predominant (21%). The major sources for country to country direct transfers were India, Italy, Pakistan and USA. These countries have large and highly capable wheat research programs thus playing a role in both direct and indirect transfer of technology.

The international transfer of improved varietal technology has been an important phenomenon in other crops also[16]. However, the importance of different sources of origin differs from crop to crop. Evenson's (1991c) analysis of the genealogy data of rice varieties provides such evidence for rice improvement research. According to his analysis, in case of rice research, the use of germplasm from other

[16] See for example Hargrove (1979), Hargrove and Cabanilla (1979) and Hargrove et al. (1985) for the documentation and analysis of direct and indirect transfers in rice breeding research.

sources as parent material has been the most widespread and pervasive (85% of total varieties released). Only about 20% of all released varieties from 1966-91, represented directly introduced varieties. Of these 20%, about 80% originated at International Rice Research Institute. Thus, compared to rice, the extent of direct transfers has been larger for wheat (55%). The differences in the extent of direct versus indirect transfer can be explained by the extent of environmental diversity a crop is grown, the type of crop (whether it is self- or open pollinated), the importance of location-specific quality traits and the research capabilities of the country growing the crop.

Given the location specificity of agricultural technology (due to G x E interactions), one would presume that varieties developed by foreign programs would not do well in a local environment. However, as indicated in Table 4.21, the success rate of directly introduced varieties was not significantly different from the success rate of varieties developed by local research programs using CIMMYT materials as a parent. The success rate of direct transfers from other countries was the highest, implying that countries in similar environments can be a useful source of technology transfers. However, one has to be cautious in interpreting these results since the commercial success rate is a very crude measure of 'transferability' of a technology. Generalizations about transferability of a technology should be based on the performance and adaptability of a technology across different environments, a topic to be discussed in the next chapter.

The trends in the origin of released varieties over the last three decades are given in Table 4.22. In general, during the period 1965-69 to 1985-90, the share of varieties originating from local crosses has gradually declined and the share of directly introduced varieties have increased. Within this general pattern the share of varieties based on CIMMYT germplasm (categories 1b and 2a) has increased over time whereas the share of other two categories (1a and 2b) has declined.

The regional picture of the origin of all the released varieties is given in Table 4.23. In sub-Saharan Africa and West Asia and North Africa, the tendency has been to rely more on the foreign-crossed varieties (either from CIMMYT or another country). The varieties

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Table 4.22: Trend in the Percentage of Wheat Varieties Released in Developing Countries by Origin of Cross, 1965-69 to 1985-90

Origin	1965 to 1969	1970 to 1974	1975 to 1979	1980 to 1984	1985 to 1990
	(Percent of all releases)				
1. Local cross (Technology creation research)	*63*	*48*	*48*	*42*	*37*
a. Using no immediate CIMMYT parent.	51.3	28.6	21.8	17.5	16.0
b. Using CIMMYT material as a parent.	11.3	19.2	25.9	24.8	21.2
2. Foreign Cross (Technology evaluation research)	*37*	*52*	*52*	*58*	*63*
a. Cross made by CIMMYT staff in Mexico	25.3	45.1	43.6	48.2	52.2
b. Cross made by other country	12.0	7.1	8.6	9.5	10.6
Total	100	100	100	100	100

Source: CIMMYT Wheat Impact Survey

Table 4.23: Origin of Wheat Varieties by Region, 1965-90

Region	Local Cross: No immediate CIMMYT parent	Local Cross: CIMMYT parent	Foreign Cross: CIMMYT Cross	Foreign Cross: Other Country Cross	Total
	(Percentage of Regional total)				
sub-Saharan Africa	19.1	20.4	40.1	20.4	100
					100
West Asia & North Africa	13.2	8.8	51.8	26.3	100
South Asia	23.3	31.0	41.0	4.8	100
Latin America	29.6	22.5	45.8	2.1	100

Source: CIMMYT Wheat Impact Survey

introduced from other sources is the highest for WANA among all the regions. In Asia, however, the tendency has been to use imported materials as parents, rather than to release varieties based on foreign crosses (because of the dominance of India which has used CIMMYT materials more as parents than directly releasing them).

These trends are also evident at the country level. Byerlee and Moya (1993) classified the countries by the percent of varietal releases

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Table 4.24: Classification of Wheat Research Programs in Developing Countries According to the Extent of Varietal Releases from Local Cross

	Percent of releases from own cross (1965-90)				
	0%	1-25%	25%-50%	50%-75%	> 75%
	Algeria	Guatemala	Ecuador[a]	Argentina	Kenya
	Bangladesh[a]	Libya	Egypt	Brazil	
	Bolivia	Mexico	Ethiopia[a]	Chile	
	Burundi	Morocco	Iran	Colombia	
	Lebanon	Saudi Arabia	Jordan	India	
	Myanmar[a]	Sudan[a]	Pakistan	Peru	
	Nepal[a]	Yemen, A.R.[a]	Paraguay	Zimbabwe	
	Nigeria		Syria		
	Tanzania[a]		Tunisia		
	Zambia		Turkey		
			Uruguay[a]		
Total	10	7	11	7	1

Source: Adapted from Byerlee and Moya (1993)
[a] Countries with significant number of varieties imported directly from other countries.

from own crosses (either local cross or foreign parent). Their results are reported in Table 4.24 by further classifying the countries into 0% release from own crosses and 1-25% release from local cross. Most of the countries (28 out of 36), particularly countries with smaller research programs depend on foreign crosses for 50% or more of their varieties; ten out of these 28 countries have depended totally on the direct transfers of technology by releasing CIMMYT or other country's varieties. Most large wheat producers, and countries with strong wheat research programs depend on own crosses for 50% or more of their varieties. Important exceptions to this rule are however, Mexico (where CIMMYT is located) and Pakistan (where the wheat growing environments are very similar to Mexico) (Byerlee and Moya 1993).

4.6 Summary

This chapter has provided an overall view on the wheat megaenvironments, wheat varieties released, national wheat research programs and size and capability of wheat breeding programs in developing countries. Based on the descriptive analysis of this chapter, following global picture of wheat research efforts emerges.

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The environmental diversity varies immensely among countries depending on the number of distinctive wheat megaenvironments and the size of wheat area encountered in a country.

2. The total number of wheat researchers in national programs of developing countries in early 1990s is estimated at 967 FTE researchers and the global wheat research expenditures are estimated at $70 million (in 1980 PPP US$). Adding the wheat research efforts of CIMMYT, the total expenditures in and for developing countries is about $82 million per year. In terms of research intensity, developing countries in general are spending 0.51% of total value of wheat production and employing 7 researchers per million tons of wheat on wheat improvement research. Overall the research expenditures on wheat improvement are comparable or higher than those in industrialized countries.

3. The average size of a technology evaluation (testing program) program in developing countries was found to be 2.7 FTE researchers and that of technology creation (breeding program) was found to be 7.4 FTE for the whole program and 4.2 FTE for the crop improvement component of wheat research program. The corresponding size of wheat breeding programs in the private and public research programs of industrialized countries was 2.6 and 3.9 FTE researchers, respectively.

4. Taking in to consideration the difference in wheat area and number of environments in the geographic region, the research programs in developing countries are found to employ at least two times more researchers than those in industrialized countries.

5. There has been an increasing trend in the number of wheat varieties released per year from 1965-90. This reflects the increasing wheat research efforts in developing countries since the Green Revolution.

6. Fifty five percentage of all the varieties released in developing countries in 1965-90 were either directly introduced (after local testing) from CIMMYT (45%) or from other countries (10%), and about 50% of all varieties released from local crosses used CIMMYT germplasm as parent material. These results indicate the enormous success of CIMMYT in generating both direct and indirect spillins to developing countries. It also indicates the importance and success of direct transfers in wheat varieties.

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CHAPTER FIVE

ASSESSMENT OF INTERNATIONAL TRANSFER OF WHEAT VARIETIES

5.1 Introduction

We have shown in our conceptual model in chapter 3 that the availability of transferable technology is an important factor influencing the decision on the size and level of research activity on a given commodity or problem in a given country. Technology spillins can enhance the productivity of domestic research programs by complementing local research efforts. However, since technology spillins can also substitute for local research (Evenson and daCruz 1992), they also determine the opportunity cost of having a given level of research capability when the existing foreign technology is directly transferable to local environment.

A technology is considered to be directly transferable after local evaluation if it can be directly released in another country/environment without requiring further research. For instance, Pak 81, a CIMMYT bred cultivar released in Pakistan, or UP262, a cultivar bred by the Indian national program and released in Nepal are examples of direct technology transfer. By contrast, a technology which requires further research by a receiving country illustrates the case of indirect technology transfer. Thus, a country using CIMMYT cultivars as parents in its crossing program would be an example of indirect technology transfer.

According to our conceptual framework, the extent to which a technology can be directly transferred depends on the 'environmental distance' between two regions and on the targeting strategy adopted by the research program of the source country[1]. Direct technology transfers are more likely between regions with less environmental distance (reflected in non-significant G x E interactions) than between

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[1] 'Environmental distance' refers to the adaptation distance rather than the physiological notion of absolute differences in the agroclimatic factors. It is basically determined by the genotype by environment interactions. Thus, for example, an environment characterized as low rainfall (say receiving less than 100 mm. of rainfall) is not necessarily distant from an environment characterized as high rainfall (receiving 1000 mm. of rainfall) if the genotypes that exist are not differentially responsive to different levels of rainfall.

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regions with dissimilar environments (significant crossover G x E interactions). Moreover, direct transfers are more likely if the research is targeted towards developing broadly adapted technologies that excel in multiple circumstances rather than narrowly adapted technologies that are only useful in a few circumstances.

One of the objectives of the CGIAR international research systems is to develop widely adapted technologies that can be used by the national research programs either directly or indirectly. The research effort of an IARC thus enters in the research production function of national research programs as one of the potential and possibly the most important sources of technology spillins.

Technology spillins from IARCs to national research programs may be constrained by the location specificity of agricultural technology (Jarrett 1982). In the case of wheat the notion of location specificity is supported by Englander (1981a;1991) who reports that "*(wheat)* varieties tend to be highly specialized to local conditions" (Englander 1991, p.307). However, the evidence provided in chapter 4 on the extent of directly introduced wheat varieties in developing countries from CIMMYT and other national programs (about 55%) suggests that wheat varietal technology may be robust than reported earlier by Englander.

In this chapter we revisit the issue of transferability of wheat varietal technology with the focus on estimating advantages of directly transferable and locally developed wheat technologies.[2] We will test some of the hypotheses presented in earlier chapters and provide empirical measurements of their quantitative significance. The specific focus is on the following issues:

1. What is the evidence regarding the location specificity of wheat varietal technologies? In other words, how do cultivars of a given environmental origin perform in different environments?
2. What are the yield advantages of cultivars bred by national programs as versus cultivars imported from other sources?

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[2] The word 'wheat technology' is used here to denote wheat varieties and does not include crop management techniques or agronomic practices associated with wheat cultivation.

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3. What is the evidence of international transferability of wheat technology from CIMMYT? and how does the technology transferability from CIMMYT differ across environments?

The degree of transferability of wheat technology is an important policy issue. The determination of whether or not to rely on direct transfers from CIMMYT or other sources requires an evaluation of the benefits from producing locally bred and imported cultivars. If the difference between the benefits from direct and indirect transfers in wheat technology proves to be nonsignificant, then technology importation would be an efficient alternative for developing countries. Also, increasing the efforts to develop directly transferable technology to smaller countries and environments by existing international research programs would be more efficient than establishing new research programs in every environmental niche.

This study devises a methodology to extract information from existing data sources that were not designed with the specific goals of this study in mind. Following Englander (1981a), Englander and Evenson (1979) and Evenson (1991b), CIMMYT's International Spring Wheat Yield Nursery (ISWYN) trial data are used for this analysis. Started in 1964, these yield trials are conducted each year by CIMMYT, Mexico, with the cooperation of national research programs (both in developed as well as in developing countries). About forty to fifty wheat cultivars developed by CIMMYT and national research programs are annually tested at different locations around the world. The main objective of these international trials is to disseminate the germplasm to different countries and to test their adaptability to different environments. Similar trials are also conducted by other international centers and national programs for different crops. Thus, there is a vast amount of experimental data available that can be used to assess the transferability of crop technology to different environments. However, except for a few studies mentioned above these data have not been exploited by economists because of the difficulties of measuring transfer flows or technological opportunities (Evenson 1991b). This chapter is focused on this broader question of technology

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transferability and on demonstrating the value of international yield trial data for the analysis of international technology transfer.

It should be noted that in this analysis, yield is considered as the sole performance indicator of a technology. This is in accordance with other studies on genotype by environment (G x E) interactions (Finlay and Wilkinson, 1963; Hardwick and Wood, 1972;) and research productivity (Evenson and Kislev, 1975;) in which yield is associated with technological attainment. Implicitly, CIMMYT and other plant breeding research programs make the same association since they use the trial data to identify superior cultivars. Several limitations of this usage should be noted, however. First, farmers may prefer varieties with attributes other than higher yields per se. For example, grain quality, yield stability, and early or late maturity may be as important or more important to a farmer than higher yields. As long as yield increments are achieved by not sacrificing these other characteristics, crop yields may be considered as an indicator of technological improvement. Second, the trial stations may not represent the typical growing conditions (environment) of the farmers' field. The relative performance of cultivars based on the yield data obtained from such experiments, therefore may not be transferable to the farmer's field. Third, the decisions about the establishment and further development of national research programs are based not on goals of achieving higher yields alone. Other goals such as national food security, regional development, or mere pride, may be more important in dictating the decisions on national research priorities. In order to offset these limitations, a broad spectrum of data need to be collected and new methodology needs to be developed that can incorporate all the important attributes promoting or constraining technology transfers.

The layout of this chapter is as follow. The statistical model used for the transfer analysis is discussed in Section 5.2 followed by the data description and the econometric estimation method in Sections 5.3 and 5.4. Sections 5.5 and 5.6 presents the empirical estimation of different model specifications to address the issues discussed above. In Section 5.7, the issue of transferability of wheat cultivars is addressed by using the national yield trial data of Pakistan. The

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present study is based on the methodology developed by Englander (1981) and explores many similar questions. However, there are some fundamental differences between that study and the present one. These differences are discussed in Section 5.8. Section 5.9 concludes the chapter by pointing out the implications and limitations of the empirical results.

5.2 The Statistical Model

Environmental variability is important for crop improvement research program design because of G x E interactions. The G x E interactions imply a differential response by genotypes to different environments. Because of these interactions, agricultural technologies are known to adapt better in one environmental niche than another. Direct transfer of agricultural technology (particularly varietal technology) from one environment to another is therefore inhibited by the presence of G x E interactions making it necessary to design new research programs for local adaptation of already developed technologies or to develop new indigenous (local) technologies in each environmental niche.

We use the multiple regression analysis used by Englander (1981a and 1991) to estimate the extent of G x E interactions (and consequently the extent of location specificity) in wheat cultivar technology originating from different environments. The model is as follows:

$$Y_{ijt} = f(E_{jt}, T_i, G_{ijt}) + \epsilon \qquad (5.1)$$

where,

- Y_{ijt} is the yield of wheat cultivar i in location j at time t.
- E_{jt} is a vector characterizing the environment at location j in time t. $E_{jt} = (E_{jt1}, \ldots, E_{jth})$
- T_i is a vector characterizing the technology embodied in cultivar i. $T_i = (T_{i1}, \ldots, T_{ik})$
- G_{ijt} is a vector characterizing the interactions between the technology and the environment. $G_{ij} = (G_{ij1}, \ldots, G_{ijp})$
- e is the error term

Thus, the performance of a cultivar is assumed to be a function of three components - environment, technology and the interaction terms. Conceptually, this statistical framework is based on the phenotypic yie

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yield response models used by plant breeders and geneticists to study the cultivar or genotype by environment (G x E) interactions and to identify superior cultivars in the presence of these interactions. However, the emphasis here, in using this conceptual framework of plant breeders is to estimate the yield variation that can be explained by factors associated with the technological origin of the cultivars. Thus, unlike the conventional approach used by biologists, we specify the three components in terms of a number of relevant variables.

The environmental, technological and interaction variables that can be used in specifying the model are described below.

Environmental variables, $E_{\underline{jt}}$'s: The E_j's are location-specific variables such as latitude, altitude, rainfall, fertilizer application, or a code representing the agro-climatic classification.

Technological variables, $T_{\underline{i}}$'s: The T_i's are cultivar specific, time invariant variables. For example, the developmental origin of a cultivar (i.e. the country or research programs that developed the cultivar), the environmental origin of a cultivar (i.e. the environment where it was selected)[3], the type of cultivar (that is whether it is a locally developed cultivar with or without CIMMYT materials, CIMMYT cross or local reselection of a CIMMYT cultivar).

Interaction variables, $G_{\underline{ijt}}$'s: The G_{ijt}'s, like Y_{ijt}'s are the interaction variables created by multiplying an environmental variable with a technology variable.

To achieve the objectives of this chapter, various specifications of a linear model of equation 1 are used. The specifications refer to the partitioning of locations and cultivars into groups. For example, the locations can be assigned to megaenvironments as described in Chapter 4 and the cultivars can be grouped by their developmental origin. The specific way in which the locations and cultivars are

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[3] The origin of a cultivar can be assessed in two ways. First, in terms of the research program that developed (crossed and selected) it and second, in terms of the environment in which it was selected. To differentiate these two concepts of origin we use the word developmental origin (referring to the country or research organization) and environmental origin (referring to the environmental adaptation).

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partitioned depends on the objective to be achieved. In general, the model can be stated as follows:

$$Y_{ijt} = a + \sum_{h=1}^{H} b_h E_{jth} + \sum_{f=1}^{F} b_f D_{fE} + \sum_{k=1}^{K} c_k T_{ik} + \sum_{g=1}^{G} D_{gT} + \sum_{p=1}^{P} d_p G_{ijtp} + e_{ijt} \quad (5.2)$$

where,

a	is the constant
E_{jh}	is the vector of environmental variables (viz. latitude, altitude). $h = 1,..,H$
b_h	are the coefficients of the h'th, location-specific environmental variables
D_{fE}	is a vector of dummy variables equal to one if the j'th location belongs to the agro-climatic group f (for example agro-climatic group based on megaenvironment classification or Papadakis classification system), zero otherwise.
b_f	are the intercept terms of the f'th agro-climatic classification group.
T_{ik}	is the vector of technological variables (viz. vintage). $k = 1,...,K$
c_k	are the coefficients of the k'th technological variable.
D_{gT}	is a vector of dummy variables equal to one if the i'th cultivar belongs to the technological group g (for example, technology group based on developmental origin or environmental origin), zero otherwise.
c_g	are the intercept terms of the g'th technological group.
G_{ijtp}	is the vector of interaction variables. $p = 1,...,P$
d_p	are the coefficients of the p'th interaction variable.

For each specification, the D_{fE} and D_{gT} will differ and so will the G_{ijt} variables, depending on how the locations and cultivars are aggregated. For example, the locations could be grouped by the megaenvironments and the cultivars could be aggregated by their environmental origin as done in Section 5.5. The G_{ijt} variables in this specification will estimate the yields of cultivars from different environmental origin in a given megaenvironment. Another way of specifying the model, as done in Section 5.6 is to classify the locations in a given country by megaenvironment and cultivars by the type of technology spillins embodied (i.e. whether the cultivar is a locally bred cultivar, locally selected or directly introduced from CIMMYT or other countries). In this specification the G_{ijt} variables will estimate the yields of locally bred and imported technologies in a given country.

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Table 5.1 Megaenvironments Described by the CIMMYT Wheat Program

ME	Lat	Moisture Regime[a]	Temperature Regime	Sown[b]	Major Breeding Objectives[c]
1	<40	Low rainfall + irrigation	Temperate	A	Resistance to lodging, SR and LR
2	<40	High rainfall	Temperate	A	As ME1 + resistance to YR, <u>Septoria</u> spp., <u>Fusarium</u> spp. and sprouting
3	<40	High rainfall	Temperate	A	As ME2 + acid soil tolerance
4A	<40	Low rainfall winter dominant	Temperate	A	Resistance to drought, <u>Septoria</u> spp. and YR
4B	<40	Low rainfall summer dominant	Temperate	A	Resistance to drought, <u>Septoria</u> spp., <u>Fusarium</u> spp., LR and SR
4C	<40	Mostly residual moisture	Temperate to hot	A	Resistance to drought
5A	<40	High rainfall	Hot[d]	A	Resistance to heat, <u>Helminthosparium</u> spp., <u>Fusarium</u> spp., and sprouting
5B	<40	Residual moisture	Hot[d]	A	Resistance to heat and SR
6A	<40	High rainfall/ part irrigated	Moderate cold	A	Resistance to cold, YR, <u>Fusarium</u> spp. and sprouting
6B	<40	Low rainfall	Moderate cold	A	Resistance to cold, drought, YR and bunt
6C	<40	High rainfall/ part irrigated	Severe cold	A	Resistance to cold, YR and LR
6D	<40	Low rainfall	Severe cold	A	Resistance to cold, drought, YR and bunt
7	>40	Low rainfall summer dominant	Temperate	S	Resistance to YR, LR, <u>Fusarium</u> spp., <u>Helminthosporium</u> spp. and sprouting

Source: DeLacy et al. (1993)

[a] Rainfall refers to just before and during the crop cycle. High = > 500mm, low = < 500mm.

[b] A = Autumn; S = Spring.

[c] Factors additional to yield and industrial quality. SR = stem rust, LR = leaf rust, YR = yellow (stripe) rust.

[d] Mean temperature of coolest month >18°c.

5.3. <u>Data Description</u>

As discussed earlier, CIMMYT's annual series of International Spring Wheat Yield Nursery (ISWYN) trial data are used to estimate the model parameters[4]. The analysis of this chapter will use the last eight years of published yield trial data (ISWYN 16-18, 20-24),

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[4] The data is published by CIMMYT as an annual series since 1964. For the present analysis however, the data were directly obtained from CIMMYT on computer diskettes.

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corresponding to years 1979-80 to 1981-82 and 1983-84 to 1987-88[5]. The data set includes more than 24,000 yield observations, of which about 23,000 were used in the analysis. All the observations pertaining to triticale and durum wheats were excluded from the analysis. Also, local checks (385 cases) were excluded because many were either not reported by the cooperators, not identifiable, or were included as one of the entries[6]. The number of entries over the period of eight years totaled 364, consisting of 209 unique wheat cultivars. The number of different locations in 81 countries totaled 195.

The ISWYN data collected by CIMMYT is uneven in quality and coverage. Data on latitude, longitude, altitude, name of the cultivars tested and probably yields are reliable and provided by all the locations. Also, most locations provide information on type of fertilizer applied, but many do not report the quantities applied. Irrigation and rainfall information collected was not only inconsistent but also unreliable for many of the reporting locations. These variables were therefore not included in the analysis. However, the environmental classification for each location used in this study and discussed below, is a good proxy of these variables.

Each location in the data set was given a CIMMYT megaenvironment code discussed in Chapter 4[7]. These are described in Table 5.1.

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[5] The data for ISWYN 19 (1982-83) were incomplete and were therefore not included in our analysis.

[6] Since local checks are likely to be the best cultivars grown by the farmers in a given location, their exclusion from the analysis may bias the results downward. However, local checks are not synonymous with locally developed varieties. In fact, about 70 percent of the local checks that were reported and identified were CIMMYT bred cultivars released by the national programs. Thus, exclusion of local checks from the analysis will reduce, if any, the yield advantages of CIMMYT technology more than that of technology developed by national programs.

[7] As discussed in chapter 3, a plant environment is not only complex but also dynamic. The dynamic nature of a plant environment implies that no location will have the same circumstances every year. In classifying the locations by a single megaenvironment we assume that the year to year variation in the circumstances of a given location are not large enough to warrant a classification of environment based on each year. Perhaps, this assumption may not hold true in a farmers field. But given that the locations are experimental sites in which the environment is partly controlled, this assumption may not be too

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Previous studies on the assessment of international research spillovers, including Englander (1981a and 1991) have used Papadakis climatic classification to characterize a location. As discussed in Chapter 4, the CIMMYT megaenvironment classification system is used in this study instead of Papadakis classification, because the latter is too general and inadequate for a specific commodity like wheat. Also, unlike the megaenvironment classification, the Papadakis classification is not based explicitly on the moisture and temperature regimes of the winter/spring season which are so important in determining the performance of wheat crop. However, the megaenvironment classification system is not free from limitations either. First, the classification system lacks objectivity as they are based on the subjective estimates of CIMMYT and national program scientists. Second, although they often account for important factors that affect the growth and performance of wheat crop, they omit some critical factors such as the cropping system and some significant secondary stresses which are important in defining environments. Thus, one has to be very cautious in interpreting and generalizing the results of this analysis[8]. CIMMYT is in the process of further subdividing the megaenvironment groups by including some of these critical factors. However, until a more refined and comprehensive classification system is developed, CIMMYT's megaenvironment classification offers the best alternative for grouping locations. The locations included in the analysis and the information on the corresponding environmental variables are given in Appendix B. Figure 5.1 depicts these locations on the world map by megaenvironments.

In the published ISWYN reports, the countries contributing a cultivar in the trials are identified as the country of origin

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restrictive.

[8] Many G x E studies use cluster analysis to classify the trial sites into different environmental groups (see for example Delacy et al. 1993). Cluster analysis provides an objective method of classifying the sites based on the relative phenotypic performance (usually measured in terms of yield). However, classification of trial sites based on the performance of plants, i.e. yields, rather than the environmental factors that affect performance, also fails to capture the whole complexity of a plant environment. It does not provide the information on what are the distinctive characteristics of the different locations that are clustered together.

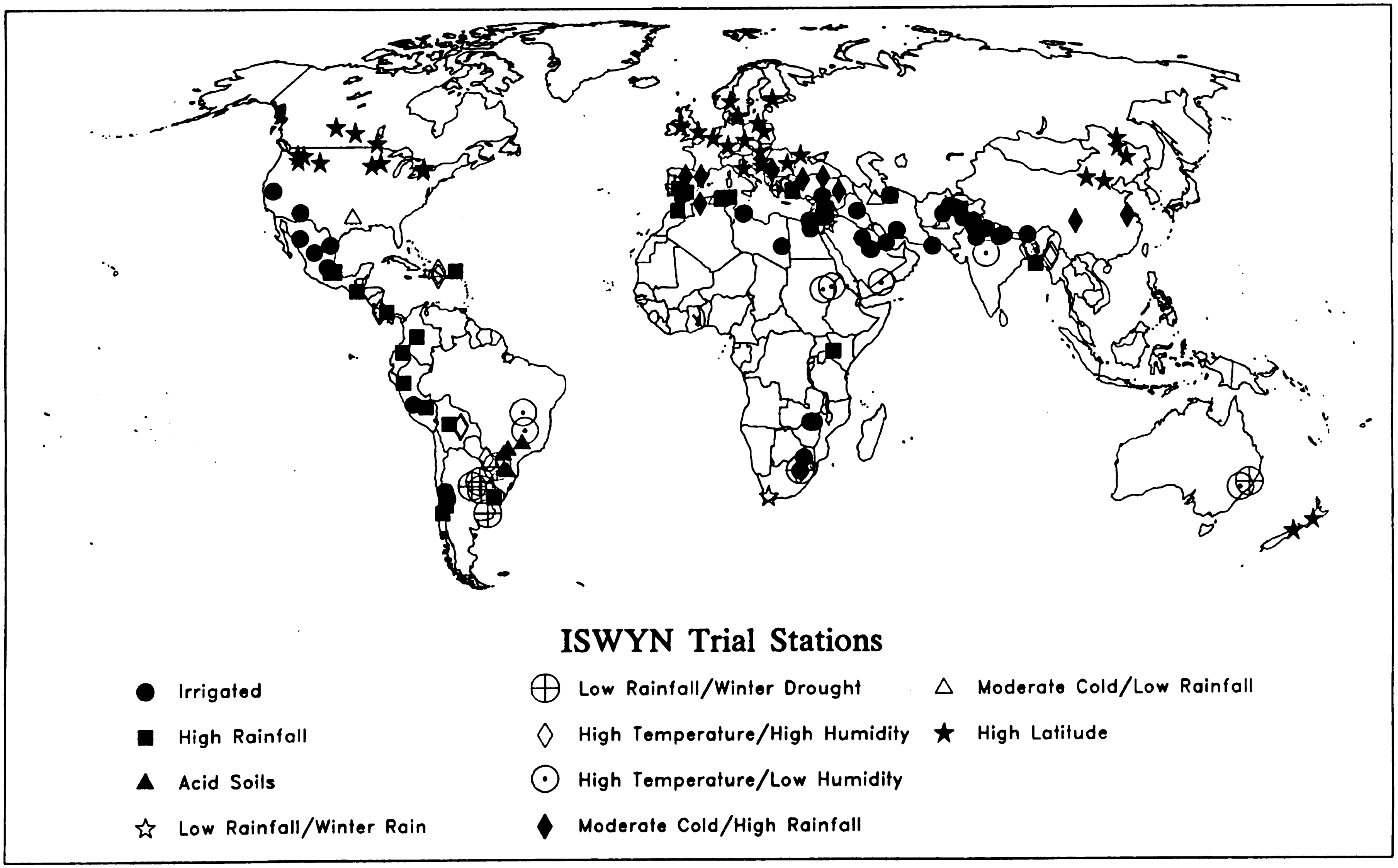

Figure 5.1: The megaenvironmental classification of ISWYN trial stations.

regardless of where the cultivar was developed. For this study, information on origin variables were obtained from the pedigree and selection history of the cultivar. The CIMMYT impact study data discussed in chapter 4 were used to classify the cultivars by developmental origin and the type of technology transfer embodied. Thus, all the cultivars were classified as either CIMMYT cultivars (crossed and selected by CIMMYT) or non-CIMMYT cultivars (crossed and/or selected by national programs). The broad CIMMYT and non-CIMMYT cultivar groups were further sub-divided into the following 6 development origin groups:

Non-CIMMYT:

1. Cultivars developed by national programs using no immediate CIMMYT germplasm as parents[9].
2. Cultivars developed by national programs using CIMMYT germplasm as at least one parent.
3. Cultivars fundamentally developed by CIMMYT (i.e. a CIMMYT cross) but released by national programs after reselection.

CIMMYT:

4. Cultivars developed by CIMMYT and released by national programs of countries other than Mexico (without further selection by the releasing country).
5. Cultivars developed by CIMMYT but not released in any country.
6. Cultivars developed by CIMMYT and released by the Mexican national program in Mexico (and often sometimes by other national programs).[10]

Except group 1 (which may or may not include materials from other countries), all the other groups represent a different degree and type of technology spillin. For example, following the definition of direct and indirect transfer, origin groups 2 and 3 represent different degrees

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[9] However, materials developed by other countries' national programs could be used as immediate parents.

[10] Often the cultivars released in Mexico are also released in other countries by national programs under local names. If these cultivars appeared with the local names they were classified under group 4.

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of indirect technology spillins, and group 4 represents the case of direct technology spillins from CIMMYT. Origin group 6 also represents the case of direct transfer (from CIMMYT to Mexico)[11]. However, because of CIMMYT's location, the Mexican national program has an advantage over other countries in terms of adaptability of CIMMYT cultivars, and hence it was necessary to differentiate these cultivars from origin group 4.

The cultivars were also classified by their environmental origin. This is a subjective classification made in consultation with CIMMYT staff well acquainted with the ISWYN data. It was based on the following information: (1) the dominant megaenvironment in the country or region within a country of developmental origin, and (2) the information on the environmental niche (rainfed, irrigated, or both) in which the cultivar was released (obtained from the CIMMYT impact study data).

The environmental origin of CIMMYT cultivars was difficult to assess because, they are not bred for any particular megaenvironment in Mexico.[12] These cultivars are the source of international technology spillins. The CIMMYT cultivars released in other countries (group 4) were assigned the dominant megaenvironment code of the releasing country or region in a country in which it was released. The other two groups (CIMMYT cultivars released in Mexico - group 6, and not released by any national program - group 5) were not assigned any megaenvironment code. These were considered as separate groups to differentiate the cultivars bred and/or released by national programs from those developed by

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[11] Note that although CIMMYT is located in Mexico, it is not synonymous with the Mexican national wheat research program. Mexico has its own national wheat research program and the cultivars developed by CIMMYT have to undergo the same procedure for release in Mexico as they would in any other country.

[12] CIMMYT uses what is popularly known as the 'shuttle' breeding system. Under this system, the crosses and selections in the winter cycle are made in Obregon and in the summer cycle they are made in El Batan and Toluca. Obregon, which is located in northwest Mexico can be characterized as ME1 (low rainfall, irrigated, temperate) whereas the summer cycle planted in El Batan and Toluca (located in central Mexico near the CIMMYT headquarters) can be characterized as ME2 (high rainfall). Thus, it is difficult to assign a particular ME code to CIMMYT cultivars, although much of the selection is done in ME1 or ME2.

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CIMMYT. The list of cultivars used in the analysis along with the corresponding information on the technological variables are given in Appendix B.

Table 5.2 lists the variables used in the regression equations that follow. The variables listed are either self-explanatory or are described above. Therefore, only a few remarks about these variables are made here.

The variable YIELD is the dependent variable measuring the yield in kg/ha of each variety at each location in a given year. DSITE is a set of dummy variables indicating the location of the ISWYN trials. There are 195 such dummy variables. Similarly, DYEAR is a set of dummy variables representing each ISWYN data set. These variables are distinct from the FISWYN variable which indicates the first ISWYN year in which the cultivar was introduced. FISWYN is the vintage variable that provides an estimate of average long-term yield increase due to new cultivar development. It measures annual absolute yield gains (in kg/ha/yr).

Each of the megaenvironment is assigned a dummy variable (DME) which has a value 1 if the yield observation corresponds to the location classified in that megaenvironment and 0 otherwise. The variable DVME, on the other hand is a set of dummy variables indicating the environmental origin (i.e the megaenvironment for which the cultivar was developed) of the cultivar. It is comprised of two sets of dummy variables. The first group abbreviated by DLVME# represents the environmental origins of cultivars developed by national programs, and the second group (DCIM1 and DCIM2) represents the CIMMYT cultivars. The dummy variables representing DLVME# megaenvironment origin are for the non-CIMMYT cultivars of origin 1 (national program cross with no immediate CIMMYT parents), 2 (national program cross with CIMMYT parents) or 3 (reselection of CIMMYT cultivars by national programs) developed by national programs for the respective megaenvironment, and the two CIMMYT dummy variables (CIM1 and CIM2) represent origin group 4 + 5 and origin group 6 respectively. In other words, CIM1 has a value of 1 if the cultivar was a CIMMYT cultivar either released in another country (except Mexico) or not released any where. CIM2 has a value of

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Table 5.2.: List of Variables Appearing in Different Model Equations and their Definitions

Variables	Abbrev. in regression	Definition	Equation
Yield (Y)	Yield	Yield in kilograms per hectare of each variety entered in the trials (Dependent variable in all models)	All
Year ($DYEAR_t$)	DIS#	A set of dummy variables indicating the ISWYN year of the data point. The ISWYN years analyzed are 16,17,18,20,21,22,23 and 24.	5.7, 5.8, 5.9
Latitude (LAT)	LAT	Latitude in degrees	5.7
Elevation(ELEV)	ELEV	Elevation in meters above sea level	5.7
Trial stations ($DSITE_j$)	DST#	A set of dummy variables indicating the location of ISWYN trials. The station # (ST#) are given in Appendix 5.1	5.8, 5.9
Megaenvironment (DME)	DME#	A set of dummy variables indicating the megaenvironment of the location. The ME# and their definitions are given in Table 5.1	5.7
Vintage (FISWYN)	FIRSTISW	The first ISWYN year in which the cultivar was introduced	5.7, 5.8, 5.9
Megaenvironment Origin (DVME)	DLVME# DCIM1 DCIM2	A set of dummy variables indicating the megaenvironment origin of non-CIMMYT cultivars (i.e. cultivars developed by NARS) A dummy variable indicating that the cultivar was developed by CIMMYT and was either released directly in other countries or not released anywhere A dummy variable indicating that the cultivar was developed by CIMMYT and released in Mexico	5.7, 5.8, 5.9
Technological origin (DT_g)	XXXDME# XXXSME# XXXIME# ME# CIMIME# CIM OTHERME	A dummy variable indicating that the cultivar was domestically bred in country XXX for ME# A dummy variable indicating that the CIMMYT cultivar was locally selected in country XXX for ME# A dummy variable indicating that the cultivar was imported (directly introduced) from country XXX in ME# A dummy variable indicating all the non-CIMMYT cultivars developed for ME# (other than XXXDME#, XXXSME#, XXXIME#) A dummy variable indicating that the cultivar was imported (directly introduced) from CIMMYT in ME#. A dummy variable indicating a CIMMYT cultivar other than the CIMIME#. A dummy variable indicating all the non-CIMMYT cultivars developed for ME other than the domestic ME#.	5.9
Mills ratio (R)	R	Inverse Mill's ratio (defined in Section 5.4)	5.7, 5.8, 5.9

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1 if the cultivar was a CIMMYT cultivar released in Mexico and a value of 0 otherwise. Thus, the DVME variables are a reclassification of origin groups to incorporate the environmental origin.

The variable (DT_g) is a set of dummy variables indicating the technological origin of cultivars. Like the DVME variable, this variable is also a reclassification of the origin groups, but from a country's perspective. Thus, it classifies the cultivars as domestically bred, selected, imported from CIMMYT, imported from another country, or foreign cultivars developed by other countries in the same megaenvironment, in other megaenvironments or by CIMMYT. Because there is a high linear dependency between the variables DVME and DT_g, they are never used together in any regression equation.

Finally, the variable R is a continuous variable denoting the inverse Mill's Ratio for each of the cultivar planted. The rationale for including this variable and the procedure used to calculate it are described in the following section.

5.4 The Econometric Estimation Procedure

For econometric purposes, the data can be characterized as incomplete panel data. This is because of the following two reasons:

1. The locations used as trial sites change every year.[13] The number of locations in each trial, varies from 55 to 72. Thus, some locations may appear in all the eight ISWYN sets analyzed, some in only one set, and some in more than one set. The incomplete location data can be, however, be characterized as randomly missing because there is no clear pattern in the selection procedure of a location in a given year.
2. The set of cultivars also varies from year to year. Each ISWYN data set was comprised of fifty cultivars (except one which comprised only forty). Thus, a given cultivar may appear in only one data set, more than one data set, or in all the eight sets that were analyzed.

