

E C O N O M I C S

Working Paper 99-11

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Greg Traxler¹ and Prabhu L. Pingali²

¹ Associate Professor, Dept. of Agricultural Economics, Auburn University, USA and Affiliate Economist, CIMMYT, Mexico. Tel: 334-844-5619; Fax: 334-844-5639

² Director Economics Program, CIMMYT, Mexico.

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Abstract: Investments over the past 35 years have created a system of national and international research centers that has revolutionized the supply of improved cereal varieties to developing country farmers. The newly created scientific ability to exploit genetic resources has been the engine of productivity growth in much of world agriculture. But the success that has been attained in building research institutions has not touched all countries or farmers, nor can it be considered permanent. The financial and political environment of the past decade has halted the expansion of agricultural research capacity and the scarcity of research resources and evolving world intellectual property rights (IPR) regimes complicates the search for stable arrangements for cooperation. This paper examines the current structure and institutional capacity of the international crop breeding systems for rice and wheat. Discussions are presented within the context of a system composed of research functions spanning the basic to applied research spectrum. The model emphasizes that an efficient and stable international system may be comprised of many partner institutions, each with a limited breadth of research activities, particularly when research budgets are fixed or declining. The paper concludes with a review of some of the trends that will influence the future direction of research cooperation.

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International Collaboration in Crop Improvement Research: Current Status and Future Prospects

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Introduction

Investments over the past 35 years have created a system of national and international research centers that has revolutionized the supply of improved cereal varieties to developing country farmers. In the late 1960s an average of 34 new wheat varieties and 30 new rice varieties were released in developing countries each year. By the late 1980s releases had increased to 63 wheat and 76 rice varieties per year (Figure 1). Developing country wheat yields have risen at 3.4%/yr between 1969 and 1995 (CIMMYT, 1996) and rice yields have risen at an annual rate above 2%/yr (Pingali and Heisey). The newly created scientific ability to exploit genetic resources has been the engine of productivity growth in much of world agriculture. But the success that has been attained in building research institutions has not touched all countries or farmers, nor can it be considered permanent. The financial and political environment of the past decade has halted the expansion of agricultural research capacity and has intensified the search for more efficient means of improving research efficiency. This new environment has created strong incentives for cooperation among institutions, but the economic incentives to free-ride on research spillovers have never been stronger either. The scarcity of research resources at all levels and evolving world intellectual property rights (IPR) regimes complicate the search for stable arrangements for cooperation.

In this paper we examine the current structure and institutional capacity of the international crop breeding systems for rice and wheat. We present our discussion within the context of a system composed of research functions spanning the basic to applied research spectrum. The model emphasizes that an efficient and stable international system may be comprised of many partner institutions, each with a limited breadth of research activities, particularly when research budgets are fixed or declining. Cooperation with complementary institutions, the regular exchange of scientific information, and open access to research results are keys for the smooth functioning of such a system. In the closing section of the paper we review some of the trends which will influence the future direction of research cooperation.

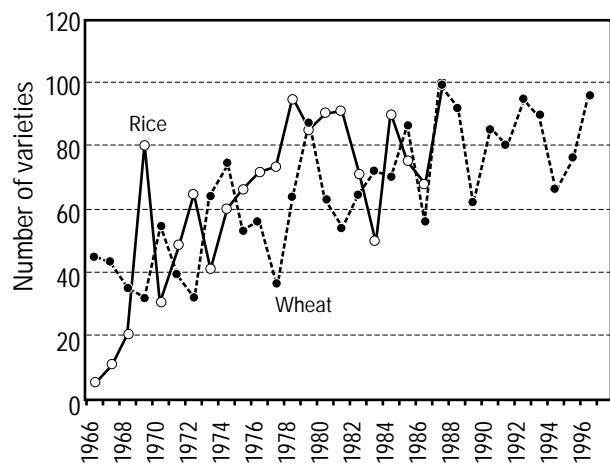


Figure 1. Total number of wheat and rice varieties released in the developing world.

The Structure of International Crop Improvement Research

The transformation of genetic resources into plant types that are useful for farmers is a cooperative enterprise that links scientists and institutions in virtually all wheat and rice growing countries. The development of a new variety involves many steps from the collection of unimproved landraces and wild species, to germplasm storage and characterization, creation and crossing of advanced lines, testing of advanced lines in targeted release areas and finally to the release of adapted varieties. Genetic resource improvement is a continuous process, with the development of a finished variety taking twenty or more years to complete.

It is difficult to capture or even to measure, the benefits produced at any research point prior to the final step of releasing and distributing a commercial variety. Prior to 1960, there was no formal system in place that provided plant breeders access to germplasm available beyond their borders. The current system for sharing crop improvement results is relatively young, evolving in the 1970s and 80s, when financial resources were expanding and plant IPR laws were weak or nonexistent. International access to research from other public institutions remains generally open and without charge. The exchange of germplasm is largely based on a system of informal exchange among plant breeders. To date the effect of reduced investment in plant breeding has been felt more keenly than have been changes in IPR regimes.

