International Journal of the Commons
Vol. 4, no 1 February 2010, pp. 452–480
Publisher: Igitur, Utrecht Publishing & Archiving Services for IASC
URL:http://www.thecommonsjournal.org
URN:NBN:NL:UI:10-1-100220

ISSN: 1875-0281

Crop improvement in the CGIAR as a global success story of open access and international collaboration

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Abstract: International agricultural research has historically been an example par excellence of an open source approach to biological research. Beginning in the 1950s and especially in the 1960s, a looming global food crisis led to the development of a group of international agricultural research centers with a specific mandate to foster international exchange and crop improvement relevant to many countries. This formalization of a global biological commons in genetic resources was implemented through an elaborate system of international nurseries with a breeding hub, free sharing of germplasm, collaboration in information collection, the development of human resources, and an international collaborative network.

This paper traces the history of the international wheat program with particular attention to how this truly open source system operated in practice and the impacts that it had on world poverty and hunger. The paper also highlights the challenges of maintaining and evolving such a system over the long term, both in terms of financing, as well the changing 'rules of the game' resulting from international agreements on intellectual property rights and biodiversity. Yet the open source approach is just as relevant today, as witnessed by the recent global food crisis and looming crop diseases problem of global significance.

Keywords: Genetic resources, international public goods, international treaties, open access, plant breeding, wheat

Acknowledgements: The authors thank G. Kingma, M. Kohli, P. Kosina, J. Lindt, I. Ortiz-Monasterio, T. Payne, R. Raab, S. Rajaram, M. Smale, K. Sayre, B. Swanson, J. Woolston, for contributing data and comments.

1. Introduction

International agricultural research has historically been an example *par excellence* of open source approaches to biological research. Agricultural technology has a long record of informal flows and free exchange across countries. These informal exchanges continued with the advent of scientific breeding after the rediscovery of Mendel's laws in the early 20th century. Indeed, many of the now-developed countries recognized the growing importance of genetic resources and mounted specific programs to accelerate the exchange and collection of exotic germplasm (Brockway 1979).

Beginning in the 1950s and especially in the 1960s, a looming global food crisis led to rapid institutional innovation to formalize international exchange and innovation in genetic materials, with a shared objective of increasing food production in developing countries. Led by the Rockefeller and Ford Foundations, the outcome of this effort was the development of a group of international agricultural research centers with a specific mandate to foster international exchange of materials and knowledge for crop improvement of relevance across many countries. This formalization of a global biological commons in genetic resources was implemented through an elaborate system of cross-country research experiments known as international nurseries, a breeding hub, free sharing of germplasm, collection and characterization of exotic germplasm, generation and sharing of information, the development of a network of trained scientists, and widely shared goals. The oldest and arguably the most successful of these programs was the international wheat breeding network, dating from the 1950s. Similar programs for rice and other crops ultimately led to high payoffs in terms of hunger and poverty reduction, and undoubtedly headed off a global food crisis.

All of these programs conformed to a classic definition of 'open-source collaboration', defined here to include (i) free distribution and redistribution of the original materials, (ii) free redistribution of materials derived from the originals, (iii) full sharing of information, including pedigrees and grain yield, disease resistance and other information relating to the materials, (iv) non-discrimination in participation in the networks, and (v) intellectual property rights on final materials that, if used, did not prevent their further use in research.

This paper traces the history and impacts of the international wheat program with which both authors were associated for decades. Particular attention is given to how an open-source system operated in practice. A major theme is that success in this program depends on key people and leadership. The paper also highlights the challenges of maintaining and evolving such a system over the long-term, both in terms of financing, as well as adjusting to changing "rules of the game" resulting from international agreements on intellectual property rights and biodiversity. Yet the open source approach that has been historically so successful in crop improvement research for the poor is just as relevant today, as witnessed by the recent global food crisis and looming crop disease problems of global significance.

2. Historical evolution of international research collaboration

2.1. Mexican beginnings

The origins of international crop breeding and the international agricultural research system date to 1940, when the US and Mexican governments requested the Rockefeller Foundation to support research on basic food crops, along with training of Mexican scientists in what became in the mid-1940s, the *Oficina de Estudios Especiales*, a special unit within the Mexican Ministry of Agriculture focusing on maize, wheat, beans and soil management (Bickel 1974).