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[13] 'Year' as used here denotes an ISWYN data set number. Given that ISWYN is an international nursery, the data collected from different locations may not correspond to the same calendar year due to differences in the seasons and quarantine rules. 'Year' is used interchangeably with 'data set number' to give a time dimension to the analysis.

Cultivar attrition can be attributed to the fact that old cultivars are replaced by better yielding cultivars developed by CIMMYT or national research programs. Thus, cultivars are missing in a given year for reasons of self-selection. The incomplete cultivar data can, therefore, be characterized as non-randomly missing data.

Since the probability of cultivar attrition is correlated with experimental response, the traditional statistical techniques for panel data will provide biased and inconsistent estimators (Hsiao 1986). To correct for the selection bias, Hsiao (1986) suggests that the structural model of equation 5.2 should be estimated by adding a new variable known as the inverse Mill's ratio (r).

The inverse Mill's ratio for all the cultivars in a given year was estimated using the Heckman's two-stage method (1979). Heckman's two-stage method is as follows. For a given year, t, an indicator variable d_{it} is defined for all cultivars observed in period t and t-1 as: $d_{it} = 1$ if cultivar i is observed in that period and $d_{it} = 0$ if it is not observed; in other words if attrition occurs. We assume that whether the cultivar i is observed or not in time period t, is a function of its previous year's performance relative to other cultivars and its past history. Specifically, $d_{it} = 1$ if the latent variable

$$d^{*}_{it} = b_0 + b_1\, y_{it-1} + b_2\, x_{it} + e_{it} \;\geq 0 \qquad (5.3)$$

where, b_0 is the constant term and b_1 and b_2 are the coefficients of variables that affect the probability of observing cultivar i in period t. Variable y_{it-1} measures the relative yield of cultivar i in period t-1, and variable x_{it} measures the number of years a cultivar has been planted in the past trials. The e_{it} are normally distributed error terms.

The probabilities of retention and attrition of cultivar i in period t are therefore the probit functions given, respectively, by

$$\begin{aligned} Prob(d_i = 1) &= \Phi\,(b_0 + b_1\, y_{it-1} + b_2\, x_{it}) \\ Prob(d_i = 0) &= 1 - \Phi\,(b_0 + b_1\, y_{it-1}\, b_2\, x_{it}) \end{aligned} \qquad (5.4)$$

where Φ (.) is the standard normal distribution function.

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Following Heckman's (1979) two stage procedure, the b coefficients were estimated from a probit analysis of the qualitative variable d_i as a function of the observed y_i and x_i. The Newton-Raphson's numerical iteration method of scoring was used to calculate the b coefficients. The estimated coefficients were then used to evaluate the probability density function ϕ (.) and distribution function Φ (.) to calculate the inverse Mill's ratio, r

$$r_{it} = \frac{\phi\,(b_0 + b_1\, y_{it-1} + b_2\, x_{it})}{\Phi\,(b_0 + b_1\, y_{it-1} + b_2\, x_{it})} \tag{5.5}$$

These steps were repeated for each time period. The Mill's ratios, r_{it}, were combined across all years (except ISWYN 16)[14] in which they were planted to form the vector R. This vector consisted of 317 observations, each corresponding to an entry in a given ISWYN. Thus, r_{it} are entry specific values for each ISWYN.

The variable r_{it} is then used in the original structural equation 5.2 resulting in the following model.

$$\begin{aligned} Y_{ijt} = a &+ \sum_{h=1}^{H} b_h\, E_{jth} + \sum_{f=1}^{F} b_f\, D_{fE} + \sum_{k=1}^{K} c_k\, T_{ik} + \sum_{g=1}^{G} D_{gT} \\ &+ \sum_{p=1}^{P} d_p\, G_{ijtp} + v\, r_{it} + e_{ijt} \end{aligned} \tag{5.6}$$

The Y_{ijt} are regressed on the environmental, technological, interaction and inverse Mill's ratio term (R) using the ordinary least squares (OLS) method. Heckman (1979) showed that this method yields consistent estimators of the parameters of Equation 5.6. Thus, in Sections 5.5 and 5.6 different specifications of the model given in Equation 5.6 are estimated using the OLS.

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[14] Since the Mill's ratio as defined in Equation 5.5 depends on the relative yields observed in the previous period, the variable R is calculated for T-1 period, i.e. for ISWYN 17-18, 20-24. Therefore, in all the regression models that follow, ISWYN 16 is not included in the analysis.

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5.5 Measuring the Transferability of Wheat Technologies Across Different Megaenvironments

Because of G x E interactions locally developed technology may perform better than technologies developed in other environments. However, to economically justify a local research program one has to quantify the difference between the performance of different technological alternatives. Therefore, one of the questions that we are interested in examining is 'how much' better the performance of locally developed technology is compared with imported technology. To examine this the model given in equation 5.6 can be specified as follows.

$$\begin{aligned} Y_{ijt} = {} & a + b_1\, LAT + b_2\, ELEV + b_3\, LAT{*}LAT + b_4\, ELEV{*}ELEV \\ & + b_5\, LAT{*}ELEV + \sum_{f=1}^{F} b_f\, DME_f + c_1{*}\, FISWYN + \sum_{g=1}^{G} c_g\, DVME_g \\ & + \sum_{f=1}^{F} \sum_{g=1}^{G} DME_f{*}DVME_g + \sum_{t=1}^{T} u_t\, DYEAR_t + v\, R + e_{ijt} \end{aligned} \tag{5.7}$$

The definitions of all the variables in this equation are given in Table 5.2.

In this specification, the cultivars are partitioned according to their environmental origin group (DVME) and the locations are partitioned according to their megaenvironment classification (DME). As before, the b coefficients represent the change in the yield due to change in an environmental variable and the c coefficients denote the change in yields due to change in a technology variable. The continuous environmental variables (i.e. latitude and elevation of the experimental locations) are entered with both quadratic and interaction terms to permit nonlinear responses to variations in these dimensions. The megaenvironment classification dummies (DME) are included as proxies for omitted environmental factors (viz. soil type, climatic and edaphic factors).

The variables FISWYN and DVME represent characteristics of a varietal technology, indicating the cultivar vintage and the environment for which the cultivar was developed. Since we are using panel data, the year dummies are included to factor out the time effect on the observed yields and as explained in previous section, the variable R (inverse Mill's ratio) is included in the equation to correct for the se

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selection bias of non-randomly missing cultivars. The coefficients d_{fg} are the coefficients of the interaction variables. They estimate the performance of different varietal technology (as differentiated by their origin) in different megaenvironments. These are the coefficients that we are most interested.

The specification given in equation 5.7 is most appropriate to measure the transferability of wheat technology across different environments. However, the number of coefficients to be estimated in equation 5.7 exceeded the capacity of the statistical package being used (because of the large number of dummy variables and interaction terms). It was therefore deemed necessary to respecify the model such that it was compatible with the software package (SPSS/PS+ Version 4.0.1, REGRESSION procedure). As an alternative, therefore, the model given in equation 5.7 was estimated for each megaenvironment. The resulting equations are:

$$\begin{aligned} Y^{f}_{ijt} = a &+ \sum_{j=1}^{M} b_j \, DLocation_j + c_1 * FISWYN + \sum_{g=1}^{G} c_g \, DVME_g \\ &+ \sum_{t=1}^{T} u_t \, DYEAR_t + v\,R + e_{ijt} \end{aligned} \qquad (5.8)$$

for, f = 1,2,...,8[15].

It is evident that this model is substantially simplified as it does not require the large number of megaenvironment dummies and the interaction terms. In this specification the coefficients c_g now measure the performance of a technology in a given megaenvironment f. Another change to be noted in this equation is the inclusion of location dummies. In equation 5.7, the location- specific environmental variables were represented by the latitude and elevation of the experiment station. These are replaced in equation 5.8 by the location

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[15] The equations were estimated for the following eight megaenvironments - ME1, ME2, ME3, ME4A, ME4B, ME5A, ME6A and ME7. Because of zero observations (in case of ME4C, ME6C and ME6D) and insufficient number of observations (for ME5B and ME6B), the equations were not estimated for these megaenvironments.

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dummies[16]. The reason for doing this is two-fold. First, location dummies provide more information than the environmental variables, and second, the reduced number of variables made it possible to include location-specific dummy variables without exceeding the capacity of the software. However, the disadvantage of this specification is that we cannot compare the coefficients c_g across megaenvironments.

The estimated coefficients of equation 5.8 are reported in Appendix C for all the eight megaenvironments. The results of the regression analysis are discussed below first in terms of their statistical significance and interpretation of some of the coefficients and second in terms of addressing the issue of transferability of CIMMYT and non-CIMMYT technology across different megaenvironments.

5.5.1 Statistical Significance and Interpretation

Table 5.3 summarizes estimated regression coefficients of continuous variables and the R^2 and the F-ratio to enter various sets of dummy variables in the equation. Appendix C (Table C.1) reports the estimated regression coefficients of all the variables for all the megaenvironments. However, in order to compare the present model that includes the attrition variable (Mill's ratio) with the simple OLS model without the attrition correction (equation 5.2), we report the results of both these models for megaenvironment 1 (low rainfall, irrigated, temperate) which are discussed later.

The coefficients of DYEAR variable estimates the average yields per hectare in a given year relative to the base year ISWYN 17 (1980-81) or ISWYN 18 (1981-82) whichever appeared first in a given megaenvironment. Average Yields over time relative to ISWYN 17 or 18 do not follow the same pattern in all the megaenvironments. The average yields of a given ISWYN data set will depend on the productivity of locations and cultivars entered in the yield trials. The observed yield fluctuations over time as revealed by the negative and positive signs of the DIS# dummy variables in most of the megaenvironments, is because of these differences in the composition of locations and cultivars in each

[16] It should be noted that one cannot include both the location dummies and location specific variables like latitude and elevation in the same equation. Doing so will make the system overidentified.

...Regression P... ...-2) for all the Megaenvironments

Table 5.3: Regression Results of the Transferability Model (Equation 5.8) for all the Megaenvironments

Independent Variables	ME1	ME2	ME3	ME4A	ME4B	ME5A	ME6A	ME7
1. Dummy Variables for Year, DIS#								
- R^2 change[a]	0.02	0.02	0.23	0.17	0.17	0.05	0.30	0.08
- F change[b]	35***	32***	184***	144***	46***	15***	167***	124***
2. Dummy Variables for Location, DST#								
- R^2 change[a]	0.56	0.44	0.27	0.40	0.21	0.29	0.48	0.52
- F change[b]	166***	131***	287***	159***	59***	113***	225***	154***
3. Dummy Variables for Technology Origin DLVME# and CIM#								
- R^2 change[a]	0.03	0.03	0.02	0.01	0.03	0.02	0.01	0.003
- F change[b]	45***	25***	6.6***	7.4***	5.3***	5.1***	1.7*	3.1***
4. FIRSTISW[c]	4.27	31.2	10.9*	2.5	28.1***	-2.2	-3.1	4.7
5. Mill's Ratio MR[c]	155***	135***	111**	93	141**	97**	99	87.7**
6. Constant[c]	4880***	3390***	336**	2041***	1942***	2221***	1487***	3394***
n	4641	4248	719	1824	850	935	513	2913
R^2	0.61	0.53	0.78	0.65	0.40	0.53	0.82	0.68

Note: *, **, *** denote significance at 10, 5 and 1% level, respectively.
[a] Number given is the change in the R^2 when a given set of dummy variables is entered in the equation that includes all the other variables.
[b] Number given is the change in the F-ratio when a given set of dummy variables is entered in the equation that includes all the other variables.
[c] Number given is the estimated coefficient.

ISWYN data set.

The coefficient of FIRSTISW estimates the vintage effect of the new cultivars developed over time. It measures the average yields/ha/year gains of new cultivars in a given megaenvironment. Note that the coefficient is an average over all the cultivars, that is it is not technology specific, and therefore may not be easy to interpret for each megaenvironment. Except in ME2 (high rainfall, temperate), ME3 (high rainfall, acid soils), and ME4B (Low rainfall, winter drought) the improvements are not significantly different from zero. The non-significant coefficients of FIRSTISW in many environments including ME1 (irrigated, temperate) indicates the difficulty that researchers are facing in maintaining high yield growth rates in the post Green-Revolution era, especially since the release of Veery's in early 1980s. The Veery lines are a product of CIMMYT's spring x winter wheat crosses, whose yield potential exceeds that of the previous generation of improved varieties by about 10%. No new varieties have been developed in the last decade either by CIMMYT or NARS that exceed this high yield potential of Veery lines.

The coefficients of the origin variables estimate the yield advantages of cultivars originating in different environments relative to the domestic environment technology. Interestingly, all the coefficients of non-CIMMYT technologies have negative signs, and are significantly different from the domestic cultivars in most megaenvironments. As against this, the coefficients of the CIMMYT cultivars (DCIM1 and DCIM2) are either positive or not significantly different from the yields of domestic technology. These results have important implications on the issue of technology transfer and are discussed in more detail in the following section.

The coefficients of the trial locations can be interpreted as the average yields at a given planting location relative to the benchmark location reported with a zero coefficient (which are CIANO in Sonora, Mexico, for ME1; Toluca, Mexico, for ME2; Cruz Alta, Brazil, for ME3; Tygerhoek in Cape Province, South Africa, for ME4A; Bethlehem, South Africa, for ME4B; Joydebpur, Bangladesh, for ME5A; Diyarbakir, Turkey, for ME6A; and, Volle Bekk, Norway, for ME7). The locations are represented by their code numbers as defined in Appendix B (Table B.1). Within a megaenvironment the coefficients of this variable provide a comparative measure of productivity of locations in different countries or regions of the world. There is a high and significant differences in the yields among different locations of the same megaenvironment. This could be due to differences in factors related to the management of experiments among different locations or it could be because of some inherent environmental differences that are not captured by the megaenvironment classification of CIMMYT. However, as long as the ranking of the genotypes do not change, the within megaenvironment variations are not critical to our results.

Lastly, the coefficients of the MR variable (inverse Mill's ratio) indicates a positive and highly significant (in most of the megaenvironments) relationship between observed yields and the probability of retention (Table 5.3). As indicated by the results of the ME1 regression results, the estimates of the location dummies were very close with or without correction for attrition (this was as expected, since the MR variable is entry specific and does not vary across locations in a given year) (Appendix C, Table C.1). However, the estimates of other parameters, particularly those of origin that we are most interested in, did change depending on the extent of cultivar attrition experienced in a technology group. For instance, the coefficient of DCIM2 which is a relatively more stable group of cultivars (i.e. less attrition) decreased from 567 to 528 with the attrition correction (almost 7% decrease) and the coefficient of DCIM1 which is a more volatile group in its cultivar composition, increased from 209 to 227 (about 8% increase).

The comparison of the two alternative models shows that the attrition bias could be a potentially important problem in estimating the parameters. It may over- or under-estimate the yields of cultivars depending on the rate of attrition and the time of occurrence of attrition in a given group. However, past studies, including Englander (1981), that have used crop yield trial data, acknowledge the problem of cultivar attrition, but have made no attempt to statistically correct for it.

5.5.2 Relative Yields of Local and Imported Wheat Varietal Technology in Different Megaenvironments

Since technology transfer is constrained by differences among environments, the objective of the model specification (equation 5.8) was to analyze technology transfer across megaenvironments and not across political boundaries (i.e. countries)[17]. Relating technology transferability to environmental zones is important because it allows us to determine the yield change as a function of variables which are based on G x E knowledge, rather than politically based categorizations. Moreover, estimates of technological transferability based on political boundaries are often difficult to interpret (since it is very unlikely that a country or politically defined region will have a homogenous crop growing environment). The important question is how the cultivars developed in a given environment perform relative to cultivars developed in other megaenvironment (irrespective of their developmental origin). Also, we are interested in the issue of transferability among megaenvironments of wheat cultivars developed by CIMMYT. Estimations of the transferability of cultivars developed in one megaenvironment to different megaenvironments will provide a basis for predicting the success of cultivars in locations which are not part of our current sample. It will also shed some light on the question of how well CIMMYT has succeeded in creating technology for different megaenvironments.

Table 5.4 gives the number of entries and unique cultivars used in the regression analysis corresponding to each megaenvironment. It gives an idea on the representation of a given technology group. There is a wide variation in the number of entries and unique cultivars representing different technologies[18]. Cultivars developed by CIMMYT (CIM1 and CIM2) represent almost 50% of the entries in each

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[17] The need to separate assessments of the impact of technologies from arbitrary geographical/political boundaries to environmental boundaries is also recognized in the literature on research spillovers (see for example Davis 1991 for the arguments and illustrations of this usage). Since decisions are based on political boundaries, these estimates can then be aggregated to geographical political regions.

[18] The number of cultivars developed for megaenvironment 4C and 5B was respectively 1 and 2 - too low to make any precise statement about the whole group. These were therefore not included in the regression analysis.

megaenvironment. Compared to non-CIMMYT cultivar groups, this is higher; but it is not unexpected, since the trials are conducted by CIMMYT with an objective of dissemination of its germplasm. Among the non-CIMMYT technological origin groups ME1, ME2 and ME7 contributed a higher number of entries and unique cultivars than the other non-CIMMYT group. These megaenvironments are dominated by countries with strong wheat research programs such as India and Pakistan in ME1, Spain, Chile, and Turkey in ME2, and the developed countries of temperate zones (in ME7). The large numbers of entries and cultivars from these megaenvironments thus, reflect the better research capability in these megaenvironments.

The coefficients of the origin variables from all the regressions reported in Appendix Table C.1 are summarized in Table 5.5. This gives a better perspective on comparing the transferability of a technology in and across different megaenvironments. Table 5.5 is a spillover matrix estimating the relative yield advantage across environments of technologies originating in different megaenvironments. For example, the second number in the first column shows that non-CIMMYT cultivars of ME2 origin yield 232 kg/ha less (significant at 1% level) in ME1 than the non-CIMMYT cultivars developed for ME1. Similarly, the last row of column 1 shows that CIMMYT cultivars released in Mexico enjoy a yield advantage of 527 kg/ha (significant at the 1% level) in ME1 compared to non-CIMMYT cultivars of ME1 origin. Thus, the positive yield advantage indicate the potential of CIMMYT technology to spillover in ME1.

Unlike other attempts to measure the spillover effects (Davis et al. (1987), for example) the spillovers are measured here in terms of absolute yield differences (kg/ha) and not in terms of percentage coefficients. But relative yields of different technology can be judged from the average yields of the benchmark variable (reported in Appendix C, Table C.2). A note of caution is needed on the comparability of the coefficients across columns. The values of the coefficients reported in Table 5.5 are relative to the benchmark technology group (represented by zeros), and are therefore comparable across rows (technologies) but not across columns (environments). Thus, we can say that in ME2, ME1 technology yields 189 kg/ha less than ME2 technology, but it is

Table 5.4: Number of Entries and Unique Cultivars Used in the Regression Analysis: Grouped by their Environmental Origin

	LOCATION ENVIRONMENT							
ORIGIN	**ME1**	**ME2**	**ME3**	**ME4A**	**ME4B**	**ME5A**	**ME6A**	**ME7**
ME1	46 (28)	46 (28)	41 (25)	46 (28)	41 (25)	46 (28)	41 (25)	46 (28)
ME2	25 (18)	25 (18)	21 (14)	25 (18)	21 (14)	25 (18)	21 (14)	25 (18)
ME3	18 (14)	18 (14)	17 (13)	18 (14)	17 (13)	18 (14)	17 (13)	18 (14)
ME4A	13 (8)	13 (8)	9 (5)	13 (8)	9 (5)	13 (8)	9 (5)	13 (8)
ME4B	16 (9)	16 (9)	15 (8)	16 (9)	15 (8)	16 (9)	15 (8)	16 (9)
ME5A	8 (5)	8 (5)	8 (5)	8 (5)	8 (5)	8 (5)	8. (5)	8 (5)
ME6A	7 (5)	7 (5)	7 (5)	7 (5)	7 (5)	7 (5)	7 (5)	7 (5)
ME7	27 (15)	27 (15)	23 (12)	27 (15)	23 (12)	27 (15)	23 (12)	27 (15)
CIM1	95 (70)	95 (70)	76 (54)	95 (70)	76 (54)	95 (70)	76 (54)	95 (70)
CIM2	59 (13)	59 (13)	51 (13)	59 (13)	51 (13)	59 (13)	51 (13)	59 (13)
<u>Total # of</u>								
-Entries	314	314	268	314	268	314	268	314
-Cultivars	(185)	(185)	(154)	(185)	(154)	(185)	(154)	(185)

Note: Numbers in the parentheses indicate number of unique cultivars.

Table 5.5: Yield Advantages of Wheat Cultivars Developed by National Programs in Different MEgaenvironments:
Results of Regression Analysis Based on Data from ISWYN 17,18,20-24 (Kg/ha)

ORIGIN[a]	LOCATION ENVIRONMENT							
	ME1	ME2	ME3	ME4A	ME4B	ME5A	ME6A	ME7
ME1	0	-189**	-406***	-374**	-346**	34	-115	-223***
ME2	-232***	0	-509***	-307*	-275*	-177	27	-175**
ME3	-507***	-141	0	-568***	-282*	-31	-214	1
ME4A	-66	-226*	-565***	0	-483**	-154	-111	-259**
ME4B	-486***	-101	-290**	-334*	0	-161	-198	-56
ME5A	-593***	-525***	-219	-672***	-328	0	-492*	-334**
ME6A	-998***	-543***	-490***	-1031***	-452*	-246	0	-603***
ME7	-588***	-395***	-414***	-507***	-270*	-264**	-272	0
CIM1	227***	230***	-138	-105	16	7	10	-131**
CIM2	527***	490***	-14	20	191	23	126	-91

Note: *, **, *** denote significance at the 10, 5, and 1% level, respectively.

[a] Origin groups ME1 to ME7 represent cultivars developed by national programs for respective megaenvironments. CIM2 indicates CIMMYT cultivars released in Mexico and CIM1 indicates CIMMYT cultivars released in countries other than Mexico or not released anywhere.

erroneous to say that ME1 technology yields 189 kg/ha less in ME2 than in ME1.

There are many important results pertaining to the issue of technology transferability that emerge from the regression results presented in Table 5.5. These are discussed in the following two sections.

5.5.3 Yield Advantage of Domestic Technology Relative to Other Non-CIMMYT Technologies

The establishment of a domestic plant breeding research program is justified on the ground that local breeding programs will develop cultivars that will perform better than those obtained from other sources. The regression results presented in Table 5.5 confirm this hypothesis for the non-CIMMYT technology group (ME1 to ME7) at least at the level of across megaenvironment transferability.

The zeros on the diagonal indicate that the coefficient of cultivar group of the same environmental origin as the test environment is defined as the "benchmark" and all the other coefficients in that column represent deviations from that value. The negative values of non-CIMMYT technology groups thus confirm the hypothesis that cultivars developed for local environment perform better than cultivars developed for other megaenvironments[19].

The magnitude of yield advantage of cultivars bred for local environment is a function of three factors. First, it depends on the genetically adjusted 'environmental distance' between the test megaenvironment and other megaenvironments. *Ceteris paribus*, the larger the 'environmental distance', the greater and significant will be the G x E interactions as reflected by the yield differences. Second, it depends on the biological and genetic diversity causing G x E interactions. The fact that cultivars developed for local environment yield better than others confirms the presence of G x E interactions and implies that there is a potential for specific adaptation. However, the

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[19] Local non-CIMMYT technologies represent cultivars developed by NARS with or without using CIMMYT germplasm as a parent in the cross, or cutivars originally developed by CIMMYT but with at least one further selection made by NARS.

extent to which the G x E interactions can be overcome and yield advantages can be realized is a function of the specific factor causing G x E. Third, it depends on the research intensity in the test environment. Given G x E interactions, higher research intensities in the test environment will tend to generate larger domestic yield bonuses. These three underlying factors also imply that the flow of technology transfer may not be equal in both directions. In other words, the spillover matrix such as given in Table 5.5 need not be symmetric.

These relationships help explain the results summarized in Table 5.5. The highly significant yield advantages enjoyed by cultivars developed in megaenvironments 1, 2, 3 and 7 can be explained by the fact that these megaenvironments are comprised of countries with strong and intensive wheat research programs -- for instance, India and Pakistan in ME1, Kenya, Turkey and Spain in ME2, Brazil in ME 3 and the developed countries of Europe and North America in ME7. Thus, domestically developed cultivars perform significantly better in these megaenvironments than technologies developed in other megaenvironments. On the other hand, the 'environmental distance' factor plays a role in explaining the significant yield advantage enjoyed by domestic technology in ME4A and ME4B. To a certain extent this also holds true for ME3 and ME7. For example, the growing conditions in ME3, except for the acid soil, is very similar to that in ME2 in terms of water supply and temperatures (i.e. environmental distance is less). One would thus expect that the yield difference between the cultivars from these two environments would not be very different when planted in either ME2 or ME3. This is true when the cultivars are planted in ME2. However, in ME3 the soil toxicity adds to the distance between the two environments, constraining the transferability of technology from ME2. This is evident from the highly significant yield disadvantage of ME2 cultivars (509 kg/ha or 19%) when planted in ME3 compared to the small and less significant yield disadvantage of ME3 cultivars (141 kg/ha or 4%) planted in ME2.

In ME5A and ME6A, the yields of cultivars developed in the same megaenvironments, although greater, is not significantly different from other non-CIMMYT technologies. The reasons for these results are not very clear. Perhaps both factors - lack of indigenous research capacity in these megaenvironments and less environmental distance to other environments (because these are high rainfall/irrigated environments) may be responsible for the lack of significantly different yield advantage of locally developed cultivars. ME5A, for instance represents the tropical wheat growing environment where wheat is not an important crop and so it lacks indigenous research capacity. ME6A is usually for winter/facultative wheats and therefore also lacks indigenous capacity for spring wheats. However, the low representation of this technology group (five unique cultivars) makes it difficult to generalize from these results.

5.5.4 Technology Transferability of CIMMYT cultivars

So far we have been concentrating on the transferability of non-CIMMYT cultivars across megaenvironments. If we look at the performance of CIMMYT cultivars (CIM1 and CIM2) across different megaenvironments, the prominent result of the regression analyses is the wide adaptability of CIMMYT cultivars in all megaenvironments. This is evident from the positive yield advantages of CIMMYT cultivars (as high as 11% and 13% in ME1 and ME2, respectively) or not significantly different negative yield disadvantages in different megaenvironments. In general, CIMMYT cultivars (CIM1 and CIM2) perform better than non-CIMMYT cultivars. The development of the Veery cultivars by CIMMYT in early eighties is one of the reasons for this significantly better performance and wide adaptability of CIMMYT technology.

There is however, a great degree of variability in the transferability of CIMMYT's technology. First, CIMMYT cultivars are highly transferable to irrigated and high rainfall regions (ME1 and ME2). CIMMYT cultivars released in Mexico (CIM2) yield a half ton per hectare more than the locally developed cultivars in ME1 and ME2. Since, CIMMYT is located in Mexico where the wheat growing environments can be characterized as either ME1 or ME2, the high productivity of CIMMYT cultivars in these megaenvironments is not surprising. In fact, CIM2 cultivars are commercially released in Mexico for these megaenvironments.

Second, the transferability of CIMMYT technology diminishes as one moves away from irrigated and high rainfall environments towards low moisture, very high temperatures, severely cold environments or soil constraints (ME3, ME4A, ME4B, ME5A, ME6A and ME7). CIMMYT cultivars (especially, CIM1) performed poorly (compared to local environment NARS technology) in ME3 and ME7 with a significant yield disadvantage of about 130 kg/ha (5% and 3%, respectively). In other megaenvironments, the performance of CIMMYT cultivars is however not significantly different from the cultivars developed by national programs in the test environment.

Thus, although the yield bonus of CIMMYT cultivars compared to cultivars developed by national programs is less (either negative or positive) in ME3 to ME7 than in ME1 and ME2, its performance is at least comparable to the locally developed cultivars. In other words, in no megaenvironment is there a large and significant yield disadvantage of CIMMYT cultivars. The results, therefore, indicate both the success of CIMMYT's wheat research program in encouraging global adaptability and the limitations of this success. The success stems from the fact that a broad band of countries appear to have the potential to benefit substantially from the research of a single international institution in the form of directly transferable wheat cultivars. However, the countries that have the potential to benefit from direct transfers of CIMMYT cultivars are those with a large wheat area under irrigated or high rainfall regions (ME1 and ME2).[20]

5.6 Measuring the Yield Advantages of Different Technologies in Some Key Wheat Producing Countries

The regression analysis presented in the previous section demonstrated two results: (1) cultivars developed by national programs in the test environment yielded significantly higher than cultivars developed by national programs in other megaenvironments, and (2) the superiority of CIMMYT cultivars in irrigated and high rainfall

[20] National programs in megaenvironments other than irrigated and high rainfall can however benefit from CIMMYT's wheat research in the form of indirect transfers (i.e use CIMMYT's germplasm in their local crosses).

megaenvironments. These are average results that apply to the megaenvironment globally. In this section we will revisit the same basic questions - the transferability of CIMMYT and non-CIMMYT technologies across megaenvironments and the performance of locally developed technology compared with imported technology - but at a country level. Studying these issues at a country level will help bring out the differences among countries in the technological alternatives available to them, and in turn will shed more light on the factors that determine these differences.

Depending on the number of yield observations and the number of cultivars locally developed, the following countries were selected for the analysis using ISWYN data: Pakistan, India, Kenya, Ecuador, Brazil, Portugal, Argentina, Bangladesh and Bolivia[21]. The trial locations within these countries were selected to represent different megaenvironments.

Table 5.6: Classification of Cultivars into Different Technology Origin Groups Based on the Cross and Selection History of the Cultivars and the Releasing Country (Used in the Model Specification 5.9)

Technology Group	National Program in Domestic Country			CIMMYT		National Programs in Similar ME			National Programs in Other ME		
	C	S	R\a	C	S	C	S	R	C	S	R
T1	X	X	X								
T2		X	X	X							
T3			X	X	X						
T4			X			X	X				
T5						X	X	X			
T6									X	X	X
T7				X	X						

\a C = Cross; S = Selection; R = Released

For a given country and megaenvironment, the cultivars were grouped into seven technological groups. These are depicted in Table 5.6 and described below.

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[21] Due to insufficient observations, many important wheat producing countries in North Africa and West Asia and sub-Saharan Africa were not analyzed.

T1. Cultivars developed (crossed and selected) by the domestic country.

T2. Cultivars developed (crossed) by CIMMYT but at least one further selection was made by the domestic country.

T3. Cultivars developed (crossed and selected) by CIMMYT and released in domestic country.

T4. Cultivars developed (crossed and selected) by other NARSs and released in domestic country for the given environment.

T5. Cultivars developed (crossed and selected) by other NARSs from the same megaenvironment as the domestic location but not released in domestic country. For some countries, this group was further divided in to cultivars from neighboring countries (T5a) and other countries (T5b).

T6. Cultivars developed (crossed and selected) by the NARSs from different megaenvironments than the domestic location.

T7. CIMMYT cultivars other than T3 listed above.

The following model specification was used to estimate the yield advantages of cultivars from different technological groups.

$$Y^{c}_{ijt} = a + \sum_{j=1}^{M} b_j \, DLocation_j + c_1 * FISWYN + \sum_{g=1}^{G} c_g \, DVME_g + \sum_{t=1}^{T} u_t \, DYEAR_t + v \, R + e_{ijt} \qquad (5.9)$$

for, c = 1,2,...

where, the superscript c denotes a country and subscript j denotes the trial location in country c for a given megaenvironment. DT_g are the dummy variables for the technological groups defined above. This model specification is similar to Equation 5.8 except that the technological origin groups are defined from the perspective of a country, rather than the worldwide megaenvironment. The number of entries and unique cultivars in each origin groups for all the countries analyzed is given in Table 5.7. From a country's perspective, the Technology group T6 (cultivars developed by NARS in other megaenvironments) and T7 (CIMMYT cultivars other than those released domestically) dominate all the other groups in terms of its representation.

Table 5.7: Number of Entries and Unique Cultivars Used in the Regression Analysis for Some Key Wheat Producing Countries (Equation 5.9)

Country by ME	Cultivars Released in Country				Cultivars Not Released in Country			
	T1	T2	T3	T4	T5a	T5b	T6	T7
ME1								
Pakistan	13(8)	--	9(7)	--	19(12)	14(8)	116(75)	145(74)
India	3(2)	2(1)	3(2)	--	4(2)	7(6)	34(30)	31(24)
ME2								
Kenya	4(4)	--	--	--	--	18(11)	113(73)	135(72)
Ecuador	5(4)	1(1)	3(3)	--	--	16(10)	113(73)	132(69)
ME3								
Brazil	12(10)	5(3)	8(5)	--	--	--	126(75)	119(60)
ME4A								
Portugal	7(4)	--	--	--	--	7(5)	149(95)	154(81)
ME4B								
Argentina	6(4)	5(3)	4(2)	--	--	4(1)	129(81)	123(63)
ME5A								
Bangladesh	--	--	4(2)	4(2)	--	4(3)	153(98)	150(79)
Bolivia	--	--	3(3)	--	--	5(4)	89(62)	78(45)

Note: Numbers in the parenthesis indicate the number of unique cultivars.
The technology groups are: T1 = Cultivars locally crossed and selected; T2 = Local selection of CIMMYT cross; T3 = CIMMYT cultivars crossed and selected in Mexico; T4 = Other NARS Cross and selection; T5a = Cultivars crossed and selected by neighboring countries in the same megaenvironment; T5b = Other NARS cross and selection in the same megaenvironment; T6 = NARS cross and selection in other megaenvironments; T7 = CIMMYT cultivars other than T3.

As in the previous model, Equation 5.9 was estimated for each country separately using the OLS method. The regression output for each country is given in Appendix Table C.3. The interpretation of the Year, Trial locations, FIRSTISW and MR variable is as in the previous model.

The coefficients of the DT_g (Technology) variable indicate the yield effects of a given technological group. In each country, the yields of domestic cultivars (either T1 or T2) were used as the benchmark coefficients. Thus, the coefficients on other technological group indicate the yields relative to domestic technology. Exceptions to this rule are the two countries - Bangladesh and Bolivia for which group 1 and 2 was non-existent. In these cases the yields of directly introduced cultivars from CIMMYT are used as the benchmark coefficient.

The coefficients of the technology variable are reported in Table 5.8 for each country. This gives a better comparative perspective on the relative yields of domestic and imported cultivars across different countries in different megaenvironment groups.

Table 5.8: Relative Yields of Cultivars of Different Technology Groups in Some Important Wheat Producing Countries Classified by Megaenvironments (Kg/ha)

	Cultivars Released in Country				Cultivars Not Released in Country			
Country by ME	T1	T2	T3	T4	T5a	T5b	T6	T7
ME1								
Pakistan	0	--	142	--	-186[a]	-209	-658***	73
India	0	173	107	--	-366[b]	-488*	-647***	-47
ME2								
Kenya	0	--	--	--	--	176	-265	326
Ecuador	0	-1690	-614	--	--	2186***	-2777***	-2125***
ME3								
Brazil	0	86	-64	--	--	--	-400***	-83
ME4A								
Portugal	0	--	--	--	--	-147	-713**	-371
ME4B								
Argentina	0	111	518	--	--	-252	-330	83
ME5A								
Bangladesh	--	--	0	-294	--	-68	-369	-230
Bolivia	--	--	0	--	--	-145	-122	-16

Note: -- indicates not applicable. *, **, *** denote significance at the 10, 5 and 1% level, respectively.
The technology groups are: T1 = Cultivars locally crossed and selected; T2 = Local selection of CIMMYT cross; T3 = CIMMYT cultivars crossed and selected in Mexico; T4 = Other NARS Cross and selection; T5a = Cultivars crossed and selected by neighboring countries in the same megaenvironment; T5b = Other NARS cross and selection in the same megaenvironment; T6 = NARS cross and selection in other megaenvironments; T7 = CIMMYT cultivars other than T3.
[a] Indian cultivars
[b] Pakistani cultivars

The results are not strikingly different from that reported in Table 5.5 for the megaenvironments as a whole. The negative relative yields of imported cultivars indicate that domestically developed (T1) or selected (T2) cultivars perform better than imported cultivars in most countries. Among the imported cultivars, the worst performance, as expected, is reported by the cultivars originating from other megaenvironments (T6). The yields of these cultivars are significantly lower than the domestically developed cultivars. Even the yields of cultivars originating from the same megaenvironment (but in other countries) (T5) and CIMMYT cultivars (T7) were lower (although not significantly) relative to the domestically developed local cultivars in most countries and megaenvironments. In the case of irrigated environment (ME1) in South Asian countries - Pakistan, India and Nepal, we tried to estimate the relative yields of foreign cultivars from neighboring countries. As the results show, in the case of India and Pakistan where wheat research programs are highly advanced, the cultivars from neighboring country yield less than the domestic cultivars (although not significantly). However, in the case of Nepal, where the wheat research program relies mainly on imported cultivars, the cultivars from India and Pakistan perform as well as the locally selected and released cultivars.

The performance of CIMMYT cultivars released in a given country (T3), compared to other CIMMYT cultivars not released in that country (T7) is better in all the countries where this comparison is possible. The yields of cultivar group T3 being consistently higher than group T7 means that national programs are efficient in selecting from CIMMYT materials those that best suit their environments. Also, except in Ecuador and Brazil, the yields of directly transferred (released) CIMMYT cultivars (T3) are relatively higher than domestic cultivars (T1 or T2). These results argue for a strong testing and selection program on the part of NARS.

Cultivars imported from other countries (T4), however, did not yield better than domestic cultivars. It is hard to conclude anything about the performance of locally selected CIMMYT cultivars (T2). One would have expected that locally reselected foreign cultivars would perform better than directly transferred cultivars (T3), because the former are better adapted to local conditions. The results, however, do not confirm this hypothesis (except for India and Brazil).

Beyond the issue of relative yield advantages of different technologies is the question of significance of the yield difference. The countries analyzed vary widely in terms of their wheat research capacity, the size of wheat area, economic development and wheat growing environments. The striking result of this regression analyses is that even across this wide range of countries, the yields of domestic cultivars are not significantly different from cultivars originating from other sources (except other megaenvironments). Even in Brazil which has the unique problem of soil toxicity, the locally developed cultivars do not seem to perform significantly better than imported or foreign cultivars from CIMMYT and other countries in the same megaenvironment. And, even in countries with strong wheat research program such as India, Pakistan, Turkey and Argentina, the yields of imported and foreign cultivars are not significantly higher or lower than the domestic cultivars.