In the following sections we discuss the interrelationship of research institutions and develop a general model of the link between yield increases and the decision of International Agricultural Research Centers (IARCs) to focus on the production of either pre-breeding material or finished varieties. The model is discussed with reference to wheat and rice improvement, but the institutional framework and yield model for other crops have many similarities.

Crop Improvement Research Activities

It is useful to view the international crop improvement system (ICIS) as comprised of four classes of germplasm improvement activities: basic research (BR), genetic resource conservation and management (GRCM), pre-breeding research (P-BR), and cultivar development (CD) (Figure 2). Scientists do not agree on precise definitions of each research category, or on the boundaries between categories¹, but a loose definition serves to illustrate the simple model to be presented here.

Neither basic research nor genetic resource conservation and management consume significant shares of IARC budgets. The IARCs are largely borrowers of basic research generated by institutions located elsewhere, often in more developed countries (MDCs). Basic research easily spills across geographic and crop species (i.e. between winter and spring wheat) boundaries. MDC genetic enhancement research has also had very large

¹ For example, it might be argued that 'strategic research' is a more relevant concept than basic research for applied research institutions. (Tony Fischer, personal correspondence)

Wheat Improvement Activities	ICIS Institutions and Roles
I. Basic Research	MDC Institutions (90 Scientists ^a) Basic Research
II. Genetic resource management	Genetic resource management
A. Acquiring & maintaining germplasm	Pre-Breeding research
B. Documenting accessions	
C. Biotic & Abiotic screening	CIMMYT (30 Scientists) Genetic resource management
III. Pre-Breeding research	Pre-Breeding research
A. New plant types/Yield frontier research	Cultivar Development
B. New sources of disease resistance	
C. Administering screening nurseries	Stage 3 NARSs (658 Scientists)
D. Administering yield nurseries	Pre-Breeding research Cultivar Development
IV. Cultivar Development	
A. Crossing program	Stage 2 NARSs (87 Scientists)
B. Testing/screening program	Crossing program (small) Testing and screening program
	Stage 1 NARSs (409 Scientists) Testing and screening program

^a Researchers in US and Australia only. Australian scientists assumed to be allocated among research foci in same ratio as reported for the US. Sources for numbers of scientists: Frey, 1996 and CIMMYT, 1993.

Figure 2. Wheat crop improvement research activities and institutions.

impacts, but on a more sporadic basis², since much of it is not relevant for developing country agroclimatic conditions. GRCM – collecting and maintaining the collection of 130,000 Triticeae (bread and durum wheat and triticale) samples is a vital activity for which CIMMYT is the only significant source of international spillovers. However, it is an activity that consumes surprisingly few resources - Pardey, et al. (1998) estimate a total annual cost of only \$224,111 (\$1.82 per accession) for maintaining the CIMMYT wheat collection.

² For example, Borlaug created the first Green Revolution wheat HYVs by introgressing the Japanese Norin 10 dwarfing gene via material acquired from Washington State University (Dalrymple, 1986). Research coordinated by Oregon State University and CIMMYT was vital to developing the most successful wheat cross of the 1980s, the Winter x Spring Veery lines.

Our discussion focuses on the IARCs decision to allocate resources between pre-breeding and cultivar development research. These activities produce the two main types of IARC research output and correspond to distinct models of the IARC/NARSs interaction. Pre-breeding research produces elite lines that can be used by NARSs breeders as parents to produce varieties precisely adapted to their home environments. IARC cultivar development research generates finished cultivars that can be tested and released directly by NARSs without further crossing or selection³.

NARSs cultivar development programs are comprised of two main program activities. A crossing program creates new varieties, while a screening/testing program evaluates varieties developed elsewhere for possible release. Both activities are designed to closely target improved germplasm to particular agroclimatic production environments. A NARSs need not have its own crossing program; it may discover useful varieties simply by screening IARC or third country varieties without investing in a more expensive crossing program. International screening and testing of advanced breeding materials in trials coordinated by the IARC centers is an essential component of all NARSs cultivar development programs. The administration of multi-site international nurseries that distribute promising lines for testing to all interested countries is an important IARC activity. These nursery networks have created enormous efficiency gains for NARSs testing programs. Even NARSs with successful crossing programs rely heavily on cultivars taken from these nurseries for much of their pre-breeding material and for finished varieties. The international flow of germplasm has had a large impact on the speed and the cost of NARSs cultivar development activities.

Precise information on the actual distribution of plant breeders is not available for either the international rice or wheat systems, but the available evidence from wheat suggests that the balance is tipped heavily toward cultivar development research, with a potentially serious lack of support for GRCM and P-BR. Using the number of scientists reported in figure 2, a rough estimate of the total number of GRCM and P-BR scientists would be perhaps seven percent of the scientists in the CIMMYT/NARSs system. This is based on the assumption that CIMMYT's wheat scientists are equally divided between GE and CD research, and that 10% of Stage 3 NARSs scientists are dedicated to GE research. If the seven percent figure is correct, the international wheat system dedicates less than half the proportion of effort to GE as the prevailing allocation in the US (Frey). Evenson (1996a) suggests that the international rice improvement system also faces a serious problem of underinvestment in genetic enhancement research.