The US scientist selected to lead the wheat research was Norman Borlaug who initially developed the program around the major limiting factor in wheat production at that time – stem rust disease – in both the central highlands of Mexico and the irrigated valleys of the northwest Mexican state of Sonora. This led to a shuttle breeding program of two seasons per year which cut the breeding time by half to 5–6 years, and eventually provided a strong base of wide adaptation in Mexican wheat materials, due to their selection in two very different environments.

2.2. The first international nurseries

Breeding lines were initially provided through informal exchange and contacts with the US and Kenya, as well as from Mexican sources. The internationalization of the program received a significant boost when stem rust (race 15B) devastated the US and Canadian wheat crops in the early 1950s, leading to estimated losses of around $US3 billion (in 2007 dollars). The urgency of action led the USDA to organize the first ever international nursery trial starting in 1950 – the International Stem Rust Trial (Plucknett et al. 1990).[1] Seven countries participated in this effort (Argentina, Chile, Canada, Colombia, Ecuador, Mexico, and the USA) to test more than 1000 wheat lines annually for rust resistance in each location. This nursery and associated breeding programs were successful in bringing the stem rust problem under control by the mid-1950s.

Meanwhile, the Mexican wheat program began using the same principles to establish collaboration within Latin America (the Inter-American Nursery Trials initiated in 1960) and the West Asia and North Africa (the Near East and North

[1] A nursery or trial in a plant breeding program is an experimental set of genetic materials or germplasm organized for a specific purpose such as crossing, observations or yield testing. It may be unreplicated or replicated.

Africa Spring Wheat Yield Nursery initiated in 1962). These two nurseries were merged in 1964 into the first truly international nursery, the International Spring Wheat Yield Nursery (ISWYN). During this period, the objectives had evolved to include screening for additional diseases, and for exchange of materials between breeding programs. These international trials served as a vehicle to establish standardized approaches to increase data quality and enable analyses over time and space.

These exchanges also greatly expanded the genetic base of the Mexican program through incoming materials. By the late 1950s, the nurseries grown in Mexico included 50,000 entries. At this time, US and Canadian wheat programs began to plant off-season nurseries in Mexico, to speed the breeding which added to the germplasm exchange and networking among programs. In the 1960s and 70s other countries joined to plant off-season nurseries in Mexico so that Mexico became a hub of ad-hoc international germplasm exchange and information in spring wheat.

Training of young scientists – both practical experience in the field, and postgraduate – was an integral part of the program from the beginning. As the nursery system and the international exchanges expanded, so did training. By 1960 the program had trained scientists from Afghanistan, Cyprus, Egypt, Ethiopia, Iran, Iraq, Jordan, Libya, Pakistan, Syria, Saudi Arabia, and Turkey – as well as from ten South American countries. These were the pioneer scientists who formed the basis of the international wheat breeding system and the "Green Revolution" of the late 1960s and the 70s.

2.3. Semidwarf genes and the seeds of the Green Revolution

A land mark in this growing formalization of exchange of materials was the sourcing of the Norin10 genes for dwarfing from Japan via the US. They were incorporated into the Mexican breeding program in the mid-1950s. This produced the first semidwarf spring wheat varieties for Mexico that were broadly adapted and day-light insensitive due to over a decade of shuttle breeding within Mexico and testing and selection through the international nursery system.

These varieties which increased yields by at least 40% (much more at higher levels of fertilizer) were particularly well adapted to the irrigated wheat areas of Pakistan and India and this led to the expansion of the Mexico-based program to these countries. Following the Mexican example, India already had a Rockefeller-funded technical assistance program that supported agricultural research from the mid-1950s (Bickel 1974; Lele and Goldsmith 1989). Likewise the Ford Foundation was supporting agriculture and rural development in Pakistan. The food situation in these countries was growing acute and through the international nurseries and trainees returning from Mexico, the semidwarf wheats were widely tested and showed excellent results in both countries.

With the active involvement of the Mexican program and strong leadership from Indian and Pakistan scientists the semidwarfs were extensively evaluated and then released in 1966. The rest is history – the new varieties were rapidly adopted and the Green Revolution was launched. India and Pakistan spectacularly increased their wheat production by 121% and 65%, respectively, from 1966 to 1971 to become largely self sufficient in wheat.