Thus, like the previous model, the results of this model specification confirm the hypothesis that locally developed technologies fit better in the local environmental niche. However, the yield difference between the domestic cultivars and CIMMYT cultivars or cultivars from same megaenvironment is not large or statistically significant. CIMMYT cultivars have performed well across all megaenvironments and have proved to be widely transferable across different countries in different megaenvironments.

5.7 Measuring Yield Advantages Using National Yield Trial Data of Pakistan

Given the fact that ISWYN trials are conducted by CIMMYT with the purpose of disseminating its germplasm, there is an overwhelmingly large representation of CIMMYT cultivars (about 50%) in the data analyzed in the previous sections. To see if the evidence of high transferability of CIMMYT cultivars is sustained when compared with large number of individual country cultivars, a model similar to equation 5.9 is estimated using the national yield trial data of Pakistan.

5.7.1 Data Sources

The National Uniform Wheat Yield Trial (NUWYT) data are used to estimate the model. The results of the NUWYT trials are published annually by the Pakistan Coordinated Wheat, Barley and Triticale Program since 1979. The trials are conducted each year at several locations across the country representing different wheat growing environments. However, for the purpose of present analysis only the average province level data (for Punjab, Sindh and NWFP) of the replicated trials for the irrigated environment are used.

Two types of yield trials with different set of cultivars are conducted each year depending on the date of planting. The normal planting (or normal duration) trials (with the date of planting ranging from 10-24 November) correspond to the ISWYN trials analyzed in the previous sections and represent the optimal planting period for the region. The late planting (or short duration) trials (with the date of planting after 1 December) represent an environmental niche that is increasingly becoming common due to the increased cropping intensity in the irrigated regions of Pakistan (Byerlee et al. 1987). Data on both these yield trials are used here to provide evidence on the relative advantage of locally developed cultivars in normal duration and short duration irrigated environments.

The analysis of this section is based on fourteen years of data (1978-79 to 1981-82) for the normal duration trials and twelve years (1978-79 to 1989-90) for the short duration trials. The number of entries in the normal duration trials varied from 16 to 24 each year with a total of 274 entries over the fourteen year period. Similarly, the number of entries in the late planting trials ranged from 7 to 15 entries each year with a total of 129 entries over the twelve years analyzed. Since we are using average province level data, the local checks, which are location specific, were excluded from the analysis[22]. Also, 17 cultivars in normal duration trials and 3 cultivars in late planting trials were not identified and were therefore excluded from the analysis. Thus, excluding the local checks and the unidentified cultivars, the data set analyzed includes 158 unique cultivars in the normal duration yield trials and 76 unique cultivars in the short duration trials.

Based on the CIMMYT's Global Wheat Impact Study database (described in Chapter 4) and personal communications with the Coordinator of the NUWYT trials, the cultivars were classified into following four origin groups.

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[22] As noted in footnote number 6 of this chapter, this does not imply a downward bias to locally developed cultivar technology as the local checks are not necessarily developed by local research programs. Given the fact that more than 50% of varieties released in Pakistan in 1965-90 were introduced CIMMYT varieties (Table 4.24) and that the share of CIMMYT varieties in irrigated environment is likely to be even more (for example, about 82% of varieties released in Punjab, Pakistan in 1981-90 were imported [mostly CIMMYT] crossed varieties [Byerlee, personal communication]), large proportion of the local checks in NUWYT trials are likely to be of CIMMYT origin rather than Pakistani origin.

1. Cultivars developed (crossed and selected) by a Pakistani wheat research program.
2. Cultivars developed (crossed) by CIMMYT but with at least one further selection made by a Pakistani wheat research program.
3. Cultivars developed (crossed and selected) by CIMMYT in Mexico.
4. Cultivars developed (crossed and selected) by another national program (mainly India).

Table 5.9: Number of Entries and Unique Cultivars in the Normal Duration and Short Duration NUWYT Trials Grouped by their Developmental Origin

Origin Group	Normal Duration Trials	Short Duration Trials
1. Cross and selection made by Pakistani research program.	90 (63)	59 (39)
2. Cross made by CIMMYT, but at least one further selection made by a Pakistani research Program.	22 (13)	7 (4)[a]
3. Cross and Selection made by CIMMYT in Mexico.	119 (79)	48 (33)
4. Cross and Selection made by another NARS.	4 (3)[a]	0 (0)[a]
Total Number of: - Entries - Unique Cultivars	235 (158)	114 (76)

Note: Numbers in the parentheses indicate the number of unique cultivars.
[a] Not included in the regression analysis.

The number of unique cultivars and total number of entries in the normal and late planting trials of these four origin groups are given in Table 5.9. The overall proportion of locally developed cultivars (Origin group 1) and cultivars imported from CIMMYT (Origin group 3) is roughly the same, although there is a clear dominance of imported CIMMYT cultivars in the normal duration trials and locally developed cultivars in the short duration trials. The number of cultivars in origin group 4 (cultivars developed by another national program) were found to be only three in the normal duration trials and zero in the short duration trials. This origin group was therefore not included in the analysis. Similarly, cultivars of the origin group 2 (CIMMYT cross with local reselection by Pakistani research program) in the short duration trials were excluded from the analysis because of its small representation.

5.7.2 Measuring the Yield Advantages of Locally Bred and Imported Cultivars in the Irrigated Environments of Pakistan

The following model specification was used to estimate the yield advantages of cultivars from different origin groups.

$$Y^{E}_{ijt} = a + \sum_{j=1}^{M} b_j \; DLocation_j + c_1 * FNUWYT + \sum_{g=1}^{G} c_g \; DOrigin_g + \sum_{t=1}^{T} u_t \; DYEAR_t + e_{ijt} \qquad (5.10)$$

for E = 1 Normal Duration Irrigated Environment
= 2 Short Duration Irrigated Environment

where, DLocation = A set of dummy variables indicating the province
FNUWYT = First NUWYT appearance of a given cultivar (vintage variable)
DOrigin = A set of dummy variables indicating the developmental origin of cultivars.

subscript
j = province - Punjab, Sindh and NWFP
g = Origin groups 1,2,3 described above for normal duration trials, and
g = Origin groups 1 and 3 for short duration trials
t = 1978-79 to 1991-92 for normal duration trials, and
t = 1978-79 to 1989-90 for short duration trials.

This model is similar to equation 5.9[23]. As in the previous models, Equation 5.10 was estimated separately for the normal planting irrigated environment and the late planting irrigated environment using the OLS method. The regression output for both these environments is given in Appendix Table C.4. Table 5.10 presents the statistical summary of these two regression equations. The interpretation of the year, location and FNUWYT variable is as in the previous models. The

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[23] Except for the exclusion of the variable R (Mill's Ratio). The estimation of Mill's ratio requires average yield data over all the locations in a given year of the trial. Since, present analysis only used the average yields of three provinces and only one environment (irrigated), data were not sufficient to estimate the Mill's ratio. The potential danger of its exclusion from the model is that it may over- or under-estimate the yields of an origin group depending on its rate of attrition in the trial data set. However, this is not likely to be an important problem in the present data set since only two or three origin groups are compared in the model. Moreover, as a group, there is no attrition over the years for Origin groups 1 and 3 (cultivars locally developed by Pakistani research program and cultivars developed by CIMMYT, respectively), and in the case of Origin group 2 (CIMMYT cultivars further selected in Pakistan), attrition occurred in only three out of fourteen years analyzed for normal planting trials.

coefficients of the DOrigin variables indicate the yield effects of a given developmental origin group. As in the previous models, the yields of the locally developed cultivars (Origin group 1) are used as the benchmark coefficients. Thus, the coefficients of other origin groups indicate the yields relative to locally developed Pakistani cultivars.

Table 5.10: Regression Results of the Normal and Short Duration Yield Trials in the Irrigated Environment of Pakistan (Model 5.10)

		Normal Duration	Short Duration
Independent Variables			
1. Dummy variables for Year	- R^2 change[a]	0.23	0.23
	- F change[b]	19.6***	9.2***
2. Dummy var. for Location	- R^2 change[a]	0.02	0.12
	- F change[b]	12.3***	27.5***
3. Vintage, FNUWYT[c]		6.55 (0.55)	-3.01 (-0.86)
4. Cultivars developed by Pakistan, DOrigin1[d]		0	0
CIMMYT cultivars selected by Pakistan, DOrigin2[c]		109 (1.64)	--[e]
Cultivars developed by CIMMYT in Mexico, DOrigin3[c]		101 (2.68)***	14.2 (0.28)
n		694	321
R^2		0.37	0.35

Note: t-values in the parenthesis. *, **, *** denote significance at the 10, 5 and 1% level, respectively.
[a] Number given is the change in the R^2 when the given set of dummy variables are entered in the equation that includes other variables.
[b] Number given is the change in the F-ratio when the given set of dummy variables are entered in the equation that includes other variables.
[c] Number given is the estimated coefficient.
[d] Benchmark coefficient for the set of DOrigin variables.
[e] Not included in the equation.

In general, the results are not very different from those given in Table 5.8 for Pakistan's ME1. Two results of these regression models are, however, worth noting. First, as indicated by the positive coefficients of the DOrigin3 variable, cultivars crossed and selected by CIMMYT in Mexico, significantly yield higher than locally developed

Pakistani cultivars in the normal planting irrigated environment. This implies that even a large country like Pakistan can import much of its varietal technology, especially in the normal duration irrigated environments. This result is in accordance with the results of Equation 5.9 using the ISWYN data set for Pakistan's ME1. The 101 kg/ha (about 3%) yield advantage of cultivars imported from CIMMYT is comparable with the 142 kg/ha yield advantage estimated using the ISWYN data set, indicating that the results based on the ISWYN trials are a good proxy of the yield advantages of different technology origin groups, at least for the environments requiring normal duration of wheat growing season.

Second, the yield difference of locally developed cultivars and CIMMYT cultivars is lower in the late planting trials (14 Kg/ha) than in the normal planting trials (101 Kg/ha) indicating that the yield advantage of CIMMYT cultivars relative to Pakistani cultivars is not the same in the normal and short duration environments. CIMMYT cultivars have not been very successful in short duration as they have been in the normal duration irrigated environment. In other words, the length of the cropping season as determined by the cropping intensity in a given environment, is an important factor constraining research spillins from other sources, thus creating a need and scope for locally developed varietal technology. The ISWYN trials used in the previous sections ignore this within environment variation due to differences in the cropping intensities. Since the ISWYN trials are normal duration yield trials the results of previous sections may not be generalizable to short duration environments.

5.8 Comparisons With Englander's Study on Wheat Technology Transfer

It is important to discuss the similarities and differences between the results of Englander (1981a; 1991) and this study. Both studies address the issue of transferability of wheat technology by asking similar questions - the yield advantages of different technologies, the transferability of technology developed by CIMMYT and the transferability across environments. Also, both studies use a similar statistical framework based on the phenotypic models of plant breeders. Moreover, although the years differ, both studies use the International Spring Wheat Yield Nursery trial data published by CIMMYT.

There are however, basic differences in the model specifications and estimation procedure used to address the questions, and the interpretation of ISWYN data set. First, Englander used the contributing country information (labeled as country of origin) published in ISWYN to represent the technological origin of a cultivar. Hence Englander's analysis is not on the technological origin but on the releasing/contributing country. Given the fact that a country frequently contributes a CIMMYT cultivar with a local name to the ISWYN, Englander's results are misleading. In the present study, a major effort was made to reclassify the origin of all the cultivars in the ISWYN data set according to their pedigree and selection history using the new data base of CIMMYT's Impact Study (discussed in Chapter 4) rather than the country of origin listed in the ISWYN reports[24]. Thus, this analysis more accurately estimates the transferability of wheat technologies of different origins.

Second, the model specification in this study differs from that of Englander in two basic ways. 1) Englander's analysis focused more on the transferability of wheat technologies across political boundaries (countries) rather than across environments. Given that a country often has multiple wheat growing environments, the results of such political-based analysis are difficult to interpret. The model specification in this study, therefore, focused on the technology transferability across environments rather than across countries. 2) This study differs from Englander's in the procedure used to estimate the models. Instead of estimating the model for all the environments in one equation, the model was estimated for each environment (and country) separately. Although, this meant more regressions and estimations, the results derived are

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[24] The extent of such misclassification of the origin can be seen from the information provided in Appendix B (Table B.2). For example, none of the cultivars (number 23 to 26) contributed by Bangladesh were bred locally by the Bangladesh national program. They were either developed by CIMMYT or by Indian national program. If these were considered as Bangladeshi cultivars (by origin) they would have given misleading results.

easier to interpret. Also, we were able to estimate more interaction terms to measure the transferability of wheat cultivars from and within different environments.

In addition to the methodological differences between this study and Englander's, there are also differences in the results and interpretation of the results. These differences stem partly from the differences in data interpretation and partly from the differences in the estimation procedures. Englander's results "suggest that varieties that incorporate CIMMYT technology and are bred locally outperform both traditional varieties[25] and CIMMYT varieties" (Englander 1991, p. 310). However, the regression results of this study presented in Tables 5.5 and 5.8 do not indicate any substantial yield gains of locally bred cultivars over the CIMMYT cultivars in most megaenvironments. Moreover, the results of Table 5.8 indicate that countries are efficient in selecting from CIMMYT cultivars. If many of the varieties that Englander classified as those 'that incorporate CIMMYT technology and are bred locally' are in fact CIMMYT cultivars released by a given country, then the results of this study confirm rather than contradict Englander's findings.

However, the incorrect origin classification led Englander to conclude that, "in order to maximize their benefits from new technology, countries must perform local research to adapt the technology to their local conditions" (Englander 1991, p. 311). In other words, Englander's results encouraged national research systems to strengthen their crop research programs by focusing on developing locally bred technologies (a full-fledged breeding program) rather than directly importing and screening from other sources (in which case a simple evaluation/testing program would suffice)[26]. This generalized conclusion of Englander was

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[25] Traditional varieties as defined by Englander (1981 and 1991) are varieties that do not incorporate CIMMYT genetic material (corresponds to our origin group 1).

[26] Given the results of this study which indicate that the locally bred technologies did not perform significantly better than imported technology from CIMMYT or other countries of similar environment, such an approach on the part of national research system may not be warranted. However, more in-depth economic analysis of these results needs to be done before making such a statement (Chapter 6).

based not only on the incorrect origin classification of the cultivars but also on the relative yield advantages rather than statistical and economic criteria. He did not take into account the statistical significance of the differences in yields of cultivars from different origins nor did he carry out an economic analysis of costs and benefits associated with different levels of research capability.

The present study can be considered as an improvement and extension, as well as an update of Englander's analysis on technology transferability in both the methodology and data interpretation. First, it has extensively revised the ISWYN data by reclassifying the origin of all the cultivars based on the pedigree and selection history; it has also classified the cultivars by megaenvironment origin to analyze the transfer of technology from and within a megaenvironment. Second, the model specifications focused on the transfer of technology based on environmental boundaries rather than political boundaries. This is not only correct theoretically, but also allowed for better interpretation of the resulting transfer coefficients.[27]

5.9 Conclusions

This chapter has provided empirical estimates of the yield advantages of different technologies and the transferability of CIMMYT's wheat varietal technology across megaenvironments. The major conclusions corresponding to the issues raised in the beginning of this chapter are: (1) The performance of foreign cultivars originating in other megaenvironments relative to locally bred cultivars was significantly lower in all the megaenvironments, thus providing evidence on the location specificity of wheat cultivar technologies and of the relevance of the megaenvironment classification. (2) Technologies

[27] Even within a politically bounded region (viz. a country or a province within a country) agricultural research is targeted by environmental zones which need not be homogenous in terms of its economic importance and biological feasibility (Pardey and Wood 1991). Estimating the transferability of technology by environments is thus relevant to a political decision making unit. It allows for differential levels of research resources and type of research for different target zones (research stations, for example) depending on the geographic area, potential research spillins and complexity of research problems in the given zone.

originating from CIMMYT have proven to be highly transferable across different countries and environments around the world. Their performance in many megaenvironments was at least comparable to the domestically developed technologies. This result is contrary to Englander's (1981a) findings which was based on different (1960s and 1970s) data set of ISWYN trials. (3) The transferability of CIMMYT's technology, however, has not been uniform across different megaenvironments. The countries with irrigated and high rainfall environments (ME1 and ME2) have the potential to benefit more from CIMMYT's technology, and (4) Yields of domestic cultivars were significantly higher than yields of cultivars developed by NARSs in other megaenvironments. However, in several important countries examined (ME1 - India, Pakistan; ME2 - Kenya, Ecuador; ME3 - Brazil; ME4a - Portugal; ME4b - Argentina) the yields of domestic cultivars relative to CIMMYT cultivars or cultivars from the same megaenvironment, were not significantly different. This was also indicated by the results of the analysis based on the national yield trial data (NUWYT) of Pakistan in the irrigated environment. In other words, there was no evidence of substantial yield gains for these countries from having a research program to develop new cultivars specifically targeted to the respective megaenvironments.

The results of this study refute the generally held notion of location specificity, at least for wheat, and fail to support Englander's (1981a;1991) results that suggest limited transferability of wheat technology from CIMMYT. By using a different model specification, megaenvironment based location and cultivar classification, and correct origin data, the results of this study indicate wide transferability of CIMMYT cultivars across different environments and countries. Although G x E interaction effects are strong and the locally developed cultivars perform significantly better than cultivars developed by NARS in other environments, developing new research programs in every environmental niche for increasing adaptability may not be the optimal choice. The wide adaptability of CIMMYT cultivars suggests that direct transfer (or local reselection) of wheat technology from CIMMYT (or other countries with similar environments) can often be considered as a superior alternative to the development of local breeding programs.

These results have important implications for CIMMYT's research strategy and for designing national wheat breeding programs. The results have demonstrated the superiority and wide adaptation of CIMMYT cultivars across different countries, especially in the irrigated and high rainfall regions. The success of CIMMYT wheats in combining high yield potential and wide adaptation can be attributed to: (1) A large number of crosses (12,000 per year); (2) the testing of advanced lines internationally; and (3) continuous alternating selection cycles referred to as 'shuttle breeding', in environments which allow expression of high yield potential but differ in altitude, latitude, photoperiod, temperature, rainfall, soil-type and disease spectrum. The real advantage of CIMMYT lies in its ability to conduct such a large and wide scale breeding operation. But if CIMMYT continues to face severe budget cuts as it has in the last three years (Eicher 1992) it may no longer be able to maintain this comparative advantage in wheat research.

This study also has important implications for NARSs in the Third world. The results indicate that CIMMYT technology has proved to be widely adapted at least in the irrigated and the high rainfall regions. There is also evidence of transferability of wheat cultivar technology from highly advanced national programs such as India, Pakistan, Argentina to other small countries within a megaenvironment. Thus, the implications for countries where wheat is not an important crop or where national agricultural research systems are not highly developed is that it can consider the option of direct transfer of cultivars developed by CIMMYT or other national wheat breeding programs as an alternative. Countries like Zambia, Zimbabwe, Bhutan, Nepal, Peru, for example, where wheat is grown under irrigated or high rainfall conditions can benefit substantially from only a testing program without incurring large costs in breeding (crossing and selection) research.

There are also implications for countries with large wheat growing areas or diverse environments and which have a strong national wheat research programs. Countries such as India, Pakistan, Brazil, Turkey, Egypt, need not devote resources for each and every environmental niche in the country. They can utilize their resources more efficiently by following a mixed strategy of direct importation of technology in some environments and local development of technologies in other environments which are unique to the country.

There are however, few caveats to be noted about this study. First, given the fact that ISWYN trials are conducted by CIMMYT with the purpose of disseminating its germplasm, there is an overwhelmingly large representation of CIMMYT cultivars (about 50%) in the data analyzed in this chapter. The results of individual country are therefore based on a small number of NARSs' cultivars and may not be conclusive. However, considering that the countries contribute their best cultivars in the ISWYN trials, the results are at least indicative of the overall trends. The similarity found between the results of the analysis based on ISWYN and NUWYT trials for Pakistan suggests that this is the case at least for the normal duration environments.

Second, the results are based on the megaenvironment classification system that may overlook important within megaenvironment variations such as late planting in intensively cropped irrigated areas (Byerlee et al. 1987). As the results based on NUWYT data for Pakistan indicate, the transferability of CIMMYT cultivars may differ within a megaenvironment depending on the cropping system of a region. Thus, the results based on the ISWYN data set, which are normal duration trials, may not be generalizable to the whole megaenvironment if there are variations within the environment in terms of cropping systems that require wheat crops of different maturity.

Third, it ignores other important factors like grain color, quality and stability which may be important in determining the transferability of a technology. Crop yields measure the adaptability of a technology in different environments. However, in terms of adoption by farmers, these other factors may sometimes be as important as yields. If the directly transferable CIMMYT (or other country's) technology is not adopted in local environment, then more research is needed on the part of national programs to make the technology adoptive. In other words, if the technology available from other sources is high yielding in local environment but not compatible with the socio-economic environment, then national programs can justify a local breeding program on the basis of other traits. As mentioned earlier, this study has made no attempt to estimate the total transferability (in terms of both environmental adaptation and adoption by farmers) of a technology, the conclusions are therefore solely based on yield advantages.

However, the measurement of yield advantages of different technologies is not sufficient to make any strategic decisions about the design of wheat breeding programs for any country. These estimates need to be put in an economic framework and the costs and benefits of all the possible alternatives must be carefully assessed before making any generalizations. This leads us to the next chapter where such an approach is developed and applied to some research programs.

CHAPTER SIX

ECONOMIC ANALYSIS OF WHEAT IMPROVEMENT RESEARCH PROGRAMS

6.1 Introduction

The empirical results of chapter 4 reveal that the size and level of resources used in a wheat improvement program is influenced by the capability (technology evaluation or technology creation) of the research program. The research capability, according to the conceptual model of chapter 3, in turn depends on the type of technology spillins. The availability of directly transferable technology may encourage research programs to focus on technology evaluation research (e.g. testing programs) and the lack of transferable technology may encourage them to focus on technology creation research (e.g. breeding program). To be sure, other factors, such as the importance of crop in the target domain, environmental complexity, research lag, product price, research costs, and availability of resources, will also influence decisions on the size and capability of crop improvement research.

In the late 1980s and early 1990s public expenditures on agricultural research in the CGIAR system and NARS came under increasing scrutiny. In addition, donors started to question the relative emphasis that should be devoted to commodity versus environmental research in the CGIAR system. As five new centers were added to the CGIAR system between 1990-92, the donor support for all the commodity focussed CG centers (e.g. CIMMYT, ICRISAT, IRRI) were quietly sliced (Eicher 1992). Finally, some of the mature NARS such as Brazil experienced rapid turnover of staff and a decline in domestic financial support during the 1980s. The net result of these actions is increasing scrutiny of investment in agricultural research and the need for solid research on the impact of research and appropriate size and type of research programs.

The purpose of this chapter is to address the size and capability of wheat research programs from an economic point of view. A general framework of benefit-cost analysis is used to address these issues. This framework is applied using average parameter values to estimate the appropriate capability of wheat research program according to the wheat production and environmental complexity in the target domain.

6.2 Classification of Wheat Improvement Research Programs for Resource Allocation Purposes

Over the past two decades numerous studies have provided additional evidence on the ex-post high rates of returns to agricultural research in general and to plant breeding research in particular. However, this evidence fails to provide specific guidelines on how a country/region should allocate limited resources on different commodities, different types of research for a given commodity (for example, plant breeding versus agronomic research), and appropriate research capability for a given type of research (for example, technology evaluation versus technology creation in plant breeding research).

Agricultural research on a given commodity or type of research with a particular research focus, can have high costs, in terms of both the resources it uses and the opportunity costs of resources in other research. As research organizations around the world increasingly struggle with financial constraints of the 1990s, justification for investment in agricultural research programs will have to be based not only on the evidence of high rates of returns but also on the opportunity costs. This means that the economic costs and benefits of investment decisions will need to be carefully assessed in terms of all the alternative opportunities available at each stage of decision making by research administrators - commodity, type of research and research capability.

In making resource allocation decisions for wheat improvement research, therefore, the appropriate questions to ask are: what is the appropriate research capability? As discussed in chapter 3, research capability in plant breeding can be broadly classified as either technology evaluation or technology creation. Within these groups, there is a continuum of research capabilities, ranging from directly introducing foreign varieties, testing them under local conditions, making selections using early generation materials from other programs, making own crosses using local and foreign materials (this could range from a few crosses to thousands of crosses per year) and conducting basic/strategic research ranging from specialized facilities for screening for disease and insect resistance to molecular biology.

As a research program grows from technology evaluation stage to technology creation it adds on new components of research capability. In fact, the difference between technology evaluation research and technology creation research is the different mix of research components in the program. A breeding program would have the components of testing; but a research program classified as testing program would not have a breeding component. Therefore, even though the different levels of research capability are not mutually exclusive as such, the decision making alternatives in the form of either focusing on technology evaluation alone or technology creation are mutually exclusive.

For the analytical purposes of this chapter the two decision alternatives corresponding to technology evaluation and technology creation are - testing and breeding. Wheat research programs that focus on evaluating imported technologies are called testing programs and those focusing on creating new technology from local crosses and selections are labeled breeding programs.

Since the decisions on whether the research program should focus on evaluation or creation of technology depends on the technology spillins which are determined by the environmental distance/closeness, the resource allocation decisions for wheat improvement research need to be made for each environment. Thus, the question of appropriate research capability needs to be asked at the environment level rather than the state or country level. The decision on the appropriate research capability in each environment can then be aggregated to determine the national wheat research budget along with the size and mix of wheat research team.

6.3 Conceptual Framework for Determining the Appropriate Capability of Wheat Improvement Research Programs

6.3.1 Returns and Costs of Wheat Improvement Research Programs

Crop improvement research basically aims at raising the general welfare of society by increasing crop productivity. It achieves this goal by enhancing the plant environment and by improving the genetic constitution of plants. Plant breeding research works on improving the latter component. The costs and returns modeled below are confined to crop improvement research with the exclusion of crop production research (e.g. agronomic research).

Gains From Improvement Research:

The gains from plant breeding research as modelled in chapter 3 can be simplified (without using the time subscripts) as follows:

$$\begin{aligned} R_e^f &= P\,Q\,g_e^f\,\alpha \\ \textit{where,}\quad g_e^f &= g(S,\ R,\ T) \end{aligned} \qquad (6.1)$$

The superscript 'f' denotes the level of research capability; subscript 'e' denotes the plant environment in the target domain; R is the (undiscounted) return from the new varieties ($); P is the crop value ($/ton); Q is the expected production in the whole target region without any contribution from the plant breeding research program (tons); g is the expected proportional gain in production (whether yield or area) through varietal improvement (%); and, α is the percentage of wheat production attributed to the adoption of new technology.

This specification is kept simple at this point by ignoring the contribution of research to improvements in grain quality and to maintenance research to avert the depreciation of varieties due to changes in pest populations. Thus, in this specification it is only g (measured in terms of yields) which the breeding research aims to improve. The rate of gain in production will depend on the resources devoted (R), the research spillins (S) and the targeting strategy (T) which will be different depending on the research capability and the environmental complexities in the target domain. Thus, g for a testing program may be different from the g for a breeding program and g for the same level of research capability may be different for different environments.

Costs of Breeding Research:

The costs associated with wheat improvement research can be grouped into - (1) labor costs (salaries of research scientists, technicians, etc.); (2) capital costs (costs associated with the equipment used in all aspects of the breeding program); and (3) general overhead and operating costs (costs of administrative services, library services, travel, communication, etc.). Unfortunately, data on the breakdown of costs of a wheat breeding program into these three components for developing countries are not available[1].

Given that more data are available on the total costs per scientist-year in plant breeding programs and agricultural research in general, a modified cost function is used in this study:

$$C^f = C_s\, S^f \tag{6.2}$$

where C^f is the total cost for a given level of research capability; C_s is the average total cost per scientist-year, including the overhead costs; and S^f is the number of scientist-years in the program at a given level of research capability.

The average total cost per scientist-year (C_s) will vary markedly from program to program depending on factors such as: (1) the degree of mechanization and the labor intensity of the program; (2) unit cost of labor and capital; (3) number of crosses compared to selection and testing of imported materials; (4) the degree of technical support provided by other disciplines to the researchers in the program. Also, in a given program, the marginal cost of an additional scientist will differ at different sizes of the program, and therefore average costs may not capture the marginal costs accurately. However, until additional data are available to clarify these issues, this study assumes that the marginal cost is closely approximated by the average

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[1] In a detailed study of the costs of operating small (single-breeder) wheat breeding program in Australia, Brennan (1988) found that less than 20% of the cost of a wheat breeding program were accounted for by capital and overhead costs, and almost 70% was direct labor costs.

cost. In other words, C_s is assumed to be the same whether a research program focuses on only testing foreign materials (requiring less number of researchers) or involves in a breeding program (requiring more number of scientist-years).

6.3.2 Modelling the Time Pattern of Costs and Returns

Plant breeding research is a continuing process, characterized by a flow of annual expenditures and a subsequent flow of annual returns. Studies analyzing plant breeding programs have used different approaches to depict the time pattern of costs and returns. The common approach taken by the rate of return studies is to use an arbitrary cut-off point for expenditures and returns, and aggregate the costs and returns over the time period (for e.g., Zentner and Peterson, 1984 and Gardiner et al. 1986). Brennan (1992a) assumed that real costs and returns are constant over time, with a fixed relationship between one year's expected returns and the expenditures for another (suitable lagged) year. Thus, he approximated the costs and returns of a breeding cycle by assuming that all costs are located in a single year (the year of maximum costs) and all returns are located in a single year (the year of maximum returns) after a research and adoption lag of n years.

Although, the alternative used by Brennan (1992a) gives a mathematically simple model, we do not believe the simplification summarizes the true underlying relationship between the total breeding expenditures and returns. Brennan's study assumed that the research program was a mature program interested in knowing the threshold rate of production gains and/or size of wheat industry to justify expenditures on a single breeding cycle. In this study, however, we are interested in the question faced by a country, region, or an environment on whether or not it should invest in wheat improvement research; and if yes, what should be the appropriate research capability (i.e whether it should focus on testing program or have a breeding program). No region/country would make such decisions based on the costs and returns of only one breeding cycle. Such investment decisions are (or should be) made on the basis of future costs and benefits over at least three decades.

Thus, the appropriate method to use would be to consider the breeding costs as an annual stream of costs starting from year 1 and relate it to a flow of returns with a distributed lag. The important issue therefore, is modeling the annual stream of costs and returns for different level of research capability. This is discussed in the following sections.

Modeling the Returns of Wheat Breeding for Testing and Breeding Program:

In this study two different model specifications of equation 6.1 are used to depict the returns from wheat improvement research at different levels of research capability. The major decisions facing research administrators are whether the research focus should be to evaluate materials from other programs or to incorporate the materials as parents and create new technologies. Thus, two levels of wheat improvement research - testing of foreign materials and breeding are considered in the model specifications. The models specified below differ in their assumption on the time pattern of production increments due to research.

Model 1:

$$R_t^1 = P_t\, Q_t\, g_1\, \alpha_t \qquad for\ t = n_1,\ldots,T \tag{6.3}$$

$$R_t^2 = \begin{cases} P_t\, Q_t\, g_1\, \alpha_t & for\ t = n_1,\ldots,n_2-1 \\ P_t\, Q_t\, g_2\, \alpha_t & for\ t = n_2,\ldots,T \end{cases} \tag{6.4}$$

where, n = research lag
$g_2 > g_1$
superscripts/subscripts
1 represents testing program
2 represents breeding program

Equation 6.4 is similar to the estimates of the gross returns from a breeding program as used by Brennan (1992a). However, the calculation of gross returns of a breeding program differs from Brennan (1992a) in the inclusion of research benefits of testing in the initial years (n_1 to n_2-1) before the breeding program starts yielding benefits.

The time pattern of production increments is depicted in Figure 6.1. In this specification, the yield advantage of locally crossed varieties is represented by the higher percentage increment in production (g_2) for a breeding program. The difference between the rate of production growth due to a breeding program and a testing program (g_2-g_1) reflects the availability of directly transferable technology from other sources. It determines the yield advantage from a local breeding program after a certain number of years. The larger the spillins, the smaller will be the difference between g_2 and g_1, and smaller will be the yield advantage of locally developed varieties.

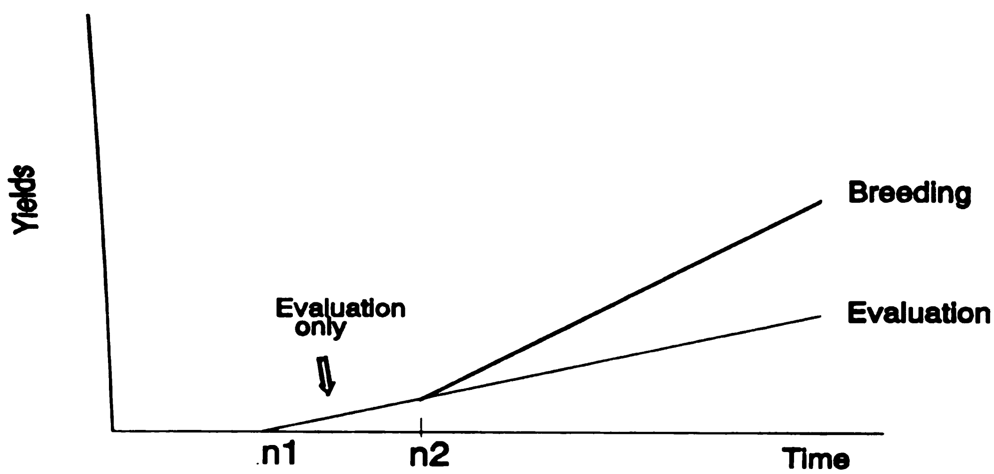

Figure 6.1: Time Pattern of Yield Increments of an Evaluation and Breeding Program, Model 1 (Divergent Rate of Increments in the Long-run)

Model 2:

$$R_t^1 = P_t\, Q_t\, g_1\, \alpha_t \qquad \text{for } t = n_1,\ldots,T \tag{6.5}$$

$$R_t^2 = \begin{cases} P_t\, Q_t\, g_1\, \alpha_t & \text{for } t = n_1,\ldots,n_2-1 \\ P_t\, Q_t\, g\ \alpha_t & \text{for } t = n_2,\ldots,n_2+N \\ P_t\, Q_t\, g_1\, \alpha_t & \text{for } t = n_2+N+1,\ldots,T \end{cases} \tag{6.6}$$

$g > g_1$

This model specification assumes the following pattern of production increments due to local breeding program (Figure 6.2) - (1) locally developed varieties enjoy absolute yield advantage over the imported technology. This is shown by the higher rate of yield increments from year n_2 to n_2+N. (2) In the long-run, the rate of production increments of a locally bred variety is same as the imported technology.

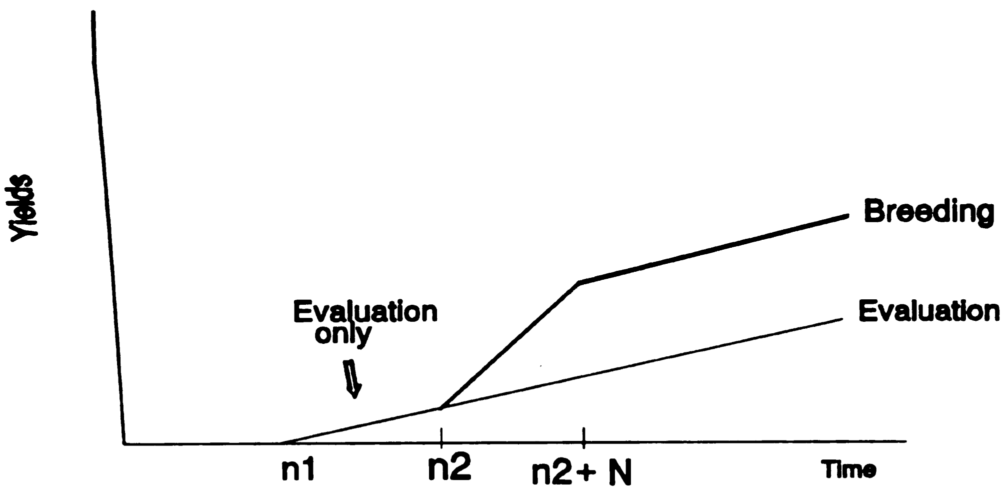

Figure 6.2: Time Pattern of Yield Increments of an Evaluation and Breeding Program, Model 2 (Parallel Rate of Increments in the Long-run)

The basic difference between model specifications 1 and 2 is that the former assumes a long-term divergent rate of production increments for testing and breeding program, whereas in model 2 the long-term rate of production increments is assumed to be the same for a testing and breeding program. In model 2, the locally developed technology (from a breeding program) enjoys an absolute yield advantage in terms of reaching a higher production levels in the first few years after the research project starts yielding benefits. This is realized over a period of N years in the form of higher rate of production increments (g) which is higher than the rate of production increment of a breeding program in model 1 (g_2).

In reality, whether the actual production increments will follow the time pattern given in model 1 or in model 2 will depend on the biological complexity. Greater the complexity, more difficult it will be to achieve absolute yield advantage in short period of time. In terms of the model parameters, greater the biological complexity larger the value of N (i.e closer will be the time pattern as given in model 1). For example, breeding for resistance to soil toxicity alone (as in ME3 - acid soils) may give a time pattern of yield increments as depicted in model 2, with N = 10 or 12 years. However, if some other complexity is added to the breeding environment, say resistance to drought or early maturity then the rate of yield increments may be less and it may take more than twelve years to achieve the same level of absolute yield advantage.

Since, the stream of expected returns are discounted to calculate the net present value of breeding investments, these model specifications will provide the sensitivity of results to different biological complexity in the given environment.

Modeling Costs of Wheat Breeding for Testing and Breeding Programs

The time pattern of costs of a wheat breeding program are modeled as follows:

$$C^f = C_s S^f \qquad for\ t = 1,\ldots,T-n \tag{6.7}$$

for f = 1 (testing)

= 2 (breeding)

$S^2 > S^1$

The cost per scientist-year (C_s) are real costs (deflated by an appropriate price index). The cost of a breeding program in time t will differ from a testing program by a constant $[C_{st}\ (S^2 - S^1)]$.

The expected pattern of costs and returns of a breeding program is illustrated in Figure 6.3 using the time pattern of yield increments as given in model 1 and the assumption of constant costs per researcher, C_s, and price of wheat, P over time.