A number of factors explain the skewing of research investments toward cultivar development. The full benefits from investments in pre-breeding are difficult to capture by any single country. They also occur with long lags, are highly uncertain, and require a more sophisticated scientific capacity. Small countries behave rationally by choosing to free ride on the international system rather than to invest in a large wheat breeding infrastructure (Maredia, Byerlee, and Eicher, 1994). As long as the international public good is available,

³ The distinction between pre-breeding and finished material is not always clear, since a line may be released for use by farmers and still be used as a parent line for further crossing.

such decisions are rational and enhance the short run efficiency of NARSs. Such NARSs may view pre-breeding research as a luxury, to be funded only after the more immediate, and more readily appropriated cultivar development research needs are met. Because the IARCs are the only institutions with worldwide mandates, they are the logical institutions to compensate for the lack of pre-breeding research in the NARSs.

The 31 NARSs with wheat breeding programs can be subdivided by the breadth and output of their research program as stage 1, 2 and 3 NARSs (Byerlee and Traxler, 1995). Stage 3 NARSs do some pre-breeding research and develop a significant amount of parent material for their crossing programs (Table 1). As of 1990, only Brazil, India, China, and Argentina, demonstrated Stage 3 capacity for wheat, while ten rice countries appear to be at this stage⁴. Stage 2 NARSs have crossing programs that have demonstrated some success, producing about one new variety every year from their own crosses. There are two Stage 2 NARSs in wheat (Chile and Kenya), and three rice countries (Malaysia, Philippine, and Mexico). The remaining NARSs, which include 25 wheat NARSs and 40 rice NARSs, do not have effective crossing programs. These NARSs are able to release useful varieties by testing imported varieties and releasing those best adapted to their environment.

Continued success of the international crop improvement effort in producing improved varieties for farmers requires "sufficient" levels of all four classes of research. In the long run, yield improvement is not possible if pre-breeding material with higher yield potential is unavailable, but these research activities compete for resources, and the effect of underinvestment in upstream research may not be felt for decades. NARSs investment favors cultivar development, because of the high cost and long development time required for pre-breeding to show results. In this section we discuss a simple model of the tradeoff implicit between pre-breeding and cultivar development research.

Table 1. Number of wheat and rice varieties released from own crossing program, and release of screened IARC varieties by country 1977–90, countries producing a total of 10 or more varieties from own crosses.

	NARSs cross	NARSs Screened	Total Releases
Stage 3 NARSs:			
Brazil ^a	84	34	118
India ^a	83	28	111
Argentina	34	35	69
Southern China	26	10	36
Stage 2 NARSs:			
Chile	14	31	45
Kenya	13	3	16
Stage 1 NARSs:			
Remaining 25 NARSs	61	275	336
Total – wheat	315	416	731
Stage 3 NARSs:			
India ^a	251	36	287
Korea	88	0	88
Brazil	66	7	73
China	51	2	53
Sri Lanka	32	0	32
Burma	32	16	48
Nigeria	27	4	31
Ivory Coast	23	0	23
Indonesia	20	13	33
Thailand	16	0	16
Stage 2 NARSs:			
Malaysia	14	2	16
Philippine	13	20	33
Mexico	10	2	12
Stage 1 NARSs:			
Remaining 40 NARS	120	85	205
Total – rice	763	187	950

⁴ For wheat, the majority of NARSs crosses contain a CIMMYT parent in all countries except Brazil. Worldwide, 85% of all spring wheat varieties released made use of CIMMYT lines either by screening or adaptive breeding.

The Trade-Off between Pre-Breeding and Cultivar Development Research

The main research priority decision facing IARC breeding programs is that of which of the two main outputs to focus on. The NARSs that have viable crossing programs desire parent material with a broad range of resistances and high yield potential. NARSs that have only a screening program require broadly adapted finished varieties with adequate yield potential so that they can test, rename and release those that perform best in their particular environment. The trade-off between IARC pre-breeding and cultivar development research can be demonstrated with a simple production function.

Yield in the NARSs home environment is drawn on the Y axis in figure 3. The plant breeding production function Y_{NARS} posits the attainable yield of the best product of a NARSs breeding program as an increasing function of the number of plant breeding scientists⁵. If the NARSs chooses to not invest in a crossing program, it could test and use IARC germplasm directly, attaining a yield of Y_{cim} . To attain a yield greater than Y_{cim} , a NARSs would need to invest in a program larger than S_{min} . Large programs would be able to produce a cultivar with a yield potential greater than that of the best IARC variety. With the existing stock of pre-breeding material, the research production function eventually flattens out to the point where employing additional scientists does not increase yields beyond Y_{max} . That is, a maximum yield potential or “yield plateau” is eventually reached, given the existing stock of pre-breeding research output.

The yield plateau can be relaxed by investing more in pre-breeding. At present, CIMMYT and IRRI are the only important sources of pre-breeding inputs for all NARSs programs, with the possible exception India and China in rice (Evenson and Gollin). The majority of varieties produced by NARSs have an IARC parent or grandparent. However if an IARC increases pre-breeding research and faces a fixed total research budget, fewer broadly adapted finished varieties will be released for NARSs to screen. The NARSs research production function under the increased level of pre-breeding is drawn as Y^*_{NARS} in figure 4. The change in IARC strategy has two effects. First, the yield plateau is released, increasing the yield potential of adapted varieties to Y^*_{max} . The second effect is to shift the yield of the best unadapted IARC variety down to Y^*_{cim} . Because fewer finished varieties are produced by the IARC, the expected yield performance of unadapted IARC varieties declines. The tradeoff therefore is between providing better parent material to NARSs with crossing programs at the expense of producing fewer broadly adapted finished varieties for NARSs screening programs.