2.4. Formalization of the international research system

Over time, the international networks established through the germplasm exchange and training programs had been evolving institutionally. The *Oficina de Estudios Especiales* was replaced by the Inter-American Food Crop Improvement Program in 1960 broadened to include all of Latin America and with a focus on three crops – wheat, maize, and potatoes.

A further development was the creation of the International Rice Research Institute in the Philippines (IRRI) by the Rockefeller and Ford Foundations in 1960. IRRI, an autonomous internationally-recognized body, drew on the wheat program model, but with a more formal and permanent institutional base. The first director general had worked in the Mexican program and the initial focus was on semidwarf rice varieties which along with the semidwarf wheats spearheaded the Green Revolution. When the Mexican president visited the Philippines in 1963, he requested that the Inter-American Food Crop Improvement Program be formalized and globalized along the same model as IRRI. The International Maize and Wheat Improvement Center, CIMMYT, came into being in 1966, based in Mexico.

In 1967 two other centers were created – the international institutes for tropical agriculture in Colombia (CIAT) and Nigeria (IITA) again largely with the support of the two Foundations. These centers had broad mandates for agricultural research for development, but had core international breeding programs in crops such as cassava, rice, forages, cowpeas, soya, and maize (Baum 1986).

The outstanding successes of IRRI and CIMMYT led to a strong demand to scale up and create even more centers. At the same time, it became clear that the Foundations would have difficulty even sustaining the centers already in existence. Other actors, especially USAID and the World Bank, were becoming involved. However, it was also clear that further institutional evolution was needed to coordinate funding of more centers from existing and potential new funding sources.

With strong leadership from the World Bank, an agreement was eventually reached to create a loose group of initially 17 member countries, international organizations and foundations for funding agricultural research – the Consultative Group for International Agricultural Research (CGIAR). The CGIAR provided for independence to the centers each with its own board. The CGIAR itself was a voluntary group of members founded on consensus decision-making. Even so doubts were voiced from the start that this structure would lead to long-term stable funding (Baum 1986). Seven new centers were added in the 1970s most of which had core breeding programs, including for livestock. Another five centers were added in the early 1980s with a strong focus on natural resources management and policy research. All relied on similar principles of networks and open sourcing (e.g. data bases for natural resources management research). By 2007, the CGIAR had grown to include 64 members.

3. The "nuts and bolts" of the international open-source system for crop improvement

The international open source for breeding of wheat and other crops is based on an elaborate network of international nurseries and germplasm exchange, information collection and sharing, human resources development, and workshops and staff exchanges. These "nuts and bolts" of the international collaborative system have evolved over time in response to experimentation and learning, and changing problems and resource availability.

3.1. The international nurseries network

As described earlier, the concept of formalized international nurseries was well established by 1970. The CIMMYT Annual Report of that year noted the role of the international nurseries was to provide participants with:

- basic information about adaptability of varieties, yield potential, disease and pest resistance,
- parental materials for accelerating their breeding programs,
- indications of which varieties might serve as immediate introductions into potentially high production areas,
- a means of evaluating promising breeding materials on a worldwide basis and fostering international cooperation.

The basic goals and methods of international nurseries have remained largely unchanged until today. This system, now known as The International Wheat Improvement Network (IWIN) is "the annual contact point between the CIMMYT wheat program and a global network of wheat research cooperators who evaluate wheat, triticale, and barley germplasm. CIMMYT's improved germplasm is dispatched through nurseries targeted to specific agro-ecological environments, to this network of researchers. Data from these trials are then returned to CIMMYT, catalogued, analyzed, and made available to the global wheat improvement community. The ultimate beneficiaries of the fruits of this network are farmers…" (Payne 2004).

Nonetheless the scope and coverage of the nurseries has grown and has become more complex and sophisticated over the decades (Table 1). A broad range of nurseries have been provided to different areas according to their requests, needs and level of program development. Thus, nurseries from segregating materials to advanced lines to crossing blocks might be sent. A range of special nurseries

Table 1: Evolution of international spring wheat nurseries, 1950s–2000s.