6.3.3 Criteria of Profitability

On the basis of the foregoing assumption about the time pattern of costs and returns of a wheat breeding program, the Net Present Value (NPV) of breeding research investment for a given research capability, is calculated as follows:

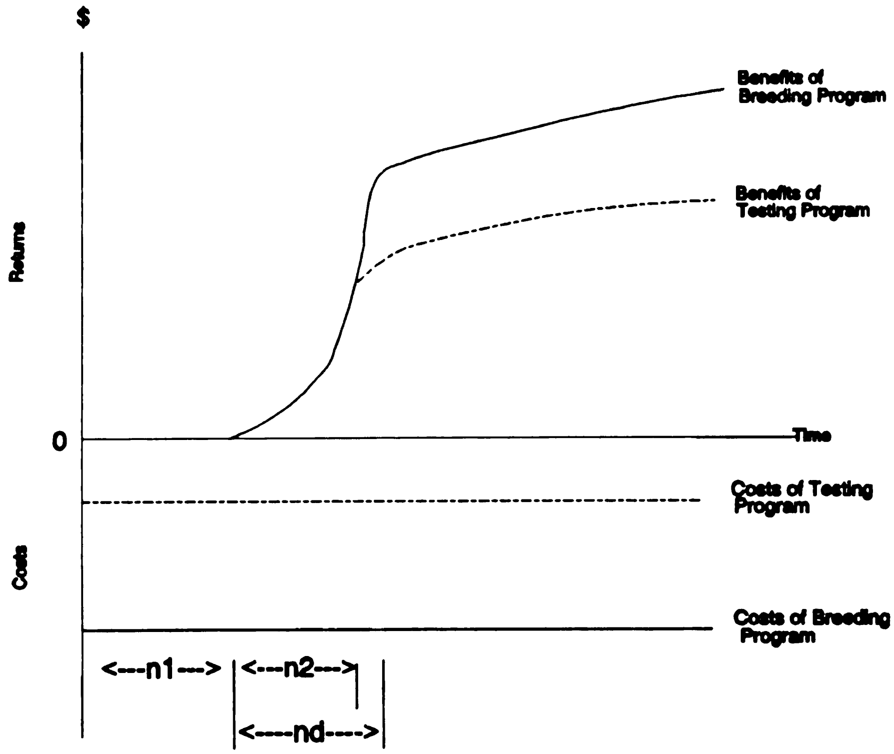

Figure 6.3: Time Pattern of Costs and Returns of a Testing and Breeding Program

$$NPV = \sum_{t=1}^{T}\left(\frac{R_{t+n}}{(1+r)^{t+n}}\right) - \sum_{t=1}^{T}\left(\frac{C_t}{(1+r)^t}\right) \tag{6.8}$$

where, R and C are respectively, the estimated annual returns and costs of a breeding program, n is the expenditures-to-returns lag (research lag between the expenditure and the release of commercial cultivar) and r is the discount rate.

To compare the profitability of investments in a testing versus a breeding program, equation 6.11 can be used to apply the commonly used profitability criterion as follows: Given the size of production and rate of production increments, accept the alternative with the largest (and positive) NPV when discounted at opportunity cost of capital.

The NPV selection criterion can also be used to estimate the threshold levels of production (Q^*) and the threshold level of rate of production increment (g^*) for a given value of other parameters. For example, in model specification 1, the NPV of the research project for a testing program and breeding program are,

Testing Program:

$$NPV = Q_o^* \sum_{t=1}^{T} \frac{P_t\ g_1^t\ \alpha_t}{(1+r)^{t+n_1}} - \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} \qquad (6.9)$$

Breeding Program:

$$NPV = Q_o^* \sum_{t=1}^{n_2-n_1} \frac{P_t\ g_1^t\ \alpha_t}{(1+r)^{t+n_1}} + \sum_{t=1}^{T} \frac{P_t\ g_2^t\ \alpha_t}{(1+r)^{t+n_2}} - \sum_{t=1}^{T-n_1} \frac{C_t}{(1+r)^t} \qquad (6.10)$$

since, $Q_t = Q_{t-1}\ g$

The threshold levels of production, Q_o^* (the initial size of wheat industry) to justify a testing program (as against no research program) and a breeding program (as against a testing research program) can be determined by setting the discounted benefits equal to discounted costs (i.e. NPV = 0) and solving the equations respectively for Q_o^*. Similarly, equations, 6.10 and 6.11 can be solved for g1 and g2 such that the NPV = 0. It is difficult to derive a simple mathematical equations that solves for g1 and g2. However, if this model is setup in a spreadsheet, it is easy to compute the g_1^* and g_2^* by substituting different values for g_1 and g_2, until the NPV = 0.

6.4 Analyses of Wheat Improvement Research Programs: General Application of the Model

The model developed in the previous section is applied to a general situation to identify 1) the threshold size of an industry to justify different levels of breeding research activity and 2) the rate of production growth rate necessary to justify spending a given amount on wheat improvement research.

6.4.1 Parameter Estimation

To compare the profitability of investments in wheat improvement research at different levels of research capability, the parameters of equations 6.4 to 6.8 need to be estimated. The parameters for estimating the cost function are - C_{st} and S^f for t = 1,...,T and f = 1,2. For estimating the benefit function we need to know the values of P_t, Q_t, g, r, n_1 and n_2.

The values of this parameters will differ from situation to situation. However, we will make an attempt to estimate parameters based on average values so as to make some general analyses of wheat breeding programs in developing countries.

Cost Per Researcher (C_{st}): As examined in chapter 4, the average expenditure per scientist (weighted by total number of agricultural researchers) in wheat producing countries of developing world was estimated to be about U.S. $ 57,000 per year. The estimates by Pardey, et al. (1991b and 1991c) ranged from U.S. $46,700 to U.S. $59,200, depending on the countries included in the calculation. Given that the model is applied to wheat research in wheat producing countries of the developing world, the average cost per researcher of U.S. $57,000 (in 1980 PPP U.S.$) is considered to be more representative.

According to the estimates of Pardey et al. (1991a), the expenditure per researcher has declined in real terms over the past two decades. However, for the purpose of this analysis the trend is assumed to discontinue in the future. In other words, real expenditures per researcher (i.e. after accounting for inflation) are assumed to remain constant in the course of a breeding project.

Number of Researchers (S^f): This is an important parameter to estimate, since it will have implications for the size of a wheat breeding program. As mentioned before, the number of researchers in a wheat breeding program will depend on the research capability. Thus, we need to estimate the number of researchers required to carry out a testing program and a breeding program.

The empirical investigations of chapter 4 indicated that the average size of a testing program in developing countries was 1.4 FTE researchers for the wheat improvement component (Table 4.15). For a breeding program the average size was found to be 4.2 FTE researchers for the wheat improvement component. However, given the premises of this study that the agricultural research systems in developing countries are over-sized relative to their research productive capacity and that the size of a research program has been guided more by the bureaucratic and political factors rather than economic viability, these figures do not represent the true number of researchers needed to run a testing and a breeding program.

The estimated parameters for this variable are therefore based on the survey of developed country wheat research programs reported in chapter 4. The number of researchers in wheat breeding programs in industrialized countries is used as a guideline for estimating the size of a full breeding program. The number of researchers (breeders + other scientific disciplines with B.S., M.S. and Ph.D. degrees) in the research programs surveyed averaged 3.1 FTE researchers per program (Table 4.16). Among the research programs surveyed, the public funded research programs tend to have a larger number of researchers (3.9 FTE) than the private sector research programs (2.6 FTE). Since the private sector invests in research with the motive of making profits, these research programs are less likely to be 'over-sized'. Thus, the number of researchers in the private sector (2.6 FTE) would be more representative of the actual number of researchers required to carry out a full breeding program. However, when the average number of production environments are compared, the public sector research programs tend to work in more heterogenous target domains than the private sector. Also, public sector research programs do more strategic/basic research - which provides source germplasm for the private sector. If these facts are taken into account, the average size of a research program in publicly funded research programs would be more representative for our analysis.

For the purposes of general analysis, therefore the number of researchers per production environment (0.98 FTE) in the public sector of developed countries (3.9 FTE per 4 environments - Table 4.16) is used as the basis for estimating the size of a breeding program. Taking the mean number of environments in the target domain to be 3.0 as estimated for developing countries (Table 4.15), the number of researchers required in a breeding program is approximated to be 3.0 FTE researchers (based on the following calculation: 0.98 * 3.0 = 2.94).[2]

Since no data on the size of a testing program in developed countries are available, it was difficult to estimate the number of FTE for a testing program. Brennan (1988) reports the total costs of an Australian wheat breeding program (F1 to F10) in terms of costs per generation (Table 6.1). Considering that a testing program would evaluate imported lines from F7 generation, Brennan's (1988) cost data can be used to estimate the ratio of costs of a testing program (F7-F10) to a full breeding program (F1-F10).

Table 6.1: Total Costs of a Representative Breeding Program Associated with Each Generation

Generation	No. of Lines Evaluated	Total Costs (Aus.$)
F1	--	3,865
F2	(35,000)[a]	30,646
F3	2,000	30,898
F4	300	4,262
F5	2,000	17,166
F6	300	63,995
F7	50	16,125
F8	10	4,040
F9	5	3,180
F10	3	2,707
F7 to F10	--	26,052
ALL	--	176,885

Source: Brennan (1988, p.66-67)
[a] Plots containing 35,000 single plants are sown in F2 generation

This ratio is estimated to be about 1:6 (i.e. the costs of F7 to F10 generations were about 15% of total costs of a breeding cycle of F1 to F10 generations). If this ratio is used to the estimated size of a breeding program of 3 FTE, the size of a testing program would be approximately 0.45 FTE. This seems very small compared to the size of a testing program in developing countries (1.4 FTE). Also, it would be an underestimation if we consider that an evaluation program would test

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[2] It should be noted that a research program (whether breeding or testing) is defined for a specific geographic domain which may be homogenous or have sub-environments with small genetically adjusted 'environmental distance'. For example, the target domain of a research program could have two distinct production environments characterized by normal planting and late planting. In this case, the whole target domain is considered to be under one research program. However, if the environments were characterized by bread wheat and durum wheats, two separate crossing programs one for each wheat type will be defined. Thus, a research program is defined for target domains which may have more than one agroclimatic environments such that the same crosses could be used with selections in each environment.

more than 50 or 10 imported lines in the F7 and F8 generations to identify the best adaptable genotypes.

As an alternative, the size of a testing program in developing countries was estimated to be one-third of the breeding program based on the actual ratio of the number of FTE researchers in a testing program to that in a breeding program (1.4 FTE/4.2 FTE) (Table 4.15). Using this information the mean size of a testing program is assumed to be 1.0 FTE (one third of 3.0).

Wheat Price (P_t): For the market price of wheat, the long-term trend price was determined based on the real wheat price from 1963 to 1991 (Appendix D). Since most developing countries are importers of wheat, the average of trend import price (c.i.f.) was used to estimate the long term wheat price. The trend price is calculated in real 1980 U.S. dollars to correspond with the estimates of cost per researcher. Assuming that the trend will continue in the future, the wheat price was estimated for the years 1993 to 2043 (the years for which the ex-ante analysis is carried out).

Discount rate (r): The selection of an appropriate real discount rate is important in assessing the NPV of research investments. Gittinger (1982) argued that the appropriate social discount rate to use for economic analysis is the opportunity cost of capital. According to his estimates, the opportunity cost of capital in most developing countries is assumed to be between 8 and 15 percent in real terms. In this study, we will use the commonly used discount rate of 12 percent per annum and use other discount rates to test for the sensitivity of the results.

Research lag (n_1 and n_2): For plant breeding research the research lag is defined as the time between the initiation of research (year 0) and release of variety (year n_1 or n_2). Assuming that the wheat varieties to be commercially released are selected from the advanced lines of F9 or F10 generations (i.e. after eight or nine generations of self-pollination), it will be at least ten years before the breeding program can identify a potential variety[3]. To commercially release an identified cultivar, it has to undergo seed certification and multiplication which would require another two to three years. Thus, on an average, for a breeding program, the research lag can be assumed to be about twelve years (ten years for variety identification and two years for release procedures).

If a research program is focusing on only testing and making selections from imported germplasm, it will take anywhere from 1 to 4 years to identify a potential variety, depending on the advancement of the foreign lines tested and another two to three years for seed certification and multiplication. Therefore, we can assume the research lag for a testing program to be about five years.[4]

In short we assume that an average research lag for a wheat breeding program is 12 years, and an average research lag for an evaluation program is 5 years.

Adoption parameter, α_t and the diffusion lag: Once the variety is commercially released (either from local crosses or selected from foreign materials), it is taken up by farmers, with the rate of adoption typically following an S-shaped curve. The area planted with the new variety gradually expands, reaching a maximum at peak adoption, and then declining as the variety is gradually replaced with new ones. The time period between the commercial release of a variety and its peak adoption is usually referred to in the literature as the adoption lag. Brennan

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[3] As noted by Brennan (1988) the length of time between the crossing to the identification of the variety can be shortened if two generations can be obtained in a year. He analyzed three different ways of reducing the breeding time in the context of Australia - 1) growing a generation over summer in the glass house or other controlled environment; 2) earlier release of cultivars after less testing; and 3) the use of tissue culture allowing fixed breeding lines to be produced for testing very rapidly. His analysis showed that reducing the time lag by any of these methods increased the profitability of plant breeding research to the society. Since these methods are not used widely in practice, we use the generally used figures of 9-10 years to reach the F9-F10 generations.

[4] A crossing program would also be involved in testing of foreign materials and based on this assumption it would release varieties from its testing program as early as the fifth year.

and Byerlee (1991) found an average adoption lag of seven to eight years based on data from several developed and developing countries.

This estimate is however, for individual varieties released. Since, we consider breeding research as a continuous process we are not interested in modeling the adoption pattern of a single variety released after the end of the research lag but the adoption pattern of the flow of all the subsequent varieties to be released during the course of a research project. A hypothetical diffusion pattern of new varietal technology attributed to a research program is depicted in Figure 6.4. The area planted to any single variety typically follows a bell-shaped curve with an initial expansion in the area planted to that variety, reaching the maximum adoption after a lag of few years and eventually declining as new varieties are released and replace the old ones.

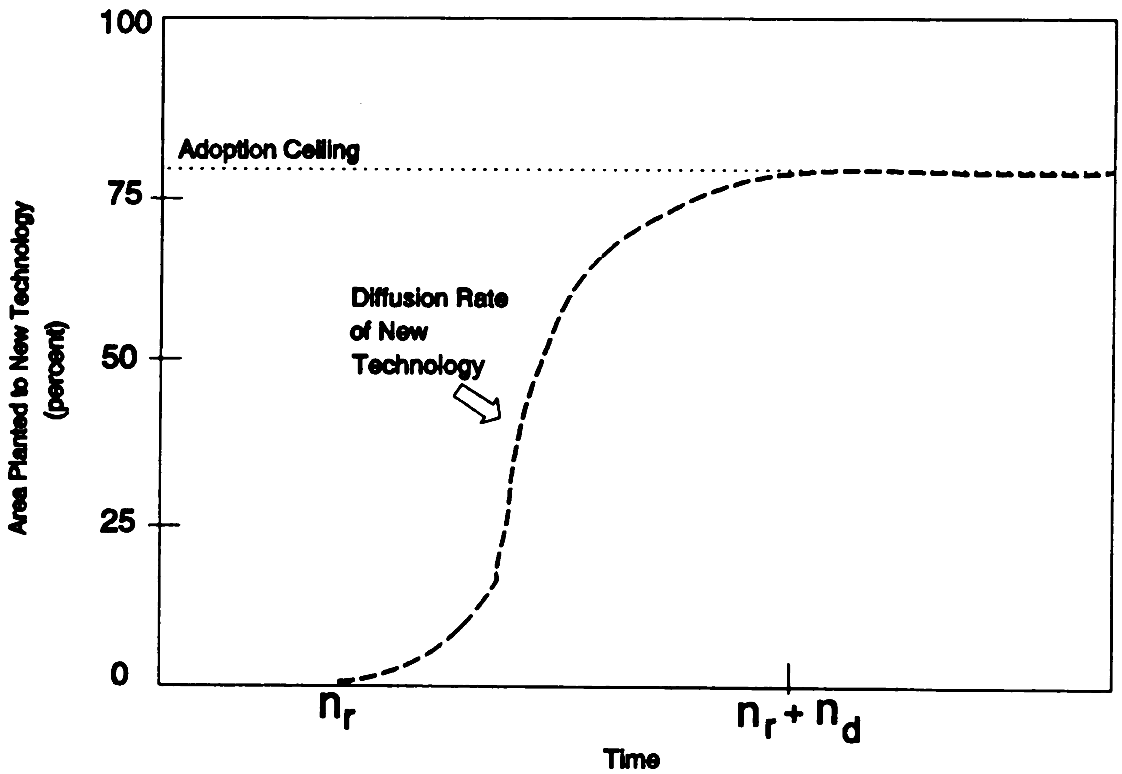

Figure 6.4: A Hypothetical Diffusion Curve of Varietal Technology

The area planted to all new varieties attributable to a research program, on the other hand typically follows a logistic growth curve (Figure 6.4). The percentage of area planted to new varieties increases, first at a slower rate and then at an increasing rate as more farmers adopt the new technology and as more varieties are released by the research program. This is followed by a slowing of adoption in the final phases as the new varieties get diffused in the target region and only the laggard farmers continue using the old varieties.

To calculate the returns from wheat improvement research, the curve we are interested in estimating is the logistic curve of total technology adoption in the target region for the period n_r to n_d. The logistic curve will determine the adoption rate in each time period (α_t) before it reaches the ceiling rate (in time period n_d). It is defined as follows:

$$\alpha_t = \frac{A}{\left(1 + e^{-(a+bt)}\right)} \qquad for\ t = 1,\ldots,n_d \qquad (6.11)$$

where, n_d = adoption lag; A = ceiling adoption level; a,b = parameters of the logistic function.

In order to model the diffusion of new varieties over the base period production (Q_o) as a smooth logistic growth curve we need to know the following parameters - A, n_d, and parameters a and b. These were estimated as follows. An initial assumption for the diffusion lag, n_d is made of 10 years[5]. For simplicity, the maximum level of adoption is

[5] Morris et al. (1992) used the same length of diffusion lag to estimate the rate of returns to wheat research in Nepal. However, in the pioneering study on the adoption of hybrid corn technology in different states of the U.S., Griliches (1957) found the diffusion lag to be ten or more years. Such large diffusion lags are expected for a totally new technology such as hybrid corn which was replacing the open pollinated varieties in the 1930s and 1940s. However, the present analysis is focused on the post-green revolution era in regions where the farmers have already adopted the semi-dwarf wheat technology. The lag of ten years, thus seems reasonable for new semi-dwarf varieties (attributed to new research program) to replace the old semi-dwarf varieties.

assumed to be 100% (i.e. A = 1)[6]. This means that the 100 percentage of production in the target region in the eleventh year after the research lag (or the first release of a variety) is attributed to the new varieties of the research program. Assuming that the rate of adoption is 5% of the wheat area in the first year after the research program releases a variety and it reaches 99% after ten years, the parameters a and b were estimated to be -3.97 and 1.02, respectively. Using these parameter values, the adoption rate, α_t was estimated using equation 6.14 for the project years six to fifteen (Appendix E). For the years seventeen onwards, α_t was assumed to be 1.

The rate of growth in productivity (g): In order to estimate the threshold size of industry, we will assume the future rate of yield increments to be as given in model 1. Thus, we need to estimate the parameters g^1 and g^2.

Over the past couple of decades, technological advance in developing countries' wheat production, as measured by the rate of yield increase, has been remarkable. However, wheat breeders are less optimistic about the future growth rates attributable to varietal improvement. For example, CIMMYT (1989) study reports the varietal component of the yield gains of only 0.7 percent per year in its most 'optimistic' and down to 0.4 percent per year in the most 'realistic' projection. In terms of different environments, they provide estimates of about 1 percent per year yield gains in a well-watered environment and from 0.3 to 0.6 percent per year for dryland production regions over a long-term period.

Following Brennan (1992a), wheat yields are optimistically assumed to increase at an average rate of 1.0 percent per year if the research program focuses on technology creation (i.e for a full breeding program). The rate of gain per year due to testing program is difficult to estimate. It is highly sensitive to the difference between the

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[6] Since we are interested in the question of what size of wheat industry is needed to justify a research program, Q_0 can be defined as the level of production at the adoption ceiling level rather than total production in the target domain. Thus, even if A is < 1 for the whole target domain, it would be equal to one in terms the definition of Q_0.

domestic environment and the environment of varietal origin (i.e. the potential technology spillins). Thus, they need to be carefully determined for a particular environment. However, the results of chapter 5 can be used as a guideline to estimate the yield growth rate for the purpose of general analysis of this chapter.

The absolute yield advantages of locally developed cultivars in different megaenvironments as reported in Appendix Table C.2 are used to calculate the yield gains of locally developed cultivars. Table 6.2 gives the yield gains of locally developed cultivars over the cultivars imported from the potential spillin environments under two scenarios - with CIMMYT as a potential source of direct spillins and without CIMMYT. The potential spillins for the 'without CIMMYT' scenario are calculated for each megaenvironment as the average of the smallest three yield disadvantages compared to the cultivars of the test environment.

If CIMMYT is considered as the potential source of direct spillins, locally developed cultivars either have minimal advantage or

Table 6.2: Yield Gains of Cultivars Developed by National Programs in Different Megaenvironments Under Two Scenarios of Potential Sources of Technology Spillins

Scenario	ME1	ME2	ME3	ME4A	ME4B	ME5A	ME6A	ME7
	(Percentage yield gains of locally developed cultivars)							
Without CIMMYT	6	4	11	9	10	3	2	2
With CIMMYT	-11	-13	1	-1	-7	-1	-3	2

no advantage at all (Table 6.2). For the purpose of this analysis however, we assume the alternative scenario where the only source of technology spillins is the national programs (i.e. without CIMMYT). The yield gains of locally developed technology across different megaenvironments varies from 2% to 12%. Taking the optimistic scenario by assuming that in twenty years (i.e. in less than two breeding cycles) a local breeding program would achieve yield gains of 6% (which is more than the average yield advantage across all the megaenvironments) over the testing program technology, implies a difference in yield gains of 0.3% per year.[7] Based on this calculations, the conservative estimate of the yield gains of a testing program is assumed to be 0.7% per year (0.3% less than the assumed yield gains for a breeding program).

The values of g_t for breeding program (1%) and for testing program (0.7%) are only indicative and would need to be carefully determined in analyzing a particular region or country. In the sensitivity analysis, several alternative future rates of yield gains (both higher and lower) and differences in yield gains are considered.

If both the area and yield could increase as a result of wheat research program, a faster rate of production could occur. However, as discussed in chapter 3, the model specification implicitly assumes a perfectly elastic demand curve and a perfectly inelastic supply curve. Thus, the outward shifts of the supply curve are due to increasing yields rather than area. In other words, the rate of production gains, g_t is the same as the rate of yield gains.

6.4.2 Analysis of Threshold Size of Wheat Industry

The decision on whether to import wheat varieties from other sources or to establish a local breeding program will depend on many environmental, biological and economic factors. First, and most importantly, it will depend on the size of the potential crop production in the target research domain. Hanson et al. (1982, p.86) argued that "any country that has 200,000 hectares of rainfed wheat or 100,000 hectares of irrigated wheat can justify supporting one or more research stations for adaptive wheat trials. Such area should produce a wheat crop of at least 200,000 tons." Although, this estimate of threshold level of wheat production was subjective, it identifies the importance

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[7] In other words, if the rate of yield gains of a crossing program is 1% per year and that of a testing program is 0.7% per year, and assuming that the rate of yield gains follow the time pattern given in model 1, then twenty years after the crossing program starts yielding higher rates, the yield difference between the two technologies as a percentage of the yields of cultivars from testing program will be 6%. Note that if the testing program would have the same research lag as the crossing program, then the yield advantage of a crossing program would be 10% in 20 years.

of the size of wheat industry in justifying the level of research resources.

The model developed in this chapter can be used to address this issue of the threshold size of wheat industry in a given environment to justify a testing or a breeding program. The threshold wheat production level for testing and breeding program is established from equation 6.10 and 6.11 by setting the NPV = 0, respectively. The returns to research were calculated using the time pattern of yield increments as given in model 1 (equation 6.4 and 6.5).

The parameters used in the analysis are summarized in Table 6.3. On the basis of these parameter estimates, the critical production level needed to justify investment in a full wheat breeding program (i.e. the level at which NPV = 0) is found to be 462,000 tons (Table 6.4). What this suggests is that, if the parameter values hold true, for environments generating less than 462,000 tons, the research capability of creating new technology by investing $171,000 each year would not be economically justified. Similarly, the threshold production level at which a testing/evaluation program (i.e. research investment of $57,000 per year) becomes economic is 198,000 tons (Table 6.4).

Table 6.3: Parameters used in the analysis

Parameters	Evaluation Research	Breeding Research
g_t Rate of production gains (%/year)	0.7	1.0
P_t Wheat Price ($/tons)	a	a
C_{st} Cost per scientist ($/year)	57,000	57,000
S_y Number of researchers (scientists/yr)	1.0	3.0
n_r Research lag (years)	5	12
α_t Adoption rate (%)	b	b
r Discount rate (%/year)	12	12

a As given in Appendix D
b As given in Appendix E

Table 6.4: Threshold size of wheat industry for different wheat breeding programs: Results of the general analysis of model 1.

Size of wheat industry (000 tons)	Results of the analysis based on the NPV selection criterion
< 198	Cannot justify any wheat breeding research program
198-462	Testing & selection only profitable research program
462-1,392	Crossing profitable but less than testing and selection
>1,392	Crossing most profitable research program

Decisions on efficient allocation of breeding resources need information not only on the production levels at which different programs become profitable, but also information on which program is most profitable at different production levels. The results summarized in Table 6.4 indicate that if the parameter values hold true, according to the NPV selection criterion, evaluating imported varieties is most profitable starting from production levels of 198,000 tons until production reaches 1,392,000 tons, when full breeding program becomes the most profitable. Thus, even though the investment of $171,000 per year is yielding a positive NPV starting from the production level of 462,000 tons, it is economically not the best alternative until the production level is more than 1,392,000 tons (i.e. the research program could reduce the size of its research team and still earn an NPV higher than the breeding program).

The results therefore suggest that making investment decisions based only on the criterion of accepting a research project with positive NPV and ignoring the opportunity costs may not be making an economically efficient investment. Given the fact that the research capability determines the size of a research program, these results have implications on the appropriate size of wheat research program. For example, if the baseline scenario holds, a country/region producing 462,000-1,392,000 tons of wheat, although earns a positive net returns with a breeding program consisting of three FTE research scientists, will be better off with only a testing program by employing only one FTE scientist.

6.4.3 Analysis of Threshold Rate of Production Improvement

The results of the above analysis depend critically on the rate of production gains for testing and breeding program. As shown by the empirical results of chapter 5 (Table 6.2), the rate of yield increments will vary widely between megaenvironments depending on the environmental complexity and research spillins. Previous analysis was based on the expected yield gain difference of 0.3%/year for a breeding program which gave the cultivars from local crosses an advantage of 6% in twenty years. The expected yield gain difference from a breeding program needed to justify a breeding program will however differ for different size wheat industry. In the following analysis model 1 is used to determine the threshold rates of production improvement for different size wheat industry.

The threshold rate of production improvement necessary to make a testing program profitable was determined from equation 6.10 by setting up the spreadsheet program such that the NPV = 0 for a given level of production (Q_o). The results are reported in Table 6.5 for different levels of wheat production.

In case of breeding program, the threshold rate of yield increments necessary to make investments in breeding program most profitable were determined from equations 6.10 and 6.11. For a given level of Q_o and g_t for testing program = 0.7% (as in the baseline scenario), the g_t for breeding program was determined such that the NPV of breeding program equaled that of testing program. The results of this analysis are also reported in Table 6.5 for different levels of production.

The yield gains per year necessary to justify a wheat improvement program (whether testing or breeding) increase exponentially as the size of wheat industry declines. The threshold rates of yield gains are so high that for countries and environments with small wheat area it becomes very difficult to justify even a testing program, unless the area and production are expected to expand very rapidly. Since size of

Table 6.5: Threshold rate of production gains (%/year) to justify a testing and crossing program at different size of wheat industry

Production (000 tons)	Testing Program	Breeding Program
25	3.90	*CJ*[a]
50	2.33	*CJ*
75	1.67	*CJ*
100	1.30	*CJ*
200	0.70	2.26
300	0.47	1.98
400	0.36	1.70
500	0.29	1.51
600	0.24	1.38
700	0.21	1.28
800	0.18	1.21
900	0.16	1.16
1,000	0.15	1.11
1,500	--[b]	0.98
2,000	--	0.91
3,000	--	0.84

[a] *CJ* = cannot justify even a testing program (given the g_t for testing = 0.7%/year).
[b] Not calculated as it is negligible.

wheat industry is measured in terms of wheat production which is positively related to yields per hectares, it follows from Table 6.4 that for a given size of wheat area planted, the threshold rate of yield gains are negatively related to the level of yields. Thus, countries with highly productive wheat environments (such as high rainfall, irrigated, temperate environments - ME1, ME2, ME6A, ME7) can justify a testing program at a smaller size of wheat area than a less productive wheat environment. Since, the rate of yield gains for a testing program are the reflection of direct research spillins, countries/regions in more productive environments are likely to justify a testing program with smaller size of wheat area than their counterparts in less productive environments.

An interesting result to note about the breeding program is that the threshold rate of yield increments are high compared to the world projections even at very high levels of wheat production. For example, the expected rate of yield increments has to be as high as 0.84% per year to justify a full breeding program in a country/region producing three million tons of wheat.

The high threshold rates of g_t for a breeding program are because of the higher opportunity costs in terms of the net benefits of a testing program that are foregone. Given the research spillins that can generate 0.7% yield gains per year from a local testing program, the yield gains of varieties from local crosses have to be quite high to justify investing resources in a breeding program. In order to facilitate comparison with the empirical evidence of Chapter 5, the threshold rates of production gains to justify a breeding program are provided in terms of differences in g_2 and g_1 and the corresponding cumulative yield gains of a local breeding program to be realized over twenty years after the release of first variety from a local crosses (Table 6.6).

Table 6.6: Cumulative Yield Advantage Over 20 Years of Varieties Developed By Crossing Program at Different Size Wheat Industry

Production (000 Tons)	Yield Gains over Testing Program to Make Breeding Most Profitable Alternative (%/year)[a]	Cumulative Yield Advantage of Breeding Program Varieties Over 20 Years (% of Yields of Imported Varieties)
200	1.56	44.7
300	1.28	29.1
400	1.00	21.7
500	0.81	17.3
600	0.68	14.3
700	0.58	12.3
800	0.51	10.7
900	0.46	9.5
1,000	0.41	8.6
1,500	0.28	5.7
2,000	0.21	4.3
3,000	0.14	2.8

[a] Indicates the difference in yield gains per year of a crossing program given the g_t for testing = 0.7%/year.

The additional yield gains per year from local crosses needed to justify a breeding program increases rapidly with the decline in the size of wheat production. These translates into large cumulative yield advantages over a twenty year period. According to the results summarized in Table 6.2, not accounting for the research spillins from CIMMYT, the most yield advantage realized by a locally developed technology was about 11% over the imported cultivars from other environment. Comparing the analytical results of Table 6.6 with the empirical results, it is evident that for environments producing less than 800,000 tons of wheat it becomes increasingly difficult to justify a local breeding program.

6.4.4 Comparison of Results With Brennan's Study

The analytical approach used in this chapter is similar to that used by Brennan (1992a) to determine the threshold levels of production to justify investments in different types of wheat research programs. The model developed in this chapter however differs from that used by Brennan in two fundamental ways. First, in modelling the relationship between costs and benefits over time, and second, in modelling the different time patterns of production increments due to local breeding program.

Although Brennan recognized that breeding research is a continuous process characterized by a flow of annual costs and a subsequent flow of annual returns, his model assumed that all breeding costs are located in the year of maximum costs of a breeding cycle and related them to the returns which were also assumed to be located in the year of maximum returns. Unlike Brennan's approach, the model in this study uses a continuous time frame in estimating the costs and returns from research. It assumes an annual flow of research expenditures from year 1 to year M and relates it to an annual flow of returns starting from year n_r to year $M+n_r$; where, n_r is the research lag and M is the total time period of analysis (fifty years in this study).

As in the present model, Brennan accounts for the advantage of a breeding program in terms of the difference in the g_t of a breeding and testing program. However, since the costs and returns in Brennan's model were calculated for a single year, he implicitly assumed a divergent rate of production increments. In the present analysis, because, the returns are calculated as an annual flow of production increments, it is possible to assume different time patterns of g_t for a breeding program to account for different biological complexities and possibilities of research spillins.

Other than the model specification, the analyses also differ in terms of the parameter estimations for the relative costs and yield growth rates of a breeding (what Brennan calls a breeding program) and testing program, and the adoption parameter. He has underestimated the research costs both in terms of number of FTE and cost per researcher.

In the light of the empirical evidence provided in Chapter 4, his estimates of 2.0 and 0.8 FTE for a breeding and selection program seem quite low. Similarly, his assumption about the annual cost per researcher of $50,000, measured in 1980 U.S. dollars, remaining constant in 1990s when measured in 1989 U.S. dollars grossly underestimates the research costs in developing countries in 1990s.

Because of these differences, the threshold levels estimated by Brennan to justify a research program are in general lower than those estimated by this study. According to the estimates of Brennan the level of production to justify a breeding, selection and testing program was 322, 146 and 82 thousand tons, respectively which are lower than our estimates of 462 thousand tons for a breeding program (what Brennan refers to as a breeding program) and 198 thousand tons for an evaluation program (akin to Brennan's selection program in terms of parameters S_y and g_t). The level of production when a breeding program becomes most profitable alternative, according to Brennan's estimates was 1,582,000 tons which is a little more than our estimate of 1,392,000 tons.

To sum up, because of some basic differences in the methodologies and parameter estimates, the results of this study differ from those reported by Brennan (1992a). Present study can be considered an extension of Brennan's approach in basically three ways. First, it has used a continuous time frame approach which is akin to the ex-ante evaluation methodologies. Second, it allows for different patterns of yield increments depending on the biological complexity and research spillins in the target domain. Third, the analysis is based on empirically estimated parameter values of important variables, such as the relative costs of a breeding and evaluation program, the cost per researcher and the yield advantage of locally developed varieties over those imported from other programs.

6.5 Sensitivity of Results to Changes in Parameter Values

6.5.1 The Effect of Absolute Changes in All the Parameters on the Threshold Size of Wheat Industry

The threshold size of wheat industry needed to justify economically the different size and capability of research program will vary for different countries/regions with the level of costs, expected rates of yield increments, research and adoption lags, prices and opportunity cost of capital. It is therefore important to identify the sensitivity of the findings to changes in the levels of these parameters. The results of sensitivity analyses (using values of +25% and -25% for each parameter) of the threshold level of production are reported in Table 6.7.

Table 6.7: Sensitivity of Results to Changes in the Parameter Values

Par.	Values[a] Testing	Values[a] Breeding	Production to justify a testing program (000 tons)	Production to justify a breeding program (000 tons)	Production at which breeding is most profitable (000 tons)
g_2-g_1 (%)	0.15		161	431	2,727
	0.30		198	462	1,392
	0.45		256	498	948
P_t ($)	$0.75 * P_t$		264	616	1,857
	P_t		198	462	1,392
	$1.25 * P_t$		158	370	1,114
C_s ($)	42,750		148	357	1,044
	57,000		198	462	1,392
	71,250		247	578	1,741
S_y	0.75	2.25	148	357	1,044
	1.00	3.00	198	462	1,392
	1.25	3.75	247	578	1,741
n_r	4.0	9.0	173	371	866
	5.0	12.0	198	462	1,392
	6.0	15.0	226	556	2,056
α_1 (%)	3.75		205	475	1,394
	5.00		198	462	1,392
	6.25		193	452	1,392
r (%)	9.0		164	372	1,024
	12.0		198	462	1,392
	15.0		240	574	1,893

[a] Parameters that differ by the type of program are given separately. The values for P_t are given in Appendix D. The parameter α_1 refers to the adoption rate in the first period after the release of variety.

The threshold level of production to justify a given type of a research program is very sensitive to the values of each parameter. In particular, the level of production at which breeding is most profitable is most sensitive of all the results. Among the parameters, those indirectly affecting the research costs, namely the research lag (n_r) and the discount rate (r) are particularly important. The time taken to develop improved varieties is therefore an important factor and needs careful evaluation in making research allocation decisions. Also, the difference in the rate of production gains (g_2 - g_1) or potential research spillins has a critical impact on the threshold levels of production when breeding is most profitable. An increase in research spillins as reflected in smaller difference in yield growth rates substantially increases the threshold level of production to make breeding program most profitable.

Although the time when adoption starts (n_r+1) is an important factor influencing the results, adoption rate in the first period after a variety is released is less important. Changing the adoption rate in the first period from 5% of total production to 3.75% or 6.25% had a negligible effect on the results.

6.5.2 Effect of Quality Differentiation on the Threshold Size of Wheat Industry

In the above analysis, the advantage of a local breeding program is measured in terms of only one trait - yields. However, a local breeding program may have an advantage in terms of developing varieties which are not only better yielding but are also of better quality as defined according to local tastes than imported varieties and therefore preferred by local consumers. In order to test the sensitivity of results to such quality differentiations, the price of wheat for locally developed varieties was assumed to be higher than that of varieties from a testing program. Thus, in the model specification different price levels for a testing and breeding program reflect the fact that a local breeding program may give a quality premium.

Table 6.8 illustrates the sensitivity of results to such quality differentiations. The threshold levels of production when research program starts earning positive returns do not seem to be very sensitive to the quality differentiation. However, a 5% quality premium of locally developed technology decreases the threshold levels of most profitable alternative by almost 15 to 20%, indicating that the level of production at which breeding program is most profitable is very sensitive to quality premiums measured in terms of price differentiations.

Table 6.8: Sensitivity of Threshold Levels of Production to Quality Premiums of Locally Developed Varieties

Quality Premium[a] of locally developed variety	Production at which NPV of breeding research program = 0 (000 tons)	Production at which breeding program is most profitable (000 tons)
0%	462	1,392
5%	440	1,136
10%	420	959
15%	402	830

[a] Measures the percentage price premium of varieties developed by a crossing program over those imported from elsewhere.