The Balance of Pre-Breeding and Cultivar Development

How is the research effort currently being shared between NARSs and IARCs? Given the large investments in NARSs over the past three decades, are NARSs now assuming a larger burden of cultivar development to allow the IARCs to redeploy their resources to upstream

⁵ Byerlee and Traxler (1996) provide evidence that the output of crop improvement research programs increases with program size.

activities that focus on raising the yield frontier? To examine these questions, we review data on releases of improved varieties of wheat and rice⁶. The wheat release data cover the 2130 wheat varieties⁷ released by NARSs in 31 countries from 1966-96. The rice data cover 1540 varieties released by NARSs in 61 countries from 1966-89.

Neither CIMMYT nor IRRI release varieties for direct use by farmers. Rather, each institution makes advanced lines available to NARSs programs. NARSs researchers may choose to rename and release these varieties after 2-3 years of in-country testing. IARC lines may also be entered into NARSs breeding collections to be used as parent material NARSs crossing programs⁸. In the analysis that follows we refer to the output of NARSs testing programs, i.e. of varieties whose cross was made at an IARC as screened CIMMYT or screened IRRI varieties. Varieties released from NARSs crosses are divided into three groups: 1) those released by “Super-NARSs” (India for rice⁹, and India and Brazil for wheat), 2) those released by all other NARSs and 3) NARSs-NARSs transfers, or third-country releases. The number of varieties in the last category is an indicator of the level of regional cooperation in plant breeding.

Recall that when measured by the increased number of varieties being made available to farmers, both the rice and the wheat research systems have been enormously successful. Even during the Post-Green Revolution, the total number of global releases from all sources (i.e. including both NARSs and IARC crosses) has continued to increase for each crop. Between 1975-79 and 1985-89 the average number of wheat varieties released worldwide each year increased from 50 to 72 and rice releases increased from 74 to 83. The number of wheat releases increased to 85/yr in the 1991-96 period. However, the institutional sources

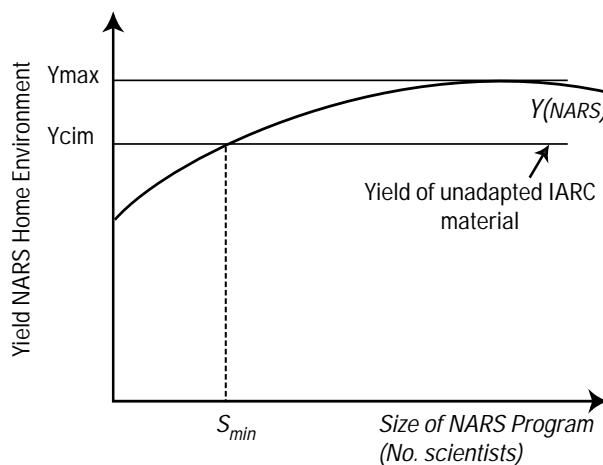


Figure 3. Crop improvement production function.

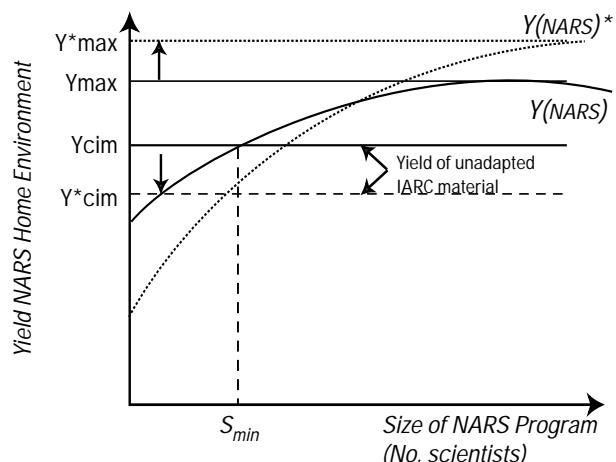


Figure 4. Effect of an increase in IARC pre-breeding research.

⁶ Wheat release data were collected by CIMMYT. Rice release data were collected by T.R. Hargrove and V. Cabanilla of IRRI.

⁷ In the analysis that follows 26 varieties with unknown parentage is omitted.

⁸ More than half of NARSs wheat releases in the 1980s had a CIMMYT parent.