Decade	Main focus	Main nurseries added
1950s (USDA)	Rusts	International Stem Rust Trial for North and South America
1960s Pre-CIMMYT and early CIMMYT	Provide best available wheat germplasm to cooperating programs with broad adaptation, high yield potential, and multiple disease resistance and test these qualities over time and space	First International Spring Wheat Yield Trial; Int Durum Yield Trial; Int Bread Wheat Screening Nursery; Int Triticale Yield Trial; Int Triticale Screening Nursery
1970s CIMMYT era	Provide high yielding, broadly adapted, daylength insensitive, multiple disease resistant germplasm. Start of spring by winter wheat breeding program. Specialty nurseries particularly for disease resistance	Crossing blocks; F2's irrigated and dryland; International Septoria Screening Nursery; Elite Spring Wheat Yield Trial; Regional Disease Trap Nursery
1980s	As before but with additional adaptation for diverse environments, designated as mega-environments. Large program on wheat for non-traditional, warmer climates	Semi-Arid Wheat Screening Nursery; Acid Soils Wheat Screening Nursery; High Rainfall Wheat Screening Nursery; International Disease Trap Nursery; Karnal Bunt Screening Nursery
1990s	As before with additional stratification of environments including higher latitudes with daylength sensitive wheat for eastern Europe and central Asia	High Rainfall Wheat Yield Trial; High Temp Wheat Yield Trial; Semi-Arid Wheat Yield Trial; Warmer Area Wheat Screening Nursery. High Latitude Wheat Screening Nursery
2000s	Additional specialty nurseries for diseases and other traits	Scab Resistance Screening Nursery International; South Asia Micronutrient Yield Trial; International Adaptation Trial; Global Adaptation Wheat Yield Trial. Other special ones such as Stem Rust Screening Nursery

for disease resistance or abiotic stresses like aluminum toxicity are also shipped. Over time too, the wheat growing regions of the world have been classified into an initial 7 megaenvironments (now 12) and specific nurseries were targeted for some of the major megaenvironments.

The international nursery system is a very large network. From 1994 to 2000, CIMMYT distributed 1.2 million samples to over 100 countries – equivalent to the shipment of over 11 tons of wheat seed annually (Fowler et al. 2001). Figure 1 shows the management of this process over a four-year cycle from seed multiplication to return of final results. Considerable care is needed to ensure the highest standards of seed health in order to reduce the risk of spreading seed borne diseases, and a special Seed Health Unit was established at CIMMYT in the late 1980s.

Until the early 1990s, seed was distributed on the understanding that the shared objective was to develop international public goods freely available to

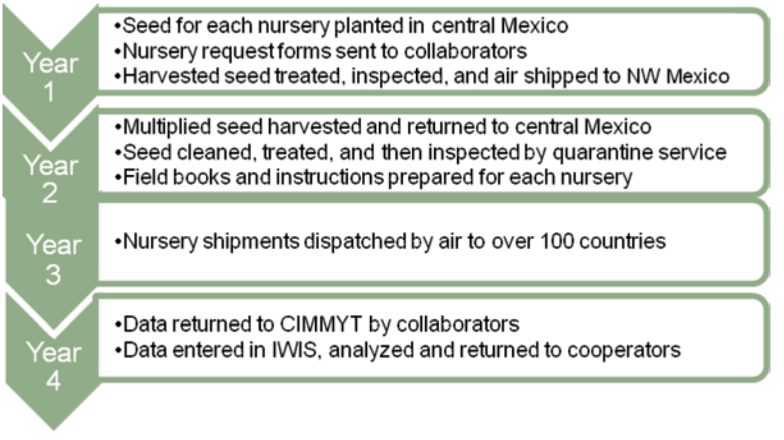


Figure 1: The Four-Year Cycle of the International Nurseries.

all for increasing food production in the developing world. Also since CIMMYT does not release varieties, countries gave their own names to released varieties so that the same variety may have different names depending on the country. This produced a sense of ownership and ensured that CIMMYT was seen as an honest broker with respect to germplasm and information sharing.

The total number of nurseries dispatched increased steadily to the 1980s, reaching over 2000 sets in the late 1980s (Figure 2), as young scientists were trained and more countries joined the system.[2] The number of nurseries declined sharply after 1988 due to funding shortfalls described below. In addition no bread wheat nurseries were distributed in 1993 due to emerging concerns about the seed-borne disease, Karnal bunt.