6.5.3 Effect of Different Time Pattern of q_t on the Threshold Size of Wheat Industry

The analysis so far undertaken assumed a divergent rate of yield gains for a testing and breeding program (as depicted in model 1). This specification of Model 1 implies that a local breeding program, although enjoying a small difference in yield gains over the testing program (0.3%/year) would continue to have an increasing cumulative yield advantage over the imported technology in the future. However, empirical evidence suggests that for some environments with only one or two limiting biological factors, such as high rainfall acid soils in Brazil (ME3) and Septoria resistance in high rainfall areas elsewhere (ME2), it was possible for the local breeding program to overcome the environmental constraints in one or two breeding cycles resulting in high rate of yield gains in the first ten to twenty years. The large percentage yield gains (11%) of cultivars developed by Brazil over the cultivars from other environments reflects this phenomenon (Table 6.2). However, once the characteristics of locally developed cultivars are incorporated by research programs, it is unlikely that the local breeding program in these environments will continue to enjoy higher rate of yield gains in future.

To see how sensitive the results are to different assumptions about the biological complexities, the threshold level of production was calculated using the baseline scenario and time pattern of yield gains represented in model 2 (equations 6.6 and 6.7) (Table 6.9).

Table 6.9: Threshold Size of Wheat Production to Justify Different Types of Wheat Breeding Program if the Yield Growth Rates Follow the Time Pattern Given in Model 1 and Model 2

Time Pattern of Yield Gains	Yield Gains $(g_2 - g_1)$[a] (%/year)	Cumulative Yield Gains After N years[b]	Production (000 tons) When NPV of testing program =0	When NPV of breeding program =0	When breeding most profitable
MODEL 2	<u>N = 10</u>				
	0.7	6.7	198	400	819
	1.0	9.4	198	350	567
	1.5	13.7	198	287	371
	<u>N = 20</u>				
	0.7	12.9	198	364	629
	1.0	17.9	198	310	432
	1.5	25.6	198	246	280
MODEL 1	0.3 (N=10)	3.2	198	462	1,392
	0.3 (N=20)	6.1	198	462	1,392

[a] Given the value of g_1 = 0.7%/year
[b] Percentage of yields of breeding program varieties in year N+1.

Since the rate of yield gains due to testing program is assumed to remain 0.7%/year, different assumptions on the time pattern have no effect on the threshold levels of production. The threshold size of industry to justify a breeding program is very sensitive to the time pattern of yield gains. In general, if the yield gains follow the time pattern of model 2, the threshold levels to justify a breeding program are much lower than if they follow the divergent growth rates all throughout the future. In fact, if a breeding program could maintain a difference in yield gains of 1.5%/year for twenty years, it could be the most profitable alternative for environments as small as 280,000 tons

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(in which case according to model 1 only testing program is most profitable). However, comparing the cumulative yield advantages of Table 6.9 with the empirical findings of Table 6.2, the difference in yield gains needed to justify a breeding program in small environments seems quite high. The yield advantages of about 11% and 10% enjoyed by locally developed varieties in ME3 and ME4B indicate that the yield difference of 1%/year due to local breeding program for ten to fifteen years seems more feasible.

A full breeding program is established in a given region with the aim that locally developed varieties will have yield advantage over imported varieties. However, as the sensitivity analysis reported in Table 6.9 points out, the time period over which the varieties from local breeding programs gain an advantage over imported varieties, has an important impact on the results. It is very unlikely, that the varieties from local crosses will enjoy the same higher rate of gains over the long-run period (as given in model 1). At some point in time, the g_t of breeding program has to level off with the g_t of testing/selecting program. The critical question however, is how much faster will the yields of locally developed varieties increase and how long will the trend continue? The answer will depend on the biological feasibility and environmental complexity of the given production environment. The results of the sensitivity analysis therefore, suggest that careful assessments of the biological and environmental complexity and technology spillins that determine the value and time pattern of g_t need to be made before making investments in a breeding program.

6.5.4 Effect of Research Spillins on the Threshold Size of Wheat Industry

As noted earlier, the decision on whether to test foreign varieties or develop new varieties from local crosses will depend on the magnitude and type of spillins. The availability of adapted varieties will encourage direct introduction of varieties through local testing research. Model 1 developed in this chapter is used to show this effect of research spillins on the efficient allocation of research resources.

In the model, the research spillins can be measured by the difference in the rate of yield gains realized from testing program and

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Table 6.10: Size of Wheat Industry to Justify a Crossing Program at Increasing Rate of Yield Gains Due to Testing Program

Difference in yield growth rate[a]	Yield gains after 20 years[b]	Production at which NPV of breeding research program = 0 (000 tons)	Production at which breeding program is most profitable (000 tons)
0.50	9.9	511	859
0.45	9.0	498	948
0.40	8.0	486	1,059
0.35	7.0	474	1,202
0.30	6.1	462	1,392
0.25	5.1	451	1,659
0.20	4.1	441	2,060
0.15	3.1	431	2,727
0.10	2.1	421	4,062
0.05	1.0	412	8,068
0.01	0.2	405	40,115

[a] Difference in the g_t of testing and breeding program when the rate of yield gains are 1%/year for breeding program
[b] Percentage of yields of varieties due to breeding program

a breeding program. Thus, the larger the spillins, the closer will be the rate of yield increments of a testing program to the breeding program. Table 6.10, shows the effect of increasing direct spillins, measured in terms of decreasing difference in the yield growth rate between the two types of research program on the threshold levels of wheat production when NPV of a breeding program equals zero and when NPV of breeding program is equal to NPV of testing program.

As expected, the effect of increased research spillins in terms of directly transferable technology is to decrease the threshold size of wheat production to justify a breeding program (because research spillins yield positive benefits to the testing component of a breeding program). An increase in the rate of yield gains from testing imported technology will make breeding profitable for smaller size wheat industry. For instance, an increment in research spillins by 0.1% resulting in the yield difference of 0.2% per year will decrease the threshold level of production by 21,000 tons, making breeding research affordable at 441,000 tons of production.

Whereas the research spillins in the form of directly transferable technology has a negative effect on the level of wheat production at which breeding is justifiable, it has a substantial positive effect on the threshold level of production at which breeding is most profitable. In other words, as the rate of expected yield gains from testing gets closer to the expected yield gains of varieties from breeding program, it requires an increasingly large size of wheat industry to justify investments in a breeding program; investments in smaller research program focusing only on testing of imported technology could be more profitable than larger size breeding program.

Viewing this is the light of the results of Chapter 5 (as summarized in Table 6.2), there are many interesting cases to note. First, consider the scenario of 'without CIMMYT' so that the only potential sources of direct technology spillins are the national wheat research programs. In countries/regions which have wheat growing environments similar to ME1 (irrigated, temperate) and ME2 (high rainfall), the yield advantage of varieties developed in ME1 over those developed in other megaenvironments is about 6 and 4%, respectively, implying that research programs in these megaenvironments need at least 1.3 million tons of wheat production so that a local breeding program is the most profitable alternative. As against this, for research programs in ME3, ME4A and ME4B which have experienced the greatest yield advantages, although require a larger size of wheat industry to earn positive NPV, can justify local breeding program at lower production levels. Due to the uniqueness of these environments along with low transferability of technology from other environments, the difference in the g_t of a testing and breeding program (g_2-g_1) will be wider. The level of production when breeding becomes most profitable will therefore be lower (less than 900,000 tons according to Table 6.10), because cultivars specific to the environment must be developed to obtain the higher rates of production increase.

If we consider the second scenario of 'with CIMMYT' so that CIMMYT is also a potential source of direct spillins then, ceteris paribus, it becomes very difficult to justify a local breeding program in most of the megaenvironments including ME4A and ME4B. Given that this scenario does hold in reality, the results have important implications on the efficient design of wheat research programs in developing countries. A strong evaluation program seems to be the most profitable alternative if

CIMMYT is considered as a potential source of direct technology transfers. This is because of the high transferability of CIMMYT's technology across different environments. In fact, CIMMYT cultivars were found to have an absolute yield advantage over the cultivars crossed by national programs in all megaenvironments except ME3 and ME7.

6.6 Conclusions of the General Analysis

The general analytical framework developed in this chapter is capable of addressing questions of resource allocation for plant breeding programs. It can provide important information to research administrators in terms of making decisions on the size and level of research capability of a plant breeding program.

The results indicate that it is possible to estimate the threshold level of wheat industry or threshold rate of production gains at which different breeding programs can be economically justified. For example, the critical production level to justify a breeding and a testing program is 462,000 tons and 198,000 tons, respectively. The analysis also demonstrates the importance of considering the returns from alternative investments in resource allocation decisions so that the investments can earn the maximum rather than just positive net returns. Taking the investments in an evaluation program as an alternative to a local breeding program (that includes breeding and selection components), the level of production at which research investments in breeding program would earn highest net returns was found to be 1,392,000 tons. Thus, the size of environment to economically justify a breeding program is comparatively quite larger than the size of environment to justify an evaluation program.

However, the sensitivity of the results to the estimates of the parameters suggests that it is difficult to draw general implications for national agricultural research systems. Only when the data applicable to that country/region are used can conclusions be drawn that will be useful for decision-makers. As noted by Brennan (1992a) the following country-specific data are required for such an analysis: 1) the expected number of researchers (FTE) for each type of breeding program; 2) the expected cost (including the operating and overhead costs) per researcher; 3) the expected research lag for each type of breeding program; 4) the expected adoption rate and adoption lags once a variety is released; 5) the appropriate price; 6) the appropriate discount rate; and 7) the expected rate of increase in production from each type of research capability. This will require careful assessment of research spillins from programs in similar environments and international research centers and the biological feasibility given the environmental complexities.

The analysis, when based on data applicable to a particular country/region, can provide important and useful information to decision makers. The analysis can also be used to assess the impact of policies to improve the efficiency of the research system, such as policies designed to reduce research and/or adoption lags. In the following section, the general model developed here is used to determine the efficiency of research resources devoted on wheat improvement research in the developing countries.

6.7 Economic Analysis of Wheat Improvement Research Programs in Developing Countries

Over the past three decades the expansion of the wheat research programs in developing countries has occurred concurrently with the increase in directly transferable wheat technologies from CIMMYT (as indicated by the results of chapter 5). This phenomenon can be attributed to three factors. First, the administrators of many public agricultural research systems have a tendency to equate the importance of a NARS or a research program by the number of research personnel rather than the quality of research. Second, the research focus has been increasingly on technology creation rather than utilizing the available technology and focussing on a strong evaluation programs. Third, plant breeding research in general is considered more prestigious than other type of crop related research. This helps explain why breeding programs are often given high priority by NARSs in developing countries.

The expansion in wheat research programs is also a manifestation of the increase in the size of NARSs in most developing countries.

Investments in agricultural research in general have been justified on the grounds that agricultural research has such high returns that any of it is worthwhile. However, Brennan (1992b) argues that it is precisely because of the high returns on the projects that could not be funded due to limited funds, that it is essential to use available research resources wisely.

As shown in the previous section, research allocation decisions must be carefully assessed in terms of alternative investments. In plant breeding research, the alternatives can be determined by the research capability. Thus, a region could either focus on evaluating foreign technology (thus invest in a testing program) or focus on generating new technology (thus invest in a full breeding program). Given the fact that these two types of breeding programs are mutually exclusive for a given environment, resource allocation decisions based only on rates of returns criterion (i.e. IRR > opportunity cost of capital) may not lead to economically efficient decisions (Gittinger, 1982). To economically justify investments in a given type of a research program, the NPV of each alternative has to be compared. Based on this economic principle, the analytical model developed in the earlier sections is used to analyze the wheat breeding programs of developing countries.

6.7.1 Data Sources and Methodology

Since, the decisions on wheat improvement research are made (and should be made) for each environment in a given country, the aggregate national level data on the size of wheat research program would be inappropriate to use in this analysis. The analysis would yield meaningful results only if environment specific size of wheat breeding programs are used. However, each country has a different research zoning system based either on major wheat growing environments, types of wheat grown, political boundaries, or a mixture of all. Thus, a country usually has more than one wheat breeding program with different geographic mandate areas, although small countries are likely to have only one program for the whole country. For the purposes of this analysis, therefore, the research program specific data collected

by CIMMYT (as described in chapter 4) was used. Specific information on the sixty nine research programs analyzed is provided in Appendix F.

The research program is defined in terms of geographic mandate (in short just geographic) area/production for a given wheat type (spring bread, spring durum, winter bread and winter durum). This eliminates at least one important environmental complexity in the target domain. However, a research program for a given wheat type may include one or more sub-environments in terms other agroclimatic factors such as maturity, altitude and moisture regimes. To the extent that the values of parameters g_t (rate of production increments) and n_r (research lag) differ across these sub-environments, the analysis based on this definition of a research program may over- or under estimate the results. However, given the lack of empirical evidence on the differences in these parameters across sub-environments, this definition is the most practical one to use.

In many developing countries that responded to the survey, there is considerable overlap in the geographic mandates of different research programs. For example, in Pakistan in addition to each province working on its own research mandate area (the whole province) there is a national level wheat research program in the Pakistan Agricultural Research Center with the whole country as the geographic mandate region (although it emphasizes rainfed wheat environment). In cases such as this, the national level program was not included in the analysis; only the provincial programs with distinct research mandate were considered. Also, the number of researchers for a given geographic region are not adjusted to include other researchers working for the same mandate area in the Universities, private sector, or other research stations. To the extent that the research done by the other programs affects the yield gains realized in the geographic region, the size of a research team is underestimated.

The parameter values for g_t, n_r, r, P_t and α_t used in the analysis correspond to the baseline scenario given in Table 6.3. The values for Q_o, S_y and C_s are program specific as reported in Appendix F. The research expenditures per researcher correspond to the estimates reported in chapter 4 for each country. Thus, all the research programs in a given country were assumed to have the same cost per researcher. The costs were estimated in terms of 1980 PPP U.S. dollars and are assumed to remain constant (in real terms) over the period of analysis. The level of production in the geographic mandate region (Q_o) was estimated using the national average yields (FAO estimates for year 1990-91) and the area reported in the survey.

6.7.2 Application of the Analytical Model

The benefit-cost analysis model developed and discussed in previous sections (equation 6.9) is applied to each research program to calculate the NPV of current level of investments devoted to wheat improvement research. The analysis is based on the following assumptions. 1) Past research costs are sunk costs and are therefore irrelevant for present analysis. The benefits of past research in the years before current research starts yielding benefits are also not accounted for. 2) The size of wheat area in the geographic mandate region, number of researchers in the program and research costs per researcher (in real 1980 dollars) are assumed to remain constant over the period of analysis. Thus, the analysis assumes the scenario where the research programs have to make decisions on whether the continuation of current level of research investments on wheat research is economically efficient or not. 3) The locally developed cultivars of a breeding program are assumed to enjoy yield increments higher than imported ones throughout the period of analysis (i.e. the time pattern of model 1 is assumed). 4) The decisions by an individual research program are made independently assuming that its research will have not affect the global technology transfer pool. Also, no uncertainty in the continuation of estimated research spillins is assumed.

The research programs analyzed are classified into three groups based on the NPV decision criterion (Table 6.11) - Group 1 consists of research programs whose current investment levels and research capability, if continued in future, would earn negative NPV; Group 2 consists of research programs whose current levels of investments in creation research would earn NPV greater than zero but less than the alternative investments in an evaluation program. Based on the

Table 6.11: Research Programs in Developing Countries Grouped by the NPV Decision Criterion Based on the Results of the Benefit-cost Analysis

Result of the Analysis	Interpretation	Number of research programs	Research programs[a]
NPV < 0	Cannot justify current levels of investments in wheat research	30	Burundi; Ethiopia; Lesotho; Kenya; Zambia; Zimbabwe; Libya; Lebanon (2); Morocco (SD); Tunisia (2); Turkey (Samsun-SB, Konya-WD); Bangladesh; India (Ludhiana-SD); Bolivia (2); Brazil (Sao Paulo); Ecuador; Chile (3); Colombia (ICA); Guatemala; Mexico (SD); Paraguay; Peru (2); Uruguay
0 < NPV < NPV of evaluation research	Current investments are earning positive NPV, but not maximum	15	Sudan; Algeria (2); Morocco (SB); Turkey (Aegean-SB, Aegean-SD, Eskisehir-WB, Eskisehir-WD, Southeast Anatolia-WB, Konya-WB); India (Vijapur-SB, SD); Nepal; Pakistan (Baluchistan); Argentina (EEA Parana);
NPV is maximum	Current investments are most profitable	24	Turkey (11)[b]; India (7)[c]; Pakistan (3)[d]; Brazil (2)[e]; Mexico (SB);

Note: SB = Spring Bread Program; SD = Spring Durum Program; WB = Winter Bread Program; WD = Winter Durum Program

[a] The list of research programs analyzed are given in Appendix F.

[b] Research Programs other than in Aegean (2), Eskisehir (2), Konya (2), Southeast Anatolia (WB) and Samsum (SB).

[c] Research Programs other than in Ludhiana (SD) and Vijapur (2).

[d] Research Programs other than in Baluchistan.

[e] Research Programs other than in Sau Paulo.

discussion of Section 6.4.1. the investment levels for the alternative evaluation program was assumed to be one-third of the current investments in creation research; and, Group 3 comprise of research programs whose current levels of investments earn maximum NPV (compared to the alternatives of evaluation research or no research at all).

The results of the analysis are surprising. If the baseline scenario holds true and research investments are continued at their current levels, then most of the research programs in developing countries would be making economically inefficient investments in wheat improvement research. Forty five out of sixty nine (about two-thirds) research programs analyzed are investing in economically unjustifiable levels of resources in wheat breeding; thirty of these (66%) would be earning negative NPV at current level of investments and in wheat research.

In terms of regional analysis, the research programs found to be earning the most profitable returns, were in major wheat producing countries of West Asia (Turkey), South Asia (India and Pakistan) and Latin America (Brazil and Mexico). Interestingly, except for Sudan, no other research program in sub-Saharan Africa was earning a positive NPV on their current investments.[8]

All the research programs in Group 2 and 3, except for spring bread program in Algeria, are technology creation programs and operate in large mandate regions. The first group which is earning NPV < 0, however, is a mixed group in terms of research capability with most of the research programs oriented towards technology creation research (the exceptions are the research programs in Burundi, Lesotho, Bolivia, and Peru). It also employs relatively more number of researchers than the other two groups (Appendix F). The unprofitable levels of investment for these research programs could therefore be due to three factors - inappropriate research capability, inefficient size of research program for the given level of capability or small size of wheat production in the mandate region.

The NPV for the research programs in group 1 were therefore calculated after correcting for the following. 1) Size of the research

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[8] One of the reasons for the observed unprofitable levels of investments in wheat research in sub-Saharan Africa could be the high research costs per scientist relative to other regions in the developing world. This could be due to the dominance of expatriate researchers in the research systems. In future, as the national scientists replace the expatriate scientists, the expenditure per researcher may decline relative to current levels. To take this into account, the NPV for the research programs in Burundi, Lesotho, Ethiopia, Kenya, Zambia and Zimbabwe was calculated after reducing the costs by 50%. After accounting for this cost reduction the NPV of the research program in Zimbabwe was found to be positive. However, the calculated NPV still remained negative for other research programs.

program relative to the research capability. For the breeding programs employing more than 3.0 FTE researchers, the NPV was calculated after reducing the size of research program to 3.0 FTE and for testing programs employing more than 1.0 FTE the NPV was calculated by reducing the size to 1.0 FTE (corresponding to the values used in the general analysis). 2) Appropriateness of the research capability relative to the size of the wheat industry. The research capability of the remaining breeding programs including those that still yielded negative NPV after correcting for the 'inflated size ' was changed from technology creation to technology evaluation by assuming that it would cost one third of current investments in a breeding program (based on the estimated difference used in the baseline scenario).

Table 6.12: The Effect of Changes in the Size and Capability on the Profitability of the Research Programs Earning NPV < 0

Results of the Analysis	# of Research Programs	Research Programs[a]
NPV > 0 if the size of research program is reduced	5	Morocco (SD); Tunisia (SD); Bangladesh; India (Ludhiana-SD); Chile (SB)
NPV > 0 if the research capability is changed from technology creation to technology evaluation requiring 1/3 of current investments	5	Zimbabwe; Tunisia (SB); Chile (WB); Peru (SB); Uruguay
NPV < 0 after all the corrections	20	Burundi; Ethiopia; Lesotho; Kenya; Zambia; Libya; Lebanon (2); Turkey (Samsun-SB, Konya-WD); Brazil (Sao Paulo); Bolivia (2); Ecuador; Chile (SD); Colombia; Guatemala; Mexico (SD); Paraguay; Peru(SD)

Note: SB = Spring Bread; SD = Spring Durum; WB = Winter Bread; WD = Winter Durum

[a] List of the research programs analyzed are given in Appendix F.

The effect of these changes on the profitability of research programs in group 1 is reported in Table 6.12. After reducing the size of the research program, five programs [Tunisia (SD), Bangladesh, India (Ludhiana-SD), Chile (SB) and Morocco (SD)] could now afford to invest in technology creation research (i.e. breeding program). Research Programs in Zimbabwe, Tunisia (SB), Chile (WB), Peru and Uruguay, on the other hand could earn NPV > 0 if they change their research capability from technology creation to technology evaluation and reduce investments in wheat research by one-third. However, even after the correction in size and research capability, twenty research programs were still earning negative NPV, indicating that the size of the production in the research mandate area is too small to justify investments in wheat improvement research even if they employed only one FTE researcher.

6.7.3 A Multivariate Model for Predicting the Profitability of Wheat Research Programs

According to the analytical model used to classify the research programs into profitable and unprofitable groups, the level of profitability is directly related to the size of mandate region. Observing the results given in Table 6.11 and 6.12, this model relationship seems to hold true in general, as most of the large wheat producing regions fall in the group earning the most profitable returns. However, some of the research programs with large wheat production were found to be earning negative NPV, indicating that profitability of a research program will depend not only on the size of the mandate region but also other factors such as the size of the research program, costs per researcher, environmental diversity and research spillins.

The analytical model developed and used in the previous section explicitly accounted for some of these factors in calculating the NPV of the research programs. In this section a statistical model is developed based on a relatively small number of research program characteristics to see if they can discriminate statistically between profitable and unprofitable research programs. The model uses a statistical technique (Discrimant analysis) that provides a procedure for assigning sample cases to predetermined populations and then determines the accuracy of the classification procedure.[9]

Methodology:

Discriminant analysis is employed to classify all the sixty nine wheat research programs into one of two groups - profitable or unprofitable - based on the results of previous section (Table 6.11). All the research programs found to be earning NPV < 0 were considered unprofitable and those earning NPV > 0 (irrespective of whether they were maximum or not) were considered as profitable. The approach is then to construct a discriminant function which combines a set of variables in such a manner as to maximize the differences between two group means, and than minimizes the likelihood of misclassification. The discriminant function takes the form:

$$Z = V_0 + V_1X_1 + V_2X_2 + \dots + V_nX_n \qquad (6.12)$$

where, V_o, V_1, $V_2,\dots,V_n$ are the discriminant coefficients, and X_1, $X_2,\dots,X_n$ are the independent variables.

After the discriminant function is determined, the independent variables for each program are multiplied by the discriminant coefficients to obtain a single Z-scores for each research program. Based on the Z-score, each program is classified as belonging to the profitable group or unprofitable group.

The Model:

The discriminant model for identifying the wheat research programs with high potential for economic inefficiency (i.e. yielding NPV < 0) is:

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[9] Discriminate analysis is a multivariate technique concerned with separating distinct sets of objects (or observations) and with allocating new objects (observations) to previously defined groups. As a separatory procedure it is often applied on a one-time basis to investigate observed differences when causal relationships are not well understood. Many of the standard applications of the technique are found in the biological sciences, but is also potentially fruitful in social sciences. See for example, Trieschmann and Pinches (1973) used the analysis to classify the insurance company as solvent or distressed so that steps can be taken to prevent bankruptcy of a distressed firm. Similarly Adelman and Morris (1968) applied the technique in an attempt to identify underdeveloped countries with good development potential so as to assist in the foreign aid policy.

$$Z = -1.296 - 0.541\ PRODC + 0.0117\ EXPD + 0.190\ FTE + 0.152\ ENV \tag{6.13}$$

where, PRODC = Production in the mandate region (million tons)
EXPD = Expenditures per researcher (thousand 1990 PPP U.S.)
FTE = Number of Researchers (FTE)
ENV = Number of distinct agroclimate environments

Relative Importance of the Variables:

The interpretation of the coefficients is similar to that in multiple regression. However, since the variables are correlated, it is not possible to assess the importance of an individual variable. The value of the coefficient for a particular variable depends on the other variables included in the function.

The mean, standard deviations and Wilk's Lambda (U-statistics) and univariate F-ratio of the four variables are presented in Table 6.13. The Wilk's Lambda is the ratio of the within-groups sum of squares to the total sum of squares. Large values of Lambda indicate that group means do not appear to be different, while small values indicate that group means do appear to be different. Thus, production and expenditures per researcher are the variables whose means are most different for profitable and unprofitable wheat research programs. As the F-values indicate, on a univariate basis, these two variables are most significant in discriminating between a profitable and an unprofitable program. The number of environments, on the other hand is the least important variable in discriminating between the two groups.

Table 6.13: Variable Means, Standard Deviations, Wilks' Lambda and F Ratio: Results of the Discriminant Analysis

Variable	Mean		Std. Deviation		Wilks' Lambda	F-ratio	Sig.of F
	Profitable	Unprof-itable	Profitable	Unprof-itable			
PROD	1.89	0.34	2.38	0.46	0.844	12.39	0.000
EXPD	61.2	79.3	19.88	32.93	0.894	7.94	0.006
FTE	2.8	4.0	3.35	3.66	0.969	2.14	0.148
ENV	2.7	3.4	1.73	1.72	0.961	2.72	0.104

Unlike the multiple regression coefficients, the signs of the coefficients of discriminant function are arbitrary. They only determine which variable values result in large or small Z-scores, where large Z-score values are associated with unprofitability and small values are associated with profitability of a research program. For example, large production size will decrease the value of the Z-score, thus increasing the probability of classifying a program as profitable. As against this, large size of a research program, high expenditures per researcher and large number of environments in the target domain will increase the values of the Z-score and will increase the probability of classifying a program as unprofitable.

Classification of the Research Programs:

One of the most useful operational aspects of the discriminant analysis is that it generates an estimation of the probability that a given research program will earn profitable or unprofitable returns from wheat research on the basis of a very small number of indicators (production, number of researchers, expenditures per researcher and number of environments). This probability can be used to assess the profitability potential of any other unclassified wheat research program. The group membership probabilities and the Z-scores of individual research programs included in the analysis are given in Appendix G.

Following the allocation rule based on the discriminant function value (the Z-score) is used to classify the research programs as profitable or not.

$$\begin{aligned} &\textit{Profitable if:} \qquad Z\text{-}score < \frac{(z_p + z_u)}{2} \\ &\textit{Unprofitable if:} \qquad Z\text{-}score \geq \frac{(z_p + z_u)}{2} \end{aligned} \qquad (6.14)$$

where, z_p is the sample mean of the Z-scores of the profitable research programs and z_u is the sample mean of the Z-scores of the unprofitable research programs. The values of the z_p and z_u were estimated to be -0.641 and 0.833 respectively. Replacing these values in equation 6.16 gives the following classification rule.

$$\begin{array}{ll} \textit{Profitable if:} & \textit{Z-score} < 0.096 \\ \textit{Unprofitable if:} & \textit{Z-score} \geq 0.096 \end{array} \tag{6.15}$$

The results of the classification are summarized in Table 6.14. Fifty nine out of sixty nine research programs (86 percent) were classified correctly. Six unprofitable programs [two in Lebanon, two in Turkey, Guatemala and Ecuador] were incorrectly classified as profitable and four profitable programs [Algeria (SB), Brazil (IAPAR-SB), Morocco and Nepal] were misclassified as unprofitable (Appendix G). Except Brazilian program, all the other three research programs misclassified as unprofitable belonged to the second group in Table 6.11 which were earning less than maximum NPV. Looking at the specific information given in Appendix F, different factors might have influenced the misclassification of these research programs. In the case of spring bread program in Algeria, the size of the mandate region (219,369 tons) seems to be the limiting factor to justify a breeding program. In the case of Nepal, the constraining factor seems to be the large size of the breeding program (8.7 FTE) and for the program in Morocco, a combination of high expenditure per researcher, large size of the program and number of environments in the target domain seem to be determining the high Z-scores for this program.

Table 6.14: Classification of Wheat Research Programs as Profitable and Unprofitable: Results of the Discriminant Analysis

Actual Group Membership	No. of cases	Predicted Group Membership	
		Profitable	Unprofitable
Profitable	39	35 (90%)	4 (10%)
Unprofitable	30	6 (20%)	24 (80%)

The failure to classify a potentially unprofitable research program as unprofitable may lead to an uneconomic use of the scarce resources. The six programs incorrectly classified as profitable, illustrates the danger of the discriminant analysis. The size of production in the mandate regions of programs in Lebanon, Guatemala and Ecuador is less than 30,000 tons and still they are classified as profitable programs. Perhaps the low expenditures per researcher and small size of the research program explain the low Z-scores and subsequent classification of these programs as profitable. In the case of two Turkish programs, the relatively high production in the mandate region along with small number of environments may have influenced their lower Z-scores.

The discriminant function used to calculate the Z-scores is based on the conservative estimates of the research spillins (i.e. 0.3%/year difference in yield gains of a breeding and testing program) as used in the previous section to calculate the NPV of the research programs. The classification of research programs by discriminant analysis therefore may be overestimating the profitability of research programs. Since there is no way of explicitly accounting for the research spillins in the discriminant function model, the resulting discriminant coefficients (in equation 6.16) are specific to the particular assumption of 0.3%/year yield gains due to breeding program. Similarly, it is based on the specific assumptions about the research lag (12 years for breeding program and 4 years for testing program) and the discount rate (12%).

Despite these limitations, discriminant analysis can be useful in determining the factors that make a program profitable or not. With the help of a discriminant function, such as equation 6.16, and the most recent data on the variables appearing in it, one can compute an individual discriminant score for each research program. This discriminant score can then be used to calculate the profitability of the research program. For example, given the size of the geographic mandate region, number of environments and expenditures per researcher, the effect of an increase or decrease in the size of a research program on the general profitability of research can be estimated.

6.8 Conclusions

The analytical model developed in this chapter has proved capable of addressing the issue of economic efficiency of resources allocated to breeding research. By applying the NPV decision criterion, the model can be used to estimate the economic efficiency of investments in wheat research such that the investments earn not only positive NPV but maximum returns. This implies that the resource allocation decisions have to be made by taking into consideration the returns from alternative investments. Since, the difference in the rate of production increments of the two alternative investments (technology evaluation versus technology creation research) determine the profitability of investments in wheat breeding, the analysis points out the need for careful assessments of technology spillins from other sources and the biological complexities of the environment that will determine the time pattern of yield increments.

The application of the model to the individual wheat research program data has provided some very interesting observations about the efficiency of research investments in public sector wheat research programs of developing countries. If the research cost estimates and size of the research program used in this analysis are a good proxy of the real expenditures on wheat improvement in the countries analyzed, one cannot escape the observation that forty five out of sixty nine research programs analyzed are overinvesting in wheat improvement research. For fifteen of these programs this can be corrected by changing the research capability from technology creation to technology evaluation and/or reducing the size of their wheat research programs by two-thirds. In the case of other thirty countries the size of wheat production and research costs in the mandate regions are such that none of the alternatives (breeding and testing) are justifiable; unless the local research is expected to lead to a large increase in wheat area or they reduce the size of their programs drastically.

The analysis however ignores the environmental diversity within the geographic mandate region and the availability of directly and indirectly transferable technologies. These factors are important in determining the expected rate of yield growth due to current and alternative breeding investments. As indicated in earlier sections, the threshold level of production at which breeding program becomes most profitable is very sensitive to the rate of yield gains from the alternative research capability (research spillins). The profitability of current investments in any research program will be sensitive to the difference in the g_t of current and alternative investments. In the baseline scenario the difference in the rate of yield gains between the two alternatives is assumed to be 0.3%. The analysis might have underestimated the benefits of current investments in technology creation research if the actual difference is more than 0.3%/year. However, in the light of the empirical results of the last chapter, this is not likely to be the case. Given that a 0.3%/year difference will give an accumulated yield advantage for locally developed material of 6.1% in twenty year period which is more than the observed yield advantages in most megaenvironments, the benefits are most probably overestimated rather than underestimated.

This is certainly the case for the spring bread research programs in Mexico (INIFAP). It is hard to imagine that the incremental rate of yield gains would be 0% if INIFAP did no research at all and directly introduced CIMMYT cultivars. To certain extent this might be the case even for the research programs in Pakistan which has a very similar environment to that of northwestern Mexico (where most of the CIMMYT technology is evaluated) or that of neighboring country (India). If the difference in the g_t between the two alternatives are adjusted for in the analysis, depending on the particular circumstances of research spillins and environmental similarity, the results might be different for research programs classified in Table 6.11 as investing at the most profitable levels.

A limitation of this study, however, is that the results are based solely on the yield gains due to breeding research. It takes no consideration of the economic implications of the tradeoffs involved in enhancing other traits. For example, a locally crossed variety using local materials may be of higher quality than an imported variety and may yield a price premium. As shown by the sensitivity analysis in Table 6.8, the threshold levels of production when a breeding program becomes most profitable is sensitive to the price differentials of a locally developed and imported variety. However, the quality advantage is more likely to be an important factor in the case of other crops such as rice and maize.

Another caveat to be noted is that the results rely heavily on the model specification and the parameter values used for the analysis. Because of the uncertainty in each parameter and general nature of some parameter estimations, the overall results of the analysis should be interpreted with some caution. Unless all the data specific to a research program are used for the analysis, the results of this chapter are only indicative rather than conclusive.

The central finding of this study is that there is substantial overinvestment in wheat improvement research in the Third World. This suggests that public investments in research systems in many developing countries are guided by the bureaucratic and political factors that inflate the size of research programs and underplay the gains from borrowing. Two general conclusions can be drawn from this analysis:

1. The wheat research programs in many developing countries are 'oversized' both in terms of actual number of researchers employed in a program (the size of research programs is larger than the size of research programs in industrialized countries) and in terms of inappropriate research capability (they are investing in research programs that are yielding less NPV than the alternative investments).
2. Strictly judging from the economic criterion of profitability (NPV > NPV of alternative investments > 0) the research programs in the developing world are overinvesting in wheat research. This finding challenges much of the research evaluation literature that argue that there is underinvestment in agricultural research. The underinvestment argument is also made on the theoretical basis of positive externalities created by agricultural research (spillover effects). However, although both the empirical evidence and economic theory suggest that societies in general are underinvesting in agricultural research, viewed from the NPV criterion of profitability, individual research programs may be overinvesting in research - either in terms of 'inefficient size' or 'inappropriate research capability'.

CHAPTER SEVEN

SUMMARY, CONCLUSIONS AND IMPLICATIONS

This chapter reviews the principal results of the study and discusses the research and policy implications. In addition, a number of suggestions are advanced for future research.

7.1 Background of the Study

In the 1950s, with the support of Rockefeller Foundation, the Ford Foundation and USAID, developing countries started to expand commodity research programs. At about the same time Shultz and Griliches published several pioneering studies of the rate of return to investment in agricultural research. These studies and others revealed high rate of returns (more than 30 percent) to agricultural research and raised questions about the apparent underinvestment in agricultural research. In the late 1960s and early 1970s, the success of the Green Revolution in Asia, which was based on plant breeding research, further reinforced the idea of promoting commodity-based research programs in developing countries as a solution to the emerging crisis in food production. Finally, studies by Evenson and Kislev (1975), Hayami and Ruttan (1971), and others noted that biological technology was not very transferable (i.e. much of it was location specific) because of the diversity in agro-climatic and socio-economic circumstances. Hence it was argued that countries and regions within countries, should establish strong national research programs with a capacity to adapt new technology to local ecosystems.

The success of the Green Revolution in Asia in the 1960s and 1970s triggered a large expansion in agricultural research in NARSs and the CGIAR system. The average size of NARSs in developing countries quadrupled from 150 in 1961-65 to 600 in 1981-85 (Pardey et al. 1991b, p.205). This increase in the national research capacity is a reflection of the proliferation of commodity-specific research programs with emphasis on plant breeding, especially for major food staples, such as rice and wheat. For example, today almost all countries (where wheat is produced) have national wheat research programs; two-thirds of these are involved in crop improvement research and are inevitably led by plant breeders (CIMMYT forthcoming).

Economists have generally failed to account for research spillins in their *ex post* or *ex ante* assessments of returns to research. For example, the study by Nagy (1984) on returns to wheat research in Pakistan incorrectly classified the main varieties as being developed by Pakistani programs, but in fact they were imported or selected from CIMMYT materials. The failure of economists to address research spillins has not only led to an overestimation of returns to research but it has also undermined the importance of research spillins. The lack of attention to spillins did not matter as long as NARSs research budgets were increasing in the seventies and early eighties.

But with stagnating and, in many cases, declining real research budgets in the late 1980s and early 1990s, research systems in the developing countries are under severe financial stress. At the international level, virtually all of the CGIAR-supported commodity research centers have been forced to reduce the number of scientists at the same time as five new centers oriented towards natural resources and environmental issues were added over the period 1990-92 (Eicher 1992). And with the higher cost of biotechnology research in the future, there will be a need to rationalize even further the allocation of resources across IARCs and national programs.

The combination of reduced Third World and donor support for agricultural research and the increasing cost of agricultural research have renewed the questions about appropriate size and investments in agricultural research. Countries are seeking advice on how much effort they should devote to each crop? and for a given crop, how much to devote on different types of research?

This study was undertaken to analyze international wheat research spillovers and develop a framework to guide decision makers on the appropriate size and capability of wheat improvement research programs. The basic premise of this study is that research spillins should be an integral part of impact assessments and research priority setting mechanisms. A cost-benefit analysis framework was developed in Chapter 3 to determine the appropriate level of research capability for an

environment by taking explicit account of research spillins. Chapter 4 documented the contemporary status of wheat improvement programs in developing countries in terms of size and investments in wheat research. Chapter 5 focused on the issue of international transferability of wheat varieties. In order to classify the cultivars by origin groups embodying different type of technology transfer, considerable time was spent on recoding and reorganizing CIMMYT's International Spring Wheat Yield Nursery (ISWYN) data set. In Chapter 5 the ISWYN trial data were used to analyze the magnitude of research spillins. Finally, the evidence on research spillins and the estimates of current levels of investments in wheat improvement research were incorporated in the cost-benefit analysis framework to assess the profitability (using the NPV criterion) in wheat improvement research by developing countries.