⁹ China would be characterized as a Super-NARSs as well, but is not included in the analysis that follows because data on releases are incomplete.

of the increased research output differed across the two crop research systems. The main increase in wheat releases was the result of increased NARSs screening of CIMMYT crosses (Figure 5). Between 1975-79 and 1985-89, the average annual release of this type of variety increased from 24 to 39 and to 40 in 1992-96. NARSs crosses have been relatively constant across the three periods (from an average of 23 to 27 to 20 varieties/year), as have third-country releases (from 2 to 6 to 3 varieties/yr). Super-NARSs wheat crosses were constant until falling recently. For rice on the other hand, the worldwide increase in releases came primarily because of increases in NARSs crosses, which increased from 30 to 40 varieties/yr (Figure 6). The number of screened IRRI varieties released actually fell by 50%, from 16 to 8 varieties between 1975-79 and 1985-89. Super-NARSs releases also fell slightly, while third-country releases were flat.

Data on the shares of global varietal releases reveal several things about how varietal improvement is currently organized (Figures 7 and 8). The wheat shares were stable across the 1985-89 to 1992-96 periods and data for the later period are not available, so we compare

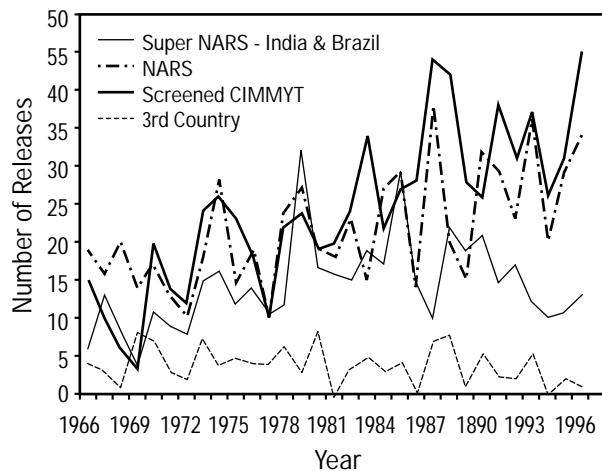


Figure 5. Number of wheat releases by source of cross.

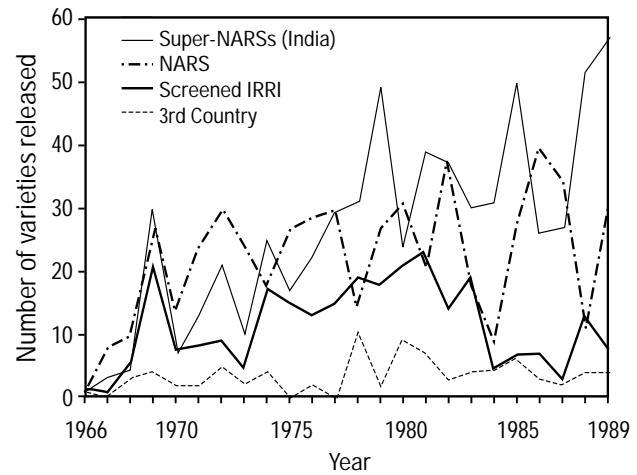


Figure 6. Number of rice releases by source of cross.

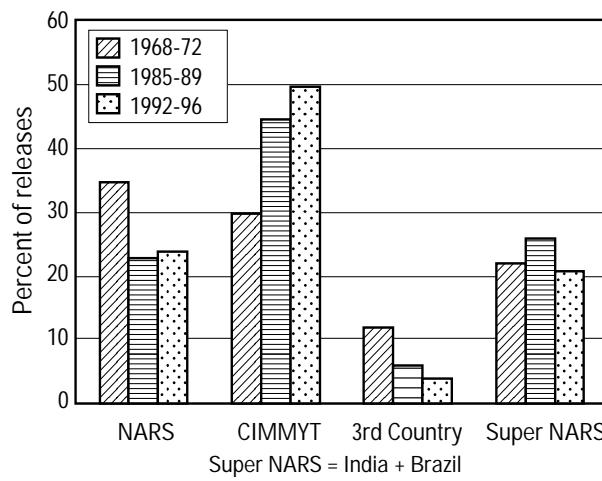


Figure 7. Shares of wheat releases by source of cross.

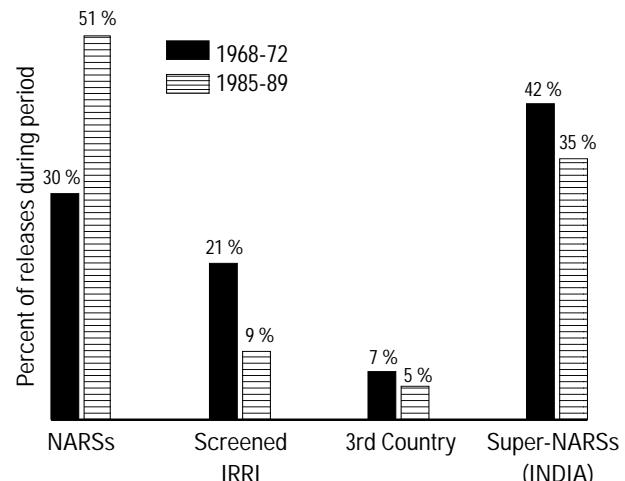


Figure 8. Shares of rice releases by source of cross.

the wheat and rice data for the common data period of 1985-89. The rice and wheat systems differ greatly in the prominence of IARC crosses as a source of varietal releases. In wheat, more than half of all releases in 1985-89 are the result of NARs screening CIMMYT crosses, and the share of releases in this category has increased over time. In fact, there are *no countries* in which screened CIMMYT varieties are not an important source of farm level technology. The number of wheat releases each year from NARSs crossing programs has increased slightly over time, but their share of total releases has declined significantly. On the other hand, IRRI is no longer an important source of finished rice varieties. Screened IRRI crosses accounted for just nine percent of rice releases in 1985-89, while NARSs crosses accounted for 85% of releases worldwide. IRRI scientific resources have been freed to move upstream to engage in work on new plant types.