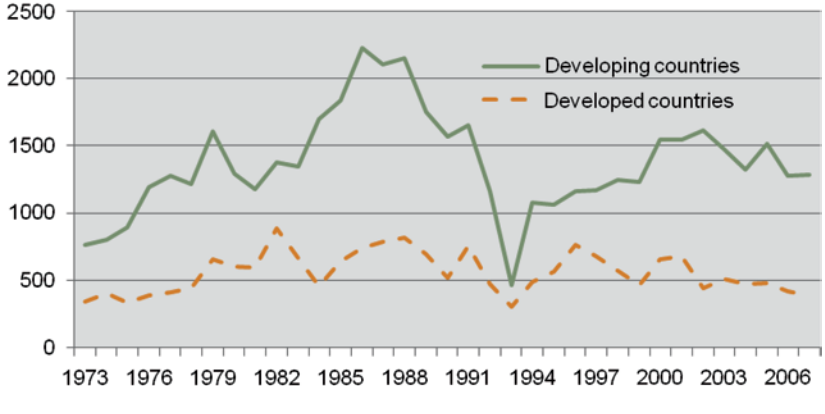


Figure 2: Annual Number of Wheat Nurseries Shipped, 1973–2007.

[2] In particular, a program to develop wheats for the more tropical environments brought in a number of nontraditional wheat producing countries.

From 1970 the number of countries receiving nurseries increased to peak at 116 countries in 1979 and then decreased with funding constraints. The regional distribution has also changed. The drop in number of nurseries has been sharpest in developed countries which were never a primary target of the program, and in sub-Saharan Africa where it was increasingly recognized that few countries had a comparative advantage in wheat production. After the breakup of the Soviet Union, the new countries of Central Asia were also included in the program.

3.2. Information collection and sharing

Data on yields, morphological and physiological traits such as plant height and days to flowering and maturity, resistance to up to 15 specific diseases and insects, grain quality, and associated climatic information are collected at each site and annually collated, analyzed and distributed to cooperators and the public via periodic reports. On average, usable data have been returned for about half of nurseries distributed. In the early years, the quality of data also increased, in large part through training and other networking activities discussed below. However, in recent years the data quality has decreased due to a reduction in support for training and concomitant loss of well-trained scientists.

As information technology improved, and the quantity of data increased, a concerted effort was made to computerize this information into user-friendly databases. In recent years, this has been formalized into the International Wheat Information System [IWIS] with two major sections – the Wheat Pedigree Management System which assigns and maintains unique identifiers and genealogies and the Wheat Data Management System which manages results from field and laboratory studies and increasingly, data on known genes (Fox et al. 1996; Payne 2004). Web access to these databases is planned.[3]

3.3. Human resources

From the beginning, human resources development has been central to the success of the international breeding system. The core activity has been six month field-based training of young scientists which was truly unique in the annals of agricultural research. The shared commitment to a common goal of increasing food production and to working in the field, often under very difficult conditions, was paramount in establishing an *esprit de corps*. Over time, more specialized and short courses have been added, depending on demand and available resources.

In total, over 1360 individuals from 90 countries have participated in these training courses. As with the international nurseries, training increased dramatically from 1967 to the mid-1980s with a peak of 69 trainees from 32 countries in 1986. Numbers then fell sharply, largely due to resource constraints, but also as collaborating programs matured (Figure 3). There was a modest recovery in the late 1990s with the increase focused on Central Asia and later Afghanistan.

[3] IWIS has given rise to a collaborative project between CIMMYT and other institutions to generate an ICIS, International Crop Information System.