7.2 Summary of Results

7.2.1 Investments and Intensity of Wheat Improvement Research in Developing Countries

A global impact survey was undertaken by CIMMYT in 1990-92 to collect information on the wheat varieties released and the size of wheat improvement efforts by national programs in developing countries. The results of this survey reveal that national research programs in developing countries (not including China) are employing 967 FTE scientists to carry out wheat improvement research at a total cost of about seventy million dollars (1980 PPP US dollars) per year (over US$100 million in 1990 dollars).[1] Adding CIMMYT's wheat research efforts of approximately thirteen million dollars per year, the total expenditures on wheat improvement in developing countries (excluding China) are estimated to be about eighty two million dollars per year. In terms of research intensity, developing countries in general are spending 0.51% of total value of wheat production and employing 7 scientists per million tons of wheat produced on wheat improvement research. Overall the research expenditures on wheat improvement are comparable or higher than those in industrialized countries.

[1] Note that this does not include crop management and other agronomic research on wheat.

A wheat improvement research program is defined as a team of researchers (breeders, agronomists, pathologist, etc.) working on wheat improvement for a particular geographic region. A country could have one or more wheat breeding programs depending on the environmental diversity, size of wheat area, private sector involvement and political setup of the country's research system. In another survey undertaken by CIMMYT in 1992-93, information about individual research programs was collected from developing countries and some developed countries. The average size of a wheat breeding program in developing countries was found to be 3.8 FTE researchers. In terms of disciplinary composition, an average breeding program comprised of seventy four percent breeders with the remaining scattered across pathologists, agronomists, cereal technologists, entomologist, physiologists, agricultural engineer, soil scientist and researchers from other disciplines.

The size of a wheat breeding program varied significantly with the level of research capability. The average size of a technology evaluation (testing) program (1.4 FTE researchers) was found to be one third the average size of a technology creation (breeding) program (4.2 FTE researchers). The average size of the geographic region of a technology evaluation program was significantly less than that of a technology creation program, both in terms of wheat area and production. This implies that the size of geographic region is an important factor influencing the decision on level of research capability. The number of production environments within the mandate region of a wheat research program was found to be three per program.

Compared to the average size of 4.2 FTE researchers in a breeding program in developing countries, the average size of a breeding programs in industrialized countries was 3.1 FTE researchers. Taking into consideration the difference in the size of the geographic region (measured by total wheat production) and the number of production environments targeted, public wheat improvement programs in developing countries are employing more than twice the number of researchers in the industrialized countries.

7.2.2 International Transferability of Wheat Varieties

Most of the early evaluations of agricultural research evaluation in the 1950s and 1960s used cross-sectional data and ignored the technology spillin issue. The studies argued that cross-sectional observations on research programs correspond to environmental regions and that there was little direct transfer between them (Evenson 1991b). Later studies in the 1970s and 1980s incorporated in their evaluation models spillins between states (as in several U.S. studies) and countries (as in international studies) utilizing agro-climatic zones. Research spillins were either estimated as a function of 'research stock' which was typically measured by expenditures or publications aggregated by agroclimatic zones (for e.g. Evenson and Kislev 1975) or based on subjective guesses (for e.g. Davis et al. 1987).

These studies however failed to differentiate between direct and indirect research spillins and failed to take into account the spillins from IARCs. Englander's study (1981a) on international transfer of wheat technology was one of the first attempts to analyze the issue of varietal transfers by differentiating between direct and indirect spillins and explicitly taking into account the spillins from CIMMYT. The present study has used an approach similar to Englander in analyzing the international transferability of wheat varieties.

The success of Green Revolution in Asia in the late sixties and the seventies triggered a large increase in wheat research in developing countries. One indicator of this success is the increase in the number of wheat varieties released per year over the last three decades. The number of varieties released per year in developing countries more than doubled from thirty per year in 1965-69 to about seventy in 1985-90. Forty five percent of all varieties released in this period were locally crossed either using CIMMYT germplasm as an immediate parent (21%) or using materials derived from CIMMYT germplasm (24%). The remaining fifty-five percent were either directly introduced CIMMYT cultivars (45%) or cultivars developed by other national programs (10%). The proportion of directly introduced wheat varieties in developing countries (55%) is high compared to other crops, indicating that international transfers (particularly direct transfers) of varietal technology has been an important phenomenon in wheat research.

Establishment of crop breeding programs is usually justified on the grounds of genotype by environment (G x E) interactions. Because of these interactions, agricultural technologies are known to adapt better in one environment than another (i.e. they have a degree of location specificity). Since the direct transfer of agricultural technology from one environment to another is inhibited by the presence of G x E interactions, it is often necessary to carry out adaptive research for local conditions (for example, soil, temperature, consumer tastes) or to develop new indigenous technologies for local environments.

CIMMYT's International Spring Wheat Yield Nursery (ISWYN) trial data for the years 1979-80 to 1987-88 was used to assess G x E interactions for wheat varietal technology. The ISWYN trials are conducted each year at many locations around the world to test cultivars developed by CIMMYT and national programs. To assess the transferability of wheat cultivars, the trial locations were grouped according CIMMYT's megaenvironments (which are based on the moisture and temperature regimes, soil type and major disease stresses) and cultivars were grouped by their developmental and environmental origins. CIMMYT-developed cultivars were considered as a separate group by itself.

The empirical estimates of the yield advantages based on these trial data confirm the limited transferability of wheat varieties developed by national programs. The performance of cultivars developed by national programs in other megaenvironments relative to cultivars developed by national programs in home megaenvironment was significantly lower in all the eight megaenvironments analyzed. The yield advantage of cultivars developed by national programs in home environment compared to those developed by national programs in other environment ranged from 2 to 11 percent with an overall average of about 6 percent. This evidence suggests a significant G x E interactions across different megaenvironments thus supporting the location-specific nature of wheat technology. The implication is that there are potential gains (as high as 11 percent) from breeding research that is undertaken by national programs tailored to their own environments, as against importing the technology from national programs in other environments.

Nevertheless, when wheat varieties originating from CIMMYT, Mexico are taken into account, the 'location specificity' argument of the literature is not sustained, at least in terms of wheat cultivars. Technologies originating from CIMMYT have proven to be highly transferable across different countries and megaenvironments around the world. The yield advantage of cultivars developed by CIMMYT and released in Mexico, was as high as 527 kg/ha (11 percent) in the megaenvironment characterized as irrigated, temperate (ME1), and 490 kg/ha (13 percent) in megaenvironment characterized by high rainfall, temperate (ME2). In other megaenvironments (such as low rainfall, acid soils, high temperatures, etc.), the yields of CIMMYT cultivars were higher or not significantly different from cultivars developed by national programs.

In several important wheat producing countries examined (India, Pakistan, Kenya, Ecuador, Brazil, Portugal and Argentina) the yields of cultivars locally developed by the national programs were not significantly different from those of CIMMYT. These results are contrary to Englander's findings (1981a; 1991) that varieties developed by national programs using CIMMYT germplasm as parent materials outperformed the directly introduced CIMMYT varieties in a given country. These differences stem partly from the differences in data interpretation and partly from the differences in the estimation procedures. Englander used the contributing country information published in ISWYN reports to represent the technological origin of a cultivar. However his results are misleading because a country frequently releases a CIMMYT cultivar under a local name. Also, Englander's measures of yield advantages were based on political boundaries (country basis) rather than on environmental boundaries (as is the case in this study). Since a country often has multiple wheat growing environments, Englander's results are open to question.

The results of this study suggest that G x E interactions are strong when cultivars from different NARSs are compared with each other. However, G x E interactions were not evident in comparisons of CIMMYT cultivars and cultivars developed by NARSs. This study reveals that the direct transfer of wheat varietal technology from CIMMYT can be a potential substitute for local breeding research in many environments and should be taken into account in designing a national and regional wheat improvement programs. For example, the similarity in the wheat growing conditions of the Punjab, Pakistan and Yaqui Valley, Mexico (ME1 - irrigated, temperate) is conducive to the transfer of CIMMYT cultivars to the irrigated regions of Pakistan. In fact, the analysis of National Uniform Wheat Yield Trial (NUWYT) data of Pakistan indicated that cultivars imported from CIMMYT yielded 100 kg/ha (6 percent) more than cultivars developed by Pakistan in the normal planting irrigated environment of Pakistan. The high transferability of CIMMYT materials can be also seen from the fact that 80 percent of varieties released in the Punjab for the normal planting date, in 1981-90 were developed from imported lines (mostly CIMMYT) (D. Byerlee, personal communication). These results, are however, based on the transferability of cultivars as measured by yields. The analysis ignores other important factors like grain color, quality and maturity of the crop which may be important in determining the transferability of a technology.

These research findings have important implications for designing crop improvement research programs. The levels of research capability in a region can be broadly classified as - technology evaluation and technology creation programs. Technology evaluation in crop improvement refers to testing and introducing germplasm developed by other research programs. Technology creation research refers to a breeding program involving crossing and selection in addition to local testing. The decisions on the level of research capability will be determined, among other things, by the magnitude and type of research spillins. The possibility of direct research spillins from CIMMYT or from other regions, as shown by this study, will encourage NARSs, especially in small countries or environments, to shift their research strategy from breeding to a technology evaluation program.

7.2.3 Economic Criteria for Establishing a Wheat Improvement Research Program in a Given Environment

The Resource Allocation Framework

The three decision variables that are influenced by research spillins, namely, the number of research programs, level of research capability and targeting strategy, define a continuum of research efforts (in terms of human and physical resource mix) of a crop improvement research program. Previous models based on production functions express this continuum of research effort in terms of research expenditures. However, expenditures per se do not affect research productivity since a given amount of money can be expended in many different ways by a research program. Among other things (such as physical and institutional infrastructure, research skills and networking abilities of scientists, serendipity) it is the level of research capability that influences research productivity.

The above considerations can be incorporated into a cost-benefit framework for designing a crop improvement research program for a given environment:

1. Given the research spillins from other sources (IARC and other countries), scientists and administrators need to determine the resource allocation alternatives such as creation and evaluation research.
2. For each alternative scenario, the research costs and benefits have to be determined taking into account the research lag, level of resources, yield advantages and other commercially important traits.
3. In principle, research resources should be allocated to the alternative whose expected present value is positive (using the opportunity cost of capital to discount future benefits and costs). However, if both the alternatives yield positive returns, than the alternative with the highest net present value (NPV) should be chosen.

Threshold Size of Wheat Production to Justify Technology Creation and Evaluation Research

The cost-benefit framework was used to chose between a wheat testing program (technology evaluation research) and a breeding program (technology creation research that includes crossing, selection and testing). In the base scenario the yield gains from a breeding program were assumed to be 0.3 percent per year more than the yield gains realized from a testing program. This assumption would generate a cumulative yield advantage from locally developed varieties of six percent in less than two breeding cycles. This is a conservative estimate given the empirical results of wide transferability of CIMMYT cultivars across environments.

The costs of a testing program were assumed to be one third of a breeding program, based on the empirical observation of the ratio of the size of a testing and breeding program in developing countries. The research lag for a testing program was assumed to be five years compared with twelve years for a breeding program. Assuming a discount rate of 12 percent and taking the averages of the long-term import price of wheat, the resource allocation framework was applied to estimate the threshold size of the target domain to justify a given alternative. The threshold size of the target domain was defined as the level of production at which the NPV of a given alternative is zero.

Given the parameter values in the base scenario, the results indicate that the critical production level to justify a testing and breeding program is 198,000 and 462,000 tons, respectively. Thus, the size of the target domain to justify a breeding program is much larger than the threshold size to justify a testing program. These threshold levels of wheat production are higher than those of Brennan (1992a). The level of production at which a breeding program would earn the highest NPV was found to be 1,392,000 tons.

The level of production that yields the highest NPV for a breeding program was found to be very sensitive to the difference in yields of the two decision alternatives. Environments with the potential of technology spillins will require a larger size of target domain to justify a breeding program (that includes crossing and early generation selection component in addition to local testing). For example, an increase in research spillins that reduces the yield difference between a breeding program and a testing program from 0.3 percent per year to 0.15 percent per year increased the level of most profitable returns for a breeding program from 1.39 to 2.73 million tons.

The threshold level of production to justify a breeding program was also found to be sensitive to quality advantages of a locally developed technology. If a country has well entrenched consumer preferences, it may hinder the transferability of an imported technology. If the varieties developed by a local breeding program generate a 10 percent price premium because of their superior quality, then the level of most profitable returns for a wheat breeding program would be reduced by 30 percent from 1.39 million tons to 0.96 million tons. These results indicate the critical importance of local consumer preferences in justifying a crop breeding program. Such considerations are likely to be important in crops such as rice and maize, because consumers are more particular about the grain color and quality of these crops.

7.2.4 Profitability of Investments in Wheat Improvement Research in Developing Countries

The resource allocation framework was used to calculate the profitability of current levels of research investments for sixty nine individual wheat research programs in thirty one developing countries. The striking result of this analysis was that forty five out of sixty nine research programs were found to be investing more than the justifiable levels of expenditures on wheat improvement research. For fifteen of these programs, wheat improvement research could be justified by changing the level of research capability from breeding to evaluation and/or reducing the size of their research programs to three FTE researchers for a breeding program and one FTE for a testing program. For the remaining thirty unprofitable programs (with NPV $\leq$ 0 at 12 percent discount rate), the small size of wheat production in the mandate region and high research costs explain their unprofitability. Thus, strictly judging from the economic criterion of profitability (i.e. NPV > 0), many research programs in developing countries are investing in wheat improvement research when it is not justifiable. Also, judging from the NPV criterion for selecting mutually exclusive research investments (NPV of breeding program > NPV of testing program > 0), many countries are 'overinvesting' in wheat research. This result challenges the conventional wisdom (supported by the high rates of returns to agricultural research) that NARSs are underinvesting in agricultural research. The finding of 'overinvestment' in wheat improvement research is based on the fact that many research programs are investing in wheat breeding research when an evaluation research program would suffice (that is to say, for these programs the NPV of testing program is > NPV of breeding program > 0).

Most rate of return to research (*ex post* and *ex ante*) have ignored direct research spillins. Investments in a given breeding program are strictly evaluated as free-standing research projects based on the criterion of NPV > 0 or rate of returns greater than the opportunity cost of capital. However, if technology evaluation is considered as an alternative to a local breeding program (i.e. they are mutually exclusive), then the criterion of positive NPV may not be an efficient allocation rule (Gittinger 1982). The NPVs of the two alternatives have to be compared and research investments need to be evaluated on the basis of following decision rule - NPV of breeding program > NPV of testing program > 0.

Discriminant analysis was used to determine the importance of different factors that make a program profitable. The results of this analysis indicated that the size of production in the geographic region and the cost per researcher were the most important factors influencing the profitability of a wheat improvement program. Thus, the small size of research mandate and the high costs of many research programs of developing countries are the factors limiting investment in wheat improvement.

7.3 General Conclusions

Three major conclusions flow from this study.

1. The location specificity argument is not sustained for wheat varietal technology. The results of this study reveal that CIMMYT cultivars have wide adaptability across different megaenvironments. A large percentage of wheat varieties released in developing countries were directly introduced from CIMMYT or other countries. The direct spillins were found to be higher than previously noted by others such as Englander (1981a). Wheat technology is more robust than other cereals because the production environments and local differences in quality preferences are not as marked as in rice or maize.

2. Wheat cultivars from CIMMYT were found to be highly transferable across different megaenvironments. The high yield advantages of CIMMYT cultivars (compared to cultivars developed by national programs in the local environment) in irrigated and high rainfall environments and, at least comparable yield advantages in other megaenvironments, demonstrates the success of CIMMYT's wheat research program in combining high yield potential and wide adaptation in wheat varietal technology. The high productivity of CIMMYT's wheat research program can be attributed to its global breeding operation. However, if the budget cutbacks of the early 1990s continues in the future, CIMMYT may not be able to maintain this global comparative advantage in wheat breeding.

3. Many research programs in developing countries are overinvesting in wheat improvement research. Viewed from the NPV criterion of profitability (NPV > NPV of alternative investments > 0), fifteen research programs were found to be overinvesting because of inefficient level of research capability (i.e. they were investing in breeding when testing was most profitable) or inefficient size of research program (employing too many researchers than justifiable). Thirty research programs were found to be investing in wheat improvement research unprofitable levels suggesting the need to reduce the size of their programs to less than one FTE researcher.

These results reveal the danger of applying 'rules of thumb' (such as spending 2% of agricultural GDP on research) in designing a national research system. Decisions on resource allocations to agricultural research must be made on a commodity by commodity basis through the use of some kind of a cost-benefit analysis that takes the following factors into account: environmental diversity, research spillins, research costs (scientists needed to carry out research, their salaries, operating expenses, etc.), research lag and the size of the target region.

7.4 The Underinvestment Hypothesis, Revisited

It is now conventional wisdom in agricultural research policy circles that the level of public investment in agricultural research, both in developed and developing countries, is too low. This underinvestment hypothesis is based on two arguments. The first is the

almost universal evidence of a high rate of return to agricultural research. The second is the lack of congruence between the costs and benefits from research due to spillover effects. One of the results of this study is the finding that a large number of research programs in developing countries are overinvesting in wheat improvement research. In order to understand why the results of this study differ from the widespread view of underinvestment in research, we shall reexamine the conceptual and analytical foundations of these two arguments.

The Argument of High Rate of Returns

Based on the evidence of a high rate of return to investments in agricultural research, many authors have concluded that investments in agricultural research have been inadequate. This conclusion is based on the economic efficiency principle that requires that the marginal value products of society's investment have to be equated across all investment opportunities. Given this economic principle and the evidence of high marginal rate of returns, Ruttan asserts that "there is little doubt that a level of expenditures that would push rates of return to below 20 percent would be in the public interest" (Ruttan 1980, p.531).

Based on the results of this study, the underinvestment hypothesis and the policy prescription of increasing research investments are challenged on the following grounds.

1) **Analytical grounds:** The *ex-post* rate of return studies evaluate research investments as a free-standing research projects based on the criterion of NPV > 0. The evidence of rate of returns greater than the opportunity cost of capital (OCC) (i.e. NPV > 0 when evaluated at OCC) is therefore interpreted to imply that investments in research should be increased to drive down the rate of return. However, this study has shown that if research programs are considered as mutually exclusive, then investment decisions based on the criterion of NPV > 0 is not an efficient allocation rule.

The fifteen wheat research programs that were found to be investing more than the optimal levels (Table 6.11) illustrate this point. The current investments in improvement research were found to be earning positive NPV (i.e. IRR > OCC). According to the conventional rate of return research evaluation framework, this evidence would be interpreted to substantiate the underinvestment hypothesis. However, if the maximum NPV criterion is applied, and investments are evaluated as alternatives, then these programs are overinvesting in wheat improvement, since the alternative of decreasing investments (by focussing on evaluation research) would earn them higher NPV.

2) **The rate of return literature is replete with success stories of high returns to wheat improvement research programs in developing countries:** This study has found that the research programs earning the highest levels of returns were located in large wheat producing countries with a long history of successful wheat research programs (India, Pakistan, Turkey, Brazil, Mexico). This conforms with the rate of return studies in these countries. The studies of returns to wheat research have been confined either to large wheat producing countries or the late sixties and the 1970s when the Green Revolution was generating large increments in wheat yields. However, studies of returns to investments in wheat research in small wheat producing countries and in large wheat producing countries during the 1980s are generally not available. In the case of countries with a small area under wheat production it was found that they were not earning high rate of returns (for example IRR of 11-12% in case of Colombia as reported by Hertford at al. [1977]). Similarly, the studies of large wheat producing countries in the 1980s have reported declining rate of returns to wheat research. For example, the IRR for the post-Green Revolution period in Punjab, Pakistan was 16-27% (Byerlee 1993) as compared to 55-71% IRR for all Pakistan for the Green Revolution period (Nagy 1984).

Since this study was based on wheat improvement programs in small and large developing countries for the post-Green Revolution period (the 1980s) it is not surprising that many research programs in developing countries were found to be overinvesting in wheat improvement research.

3) **The rate of return studies have not considered direct spillins:** Economists have generally failed to incorporate direct spillins in estimating the rate of return. They have either incorrectly classified directly introduced varieties as locally developed and attribute all the benefits to local research or used the 'free good' argument and not

adjusted the local research costs. This has led to an overestimation of research benefits attributable to local research and exaggeration of the rate of return. Although, the 'free good' argument may be valid for an independent decision maker, it may lead to an incorrect evaluation of a research program. If direct spillins are available, then the rate of returns should be calculated for the incremental costs and benefits (i.e. above those attributed to a research program that is only depending on direct spillins) attributed to local research effort, rather than the total costs and benefits.

The Argument of Spillover Effects

The second argument underlying the underinvestment hypothesis lies in the spillover effects and the resulting lack of congruence between the costs and the benefits of agricultural research. This is the externality argument of economic inefficiency that implies that a research program making independent decisions without consideration of its positive externalities to other research programs is investing less than socially optimum. Thus, Ruttan in the context of U.S. research system, argues that:

> "The significant spillover benefits from state agricultural research to other states implies that the optimum level of investment by an individual state is below the level that would be optimum if it were evaluated at a regional or national level." (Ruttan 1982, p. 256)

Theoretically this is a valid argument. However, the underinvestment hypothesis based on the spillover effects differs from the overinvestment results of this study in the following respects.

According to the spillover argument, an individual state (or a political decision-making unit) generating positive externalities underinvests in research from a national perspective. Similarly, a country generating positive externalities underinvests in research from an international perspective. The approach taken by this study is based on the perspective of an individual research program that makes independent decisions without consideration of its effects on other research programs. Returns are assessed only from the perspective of an individual research program. Research spillins rather than research spillovers are, therefore, given greater emphasis in this study. Given the fact that spillins from other programs may substitute for local research, a research program overinvests in research if it ignores direct spillins.

Whereas the underinvestment hypothesis considers only the spillover effects, the overinvestment results of this study are based only on research spillins. Theoretically, there are potential limitations of both approaches when the optimal decisions of individual research programs are aggregated. The danger in only considering the spillover effects is that if all the research programs made decisions only on the basis of spillover effects, the higher socially optimal levels of investment required by individual research programs may duplicate research efforts and lead to overinvestment in research when aggregated at the national level. On the other hand, the danger in only considering research spillins is that if all the research programs made decisions based on research spillins from other programs, the optimal levels of investment required by an individual research program will decrease and lead to underinvestment in research at the aggregate (national and international) level. At an extreme, this may result in no generation of research spillins at all (if no other external source of spillin exists).

Thus, theoretically, both arguments may be discredited. However, the approach used in this study is defended on the following grounds:

1) The approach of estimating costs and benefits from an individual research program perspective (that ignores spillover effects) is in accordance with reality. A research program in Zimbabwe will not justify its research budget based on its effect on Malawi or Zambia. This same reasoning is also applied by researchers carrying out rate of return studies.

2) The decision of an individual research program to change its research strategy based only on the consideration of direct spillins will not affect the global 'technology transfer pool' if an independent source of technology transfer already exists (such as CIMMYT in the case of wheat improvement research). Thus, the decision of Nepal to eliminate its wheat breeding program and only concentrate on evaluation research will not affect the global technology transfer pool or research

spillins to research programs in Punjab. Similarly, the decision of Burundi to eliminate wheat improvement program will not reduce the spillovers to other research programs in neighboring countries. Thus, as long as the decisions of major spillover producing programs (such as CIMMYT) do not change, the approach used in this study to evaluate each program's decision independently is valid.

3) Because of the location-specificity argument, spillins in crop research were usually considered to be indirect in nature (i.e. exchange of germplasm for parent materials, exchange of breeding methods, scientific information, etc.). Thus, research spillovers were assumed to affect only the research productivity of other research programs. The underinvestment hypothesis is based on this basic premise. However, if direct research spillins are possible, then research spillins will not only affect research productivity but also the choice of the research strategy. This is the basic premise of the conceptual framework of this study. The evidence of direct spillins in wheat improvement research provided by this study supports this basic premise.

To sum up, the underinvestment hypothesis based on the evidence of high rate of returns and spillover effects is not substantiated by this study. By taking account of research spillins and using the criterion of maximum NPV, more than half of the research programs in developing countries were found to be overinvesting in wheat improvement research.

7.5 Policy Implications

Several policy implications can be drawn from the results of this study. Some apply to wheat improvement research in developing countries alone, while others may be applicable to other crops and to all countries - developing and industrialized.

7.5.1 Implications for Research Administrators

The results of this study indicate that two-third of the wheat improvement research programs in developing countries were found to be overinvesting in research. This overinvestment is caused by many institutional, bureaucratic and political factors that inflate the size of wheat research programs in terms of the number of scientists, duplication of wheat research programs and that pay too little attention

to borrowing technology from the global research system. However, because of the severe budget constraints of the mid-1990s, the justification for agricultural research will have to be based on hard economic realities. To efficiently utilize available research resources, funding for wheat research should be based on the following considerations:

1. The establishment of crop improvement research programs should be based on environmental rather than political boundaries. For example, instead of India pursuing over 50 wheat research programs (Jain and Byerlee 1993) with at least one in each state where wheat is grown, it should develop one major program for each of the nine major agro-climatic zones.

2. For a given environment, the appropriate type of a wheat research program (technology evaluation or technology creation) needs to be carefully determined based on the availability of research spillins from other national programs and international centers.

3. The decision *ex ante* to establish a research program or to change an existing research program by adding new components to it (viz. local crossing and early generation selection components to the existing evaluation program) should be based on the alternative with the highest NPV. For example, if both evaluation and breeding research alternatives are earning a positive NPV but the NPV of a breeding program is less than that of a testing program, then investments in a technology creation programs engaged in local crosses and selections (in addition to testing imported materials) would imply a serious waste of resources. This study demonstrates the importance of developing research resource allocation mechanism based on the economic criterion of maximum NPV rather than merely a positive NPV.

This framework is useful for research administrators faced with the decision *ex ante* of whether and what type of crop improvement research program is optimal for an environment. For research programs that have been already established and are earning negative returns (such as the thirty research programs analyzed in this study), it is suggested that they should either - reduce the size of their wheat improvement research programs (comparable to that of programs in developed countries), change the level of research capability (from technology creation to technology evaluation), consolidate research programs of different commodities (for example, wheat evaluation research can be combined with other crops in one evaluation program), conduct no wheat improvement research at all, or participate in a regional collaborative research program. However, because of institutional rigidities it will be difficult for many NARSs to change their wheat research strategies in a short period of time. In many countries, human resources can be transferred from wheat to other areas of research that are more profitable. This will increase the overall efficiency of resources devoted to agricultural research.

Since the NPV of alternative levels of research capability change with the availability and type of research spillins over time, it is essential that research administrators periodically review the research commitments and reallocate research resources on the basis of new information about the potential research payoffs of other alternatives. Since the efficiency of research resources will depend on the magnitude of research spillins, research administrators should examine the crops in terms of transferability potentials. Crops with the potential for direct spillins will be less researched than those whose results are location-specific. Similarly, for a given commodity, research areas with smaller possibilities of direct spillins will be more researched. For example, in a crop such as wheat, some NARS should probably reallocate resources from plant breeding research to crop management and natural resource management research which are likely to be more location-specific.

7.5.2 <u>Implications for Research Scientists</u>

The economic justification of a crop improvement research program will require an estimation of expected costs and returns from local research based on the expected yield gains and expected research spillins which are determined by the biological complexities of genotype x environment interactions. Thus, in order to justify a breeding program on economic grounds, research scientists will have to improve their understanding of the complexities of G x E interaction and their implications for the type of improvement program and the relative allocation to different components of a chosen strategy (number of testing sites, early versus late generation testing strategy, etc).

In the past, many scientists have been overly concerned about the appropriate statistical method to estimate G x E interactions. These methods help detect the interactions but they do not explain their cause and consequences for resource allocations for plant breeding. Establishment of new research programs should be justified on the grounds that exploitation of G x E interactions will enhance the genetic gains due to selection. However, whether G x E interactions should be exploited or not will depend on the cause of such interactions. For example, the decision on whether separate breeding programs are needed for low-input environments depends on the extent to which yields in low- and high-input environments are under separate genetic control. Before separate programs can be recommended, it must be demonstrated that alleles controlling yield in the two situations are different. However, it is possible that breeders can strive to incorporate new alleles which are superior in both situation, thus eliminating the need for a separate breeding program (Ramogosa and Fox 1993). Careful assessments of G x E interactions, their cause and consequences are therefore important in justifying the establishment of a research program, the breeding strategy pursued by a program, early versus late generation testing and location of trial sites, all of which have important implications for the efficiency of the resources allocated to breeding research.

7.5.3 Implications for International and Regional Research Cooperation

The results of the analysis of research spillins emphasize the importance and need for regional cooperation in crop improvement research. The results of the analysis indicate that research programs that could not justify any wheat research (i.e. earning NPV < 0) need to face the issue of whether they should participate in regional research cooperation. The resource allocation framework discussed above can be used to determine the level of research capability for the regional program. A regional cooperative program can be based on the commonality of interests (i.e. all the participating countries should be worse off without participation) of the cooperating countries and should be formed by countries with similar agroclimatic environments. A successful example of such a regional cooperative program is the PROCISUR program agreement of the six countries of the Southern Cone, South America that conducts research on commodities of regional importance (Evenson and daCruz 1992).

The success of CIMMYT cultivars across different environments demonstrates the possibility of producing wheat technology that is directly transferable to many developing countries. From an economic perspective, national programs should utilize CIMMYT technology in environments where they are directly transferable and concentrate their efforts on finding solutions to local research challenges such as genetic improvement for local quality preferences and storage practices, crop maturity to fit with the local cropping system, etc.

To the extent that an environment is shared by many countries, CIMMYT should assist these countries through a breeding program to produce directly transferable technology. However, for environments that are country specific, the alternative of letting the NARS produce its own technology would be optimal from a global perspective.

7.6 Suggestions for Further Research

Perhaps the greatest weakness of this study is the use of yield as the sole performance indicator of a technology. The transferability of a technology is overestimated if yields negatively interact with other traits such as crop maturity, stability and grain quality. New methodologies need to be developed that can estimate the G x E interactions not only in terms of yield but also in other traits. Meanwhile, the negative interactions of yields with other traits can be accounted for by making the price and level of adoption a function of level of research capability.

Another limitation of this study is the general nature of the analysis of the resource allocation framework. The sensitivity of results (as high as 100% increase in threshold level of production to a 25% increase in research spillins) suggests that it is difficult to generalize for any particular national wheat research program. However, if the analysis is based on data applicable to a particular country/research program, it can provide important and useful information to decision makers of that country. Thus, more country-specific studies need to be undertaken to provide specific guidelines about resource allocation.

The estimation of research benefits is based on many restrictive assumptions about the supply shifts and the price elasticities for demand and supply. The research benefits may have been slightly underestimated compared to the conventional approach of estimating the economic surplus. This may not be a serious limitation since the study was more interested in comparing the profitability of alternative investments rather than the level of profitability per se. However, this limitation could also be offset if the framework is applied to a particular country/region for which information on the price elasticities of demand and supply is available.

Finally, the resource allocation framework is based on the assumption that potential research costs and payoffs can be determined *ex ante* fairly precisely. As a result, where importing foreign technology seems most profitable *ex ante*, no creation research is suggested to be done at all. This conclusion may not hold when research payoffs are very uncertain *ex ante* due to the uncertainty in the parameter values or continuation of research spillins. The risk of depending on spillins have to carefully assessed. These risks may be due to political reasons (for example, dependence on a country which is politically not in good terms, such as Pakistan depending on India), institutional factors (for example, can countries depend on CIMMYT forever; what is the reliability of the north to adequately fund CIMMYT for next 5, 25 or 50 years), economic instability (Uruguay depending on Argentina faces the risk of discontinuity of research spillins if the NARS of Argentina undergoes an economic crisis), or the risk of reducing the genetic diversity (direct use of spillins reduces genetic diversity since neighboring countries will often grow the same varieties). Theoretically, this limitation can be corrected by calculating the probability distributions of parameters to assess the riskiness of each alternative and calculating the NPV based on the weighted parameters. Alternatively, a differential risk premium can be added to the discount factor to take into account the risks associated with pursuing one alternative as against the other.

7.7 Conclusion

This study has developed a general analytical framework to address the question of global resource allocation for wheat improvement research. Numerous rate of return studies have confirmed Griliches (1958) finding of a high rate of return to research and have concluded that there is underinvestment in agricultural research in many countries. However, rate of return studies have generally failed to account for research spillins. The present study has attempted to consider some of the economic and biological factors that determine the profitability of research investments in crop improvement research and has developed a framework that explicitly takes into account research spillins from IARC and other national programs. It has directly measured technology spillins which have hitherto been based on subjective guesses and revealed that many developing countries are over- rather than underinvesting in wheat improvement research.

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APPENDICES

APPENDIX A

WHEAT AREA AND PRODUCTION UNDER DIFFERENT MEGAENVIRONMENTS FOR DIFFERENT WHEAT PRODUCING DEVELOPING COUNTRIES, 1980

APPENDIX A

WHEAT AREA AND PRODUCTION UNDER DIFFERENT MEGAENVIRONMENTS FOR MAJOR WHEAT PRODUCING DEVELOPING COUNTRIES, 1980.

Country		Megaenvironment 1	2	3	4A	4B	4C	5A	5B	6A	6B	6C	6D	7	Total
1 Afghanistan	Area[a]	1000	0	0	1100	0	0	0	0	0	0	200	0	0	2300
	Prod[b]	1700	0	0	800	0	0	0	0	0	0	260	0	0	2760
2 Algeria	Area	0	370	0	1780	0	0	0	0	0	0	0	0	0	2150
	Prod	0	481	0	1360	0	0	0	0	0	0	0	0	0	1841
3 Argentina	Area	0	2800	0	0	3065	0	0	65	0	0	0	0	0	5930
	Prod	0	7315	0	0	3877	0	0	97	0	0	0	0	0	11289
4 Bangladesh	Area	0	0	0	0	0	0	500	195	0	0	0	0	0	695
	Prod	0	0	0	0	0	0	1205	273	0	0	0	0	0	1478
5 Brazil	Area	0	0	1680	0	0	0	20	0	0	0	0	0	0	1700
	Prod	0	0	2394	0	0	0	36	0	0	0	0	0	0	2430
6 Chile	Area	90	125	0	0	80	0	0	0	120	45	120	35	0	615
	Prod	360	312	0	0	120	0	0	0	300	67.5	300	52.5	0	1512
7 China	Area	8610	2020	0	0	0	500	600	0	5270	990	3900	2250	4830	28970
	Prod	29274	6868	0	0	0	750	2040	0	17918	1485	12684	3375	12939	87333
8 Egypt	Area	385	0	0	0	0	0	170	0	0	0	0	0	0	555
	Prod	1424	0	0	0	0	0	629	0	0	0	0	0	0	2053
9 Ethiopia	Area	0	545	0	0	0	0	0	0	0	0	0	0	0	545
	Prod	0	639	0	0	0	0	0	0	0	0	0	0	0	639
10 India	Area	14450	0	0	0	0	3350	2150	2750	0	0	0	0	0	22700
	Prod	34095	0	0	0	0	3420	3975	2200	0	0	0	0	0	43690
11 Iran	Area	510	0	0	1020	0	0	0	0	0	3060	1530	0	0	6120
	Prod	663	0	0	515	0	0	0	0	0	1836	1989	0	0	5003

Country		Megaenvironment 1	2	3	4A	4B	4C	5A	5B	6A	6B	6C	6D	7	Total
12 Iraq	Area	561	186	0	1117	0	0	0	0	0	0	0	0	0	1864
	Prod	1010	298	0	1340	0	0	0	0	0	0	0	0	0	2648
13 Jordan	Area	5	20	0	130	0	0	0	0	0	0	0	0	0	155
	Prod	9	24	0	65	0	0	0	0	0	0	0	0	0	98
14 Kenya	Area	0	110	0	0	0	0	0	0	0	0	0	0	0	110
	Prod	0	201	0	0	0	0	0	0	0	0	0	0	0	201
15 Libya	Area	50	50	0	690	0	0	0	0	0	0	0	0	0	790
	Prod	120	85	0	306	0	0	0	0	0	0	0	0	0	511
16 Mexico	Area	370	100	0	0	0	0	280	0	0	0	0	0	0	750
	Prod	1702	120	0	0	0	0	1288	0	0	0	0	0	0	3110
17 Morocco	Area	70	780	0	1100	0	0	0	0	0	0	0	0	0	1950
	Prod	140	1560	0	984	0	0	0	0	0	0	0	0	0	2684
18 Nepal	Area	125	0	0	0	0	340	0	0	10	0	0	0	0	475
	Prod	226	0	0	0	0	340	0	0	17	0	0	0	0	583
19 Pakistan	Area	5850	0	0	0	0	1650	0	0	0	0	0	0	0	7500
	Prod	11700	0	0	0	0	1440	0	0	0	0	0	0	0	13140
20 Paraguay	Area	0	30	0	0	0	0	0	160	0	0	0	0	0	190
	Prod	0	60	0	0	0	0	0	272	0	0	0	0	0	332
21 Peru	Area	0	100	0	0	0	0	0	0	0	0	0	0	0	100
	Prod	0	120	0	0	0	0	0	0	0	0	0	0	0	120
22 Sudan	Area	0	0	0	0	0	0	170	0	0	0	0	0	0	170
	Prod	0	0	0	0	0	0	221	0	0	0	0	0	0	221
23 Syria	Area	175	490	0	860	0	0	0	0	0	0	0	0	0	1525
	Prod	350	833	0	860	0	0	0	0	0	0	0	0	0	2043
24 Tunisia	Area	0	510	0	800	0	0	0	0	0	0	0	0	0	1310
	Prod	0	867	0	558	0	0	0	0	0	0	0	0	0	1425

Country		Megaenvironment 1	2	3	4A	4B	4C	5A	5B	6A	6B	6C	6D	7	Total
25 Turkey	Area	0	1400	0	1510	0	0	0	0	85	380	955	4830	0	9160
	Prod	0	4455	0	2114	0	0	0	0	510	532	3135	6992	0	17738
26 Uruguay	Area	0	210	0	0	0	0	0	0	0	0	0	0	0	210
	Prod	0	273	0	0	0	0	0	0	0	0	0	0	0	273
TOTAL	Area	32251	9846	1680	10107	3145	5840	3890	3170	5485	4475	6705	7115	4830	98539
	Prod	82773	24511	2394	8902	3997	5950	9394	2842	18745	3921	18368	10420	12939	205155

Source: CIMMYT Wheat Megaenvironment Data Files
[a] '000 ha
[b] '000 tons

APPENDIX B

INFORMATION ON ISWYN TRIAL LOCATIONS AND ENTRIES

Table B.1: Information on the ISWYN Trial Stations Appearing in ISWYN 16-18, 20-24.