NARSs-NARSs transfers are not an important source of finished varieties in 1985-89 for either crop – 6% of all wheat releases and 5% of rice releases. However, for rice other NARSs are an important source of parent material. Some 36% of NARSs rice releases contained a third country parent, most of which were obtained through the IRRI administered international nurseries (Evenson and Gollin). On the other hand very few wheat releases had a parent from another NARSs. Parents were almost exclusively from the country's own breeding program or from CIMMYT. In 1986-90, nearly 70% of the varieties released from NARSs crosses had at least one CIMMYT parent. This compares to only 20% of NARSs-cross rice varieties using an IRRI parent in the 1986-91 period (Evenson, 1996). Evenson and Gollin conclude that the importance of IRRI in delivering genetic material through even further upstream research (i.e. embodied in grandparents, etc.) has increased over time.

Regional cooperative programs have begun to make important contributions in some crops, including the Central American regional maize and bean programs. Even these programs however are largely a conduit for moving IARC germplasm (Sain, 1998, Viana, 1998) so might most appropriately be considered to be important compliments to IARC activity. Work remains on addressing complex institutional issues of funding and operating such regional systems before they can be considered as sustainable. This suggests that whatever the potential merit of moving to regional rather than - or more likely, in addition to- global research systems may be decades off.

Incentives for NARSs to Invest in Cultivar Development

There are a number of factors contribute to the higher number of rice varieties produced from NARSs crosses when compared to wheat NARSs. The leading rice producing countries are slightly larger and may have stronger research systems overall than the leading wheat producers. The world rice market is much thinner than the wheat market, with ten times as much wheat as rice entering world trade annually. This makes self-sufficiency a more reasonable policy for rice than for wheat since it is difficult and expensive to import production shortfalls (Pingali, et al.). Rice ecologies are more diverse than for wheat, requiring different plant types for each environment (Pingali et al., p 14). Quality and taste

¹⁰ Hargrove, et al. report that NARSs cross tall varieties to transfer a preferred grain type to agronomically suited IRRI material.

Table 2. Number of releases from own crosses 1977-89, releases per million ha, and releases per \$ billion crop value for major rice and wheat producing countries. Countries in bold type have more than 10 releases per \$ billion crop value.

Country	NARS Rice Releases	Rice Area (m ha)	Rice Rel per m ha	Rice value (\$ Bil)	Rice rel per \$ Bil	Country	NARS Wheat Releases	Wheat Area (m ha)	Wheat Rel per m ha	Wheat value (\$ Bil)	Wheat rel per \$ Bil
1 India	251	40.90	6	27.27	9	Brazil ^{a,b}	84	3.40	25	0.78	107
2 S. Korea ^{a,b}	88	1.26	70	2.16	41	India ^b	83	23.43	4	6.51	13
3 Brazil ^{a,b}	66	5.74	12	3.00	22	Argentina ^b	34	4.91	7	1.24	27
4 Sri Lanka ^{a,b}	32	0.73	44	0.60	53	Chile ^{a,b}	14	0.60	23	0.24	58
5 Myanmar	32	4.58	7	3.67	9	Kenya ^{a,b}	13	0.15	85	0.03	422
6 Nigeria ^{a,b}	27	1.15	24	0.65	42	Uruguay ^{a,b}	7	0.19	37	0.06	123
7 Ivory Coast ^{a,b}	23	0.53	44	0.14	167	Turkey	7	9.31	1	2.51	3
8 Indonesia	20	10.20	2	11.42	2	Pakistan	6	7.58	1	1.76	3
9 Thailand	16	9.64	2	5.44	3	Morocco	4	2.41	2	0.47	9
10 Malaysia ^{a,b}	14	0.66	21	0.48	29	Egypt ^b	4	0.61	7	0.39	10
11 Philippines	13	3.38	4	2.44	5	Paraguay ^{a,b}	4	0.17	23	0.04	92
12 Mexico ^{a,b}	10	0.14	69	0.14	70	Libya ^{a,b}	3	0.20	15	0.02	128
13 Bangladesh	9	10.34	1	6.61	1	Nepal ^b	3	0.58	5	0.10	29
14 Nepal	8	1.44	6	0.87	9	Mexico	2	1.01	2	0.56	4
15 Peru ^{a,b}	8	0.22	36	0.31	26	Iran	2	6.47	0	0.94	2
16 Colombia ^{a,b}	5	0.42	12	0.52	10	Syria	2	1.17	22	0.21	9
17 Uruguay ^{a,b}	4	.085	47	0.11	35	Tunisia ^b	1	0.61	2	0.09	11
18 Pakistan	4	2.04	2	1.31	3	Sudan ^b	1	0.14	7	0.03	38
19 Ecuador ^{a,b}	4	0.28	14	0.24	17	Zimbabwe ^{a,b}	1	0.04	23	0.03	29
20 Dom. Rep	3	0.11	28	0.13	24	Saudi Arabia	1	0.70	1	0.42	2
21 Egypt	3	0.39	8	0.65	5	Algeria	0	1.34	0	0.13	0
22 Argentina ^{a,b}	3	0.10	31	0.11	27	Afghanistan	0	1.67	0	0.27	0
23 Iran	2	0.50	4	0.46	4	Bangladesh	0	0.58	0	0.14	0
Total or avg.	646	94.9	7	68.7	9	Total or avg.	276	67.3	4	17.0	16