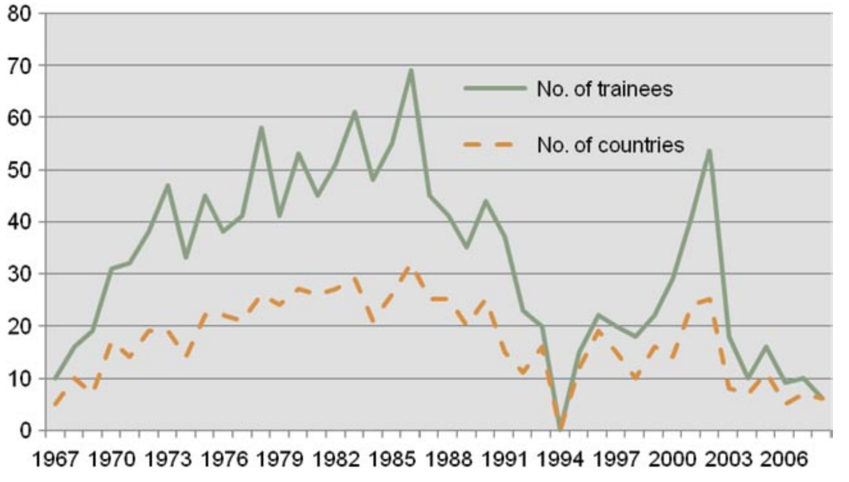


Figure 3: Annual Number of Wheat Trainees and Countries of Origin, 1967–2008.

In addition, over 2000 short-term visiting scientists, usually senior scientists, spent from several days to several months on focused germplasm collection, working on special research projects, or updating to new methodologies (Table 2). Some 800 graduate students from 76 countries and 176 academic institutions have also been associated with the CIMMYT wheat program.

These human resource activities were important in several respects. First, they helped build the capacity of developing country wheat programs. Second, they helped build a symbiotic relationship between distribution of materials and information collection for the common good, by emphasizing accurate and standardized data and note taking in the international nurseries to provide comparable data over time and space. Finally, the training programs built up a strong bond and trust among scientists from many countries that furthered the sharing of information, integration of regional efforts, and cooperation, even when international politics interfered.

Table 2: Number of visiting scientists to CIMMYT by region, 1966–2000 (Source: Villareal, 2001).

Origin	Number
Sub-Saharan Africa	133
West and North Africa	177
East, South and Southeast Asia	451
Latin America	499
Eastern Europe, Central Asia, Caucasus	60
High-income countries	546
Total	1866

3.4. Face-to-face networking

Networking activities that emphasized direct interaction among scientists within collaborating countries and regions were also central to the success of the international effort. Senior scientific staff from CIMMYT were based in key regions and sometimes countries, to work with national colleagues, to strengthen the programs and improve data quality. This close contact in the field, laboratory, and office was invaluable in strengthening the network and producing high quality results.

Workshops and symposia were also important. A unique type of seminar was the traveling seminar where scientists from several countries traveled together during the wheat season and met with other scientists at experiment stations and with farmers as well. The interchange of ideas and information was instructive and broadened the horizon of the participants.

3.5. Upstream and downstream linkages – Open source too

The international breeding and nursery system was facilitated by entry of new sources of germplasm from gene banks which operated on an open source mode as well. In addition, the varieties developed through the system were freely distributed to the end users, the farmers of developing countries.

3.5.1. Gene banks as common heritage of mankind

Gene banks and informal sharing of seed, especially for unimproved or land races have been established in many countries since the 19th century through the efforts of several well-known ‘plant hunters’. The most famous and also most tragic of these efforts was that of Nikolai Vavilov who built up a collection of 250,000 seed samples at the then Research Institute of Plant Industry in St Petersburg through his own extensive collecting expeditions, and through a wide network of correspondence (Pringle 2008).

The wheat gene bank at CIMMYT was established in the 1980s and now has about 150,000 accessions, one of the world’s largest collections of germplasm for wheat and related species (Pardey et al. 1998). In line with other activities of the international collaboration system, these germplasm collections were made freely available to all legitimate requesters. An annual average of 7000 samples were dispatched in 1992–1996 including to the private sector (Pardey et al. 1998; Lantican et al. 2005). This free exchange of materials in the CGIAR gene banks was formalized in 1983 through the International Undertaking on Plant Genetic Resources under the auspices of the UN Food and Agricultural Organization, which recognized the genetic resources in these banks as the common “heritage of mankind”. Material Transfer Agreements (MTAs) were introduced in the early 1990s to protect this heritage (discussed further below).