ST#	Country	State	City/Institute	Lat	Long	Elev[a]	ME[b]
10009	South Africa	OFS (3)	SENSAKO	028	028	1631	1
10012	South Africa	TRANSVAAL (3)	GROBLERSDAL	025	029	950	1
11101	Zimbabwe	HARARE (2)	GWEBI	017	030	1448	1
11103	Zimbabwe	HARARE (1)	CHISIPITE	017	031	1300	1
11109	Zimbabwe	RATTRAY ARN	CHISIPITE	017	030	1300	1
19101	Egypt	EL GEMMEIZA	EL GARBIA	030	031	8	1
19103	Egypt	SAKBA	KAFR EL SHEIKH	031	030	6	1
19106	Egypt	SIDS	BENI-SUEF	029	031	28	1
19201	Libya	TRIPOLI	TAJOURA	032	013	11	1
19207	Libya	KUFRA	KUFRA	025	023	415	1
19210	Libya	MISURATA	TOMENA	032	012	32	1
19211	Libya	AL-ZAHERA	ZAWIA AL-ZAHRA	032	012	15	1
20002	Afghanistan	SHISHAM BAGH	JALALABAD	034	070	552	1
20306	Iran	FARS(1)	DARAB	028	054	1100	1
20309	Iran	GORGAN	MAZANDARAN	036	054	5	1
20401	Iraq	ABU'GHRAIB	BAGHDAD	033	044	34	1
20501	Jordan	JORDAN VALLEY	DEIR ALLA	032	035	-224	1
20901	Qatar	RAWDAT HARM	DOHA	025	051	50	1
21002	Saudi Arabia	AL KHARJ	AL KHARJ	024	047	540	1
21004	Saudi Arabia	ONAIZAH	AL GASSIM	026	044	724	1
21005	Saudi Arabia	RIYADH (1)	DIRAB	024	046	600	1
21201	Turkey	CUKUROVA	ADANA	036	035	20	1
22102	Bhutan	BHUR	BHUR	027	089	460	1
22207	India	NEW DELHI	IARI	028	077	228	1
22208	India	PUNJAB	LUDHIANA	030	075	247	1
22209	India	RAJASTHAN	DUNGARPUR	026	075	450	1
22210	India	U.P.(5)	PANTNAGAR	029	079	243	1
22225	India	HARYANA(2)	HISSAR	029	075	215	1
22501	Nepal	RUPANDEHI(2)	BHAIRAHWA	027	083	105	1
22511	Nepal	RUPANDEHI(1)	BHAIRAHWA (IAAS)	027	082	105	1
22601	Pakistan	NWFP	PESHAWAR	032	068	340	1
22603	Pakistan	FAISALABAD	FAISALABAD(LYALLPUR)	031	073	213	1
22604	Pakistan	SIND	TANDOJAM	025	063	19	1
22608	Pakistan	NWFP	PIRSABAK	034	072	288	1
41001	U.S.A.	ARIZONA (4)	MESA	033	111	375	1
41003	U.S.A.	CALIFORNIA (4)	DAVIS	038	121	18	1
42004	Mexico	SONORA (1)	CIANO	027	109	38	1
42010	Mexico	NUEVO LEON (2)	LA LEGANA NAVIDAD	025	100	1895	1
42012	Mexico	DURANGO (1)	VALLE DEL GUADIANA	024	104	1889	1
42101	Mexico	GUANAJUATO (2)	EL BAJIO	020	100	1765	1
51204	Chile	SANTIAGO (1)	LA PLATINA	033	070	629	1
51205	Chile	SANTIAGO (2)	PIRQUE	033	070	654	1
51206	Chile	RANCAGUA	GRANEROS	034	070	500	1
53503	Peru	LIMA (2)	LA MOLINA	012	076	251	1
65408	Spain	CORDOBA (4)	EL ENCINAR	038	004	180	1
65409	Spain	SEVILLA (4)	LA RINCONADA	037	005	20	1
12209	Ethiopia	SHOA (4)	AMBO (SHEWA)	008	038	2225	2
12302	Kenya	RIFT VALLEY (5)	NJORO	000	036	2165	2
12307	Kenya	RIFT VALLEY (4)	N.P.B.S.	000	035	2166	2
19003	Algeria	GUELMA	GUELMA	036	007	263	2
19005	Algeria	CONSTANTINE	EL KHROUB	036	006	640	2
19303	Morocco	RABAT (3)	MARCHOUCH	033	006	500	2
19402	Tunisia	BEJA	BEJA	036	009	150	2
20304	Iran	ARAGHEE MOH	GORGAN	036	054	132	2
20702	Lebanon	TEL AMARA	BEKA'A VALLEY	033	035	950	2
21205	Turkey	IZMIR	AEGEAN	038	027	20	2
21209	Turkey	IZMIR (1)	E.B.Z.A.	038	027	10	2
21601	Israel	KIRYAT-GAT	MIVHOR FARM	031	034	120	2
21602	Israel	BET DAGAN	VOLCANI	032	034	30	2
22401	Myanmar	SHAN	HEHO	020	090	1140	2
22607	Pakistan	ISLAMABAD	ISLAMABAD	033	073	683	2
42103	Mexico	TOLUCA	ATIZAPAN	019	099	2640	2
42117	Mexico	CAEVAMEX	CHAPINGO	019	098	2249	2

Table B.1 (cont'd)

ST#	Country	State	City/Institute	Lat	Long	Elev \1	ME \2
42121	Mexico	TEXCOCO	EL BATAN	019	098	2249	2
45301	Guatemala	QUEZALTENANGO	LABOR OVALLE	014	091	2407	2
51201	Chile	CAUTIN (1)	TEMUCO	038	072	200	2
51202	Chile	NUBLE	CHILLAN (QUILAMAPU)	036	071	217	2
51501	Uruguay	COLONIA	LA ESTANZUELA	034	057	81	2
53002	Bolivia	COCHABAMBA (3)	SAN BENITO	017	066	2730	2
53004	Bolivia	POTOSI	CHINOLI	019	065	3450	2
53101	Colombia	CUNDINAMARCA	TIBAITATA	004	074	2550	2
53201	Ecuador	PICHINCHA (1)	STA. CATALINA	000	078	3050	2
53504	Peru	CAJAMARCA (2)	CAJAMARCA	007	078	2600	2
53506	Peru	CUSCO (2)	ANDENES	013	072	3391	2
53508	Peru	CUSCO (1)	TARAY	013	072	2910	2
65406	Spain	SEVILLA (3)	TOMEJIL	037	005	72	2
65412	Spain	BADAJOZ (3)	LA ORDEN	038	006	200	2
65413	Spain	CORDOBA (3)	ALAMEDA DEL OBISPO	037	004	110	2
50101	Brazil	RGS (3)	CRUZ ALTA	028	053	473	3
50102	Brazil	RGS (1)	PASSO FUNDO	028	052	684	3
50103	Brazil	SAO PAULO (3)	CAMPINAS	022	047	663	3
50104	Brazil	PARANA (1)	LONDRINA	023	051	540	3
50108	Brazil	PARANA (4)	PALOTINA (OCEPAR)	024	053	300	3
10007	South Africa	CAPE PROV. (9)	TYGERHOEK	034	019	168	4A
20202	Cyprus	NICOSIA (1)	LAXIA	035	033	200	4A
20203	Cyprus	NICOSIA (3)	ATHALASSA	035	033	142	4A
20502	Jordan	AMMAN	JUBEIHA	030	035	980	4A
20508	Jordan	MADABA	MOUSHAKER	031	035	785	4A
21101	Syria	IZRAA A.R.S	DERRA MOUHAPHAZA	032	036	575	4A
21102	Syria	ALEPPO (1)	BREDA	035	037	300	4A
21103	Syria	ALEPPO (2)	TEL HADYA	036	036	282	4A
21105	Syria	JELLIN-ACSA	DARAA	032	035	421	4A
65001	Greece	THESSALONIKI-1	EPANOMI P.B.I.	040	022	10	4A
65002	Greece	PLATY	PLATY	040	022	10	4A
65301	Portugal	ALENTEJO	ELVAS	038	007	208	4A
65401	Spain	MADRID (3)	EL ENCIN	040	003	600	4A
65405	Spain	CADIZ	JEREZ LA MERCED	036	006	20	4A
10002	South Africa	OFS (2)	BETHLEHEM	028	028	1687	4B
35005	Australia	NSW (1)	TAMWORTH	031	151	600	4B
51002	Argentina	BA (7)	LA DULCE	038	059	72	4B
51003	Argentina	BA (1)	PERGAMINO	033	060	65	4B
51004	Argentina	CORDOBA	MARCOS JUAREZ	032	062	110	4B
51009	Argentina	PARANA	ENTRE RIOS	031	060	110	4B
51402	Paraguay	ITAPUA (2)	CAP. MIRANDA	027	055	200	4B
22001	Bangladesh	JOYDEBPUR	BARI	023	090	8	5A
22002	Bangladesh	PABNA	ISHURDI	024	089	8	5A
22006	Bangladesh	MYMENSINGH	BAU CAMPUS	024	090	19	5A
22403	Myanmar	YE-U SAGAIN	PANGON	023	095	120	5A
22404	Myanmar	SAGAING	ZALOKE FARM	022	095	24	5A
51401	Paraguay	CORDILLERA	CAACUPE	025	057	228	5A
53005	Bolivia	SANTA CRUZ (3)	ABAPO IZOGZOG	018	063	386	5A
53007	Bolivia	SANTA CRUZ (2)	SAAVEDRA	017	063	320	5A
12701	Sudan	GEZIRA	WAD MEDANI	014	033	411	5B
12703	Sudan	KASSALA	KHASHM ELGIRBA	015	035	400	5B
21501	Yemen Dem.	HADRAMOUT	SEIYUN	016	049	600	5B
22205	India	M.P.(2)	POWARKHEDA	022	077	299	5B
35008	Australia	NSW (2)	CASTLEHILL	033	150	122	5B
50001	Brazil	DF	BRASILIA	015	047	1000	5B
50004	Brazil	M. GERAIS	SAO GOTARDO	019	046	1100	5B
19006	Algeria	SIDI-BEL-ABBES	SIDI-BEL-ABBES	035	000	450	6A
21202	Turkey	SAKARYA	ADAPAZARI	040	030	30	6A
21206	Turkey	DIYARBAKIR	DIYARBAKIR	037	040	660	6A
21213	Turkey	SAMSUN	BLACKSEA AGR.RES.INST.	041	036	10	6A
24006	P.R.China	JIANGSU (1)	NANJING	032	118	67	6A
24014	P.R.China	SICHUAN (1)	CHENGDU	030	104	506	6A
61703	Yugoslavia	MACEDONIA	MACEDONIA	043	022	250	6A
65420	Spain	LLEIDA (2)	BOLDU	041	001	250	6A

Table B.1 (cont'd)

ST#	Country	State	City/Institute	Lat	Long	Elev \1	ME \2
65422	Spain	LLEIDA (3)	FINCA LA CARRERADA	041	004	360	6A
19004	Algeria	SETIF	SETIF	036	005	1033	6B
20003	Afghanistan	DARUL AMAN	KABUL	034	069	1803	6B
20308	Iran	CHALOOS	KELARDASHT	036	050	1200	6B
22606	Pakistan	BALUCHISTAN	SARIAB QUETTA	030	066	1730	6B
41119	U.S.A.	TEXAS (5)	OVERTON	032	095	110	6B
65404	Spain	MADRID (2)	I.N.I.A.	040	003	490	6B
24001	P.R.China	BEIJING	BEIJING	039	116	50	7
24010	P.R.China	HEILONGJIANG-2	KESHAN	048	125	1234	7
24015	P.R.China	HEILONGJIANG-5	HEIHEI	050	127	168	7
24024	P.R.China	IN. MONGOLIA-1	HU HEHAOTE	040	111	1041	7
24034	P.R.China	HEILONGJIANG-1	HARBIN (AC.AGR.SCS.)	045	126	172	7
36010	New Zealand	MANAWATU	PALMERSTON NTH	040	175	15	7
36011	New Zealand	CANTERBURY	LINCOLN	043	172	11	7
40001	Canada	ALBERTA (3)	ELLERSLIE	053	113	677	7
40002	Canada	MANITOBA	WINNIPEG	049	097	235	7
40003	Canada	SASKATCHEWAN-3	SASKATOON	052	106	501	7
40103	Canada	ONTARIO (1)	GUELPH	043	080	333	7
40104	Canada	ONTARIO (2)	ELORA	043	080	380	7
41008	U.S.A.	MONTANA	BOZEMAN	045	111	1456	7
41009	U.S.A.	WASHINGTON (1)	PULLMAN	046	117	768	7
41012	U.S.A.	WASHINGTON (2)	ROYAL SLOPE	046	119	365	7
41014	U.S.A.	OREGON (3)	PENDLETON	045	118	454	7
41103	U.S.A.	STH DAKOTA	BROOKINGS	044	096	591	7
41105	U.S.A.	MINNESOTA (5)	ST. PAUL	044	093	260	7
61201	Czechoslovakia	BOHEMIA (3)	STUPICE	050	014	270	7
61410	Hungary	MARTONVASAR	MARTONVASAR	047	018	150	7
61505	Poland	WARSAW	RADZIKOW	052	020	90	7
61509	Poland	ELBLAG	DEBINA	054	019	-1	7
61601	Romania	FUNDULEA	CALARASI	044	026	66	7
61702	Yugoslavia	NOVISAD	VOYVODINA	045	019	84	7
61704	Yugoslavia	BOSNIA 1ST	SOKOLAC	043	018	860	7
63101	Belgium	GEMBLOUX	GEMBLOUX	050	004	160	7
63201	England	CAMBRIDGE	P.B.I.	052	000	17	7
63405	Germany	BADEN-WURT (2)	HOHENHEIM	048	009	407	7
63501	Ireland	KILDARE	BACKWESTON	053	006	50	7
65113	Italy	ENEA & CERM	MACERATA	043	013	190	7
67102	Finland	HYRLA	HANKKIJA	060	025	38	7
67401	Norway	AAS	VOLLE BEKK	059	010	90	7
67501	Sweden	LANDSKRONA (2)	SVALOV	056	013	50	7

[a] meters above sea level
[b] ME code description are given in Table 5.1

Table B.2: Information on the Cultivars Appearing in ISWYN 16-18,20-21

	Unique No.	Cultivar	Origin code[a]	Contributing country	Developmental origin	ME origin[b]	First ISWYN appearance
1	1074	Buck Mapuche	1	Argentina	Argentina	4B	22
2	1076	Buck Patacon	2	Argentina	Argentina	4B	22
3	313	CGT 700	1	Argentina	Argentina	4B	17
4	1028	Lap 286	2	Argentina	Argentina	4B	16
5	1260	Klein Chamaco	2	Argentina	Argentina	4B	16
6	1152	Victoria Inta	2	Argentina	Argentina	4B	22
7	1262	Norkin Churrinche	2	Argentina	Argentina	4B	23
8	1111	LAJ 2484	4	Argentina	CIMMYT	4B	20
9	1160	Pionero Inta	3	Argentina	CIMMYT	4B	24
10	10	Marcos Juarez Inta	3	Argentina	CIMMYT	4B	9
11	1161	Buck Ombu	4	Argentina	CIMMYT	4B	22
12	1193	Cruz Alta INTA	3	Argentina	CIMMYT	4B	24
13	1011	Banks	1	Australia	Australia	4A	17
14	369	Cook	1	Australia	Australia	4A	17
15	1057	Sun 278	1	Australia	Australia	4A	17
16	1050	QT 4081	1	Australia	Australia	4B	16
17	22	Oxley	1	Australia	Australia	4A	17
18	1056	Sun 11B-15	1	Australia	Australia	4A	16
19	1051	QT 4083	1	Australia	Australia	4B	16
20	1109	Sunelg	1	Australia	Australia	4A	23
21	1257	Quimori	4	Australia	CIMMYT	4A	18
22	1031	MN 7086	1	Australia	U.S.A.	4A	16
23	1229	Akbar	4	Bangladesh	CIMMYT	5A	22
24	362	Barkat	4	Bangladesh	CIMMYT	5A	15
25	1136	Kanchan	22	Bangladesh	India	5A	20
26	1086	Balaka	22	Bangladesh	India	5A	20
27	1233	Moncho S B	4	Bolivia	CIMMYT	5A	20
28	1163	PAI 4	4	Bolivia	CIMMYT	5A	18
29	1182	Chat	4	Bolivia	CIMMYT	5A	16
30	1252	Iapar 18 Marumbi	2	Brazil	Brazil	3	24
31	1048	PF 8237	1	Brazil	Brazil	3	23
32	1148	Minuano 82	1	Brazil	Brazil	3	20
33	1134	Iapar 6 Tapejara	1	Brazil	Brazil	3	20
34	1100	Mitacore	2	Brazil	Brazil	3	20
35	1046	PAT 73121	1	Brazil	Brazil	3	18
36	1250	Thornbird	2	Brazil	Brazil	3	23
37	1047	PF 70100	1	Brazil	Brazil	3	18
38	1101	IAC 24	2	Brazil	Brazil	3	23
39	226	IAS 54	2	Brazil	Brazil	3	17
40	1157	Alondra	4	Brazil	CIMMYT	3	16
41	1156	Alondra 4546	4	Brazil	CIMMYT	3	20
42	1202	Iapar 17 Caete	4	Brazil	CIMMYT	3	24
43	1077	IA 7873	4	Brazil	CIMMYT	3	20
44	1213	Macuta	3	Brazil	CIMMYT	3	22
45	1155	Alondra	4	Brazil	CIMMYT	3	21
46	1214	Perdiz	3	Brazil	CIMMYT	3	22
47	1212	Juriti	3	Brazil	CIMMYT	3	22
48	1159	Batuira (=Kea)	4	Brazil	CIMMYT	3	18
49	241	Glenlea	1	Canada	Canada	7	14
50	1275	Cisne INIA	4	Chile	CIMMYT	2	22
51	1162	Trisa INIA	4	Chile	CIMMYT	1	17
52	1154	Aurifen	2	Chile	Chile	1	22
53	1121	Jinmai 4058	1	China	China	5A	22
54	1030	Long Mai #10	1	China	China	7	24
55	1071	Yang Mai 6	1	China	China	6A	23
56	1285	Nanjing 82049	1	China	China	6A	24
57	1141	Ning 8331	1	China	China	6A	23
58	1043	Nanjing 4840	1	China	China	6A	22
59	1259	Antizana	4	Ecuador	CIMMYT	2	14
60	1226	TOB/CC//PTO/3/BB/GLL	3	Ecuador	CIMMYT	2	18
61	1099	HYSLOP/PVN	4	Ecuador	CIMMYT	2	20
62	1075	BUCKY/TOB/CNO	4	Ecuador	CIMMYT	2	20
63	1247	Zaraguro	2	Ecuador	Ecuador	2	16

Table B.2 (Cont'd)

	Unique No.	Cultivar	Origin code	Contributing country	Developmental origin	ME origin	First ISWYN appearance
64	1248	Tungurahua	2	Ecuador	Ecuador	2	20
65	1022	Imbabura	2	Ecuador	Ecuador	2	17
66	1007	Altar INIAP	2	Ecuador	Ecuador	2	17
67	1021	Iliniza	2	Ecuador	Ecuador	2	17
68	1249	ISWYN24 E38	2	Ecuador	Ecuador	2	24
69	1186	Gara	4	Ethiopia	CIMMYT	2	24
70	1005	Aintree	1	Great Britain	Great Britain	7	17
71	1232	Balanya 80	4	Guatemala	CIMMYT	2	18
72	1016	Chivito	4	Guatemala	CIMMYT	2	16
73	1168	Icta Sara 82	4	Guatemala	CIMMYT	2	20
74	1089	HI 977	4	India	CIMMYT	5B	24
75	1230	WL 2265	3	India	CIMMYT	1	20
76	1177	HUW 206	4	India	CIMMYT	1	23
77	74	Sonalika	4	India	CIMMYT	1	6
78	1108	HUW 37	2	India	India	1	18
79	1092	HD 2177	2	India	India	1	20
80	1063	UP 201	1	India	India	1	18
81	1126	UP 262	2	India	India	1	16
82	1019	HB 501	1	India	India	1	21
83	1096	HD 2281	1	India	India	1	21
84	1094	HD 2236	1	India	India	5B	18
85	1095	HD 2172	2	India	India	1	16
86	1085	HP 1209	2	India	India	1	16
87	1127	WL 711	2	India	India	1	17
88	1084	HUW 55	1	India	India	1	21
89	212	S331/NOR	2	India	India	1	12
90	1116	MLKS-11	2	India	India	1	18
91	1129	WL 410	2	India	India	1	18
92	1135	UP 1109	2	India	India	1	24
93	1020	HW 135	1	India	India	2	18
94	240	Abu-Ghraib #3	4	Iraq	CIMMYT	1	14
95	370	Hazera 806/1976	2	Israel	Israel	2	16
96	1027	Lakhish Line #757	2	Israel	Israel	2	18
97	1024	Kenya Kifaru	1	Kenya	Kenya	2	18
98	1023	Kenya 6106.3	1	Kenya	Kenya	2	16
99	1025	Kenya Paa	1	Kenya	Kenya	2	20
100	1138	Kenya Nungu	2	Kenya	Kenya	2	18
101	1110	Kenya Tumbili	2	Kenya	Kenya	2	23
102	1219	BUC/PVN	5	Mexico	CIMMYT	CIMMYT	21
103	1184	Bobwhite	5	Mexico	CIMMYT	CIMMYT	16
104	1188	Bobwhite "S"2	5	Mexico	CIMMYT	CIMMYT	18
105	1185	Bobwhite #1	5	Mexico	CIMMYT	CIMMYT	20
106	1170	Buck Buck	5	Mexico	CIMMYT	CIMMYT	16
107	1201	Caete	5	Mexico	CIMMYT	CIMMYT	18
108	1194	Chova	5	Mexico	CIMMYT	CIMMYT	18
109	1158	Chukar	5	Mexico	CIMMYT	CIMMYT	16
110	1205	Crow	5	Mexico	CIMMYT	CIMMYT	17
111	1208	Cucurpe 86	5	Mexico	CIMMYT	CIMMYT	16
112	1273	FLN/ACC//ANA	5	Mexico	CIMMYT	CIMMYT	21
113	323	Flicker D	5	Mexico	CIMMYT	CIMMYT	15
114	1192	Hahn	5	Mexico	CIMMYT	CIMMYT	18
115	1190	Junco	5	Mexico	CIMMYT	CIMMYT	22
116	1224	Kauz	5	Mexico	CIMMYT	CIMMYT	24
117	1189	MAI/PJ62//EMU	5	Mexico	CIMMYT	CIMMYT	16
118	1164	MAYA/MON	5	Mexico	CIMMYT	CIMMYT	16
119	1197	Minivet	5	Mexico	CIMMYT	CIMMYT	17
120	1204	Neelkant "S"A	5	Mexico	CIMMYT	CIMMYT	17
121	1167	Neelkant "S"B	5	Mexico	CIMMYT	CIMMYT	18
122	1200	PFAU	5	Mexico	CIMMYT	CIMMYT	21
123	1236	Pavon ReSel	5	Mexico	CIMMYT	CIMMYT	23
124	127	Pavon S1	5	Mexico	CIMMYT	CIMMYT	12
125	1128	SAP/MON	5	Mexico	CIMMYT	CIMMYT	17
126	1165	Tanager	5	Mexico	CIMMYT	CIMMYT	18

Table B.2 (Cont'd)

	Unique No.	Cultivar	Origin code	Contributing country	Developmental origin	ME origin	First ISWYN appearance
127	1195	Thrush	5	Mexico	CIMMYT	CIMMYT	17
128	307	Titmouse	5	Mexico	CIMMYT	CIMMYT	15
129	1206	Tyrant	5	Mexico	CIMMYT	CIMMYT	20
130	1172	Veery #4	5	Mexico	CIMMYT	CIMMYT	17
131	303	Veery #5	5	Mexico	CIMMYT	CIMMYT	17
132	1179	Veery #5"S"	5	Mexico	CIMMYT	CIMMYT	18
133	1178	Veery #7	5	Mexico	CIMMYT	CIMMYT	20
134	1173	Veery #8	5	Mexico	CIMMYT	CIMMYT	21
135	365	Vireo	5	Mexico	CIMMYT	CIMMYT	17
136	312	Vulture	5	Mexico	CIMMYT	CIMMYT	17
137	236	Choli (=Pima 77)	6	Mexico	CIMMYT	CIMMYT	12
138	317	Ciano 79	6	Mexico	CIMMYT	CIMMYT	15
139	1215	Esmeralda 86	6	Mexico	CIMMYT	CIMMYT	21
140	1191	Galvez 87	6	Mexico	CIMMYT	CIMMYT	24
141	1175	Genaro 81	6	Mexico	CIMMYT	CIMMYT	16
142	1181	Glennson 81	6	Mexico	CIMMYT	CIMMYT	17
143	1169	Imuris T79	6	Mexico	CIMMYT	CIMMYT	16
144	150	Nacozari 76	6	Mexico	CIMMYT	CIMMYT	12
145	1203	Opata 85	6	Mexico	CIMMYT	CIMMYT	21
146	1216	Papago 86	6	Mexico	CIMMYT	CIMMYT	23
147	327	Pavon 76	6	Mexico	CIMMYT	CIMMYT	13
148	1180	Seri 82	6	Mexico	CIMMYT	CIMMYT	18
149	136	Siete Cerros	6	Mexico	CIMMYT	CIMMYT	1
150	1276	Tonichi 81	6	Mexico	CIMMYT	CIMMYT	17
151	1174	Ures 81	6	Mexico	CIMMYT	CIMMYT	17
152	1008	BL 1022	4	Nepal	CIMMYT	1	24
153	1059	BL 1049	3	Nepal	CIMMYT	1	24
154	1124	T 8017	1	Norway	Norway	7	18
155	1125	T 8020	1	Norway	Norway	7	20
156	1176	Veery 7	4	Pakistan	CIMMYT	1	22
157	1067	V 5648	4	Pakistan	CIMMYT	1	22
158	1183	Bobwhite	4	Pakistan	CIMMYT	1	21
159	1198	Kohinoor	4	Pakistan	CIMMYT	1	21
160	1211	Faisalabad 85	4	Pakistan	CIMMYT	1	24
161	1187	Sarhad 82	4	Pakistan	CIMMYT	1	22
162	1171	Barani 83	3	Pakistan	CIMMYT	4C	24
163	1220	NR86-I	4	Pakistan	CIMMYT	1	24
164	1053	SA75	2	Pakistan	Pakistan	1	17
165	1266	Punjab 81	2	Pakistan	Pakistan	1	16
166	1049	PR 3	2	Pakistan	Pakistan	1	22
167	1065	V 1130	2	Pakistan	Pakistan	1	21
168	1066	V 1287.GII	2	Pakistan	Pakistan	1	22
169	1026	LU 265	2	Pakistan	Pakistan	1	22
170	1123	Chenab 79	1	Pakistan	Pakistan	1	16
171	1139	Khyber 79	2	Pakistan	Pakistan	1	22
172	1068	V 79143	2	Pakistan	Pakistan	1	22
173	1133	C 7659	4	Paraguay	CIMMYT	5A	21
174	1061	Trigo 1	1	Philippines	Philippines	5A	21
175	1082	Sado	2	Portugal	Portugal	4A	20
176	1060	Tejo	2	Portugal	Portugal	4A	23
177	1029	Liz	2	Portugal	Portugal	2	24
178	1083	Almansor 1	2	Portugal	Portugal	4A	20
179	1117	W84/14	2	South Africa	South Africa	1	23
180	1107	W84/11	2	South Africa	South Africa	1	23
181	1120	Olmill	1	South Korea	South Korea	7	20
182	1140	Romi	4	Spain	CIMMYT	2	16
183	1036	Mahissa 18	2	Spain	Spain	2	16
184	1015	Castan	2	Spain	Spain	2	18
185	1035	MR SIM	1	Thailand	Thailand	5A	20
186	197	Soltane	4	Tunisia	CIMMYT	4A	17
187	195	Dougga	4	Tunisia	CIMMYT	2	12
188	1010	BT 501	2	Tunisia	Tunisia	2	24
189	1235	Pavon S5	4	Turkey	CIMMYT	1	18

Table B.2 (Cont'd)

Unique No.		Cultivar	Origin code	Contributing country	Developmental origin	ME origin	First ISWYN appearance
190	1073	Cukurova 86	4	Turkey	CIMMYT	1	24
191	1088	Orso	11	Turkey	Italy	2	18
192	1037	Malabadi	2	Turkey	Turkey	2	16
193	1272	Kavko	2	Turkey	Turkey	2	16
194	1114	ATA 81	2	Turkey	Turkey	2	18
195	21	Anza	4	U.S.A.	CIMMYT	1	5
196	1132	Angus	1	U.S.A.	U.S.A.	7	24
197	1131	Kitt	1	U.S.A.	U.S.A.	7	17
198	1080	MN 7357	1	U.S.A.	U.S.A.	7	20
199	1102	MN 7663	1	U.S.A.	U.S.A.	7	24
200	1118	ND 610	1	U.S.A.	U.S.A.	7	24
201	1038	NK 7751817	1	U.S.A.	U.S.A.	7	17
202	1278	Westbred 911	1	U.S.A.	U.S.A.	1	20
203	1081	Wheaton	2	U.S.A.	U.S.A.	7	20
204	242	Estanzuela Dakaru	11	Uruguay	U.S.A.	2	14
205	1041	NS 14.13	1	Yugoslavia	Yugoslavia	7	17
206	1072	NS 51.28	1	Yugoslavia	Yugoslavia	7	18
207	1105	NS 54.17	2	Yugoslavia	Yugoslavia	6A	24
208	1268	TOK*3/S111LAI	1	Zimbabwe	Zimbabwe	1	23
209	1269	ZA75/ZP	1	Zimbabwe	Zimbabwe	1	24

[a] The origin codes refer to the following:
1 = cross made by contributing country with no immediate CIMMYT germplasm
11 = cross made by other country with no immediate CIMMYT germplasm
2 = cross made by contributing country with CIMMYT germplasm
22 = cross made by other country with CIMMYT germplasm
3 = CIMMYT cross, but atleast one further selection made by contributing country.
4 = cross made by CIMMYT and released in contributing country
5 = cross made by CIMMYT but not released any where
6 = cross made by CIMMYT but released in Mexico

[b] For the ME code descriptions see Table 5.1

APPENDIX C

COEFFICIENTS AND T STATISTICS FOR REGRESSION MODELS

Table C.1: Coefficients of the Regression Model (Equation 5.8) for all Megaenvironments

Variable[a]	Abbrev.	With attrition correction by including Mill's ratio Coeff.	SE	T stat.	Without attrition correction Coeff.	SE	T stat.
Coefficient estimates for ME1 (irrigated, low rainfall, temperate)							
Intercept	Constant	4880.11	130.44	37.41	4930.58	129.82	37.98
Year	DIS17	0			0		
	DIS18	667.23	81.64	8.17	650.09	81.60	7.97
	DIS20	-76.35	89.90	-0.85	-92.90	89.89	-1.03
	DIS21	475.79	81.60	5.83	454.67	81.48	5.58
	DIS22	796.42	86.36	9.22	786.54	86.42	9.10
	DIS23	727.39	95.09	7.65	744.47	95.09	7.83
	DIS24	209.86	95.37	2.20	187.68	95.28	1.97
Origin	DLVME1	0			0		
	DLVME2	-232.42	84.22	-2.76	-246.91	84.23	-2.93
	DLVME3	-507.39	90.99	-5.58	-536.91	90.73	-5.92
	DLVME4A	-66.47	105.54	-0.63	-69.91	105.66	-0.66
	DLVME4B	-485.93	95.47	-5.09	-523.00	95.02	-5.50
	DLVME5A	-593.30	129.64	-4.58	-607.90	129.74	-4.69
	DLVME6A	-998.02	126.71	-7.88	-1024.97	126.64	-8.09
	DLVME7	-587.84	81.02	-7.26	-582.28	81.10	-7.18
	DCIM1	226.84	59.89	3.79	209.14	59.75	3.50
	DCIM2	527.38	68.80	7.67	566.88	67.97	8.34
Trial sites	DST10012	-1199.47	208.87	-5.74	-1199.61	209.14	-5.74
	DST11101	-145.36	104.79	-1.39	-145.36	104.92	-1.39
	DST11103	-1021.01	161.09	-6.34	-1020.97	161.30	-6.33
	DST11109	-2019.27	208.87	-9.67	-2019.42	209.14	-9.66
	DST19101	912.73	121.54	7.51	912.71	121.70	7.50
	DST19103	-860.61	135.51	-6.35	-860.65	135.68	-6.34
	DST19106	901.49	155.33	5.80	901.49	155.52	5.80
	DST19201	-3022.90	204.09	-14.81	-3022.88	204.34	-14.79
	DST19207	-2246.49	231.23	-9.72	-2246.46	231.52	-9.70
	DST19210	-2548.97	204.72	-12.45	-2548.93	204.98	-12.44
	DST19211	-2637.29	204.72	-12.88	-2637.25	204.98	-12.87
	DST20002	-1078.80	207.72	-5.19	-1078.80	207.99	-5.19
	DST20306	532.87	208.87	2.55	532.72	209.14	2.55
	DST20309	-1225.56	231.23	-5.30	-1225.53	231.52	-5.29
	DST20501	-1244.56	121.36	-10.26	-1244.53	121.52	-10.24
	DST20901	-742.24	113.32	-6.55	-741.90	113.46	-6.54
	DST21002	-2751.24	208.28	-13.21	-2751.24	208.55	-13.19
	DST21004	-2835.97	207.72	-13.65	-2835.97	207.99	-13.64
	DST21005	-2140.21	135.05	-15.85	-2140.18	135.22	-15.83
	DST21201	1171.74	162.43	7.21	1171.67	162.64	7.20
	DST22207	-1530.20	231.23	-6.62	-1530.17	231.52	-6.61
	DST22208	-950.16	208.87	-4.55	-950.31	209.14	-4.54
	DST22209	-3571.89	208.87	-17.10	-3572.03	209.14	-17.08
	DST22210	-592.85	208.87	-2.84	-593.00	209.14	-2.84
	DST22225	-2453.02	231.23	-10.61	-2452.99	231.52	-10.60
	DST22501	-3360.76	119.26	-28.18	-3360.79	119.41	-28.15
	DST22511	-4209.35	161.09	-26.13	-4209.31	161.30	-26.10
	DST22603	-1259.63	101.27	-12.44	-1259.63	101.40	-12.42
	DST22604	-737.17	118.97	-6.20	-737.18	119.12	-6.19
	DST22608	-675.21	131.43	-5.14	-675.17	131.60	-5.13
	DST41001	1145.41	155.33	7.37	1145.41	155.52	7.37
	DST41003	-1125.99	132.10	-8.52	-1125.97	132.27	-8.51
	DST42004	0			0		
	DST42010	-2310.17	131.23	-17.60	-2310.14	131.40	-17.58

Variable	Abbrev.	Coeff.	SE	T stat.	Coeff.	SE	T stat.
	DST42012	-3143.34	204.09	-15.40	-3143.31	204.34	-15.38
	DST42101	846.16	106.02	7.98	846.18	106.15	7.97
	DST51204	557.21	112.26	4.96	557.20	112.40	4.96
	DST51205	5801.69	208.87	27.78	5801.55	209.14	27.74
	DST51206	-3094.50	208.87	-14.82	-3094.65	209.14	-14.80
	DST65408	1398.46	106.02	13.19	1398.49	106.15	13.18
	DST65409	-904.77	153.58	-5.89	-904.75	153.77	-5.88
Vintage	FIRSTISW	4.27	4.72	0.91	5.34	4.71	1.13
Mills Ratio	R	154.84	43.69	3.54	ne		

Coefficient estimates for ME2 (high rainfall, temperate)

Intercept	Constant	2989.76	145.14	20.60
Year	DIS17	0		
	DIS18	-445.66	81.91	-5.44
	DIS20	-80.37	81.68	-0.98
	DIS21	188.46	77.12	2.44
	DIS22	431.90	79.11	5.46
	DIS23	491.90	91.50	5.38
	DIS24	-36.75	93.93	-0.39
Origin	DLVME1	-188.74	84.00	-2.25
	DLVME2	0		
	DLVME3	-140.64	104.83	-1.34
	DLVME4A	-225.57	116.25	-1.94
	DLVME4B	-100.64	107.60	-0.94
	DLVME5A	-524.52	133.03	-3.94
	DLVME6A	-543.44	160.52	-3.39
	DLVME7	-395.07	92.60	-4.27
	DCIM1	229.90	75.30	3.05
	DCIM2	489.95	83.78	5.85
Trial sites	DST12209	-1012.89	141.91	-7.14
	DST12302	-1075.43	122.52	-8.78
	DST12307	-1660.00	202.56	-8.20
	DST19003	2053.37	232.54	8.83
	DST19303	764.66	146.82	5.21
	DST19402	982.40	113.86	8.63
	DST20304	1134.51	138.85	8.17
	DST20702	-2616.95	156.27	-16.75
	DST21205	1137.70	131.25	8.67
	DST21209	1417.57	159.13	8.91
	DST21601	2206.07	157.14	14.04
	DST21602	-29.37	209.21	-0.14
	DST22401	116.64	209.21	0.56
	DST22607	-103.78	113.86	-0.91
	DST42103	0		
	DST42117	-240.39	205.68	-1.17
	DST42121	1047.92	116.88	8.97
	DST45301	-206.81	127.75	-1.62
	DST51201	-96.30	129.49	-0.74
	DST51202	1337.56	113.86	11.75
	DST51501	-1761.96	156.36	-11.27
	DST53002	-1018.60	124.16	-8.20
	DST53004	-2440.36	205.75	-11.86
	DST53101	-64.90	155.95	-0.42
	DST53201	-1297.09	116.88	-11.10
	DST53504	-2617.79	205.75	-12.72
	DST53506	-1075.28	202.90	-5.30
	DST53508	1179.72	139.27	8.47
	DST65406	3147.20	202.56	15.54