Major rice producers China, N. Korea and Laos and major wheat producers China and Iraq omitted due to incomplete data.

characteristics are more universal for wheat than for rice, precluding the need for adaptation to satisfy local taste preferences¹⁰. However the key factor is that rice is a higher value crop, so the incentives are stronger to invest in rice research. Table 2 lists the 23 largest wheat and rice producing countries. As noted previously, while 12 rice countries produced 10 or more varieties from their own crosses in 1977-89, only 5 wheat countries did so. The rice countries had more releases per crop area than the wheat countries. Thirteen rice countries had more than 10 releases per million ha, compared to only eight wheat countries. The world price for rice is nearly three times the wheat price, and the total value of the rice produced by the table 2 producers is \$ 68.7 billion compared to just \$17 billion for wheat. When account is taken of this fact, the weighted rate of varietal release is similar for the two crops - for both rice and wheat there were thirteen countries with more than 10 releases per billion dollars of crop value. In fact the average number of releases per billion dollars value was higher for the wheat countries than the rice countries (16 for wheat, 9 for rice).

It would be useful to directly compare the rate of NARSs investment per unit crop value for rice and wheat, but this information is not available. However, the similarity of numbers of releases when weighted to account for the higher value of rice suggests that the effort devoted to NARSs wheat research is less than the rice research effort for simple economic reasons. The notion that it is inefficient for countries with a small crop value to invest in crossing programs is supported analytically in Marekia and Byerlee. They find given the good performance of CIMMYT varieties across a wide range of agroclimatic environments, 31 of 71 NARSs wheat programs are overinvesting in wheat research. The model is based on a comparison of the performance of NARSs adapted varieties to CIMMYT imported varieties and the high cost of maintaining a crossing program relative to a simple screening program. Traxler, Byerlee and Jain reach a similar conclusion when examining wheat programs in India. Given the seeming economic rationality for countries to forego investing in crossing programs, it seems likely that the countries that depend on CIMMYT for finished varieties today will continue to do so in the future.

The fact that IRRI is no longer an important source of finished varieties has allowed IRRI to divest itself of work in producing finished varieties, turning CD responsibility over to the NARSs crossing programs. Evenson (1996b) presents evidence of that IRRI is playing a central role in rice genetic enhancement research. He describes the role that IRRI has played in incorporating landraces into breeding material, serving as an essential conduit for the global distribution of landrace genes. Some 70% of all landraces that have appeared in the background of NARSs rice varieties have entered through the use of IRRI crosses. IRRI would not have been able to invest as heavily in this important activity which increases diversity had not NARSs been so successful in conducting crossing programs.

CIMMYT, on the other hand, is faced with a dilemma. CIMMYT is the only important international supplier of upstream GRCM and P-BR research, and there appears to be substantial underinvestment in these activities worldwide. Yet, with so few NARSs having demonstrated the ability to develop varieties from their own crosses, it would be risky for CIMMYT to reduce its efforts in producing varieties for NARSs screening programs in order to increase pre-breeding research. This puts an extreme strain on CIMMYT resources, since

the implied mandate is to do more upstream research without reducing its cultivar development research — all with a stagnant total wheat breeding budget. The fact that NARSs research budgets are now also stagnant or declining in most areas suggests that they will be hard pressed to improve their performance in cultivar development.

NARSs/IARC Systems: Looking Ahead

It is clear that the need for international cooperation in wheat research will persist in the 21st century. The international public good nature of crop breeding and genetic enhancement research ensures that some sort of international transfer of germplasm and information will continue to exist. What remains uncertain is the organizational structure that will allow cooperation in wheat research to occur. Will nation states organize themselves to generate an international public good? The will to serve developing country farmers is strong on the part of all participants, but the challenges facing the system are large, dynamic, and different for each participant. In this section we review some of the trends which will be key determinants of the future organization of crop improvement research.

Evolving Intellectual Property Rights Regimes

Intellectual property rights and their implications for the flow of genetic material can be expected to transform the way the global crop improvement systems operate. The green revolution would not have progressed as rapidly as it did without the free and widespread global exchange of germplasm and information. International spillovers of research results, and the consequent economies of scale that resulted from the global flow of genetic resources, enabled both large and small countries to benefit from global research efforts. In the past germplasm flows were uninhibited by concerns for IPR – exchanges were largely based on the informal exchange of lines among breeders. A major determinant of the future access of developing country farmers to a flow of improved varieties will be whether a formal system of material transfer agreements will evolve to replace the informal system of the past. Restrictions imposed on germplasm movement by intellectual property protection could have serious consequences on developing countries' ability to sustain growth in cereal productivity.