3.5.2. Lateral spread of varieties within countries

Arrangements for seed multiplication and distribution varied considerably among countries but up to the 1980s, no proprietary rights were exercised by the breeding programs in developing countries, except in Argentina. Typically parastatal seed corporations were responsible for seed multiplication and much of the distribution as well. Breeder seed of approved varieties was made freely available under non-exclusive arrangements to seed companies and in practice after initial distribution, much of the spread of varieties was from farmer to farmer. For example, in Pakistan, Tetley et al. (1990) meticulously traced channels of varietal diffusion in the 1980s and found that about one half of farmers ***initially*** received seed of new varieties from other farmers, and most of the rest from a public seed company. For most food crops, farmers also commonly save seed from one season to another, if they are not changing varieties. The speed of diffusion of new varieties depended largely on their yield or other advantages. During the Green Revolution period, the new high yielding wheat varieties were adopted in Pakistan by half of all farmers within just six years.

3.6. Governance

The international wheat breeding system evolved through CIMMYT as the central hub and with the majority of entries in the nurseries being provided from CIMMYT crosses which were very extensive (about 8000 per year in the 1990s (Rajaram and van Ginkel 2001)). The members of the international network participate according to their strengths. Strong leadership was essential especially in the early years, and Norman Borlaug provided this – later recognized as the first agricultural scientist to receive the Nobel Peace Prize.

Over time, efforts have been made to ensure that the whole system is more "demand driven" and participatory. In later years, scientific leaders from the collaborating countries have been more formally consulted on priorities for the networks and on data collection methods and analysis. For example, international workshops are held periodically to discuss progress and adjust approaches. Other international networks, such as the International Network for Genetic Enhancement of Rice have established formal advisory committees from collaborating countries. In one case, the Fund for Research on Irrigated Rice in Latin America (FLAR), the whole system has been devolved to a decentralized governance structure (see below).

On the downstream side, farmers, miller, bakers, and consumers, the ultimate users have also been more widely consulted on breeding priorities through a variety of participatory approaches. Surveys of farmers to elicit demands for crop traits or how varieties fit into complex cropping systems have become standard. Several programs have also moved toward participatory varietal selection and consultation with farmers on priority traits for crosses. These programs have met with some successes, especially in more marginal areas (Walker 2007). For example, in South Asia varieties selected by resource-poor farmers for the adverse conditions of eastern Uttar Pradesh and Nepal provided yield increases of 15–17% (Ortiz-Ferrara et al. 2007).

4. Scientific and economic impacts of the system

4.1. The products

Since the beginning of the international program in the 1960s, over 2000 new wheat varieties have been released in the developing world with an increasing trend over time (Dixon et al. 2006). A growing share of these varieties has been derived from crosses made at CIMMYT and selected by collaborators. In the decade of the 1980s, for example, nearly half of bread wheat varieties derived from CIMMYT crosses, and another 30% from using CIMMYT lines as parents for breeding for local adaptation (Table 3). Larger and stronger collaborating programs tend to use CIMMYT lines as parents, whereas smaller programs often release the lines directly after local selection.

A major benefit of the international network and free sharing of germplasm has been the continuing incorporation of diverse germplasm from many countries into varietal pedigrees. Tracing back to the first known ancestors shows that the number of base land race ancestors has increased from 24 in 1966 to about 60 in 1997 (Figure 4). The network has vastly accelerated the flow of germplasm across national boundaries so that most varieties in use today are truly globalized varieties in terms of their ancestry (Table 4). Genetic diversity has been continuously augmented by introgression of new materials from collaborating countries, and non-traditional sources such as wheat progenitors, other wheat species, and alien species.

This underlying genetic diversity is also being expressed at the molecular level. Studies on lines from 1950 to 2003 using 16 microsatellite molecular markers indicated that after initial narrowing of diversity, molecular diversity has been increasing from 1982 in terms of genetic distance (Warburton (2002) cited in Lantican et al. 2005).

4.2. The scientific impacts

The impacts of the program in terms of its primary objectives of increasing yields and disease resistance have been widely evaluated and documented (e.g. Reynolds and Borlaug 2006; Ortiz et al. 2008). However, there have been many

Table 3: Origin of Spring Bread Wheat Varieties Released in Developing Countries, 1966–1997 (Source: Heisey et al. 2003).