Variable	Abbrev.	Coeff.	SE	T stat.
	DST65412	2601.50	205.68	12.65
	DST65413	400.08	138.85	2.88
Vintage	FIRSTISW	31.16	4.78	6.52
Mills Ratio	R	135.03	43.51	3.10

Coefficient estimates for ME3 (acid soils, high rainfall, temperate)

Variable	Abbrev.	Coeff.	SE	T stat.
Intercept	Constant	740.42	159.63	4.64
Year	DIS17	0		
	DIS18	-404.39	86.24	-4.69
	DIS21	280.90	84.98	3.31
	DIS22	372.38	91.33	4.08
	DIS23	1615.69	105.51	15.31
	DIS24	1932.47	88.83	21.75
Origin	DLVME1	-405.66	110.88	-3.66
	DLVME2	-508.80	123.32	-4.13
	DLVME3	0		
	DLVME4A	-565.44	156.67	-3.61
	DLVME4B	-289.96	138.09	-2.10
	DLVME5A	-219.15	161.57	-1.36
	DLVME6A	-489.96	174.22	-2.81
	DLVME7	-413.91	122.18	-3.39
	DCIM1	-138.41	103.13	-1.34
	DCIM2	-14.06	114.80	-0.12
Trial sites	DST50101	0		
	DST50102	1164.55	114.30	10.19
	DST50103	762.97	66.93	11.40
	DST50104	1626.72	56.12	28.98
Vintage	FIRSTISW	10.96	5.75	1.91
Mills ratio	R	111.48	55.07	2.02

Coefficient estimates for ME4a (Low rainfall, temperate, winter rain)

Variable	Abbrev.	Coeff.	SE	T stat.
Intercept	Constant	2040.75	222.18	9.19
Year	DIS17	0		
	DIS18	-50.99	113.11	-0.45
	DIS20	1730.71	119.87	14.44
	DIS21	-688.79	123.13	-5.59
	DIS22	-69.11	124.28	-0.56
	DIS23	1807.09	155.94	11.59
	DIS24	375.37	139.19	2.70
	DLVME1	-373.82	151.64	-2.47
	DLVME2	-307.30	164.74	-1.87
	DLVME3	-568.48	175.89	-3.23
	DLVME4A	0		
	DLVME4B	-334.29	178.08	-1.88
	DLVME5A	-672.13	205.71	-3.27
	DLVME6A	-1031.27	237.72	-4.34
	DLVME7	-506.56	161.45	-3.14
	DCIM1	-105.06	143.29	-0.73
	DCIM2	20.16	152.11	0.13
Trial sites	DST10007	0		
	DST20202	1606.09	171.99	9.34
	DST20203	1219.31	132.95	9.17
	DST20502	-249.92	194.47	-1.29
	DST20508	-91.90	181.93	-0.51
	DST21101	400.86	150.92	2.66
	DST21102	1399.60	146.91	9.53
	DST21103	1013.87	131.45	7.71

Variable	Abbrev.	Coeff.	SE	T stat.
	DST21105	1480.90	216.57	6.84
	DST65001	1832.95	120.20	15.25
	DST65002	3527.09	212.21	16.62
	DST65301	1099.37	120.20	9.15
	DST65401	-1566.72	217.49	-7.20
	DST65405	4469.76	132.95	33.62
Vintage	FIRSTISW	2.51	6.61	0.38
Mills ratio	R	93.25	61.20	1.52

Coefficient estimates for ME4b (Low rainfall, temperate, winter drought)

Variable	Abbrev.	Coeff.	SE	T stat.
Intercept	Constant	1942.20	182.87	10.62
Year	DIS17	ne		
	DIS18	0		
	DIS20	743.70	86.31	8.62
	DIS21	-287.03	95.92	-2.99
	DIS22	631.61	112.06	5.64
	DIS23	180.20	118.07	1.53
	DIS24	-678.57	133.69	-5.08
Origin	DLVME1	-345.75	141.33	-2.45
	DLVME2	-275.05	156.40	-1.76
	DLVME3	-281.82	165.93	-1.70
	DLVME4A	-482.84	197.33	-2.45
	DLVME4B	0		
	DLVME5A	-327.77	202.23	-1.62
	DLVME6A	-452.21	236.10	-1.92
	DLVME7	-269.53	154.85	-1.74
	DCIM1	16.04	130.76	0.12
	DCIM2	190.56	140.44	1.36
Trial sites	DST10002	0		
	DST51002	829.44	108.15	7.67
	DST51003	87.48	110.06	0.80
	DST51004	261.92	110.29	2.38
	DST51009	-1249.39	176.80	-7.07
	DST51402	-121.34	156.62	-0.78
Vintage	FIRSTISW	28.13	7.11	3.96
Mills ratio	R	140.95	67.15	2.10

Coefficient estimates for ME5a (high temperature, high humidity)

Variable	Abbrev.	Coeff.	SE	T stat.
Intercept	Constant	2382.20	156.33	15.24
Year	DIS17	0		
	DIS18	-118.19	72.47	-1.63
	DIS20	-250.18	78.52	-3.19
	DIS21	-304.33	83.56	-3.64
	DIS22	19.91	86.07	0.23
	DIS23	598.78	111.08	5.39
	DIS24	107.03	82.77	1.29
Origin	DLVME1	34.87	110.22	0.32
	DLVME2	-177.28	118.85	-1.49
	DLVME3	-31.17	122.16	-0.26
	DLVME4A	-154.53	132.85	-1.16
	DLVME4B	-160.65	125.07	-1.28
	DLVME5A	0		
	DLVME6A	-245.81	150.92	-1.63
	DLVME7	-264.10	116.45	-2.27
	DCIM1	6.93	106.09	0.07
	DCIM2	23.16	111.97	0.21
Trial sites	DST22001	0		

Variable	Abbrev.	Coeff.	SE	T stat.
	DST22002	-448.11	80.06	-5.60
	DST22006	-647.01	113.64	-5.69
	DST22403	-435.56	68.23	-6.38
	DST22404	-642.38	111.41	-5.77
	DST51401	-798.16	79.17	-10.08
	DST53005	-447.24	75.26	-5.94
	DST53007	-2099.48	76.39	-27.48
Vintage	FIRSTISW	-4.50	4.21	-1.07
Mills ratio	R	112.64	39.37	2.86
Coefficient estimates for ME6a (Moderate cold, high rainfall)				
Intercept	Constant	1486.61	321.38	4.63
Year	DIS17	ne		
	DIS18	0		
	DIS20	1638.42	235.22	6.97
	DIS21	-40.87	167.33	-0.24
	DIS22	4384.41	236.04	18.58
	DIS23	1703.52	297.60	5.72
	DIS24	745.60	238.97	3.12
Origin	DLVME1	-115.16	207.58	-0.56
	DLVME2	26.94	231.48	0.12
	DLVME3	-214.41	236.69	-0.91
	DLVME4A	-110.52	269.08	-0.41
	DLVME4B	-197.54	249.12	-0.79
	DLVME5A	-492.18	281.08	-1.75
	DLVME6A	0		
	DLVME7	-272.16	223.23	-1.22
	MEX3032	10.03	201.07	0.05
	MEX31	125.61	211.76	0.59
Trial sites	DST21202	4119.52	164.72	25.01
	DST21206	0		
	DST21213	2338.15	166.50	14.04
	DST24006	2054.74	166.50	12.34
	DST24014	2993.88	251.69	11.90
	DST65422	343.11	166.50	2.06
	DS61703M[b]	4983.08	164.72	30.25
Vintage	FIRSTISW	-3.14	8.50	-0.37
Mills ratio	R	99.29	86.52	1.15
Coefficient estimates for ME7 (Severe winter, high latitude)				
Intercept	Constant	3394.63	125.36	27.08
Year	DIS17	0		
	DIS18	-255.78	62.53	-4.09
	DIS20	1202.25	81.38	14.77
	DIS21	-749.93	86.85	-8.64
	DIS22	534.98	97.71	5.48
	DIS23	420.81	101.78	4.13
	DIS24	-819.18	103.02	-7.95
Origin	DLVME1	-222.64	78.29	-2.84
	DLVME2	-174.96	85.04	-2.06
	DLVME3	1.26	100.45	0.01
	DLVME4A	-258.64	103.67	-2.50
	DLVME4B	-55.77	105.11	-0.53
	DLVME5A	-334.13	150.88	-2.22
	DLVME6A	-602.72	155.73	-3.87
	DLVME7	0		
	DCIM1	-130.55	69.07	-1.89

Variable	Abbrev.	Coeff.	SE	T stat.
	DCIM2	-90.74	77.81	-1.17
Trial sites	DST24001	-274.53	160.60	-1.71
	DST24010	1177.42	167.26	7.04
	DST24015	-3290.12	183.02	-17.98
	DST24024	-1427.22	128.82	-11.08
	DST24034	-714.00	183.02	-3.90
	DST25101	-299.30	76.70	-3.90
	DST36010	-217.05	183.02	-1.19
	DST36011	-122.61	128.71	-0.95
	DST40001	572.52	120.54	4.75
	DST40002	1121.74	158.90	7.06
	DST40003	1919.12	158.90	12.08
	DST40104	-678.96	120.54	-5.63
	DST41008	1819.44	120.54	15.10
	DST41009	511.55	120.54	4.24
	DST41014	2755.06	167.26	16.47
	DST41103	-718.94	160.60	-4.48
	DST41105	-254.11	160.60	-1.58
	DST61201	1422.30	76.70	18.54
	DST61410	-449.36	120.54	-3.73
	DST61505	2396.06	119.69	20.02
	DST61509	-912.80	160.60	-5.68
	DST61601	-970.95	102.47	-9.48
	DST61702	764.66	103.21	7.41
	DST61704	-1019.64	128.71	-7.92
	DST63101	637.31	160.60	3.97
	DST63201	3405.42	103.21	32.99
	DST63405	2395.50	160.60	14.92
	DST63501	-659.08	161.73	-4.08
	DST65113	-937.56	164.29	-5.71
	DST67102	-722.17	119.69	-6.03
	DST67401	0		
Vintage	FIRSTISW	4.67	4.79	0.98
Mills ratio	R	87.68	40.19	2.18

Note:ne = not estimated because not applicable.
The location IDs of the trial sites are described in Appendix Table B.1

[a] Variable description is given in Table 5.2

Table C.2: Average Yields (kg/ha) of Cultivars From Different Origins, Based on the Regression Coefficients of Equation 5.8

		LOCATION ENVIRONMENT							
	ORIGIN	1	2	3	4A	4B	5A	6A	7
T	ME1	4769[a]	3481	2210	3405	2528	1665	3582	3733
E	ME2	4537	3670[a]	2107	3472	2599	1454	3724	3781
C	ME3	4262	3529	2616[a]	3211	2592	1600	3483	3957
H	ME4A	4703	3444	2051	3779[a]	2391	1477	3586	3697
N	ME4B	4283	3569	2326	3445	2874[a]	1470	3499	3900
O	ME5A	4176	3145	2397	3107	2546	1631[a]	3205	3622
L	ME6A	3771	3127	2126	2748	2422	1385	3697[a]	3353
O	ME7	4181	3275	2202	3272	2604	1367	3425	3956[a]
G	CIM1	4996	3900	2478	3674	2890	1638	3707	3825
Y	CIM2	5296	4160	2602	3799	3065	1654	3823	3865

Note: CIM1: indicates CIMMYT cultivars either released in another country or not released anywhere. CIM2: indicates CIMMYT cultivars released in Mexico. Technology from ME 1 to 7 represent non-CIMMYT cultivars bred and selected for respective megaenvironment.

[a] Denotes arithmetic mean

Table C.3: Coefficients for the Regression Model (Equation 5.9) for all the Countries

Variable	Abbrev.	Coeff.	SE	T statistics
Coefficient estimates for Pakistan ME1 (irrigated, temperate)				
Intercept	Constant	3158.84	195.89	16.13
Year	DIS16	ne		
	DIS17	0		
	DIS18	1904.03	139.44	13.66
	DIS20	795.30	122.15	6.51
	DIS21	1785.51	122.25	14.61
	DIS22	2252.38	123.47	18.24
	DIS23	-503.31	152.85	-3.29
	DIS24	1636.71	130.43	12.55
Trial sites	DST22603	0		
	DST22604	28.84	69.10	0.42
	DST22608	141.91	77.26	1.84
Technology	PAKDME1	0		
	INDDME1	-185.68	170.33	-1.09
	CIM	72.95	136.71	0.53
	ME1	-209.36	181.17	-1.16
	OTHERME	-658.10	135.57	-4.85
	CIMIME1	141.81	187.78	0.76
Vintage	FIRSTISW	-2.35	6.32	-0.37
Mills ratio	R	234.66	60.04	3.91
Coefficient estimates for India ME1 (irrigated, temperate)				
Intercept	Constant	2003.68	295.07	6.79
Trial sites	DST22207	2619.92	136.17	19.24
	DST22208	2623.73	123.14	21.31
	DST22209	0		
	DST22210	2976.56	123.14	24.17
	DST22225	1697.10	136.17	12.46
Technology	INDDME1	0		
	CIMIME1	106.69	481.10	0.22
	INDSME1	172.90	345.35	0.50
	CIM	-46.59	221.21	-0.21
	ME1	-488.28	260.41	-1.88
	OTHERME	-647.12	224.10	-2.89
	PAKDME1	-366.44	285.16	-1.29
Vintage	FIRSTISW	-4.79	9.74	-0.49
Mills ratio	R	33.54	102.66	0.33
Coefficient estimates for Kenya ME2 (high rainfall, temperate)				
Intercept	Constant	1240.39	510.38	2.43
Year	DIS16	ne		
	DIS17	0		
	DIS18	947.28	179.22	5.29
	DIS20	-950.17	179.72	-5.29
	DIS21	-235.88	180.45	-1.31
	DIS22	1328.25	182.52	7.28
	DIS23	-297.84	201.81	-1.48
Technology	KENDME2	0		
	CIM	326.20	442.97	0.74
	ME2	176.34	478.06	0.37
	OTHERME	-265.31	441.06	-0.60
Vintage	FIRSTISW	58.34	13.00	4.49
Mills ratio	R	208.05	114.11	1.82

Variable	Abbrev.	Coeff.	SE	T statistics
Coefficient estimates for Ecuador ME2 (high rainfall, temperate)				
Intercept	Constant	3394.69	716.94	4.74
Year	DIS16	ne		
	DIS17	0		
	DIS18	995.07	292.49	3.40
	DIS20	345.23	288.21	1.20
	DIS21	-1051.53	289.68	-3.63
	DIS22	-424.28	293.65	-1.45
	DIS23	1346.83	323.78	4.16
	DIS24	ne		
Technology	ECUDME2	0		
	CIMIME2	-613.78	1002.89	-0.61
	ECUSME2	-1690.44	1513.87	-1.12
	CIM	-2124.97	633.40	-3.36
	ME2	-2186.07	715.13	-3.06
	OTHERME	-2776.83	634.57	-4.38
Vintage	FIRSTISW	72.51	20.74	3.50
Mills ratio	R	-145.44	181.44	-0.80
Coefficient estimates for Brazil ME3 (acid soils, high rainfall, temperate)				
Intercept	Constant	2710.97	164.11	16.52
Year	DIS16	ne		
	DIS17	0		
	DIS18	-708.09	74.15	-9.55
	DIS20	-293.92	84.40	-3.48
	DIS22	98.13	85.37	1.15
	DIS23	1330.95	92.89	14.33
	DIS24	1657.22	75.50	21.95
Trial sites	DST50101	-1625.64	55.87	-29.10
	DST50102	-480.16	113.32	-4.24
	DST50103	-861.80	62.80	-13.72
	DST50104	0		
Technology	BRZDME3	0		
	CIMIME3	-63.88	169.70	-0.38
	BRZSME3	85.96	218.75	0.39
	CIM	-82.85	115.70	-0.72
	OTHERME	-399.94	113.40	-3.53
Vintage	FIRSTISW	7.14	5.43	1.32
Mills ratio	R	114.04	51.12	2.23
Coefficient estimates for Portugal ME4a (low rainfall, temperate, winter rains)				
Intercept	Constant	2424.54	363.71	6.67
Year	DIS16	ne		
	DIS17	0		
	DIS18	786.00	151.25	5.20
	DIS20	3443.83	153.43	22.45
	DIS21	1003.63	153.57	6.54
	DIS22	1550.17	154.61	10.03
	DIS23	3694.62	168.65	21.91
	DIS24	1156.59	160.60	7.20
Technology	PORDME4a			
	CIM	-371.37	303.29	-1.22
	ME4A	-146.51	408.39	-0.36
	OTHERME	-712.75	301.31	-2.37

Variable	Abbrev.	Coeff.	SE	T statistics
Vintage	FIRSTISW	-7.14	9.86	-0.72
Mills ratio	R	13.75	89.07	0.15

Coefficient estimates for Argentina ME4b (low rainfall, temperate, winter drought)

Intercept	Constant	2876.26	289.74	9.93
Year	DIS16	ne		
	DIS17	ne		
	DIS18	0		
	DIS20	706.39	96.77	7.30
	DIS21	-307.94	97.33	-3.16
	DIS22	559.39	112.81	4.96
	DIS23	536.60	125.04	4.29
	DIS24	-1406.40	148.78	-9.45
Trial sites	DST51002	0		
	DST51003	-803.94	81.68	-9.84
	DST51004	-718.68	83.66	-8.59
	DST51009	-2109.82	149.96	-14.07
Technology	ARGDME4b	0		
	CIMIME4b	517.98	334.53	1.55
	ARGSME4b	110.70	325.92	0.34
	CIM	83.31	237.91	0.35
	ME4b	-251.64	330.33	-0.76
	OTHERME	-329.53	234.43	-1.41
Vintage	FIRSTISW	26.28	7.77	3.38
Mills ratio	R	211.57	68.93	3.07

Coefficient estimates for Bangladesh ME5a (high temperature, high humidity)

Intercept	Constant	2440.13	282.97	8.62
Year	DIS16	ne		
	DIS17	0		
	DIS18	454.85	98.27	4.63
	DIS20	188.84	99.14	1.91
	DIS21	-654.97	99.27	-6.60
	DIS22	102.41	139.79	0.73
	DIS23	966.70	147.00	6.58
	DIS24	619.01	142.56	4.34
Trial sites	DST22002	-328.82	97.42	-3.38
	DST22006	0		
Technology	CIMIME5a	0		
	INDIME5a	-294.15	321.61	-0.92
	CIM	-230.14	242.39	-0.95
	ME5A	-68.12	319.88	-0.21
	OTHERME	-369.10	241.73	-1.53
Vintage	FIRSTISW	-11.00	5.97	-1.84
Mills ratio	R	145.65	55.94	2.60

Coefficient estimates for Bolivia ME5a (high temperature, high humidity)

Intercept	Constant	1363.96	318.93	4.28
Year	DIS16	ne		
	DIS17	ne		
	DIS18	0		
	DIS20	337.91	101.73	3.32
	DIS21	ne		
	DIS22	555.70	102.86	5.40

Variable	Abbrev.	Coeff.	SE	T statistics
	DIS23	1010.04	153.91	6.56
	DIS24	ne		
Trial sites	DST53005	0		
	DST53007	-1734.04	101.52	-17.08
Technology	CIMIME5a	0		
	CIM	-15.67	290.12	-0.05
	ME5a	-145.32	339.09	-0.43
	OTHERME	-122.37	288.76	-0.42
Vintage	FIRSTISW	5.24	7.77	0.67
Mills ratio	R	153.57	70.91	2.17

NOTE:

1. ne = not estimated because not applicable.
2. The year and or trial sites dummies for some countries are missing because of one of the following reasons:
   a. There was only one trial site in the country for the given years.
   b. Either the site or year dummies were dropped out from the regression because of perfect collinearity. This would happen in cases where a trial site appears in only one year and that year has only one trial site.
3. The location IDs for the trial sites are described in Appendix Table B.1
4. Variables are described in Table 5.2

Table C.4: Coefficients of the Regression Model (Equation 5.10) for the Normal and Short Duration Irrigated Environment in Pakistan

Variable	Abbrev.	Coeff.	SE	T stat.	Sig. T
NORMAL DURATION REGRESSION					
Intercept	Constant	3304.14	88.60	37.30	0.00
Year	DY1	0.00			
	DY2	17.20	102.46	0.17	0.87
	DY3	300.97	103.30	2.91	0.00
	DY4	658.77	114.41	5.76	0.00
	DY5	-47.44	112.84	-0.42	0.67
	DY6	91.27	118.68	0.77	0.44
	DY7	292.32	119.86	2.44	0.02
	DY8	930.57	129.19	7.20	0.00
	DY9	597.55	129.41	4.62	0.00
	DY10	651.35	141.29	4.61	0.00
	DY11	954.25	149.73	6.37	0.00
	DY12	665.52	166.92	3.99	0.00
	DY13	354.62	169.77	2.09	0.04
	DY14	286.47	178.43	1.61	0.11
Technology	DO1	0.00			
	DO3	100.78	37.58	2.68	0.01
	DO2	108.63	66.17	1.64	0.10
Trial Sites	DPunjab	0.00			
	DNWFP	-210.21	42.56	-4.94	0.00
	DSindh	-124.63	42.57	-2.93	0.00
Vintage	FNUWYT	6.55	11.77	0.56	0.58
SHORT DURATION REGRESSION					
Intercept	Constant	3312.00	129.75	25.53	0.00
Year	DY1	0.00			
	DY2	-102.26	152.30	-0.67	0.50
	DY3	59.71	184.48	0.32	0.75
	DY4	231.03	185.43	1.25	0.21
	DY5	-102.33	183.48	-0.56	0.58
	DY6	-288.46	215.00	-1.34	0.18
	DY7	-126.93	235.48	-0.54	0.59
	DY8	157.32	282.22	0.56	0.58
	DY9	-119.78	307.04	-0.39	0.70
	DY10	-80.06	322.33	-0.25	0.80
	DY11	575.55	359.97	1.60	0.11
	DY12	178.14	359.97	0.50	0.62
Technology	DO1	0.00			
	DO3	14.22	49.47	0.29	0.77
Trial Sites	DPunjab	0.00			
	DNWFP	-416.63	56.27	-7.41	0.00
	DSindh	-227.91	56.27	-4.05	0.00
Vintage	FNUWYT	-3.01	34.89	-0.09	0.93

APPENDIX D

LONG-TERM TREND PRICES FOR WHEAT

APPENDIX D

LONG-TERM TREND PRICES FOR WHEAT

C.i.f. Prices for hard winter, 13.5% (Rotterdam) from 1963-1991 were deflated by the U.S. consumer price index (all items) to obtain real-price series in 1980 dollars. A log-linear trend was fitted to these price series resulting in the following trend equation.

$$P_t = 1067 - \underset{(210.8)}{475} \log T$$

$$R^2 = 15.8$$

where, P_t is the real price in 1980 dollars and T is the number of years since 1900.

Using this equation the respective trend prices were calculated for each year in 1980 dollar. Using the same equation, the prices were projected for the years 1992-2040. These are reported at five-year intervals in Table F.1.

Table D.1: Real Price Trends for Wheat[a], 1963-2040

Year	Current Price (US$/ton)	Real Price[b]	Trend Price
		(1980 US$/ton)	
1963	72	195	212
1964	75	199	209
1965	64	166	206
1966	69	174	203
1967	72	178	200
1968	68	161	197
1969	65	146	194
1970	65	139	191
1971	67	137	188
1972	76	149	185
1973	153	284	182
1974	210	350	179
1975	177	270	176
1976	161	234	174
1977	126	171	171
1978	147	186	168
1979	186	211	166
1980	213	213	163
1981	210	190	161
1982	187	160	158
1983	185	153	156
1984	180	143	153
1985	169	129	151
1986	148	111	148
1987	141	102	146
1988	176	123	144
1989	190	126	141
1990	164	103	139
1991	154	93	137
1995	--	--	128
2000	--	--	117
2005	--	--	107
2010	--	--	97
2015	--	--	88
2020	--	--	80
2025	--	--	71
2030	--	--	63
2035	--	--	55
2040	--	--	48

Source: USDA, Wheat Situation and Outlook Report

[a] c.i.f. price for U.S. No. 2 Hard Winter , 13.5% (Rotterdam)

[b] Deflated by the U.S. consumer price index.

APPENDIX E

ESTIMATION OF THE RATE OF DIFFUSION OF VARIETAL TECHNOLOGY ATTRIBUTED TO NEW RESEARCH PROGRAM

APPENDIX E

ESTIMATION OF THE RATE OF DIFFUSION OF VARIETAL TECHNOLOGY ATTRIBUTED TO NEW RESEARCH PROGRAM

The parameter α_t was estimated using the following logistic equation.

$$\alpha_t = \frac{A}{1 + e^{-(a+bt)}} \qquad for\ t = 1,2,\ldots,n_d \qquad (E.1)$$

where,

	n_d	is the adoption lag (time required for the technology to diffuse in A% of total area)
	A	is the adoption ceiling rate
	a,b	are the parameters of the logistic function.

The estimates of α_t were based on the following assumptions of the parameters of equation E.1: $n_d = 10$; $A = 1$; $\alpha_1 = 0.05$; $\alpha_{10} = 0.99$

On the basis of these assumptions, equation A6.2.1 was solved for parameters a and b. Their estimates are: a = -3.97; b = 1.02. Given the parameter values of a and b the estimated rate of adoption in the ten years following the first release of a variety by the research program is given in Table E.1.

Table E.1: Parameter Values for α_t

Year[a]	α_t
1	0.05
2	0.13
3	0.29
4	0.53
5	0.76
6	0.90
7	0.96
8	0.99
9	0.99
10	1.00

[a] refers to years after the first release of variety

APPENDIX F

INFORMATION ON THE WHEAT IMPROVEMENT PROGRAMS IN DEVELOPING COUNTRIES USED IN THE ANALYSIS

APPENDIX F

INFORMATION ON THE WHEAT IMPROVEMENT PROGRAMS IN DEVELOPING COUNTRIES USED IN THE ANALYSIS

	Country	Geographic Mandate Organization/Region	Wheat Type[a]	Research Focus[b]	Expd. per Researcher ('000 1980 $)	Wheat Area (000 ha)	Wheat Prod. (000 tons)	Number of Researchers (FTE)	Number of Environments
1	Algeria	ITGC	SB	T	69.84	250	219	1.1	3
2	Algeria	ITGC	SD	C	69.84	350	307	1.1	3
3	Argentina	INTA	SB	C	58.10	125	251	1.1	2
4	Bangladesh	country	SB	C	73.79	575	914	16.1	4
5	Bolivia	Est.Expt.(San Benito)	SB	T	22.12	65	54	4.5	4
6	Bolivia	Est.Expt.(San Benito)	SD	T	22.12	17	14	4.5	4
7	Brazil	IAPAR	SB	C	77.04	1500	1911	2.8	6
8	Brazil	Inst.Agron.(SaoPaulo)	SB	C	77.04	105	134	1.9	3
9	Brazil	OCEPAR	SB	C	77.04	1700	2166	1.5	5
10	Burundi	ISABU	SB	T	78.57	9	9	1.0	3
11	Chile	country	SB	C	99.26	300	946	7.0	4
12	Chile	country	SD	C	99.26	35	110	2.1	1
13	Chile	country	WB	C	99.26	200	631	5.1	4
14	Colombia	ICA	SB	C	105.29	40	77	6.1	2
15	Ecuador	INIAP	SB	C	63.03	16	12	2.4	1
16	Ethiopia	country	SB	C	86.76	350	446	9.7	4
17	Guatemala	ICAA	SB	C	45.63	20	29	1.7	3
18	India	Durgapur (Rajasthan)	SB	C	53.64	1800	3957	1.0	4
19	India	Durgapur (Rajasthan)	SD	C	53.64	400	879	1.0	2
20	India	ICAR, Almora	SB	C	53.64	1000	2198	1.5	4
21	India	Kalyani	SB	C	53.64	269	591	0.6	3
22	India	Ludhiana	SB	C	53.64	2900	6375	11.0	3
23	India	Ludhiana	SD	C	53.64	300	659	4.7	3
24	India	Powerkheda	SB	C	53.64	3565	7837	6.0	4
25	India	Varanasi & Faizabad	SB	C	53.64	2827	6215	4.9	8
26	India	Vijapur	SB	C	53.64	600	1319	3.5	3
27	India	Vijapur	SD	C	53.64	150	330	2.1	1
28	Kenya	country	SB	C	58.66	130	176	3.9	3
29	Lebanon	country	SB	C	43.28	9	18	0.9	2
30	Lebanon	country	SD	C	43.28	9	18	0.9	2
31	Lesotho	country	SB	T	70.88	24	15	0.7	5
32	Libya	country	SB	C	158.27	371	460	9.2	3
33	Mexico	INIFAP (N.W.Mexico)	SB	T	121.93	374	1568	1.1	2
34	Mexico	INIFAP (N.W.Mexico)	SD	T	121.93	65	272	1.1	2
35	Morocco	country	SB	C	116.13	1400	2234	7.0	8

	Country	Region/Organization	Wheat Type	Research Focus	Expd. per Researcher ('000 1980 $)	Wheat Area (000 ha)	Wheat Prod. (000 tons)	Number of Researchers (FTE)	Number of Environments
36	Morocco	country	SD	C	116.13	1300	2074	7.0	8
37	Nepal	country	SB	C	23.99	600	848	8.7	4
38	Pakistan	ARI (Baluchistan)	SB	C	25.00	301	552	3.0	2
39	Pakistan	NWFP	SB	C	25.00	830	1522	7.0	3
40	Pakistan	WRI (Sindh)	SB	C	25.00	1058	1941	2.0	2
41	Pakistan	WRI (Faisalabad)	SB	C	25.00	4800	8803	16.3	3
42	Paraguay	country	SB	C	118.60	200	329	9.9	2
43	Peru	country	SB	C	77.48	90	111	0.9	7
44	Peru	country	SD	T	77.48	25	31	0.6	7
45	Sudan	country	SB	C	58.74	380	573	2.1	1
46	Tunisia	country	SB	C	121.49	179	269	1.7	4
47	Tunisia	country	SD	C	121.49	893	1344	4.7	4
48	Turkey	ARI (Eskisehir)	WB	C	66.63	732	1569	3.5	1
49	Turkey	ARI (Eskisehir)	WD	C	66.63	244	523	1.2	1
50	Turkey	Aegean	SB	C	66.63	220	472	1.3	2
51	Turkey	Aegean	SD	C	66.63	137	294	0.7	2
52	Turkey	Akcakale	SB	T	66.63	181	389	1.0	2
53	Turkey	Akcakale	SD	T	66.63	181	389	1.0	3
54	Turkey	BSARI (Samsun)	SB	T	66.63	70	150	0.7	1
55	Turkey	BSARI (Samsun)	WB	T	66.63	240	515	0.7	1
56	Turkey	BSARI (Samsun)	WD	T	66.63	50	107	0.4	1
57	Turkey	Cukurova	SB	C	66.63	4000	8575	0.4	1
58	Turkey	Cukurova	SD	C	66.63	150	322	0.4	1
59	Turkey	Erzurum	WB	C	66.63	699	1499	1.3	4
60	Turkey	Konya	WB	C	66.63	918	1969	4.6	3
61	Turkey	Konya	WD	C	66.63	38	82	0.5	3
62	Turkey	South and East Marmar	SB	C	66.63	608	1303	0.9	2
63	Turkey	Southeast Anatolia	SB	C	66.63	35	75	0.1	2
64	Turkey	Southeast Anatolia	SD	C	66.63	640	1372	1.9	2
65	Turkey	Southeast Anatolia	WB	C	66.63	15	32	0.1	1
66	Turkey	Thrace & Marmara	WB	C	66.63	860	1844	2.3	2
67	Uruguay	country	SB	C	53.25	200	386	2.9	3
68	Zambia	Mount Makulu	SB	C	36.36	9	60	6.0	2
69	Zimbabwe	country	SB	C	100.00	55	312	2.0	5

Source: CIMMYT Survey on Wheat Breeding Programs, 1992-93

[a] SB = Spring Bread; SD = Spring Durum; WB = Winter Bread; WD = Winter Durum

[b] T = Testing/evaluation program; C = Crossing/breeding program

APPENDIX G

Z-SCORES AND GROUP MEMBERSHIP PROBABILITIES OF INDIVIDUAL RESEARCH PROGRAMS: RESULTS OF THE DISCRIMINANT ANALYSIS

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Z-SCORES AND GROUP MEMBERSHIP PROBABILITIES OF INDIVIDUAL RESEARCH PROGRAMS: RESULTS OF THE DISCRIMINANT ANALYSIS

	Country	Region/Program	Wheat Type[a]	Predicted Group[b]	Z-scores	Probability of Membership in Unprofitable Group	Probability of Membership in Profitable Group
	UNPROFITABLE PROGRAMS						
1	Bangladesh	country	SB	U	2.78	0.98	0.02
2	Bolivia	Est.Expt.(San Benito)	SD	U	0.39	0.61	0.39
3	Bolivia	Est.Expt.(San Benito)	SB	U	0.37	0.60	0.40
4	Brazil	Inst.Agron. SaoPaulo	SB	U	0.44	0.62	0.38
5	Burundi	ISABU	SB	U	0.36	0.60	0.40
6	Chile	country	WB	U	1.29	0.85	0.15
7	Chile	country	SB	U	1.47	0.88	0.12
8	Chile	country	SD	U	0.38	0.60	0.40
9	Colombia	ICA	SB	U	1.43	0.88	0.12
10	Ecuador	INIAP	SB	** P	-0.03	0.45	0.55
11	Ethiopia	country	SB	U	2.06	0.95	0.05
12	Guatemala	ICAA	SB	** P	0.00	0.46	0.54
13	India	Ludhiana	SD	U	0.33	0.58	0.42
14	Kenya	country	SB	U	0.52	0.65	0.35
15	Lebanon	country	SB	** P	-0.39	0.33	0.67
16	Lebanon	country	SD	** P	-0.39	0.33	0.67
17	Lesotho	country	SB	U	0.60	0.68	0.32
18	Libya	country	SB	U	2.76	0.98	0.02
19	Mexico	INIFAP (N.W.Mexico)	SD	U	0.64	0.69	0.31
20	Morocco	country	SD	U	1.94	0.94	0.06
21	Paraguay	country	SB	U	2.18	0.96	0.04
22	Peru	country	SB	U	1.11	0.82	0.18
23	Peru	country	SD	U	1.10	0.81	0.19
24	Tunisia	country	SB	U	1.17	0.83	0.17
25	Tunisia	country	SD	U	1.15	0.83	0.17
26	Turkey	Konya	WD	** P	0.05	0.48	0.52
27	Turkey	BSARI, Samsun	SB	** P	-0.36	0.34	0.66
28	Uruguay	country	SB	U	0.14	0.52	0.48
29	Zambia	Mount Makulu	SB	U	0.43	0.62	0.38
30	Zimbabwe	country	SB	U	1.12	0.82	0.18

	Country	Region/Program	Wheat Type[a]	Predicted Group[b]	Z-scores	Probability of Membership in Unprofitable Group	Profitable Group
	PROFITABLE PROGRAMS						
31	Algeria	ITGC	SD	P	0.08	0.49	0.51
32	Algeria	ITGC	SB	** U	0.13	0.51	0.49
33	Argentina	INTA	SB	P	-0.26	0.37	0.63
34	Brazil	IAPAR	SB	** U	0.27	0.56	0.44
35	Brazil	OCEPAR	SB	P	-0.32	0.35	0.65
36	India	Vijapur	SD	P	-0.40	0.33	0.67
37	India	Vijapur	SB	P	-0.26	0.37	0.63
38	India	Durgapur	SD	P	-0.68	0.24	0.76
39	India	Ludhiana	SB	P	-1.62	0.07	0.93
40	India	Powerkheda	SB	P	-3.11	0.01	0.99
41	India	Kalyani	SB	P	-0.39	0.33	0.67
42	India	ICAR, Almora	SB	P	-0.89	0.19	0.81
43	India	Durgapur	SB	P	-1.93	0.05	0.95
44	India	Varanasi & Faizabad	SB	P	-1.58	0.08	0.92
45	Mexico	INIFAP (N.W.Mexico)	SB	P	-0.06	0.44	0.56
46	Morocco	country	SB	** U	1.86	0.93	0.07
47	Nepal	country	SB	** U	0.75	0.72	0.28
48	Pakistan	ARI (Baluchistan)	SB	P	-0.55	0.28	0.72
49	Pakistan	WRI (Faisalabad)	SB	P	-2.37	0.03	0.97
50	Pakistan	NWFP	SB	P	-0.13	0.42	0.58
51	Pakistan	WRI (Sindh)	SB	P	-1.49	0.09	0.91
52	Sudan	country	SB	P	-0.46	0.31	0.69
53	Turkey	South & East Marmara	SB	P	-0.74	0.22	0.78
54	Turkey	Southeast Anatolia	WB	P	-0.42	0.32	0.68
55	Turkey	Konya	WB	P	-0.22	0.39	0.61
56	Turkey	Akcakale	SB	P	-0.23	0.38	0.62
57	Turkey	Cukurova	SD	P	-0.52	0.29	0.71
58	Turkey	Cukurova	SB	P	-4.98	0.00	1.00
59	Turkey	Akcakale	SD	P	-0.02	0.46	0.54
60	Turkey	Aegean	SB	P	-0.21	0.39	0.61
61	Turkey	BSARI (Samsun)	WD	P	-0.41	0.32	0.68
62	Turkey	BSARI (Samsun)	WB	P	-0.56	0.28	0.72
63	Turkey	Southeast Anatolia	SD	P	-0.59	0.27	0.73
64	Turkey	Southeast Anatolia	SB	P	-0.22	0.38	0.62
65	Turkey	Thrace & Marmara	WB	P	-0.79	0.21	0.79
66	Turkey	Aegean	SD	P	-0.24	0.38	0.62
67	Turkey	Erzurum	WB	P	-0.35	0.34	0.66
68	Turkey	ARI (Eskisehir)	WB	P	-0.62	0.26	0.74
69	Turkey	ARI (Eskisehir)	WD	P	-0.48	0.30	0.70

[a] SB = spring bread; SD = spring durum; WB = winter bread ; WD = winter durum
[b] U = Unprofitable group; P = Profitable group