Some public sector research administrators envision royalty income as a means of making up for declining hard money support. The long-term impact of this perception may be most acutely felt in two ways. First, breeders may become less open in the sharing of breeding lines for fear of jeopardizing future royalty income. Secondly, because pre-breeding research holds the least potential for generating appropriable discoveries, resources may be diverted away from these efforts toward downstream with greater revenue potential. As public sector institutes migrate to focus on downstream activities in hope of obtaining plant patents, they begin to duplicate, rather than complement private sector activities. This is a potentially serious threat to genetic improvement, as many observers already consider investment in pre-breeding research to be inadequate (Evenson, 1996). Genetic conservation

efforts may also be seriously hampered by the fear that the collecting agency stands to gain from patenting economically useful genes obtained from the collections. To date few public institutions have been able to generate significant revenue from biological patents.

On the other hand, improved ability to protect intellectual property may induce the private sector to increase their investment in some crops. The increased level of private sector participation in wheat and rice research and development could have an important bearing on the roles of NARS and IARCs. In research and cultivar development for pure-line cereals (wheat, rye, triticale, rice, oats, and barley) and grain legumes in developing countries, the private sector has yet to play an active role. In research on hybrid cereals (maize, sorghum, and millet), where investments are protected by trade secrecy, the private sector has taken the lead in genetic enhancement and cultivar development. The role of the private sector in developing country hybrid maize production has been expanding rapidly. Hybrid wheat and rice may generate a similar level of interest from the private sector.

Future NARSs Capacity: Are We Headed Toward a Dual System?

The number of public sector agricultural scientists quadrupled from the early 1960s to 1990, but has been either stagnant or declining in most countries since then. Research capacity has developed unevenly across countries and across commodities. The evidence for wheat, rice and maize suggest that from 75% to 90% of all NARSs are currently in Stage I, with the capacity to screen cultivars developed elsewhere, but with little or no capacity to develop successful varieties from their own crosses. We find it unlikely that there will be fewer Stage I countries in the future as public sector research investment constricts. The logical imperative of cooperation increases as research funding becomes tighter, but the financial lure and need to freeride on others' research may overcome the rationale of cooperation .

Nonetheless, the majority of the poor, and the majority of developing country cereal crop area reside in the super NARSs of India, China and Brazil. These countries will continue to develop their upstream research capacity, likely exceeding IARC capacity in some areas, but heavily dependent on the international flow of germplasm to maintain momentum in their cereal breeding programs. The more sophisticated NARS programs are in fact more likely to appreciate the resource saving nature of international spillovers in germplasm enhancement and breeding research. Strong NARS capacity does not mean independence in crop breeding research, it may lead to greater international interdependence in germplasm enhancement activities. The challenge for the IARCs will be how best to serve these diverse clients in the future.

Advances in Agricultural Science: Will NARSs Share in the Benefits?

The big breakthroughs in crop breeding research in the 21st Century can be expected to result from the application of modern science to traditional problems of shifting the yield frontier and enhancing yield stability. Recent advances in biotechnology, specifically gene mapping and genetic engineering tools can have a significant impact on the supply of cereal germplasm with durable resistance to diseases and improved tolerances to physical stresses such as high temperatures, soil toxicities, etc. Improved understanding of plant physiology and crop modeling could also help in breeders' efforts to shift the yield frontier of wheat.

The role of the international linkages in wheat improvement will be enhanced with the increased application of modern science to crop breeding. No single national or international institution will possess the capacity to take full advantage of all of the new scientific possibilities on the horizon. Applications of modern scientific tools to plant breeding will require high levels of collaboration between the developed country universities, advanced research laboratories, international centers, national programs and the private sector. The private sector will be called upon to play a major role in this effort, but the constraints to the private sector participation, especially where proprietary information is involved must be overcome. The spillover benefits from the application of modern tools to crop breeding are very high and most developing countries may choose to benefit from them rather than invest in fullfledged scientific capacity themselves. The size of a country's cropped area is a determining factor in the level to which particular countries choose to invest in biotechnology and other modern science capabilities.

Conclusions

The international community faces the challenge of devising a system of crop improvement research that supplies germplasm with ever-increasing yield potential, while at the same time devoting adequate resources to longer-term concerns for genetic diversity and genetic resource conservation. At present insufficient NARSs resources are being devoted to pre-breeding; most of the upstream research that is being conducted is done by the IARCs.

How can the system increase the attention given to pre-breeding research at a time when both IARCs and NARSs are facing stagnant real budgets? One option would be to increase regional research coordination, but few such regional mechanisms are in place today, and the increasingly complex IPR environment may further complicate this effort in the future. It seems likely therefore that the CGIAR centers will be the key providers of pre-breeding research for the foreseeable future. In a world of shrinking budgets, the international system faces a difficult choice, providing finished varieties would come at the cost of diverting resources from prebreeding and genetic enhancement research. Without adequate levels of investment in pre-breeding research, the ability of the international research system to provide desirable varieties over the long term is limited.

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