	Percent of Varieties from				Total
	CIMMYT cross	CIMMYT parent	CIMMYT ancestor	Other origin	
1966–1970	37.7	20.4	6	35.9	100
1971–1975	48.2	23.9	6.2	21.7	100
1976–1980	40.9	38.5	6.1	14.5	100
1981–1985	45.8	32.0	9.1	13.1	100
1986–1990	52.3	28.6	10.1	9.0	100
1991–1997	52.7	29.2	8.3	9.8	100

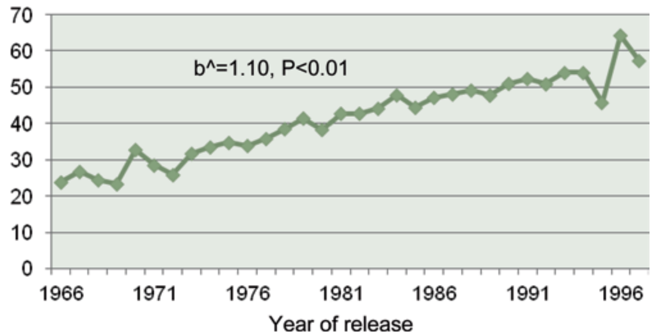


Figure 4: Average Number of Landrace Ancestors for Spring Bread Wheat Varieties in Developing Countries, 1965–1997 (Source: Smale et al. 2002).

Table 4: Percent origin of land race ancestors of bread wheat varieties grown in the developing world in 1990. (Based on Smale and McBride 1996.)

Origin of base land races (%)	Region of variety release					
	SS Africa	N. Africa	W. Asia	South Asia	Mexico and CA	Southern Cone
SS Africa	12	9	7	9	10	7
N. Africa	2	4	2	3	2	1
W. Asia	2	1	7	2	1	1
S. Asia	10	8	7	21	6	6
Mexico and CA	4	3	7	6	9	5
Southern Cone	14	16	8	11	17	32
Transitional	15	21	16	18	21	14
High-income	27	27	33	20	17	27
Other-unknown	14	11	13	10	5	7
Total	100	100	100	100	100	100

unanticipated impacts, especially in terms of yield stability and adaptability, which can be traced to the nature of the research process itself. The combination of a continuous feedback from international nursery observations over time and space permits the recycling of diverse germplasm with the most appropriate traits into the crossing program. Over time the best genes and linkages for wide adaptation and resistance to known and unknown biotic and abiotic stresses are selected, among other characters. Similarly, undesirable linkages may be broken. Since data are returned from many sites where the stresses have not been clearly determined, this provides a type of insurance via the breeding process.

4.2.1. Yields

Yield potential – that is, yields under optimal conditions – has increased steadily at a rate of nearly 1% per year since the program was initiated in the 1960s (Sayre et al. 1997). Over time, as the program became more targeted on specific environments in the 1980s, yields in suboptimal environments have increased even more rapidly (Table 5). Likewise, impressive gains have been made under low input conditions with respect to water and nutrients (N and P) (Ortiz-Monasterio 1997; Smale et al. 2002). Initially, these lines were selected under optimal management regimes so their superior performance under suboptimal conditions is an example of the wide adaptation of germplasm selected at many locations.

4.2.2. Disease resistance

It is estimated that about half of the international wheat breeding effort is allocated to increasing resistance to diseases. Since stem rust had been effectively controlled, major attention has been given to leaf rusts as the most widespread disease problem in spring wheat production. Sayre et al. (1998) demonstrate much more rapid yield gains in plots not treated by fungicide, indicating superior rust resistance of the new varieties. Good resistance is also available for other major diseases such as yellow rust, septorias, barley yellow dwarf virus, smuts and bunts.

The focus is on durable types of resistance incorporated into the derived germplasm using non-specific, polygenic resistance, from diverse sources. However, continued investment is critical just to maintain resistance (Sayre et al. 1998). Durable resistance to stem rust which was the initial target of the program in the 1940s lasted over 50 years but due to several factors including the decline in funding, research did not keep up with the evolution of the fungus, and at this writing, stem rust (race Ug99) is again threatening wheat harvests in the developing world (Singh et al. 2005).

4.2.3. Stability and wide adaptation

The products of the collaborative program have proven to be especially stable over space and time. Wide adaptability is shown by an analysis of 23,000 yield observations from the ISWYN over the decade 1979–1989. CIMMYT varieties out-yielded locally bred varieties in 5 of the 7 megaenvironments studied with yield advantage of over 10% in the irrigated and high rainfall environments (Maredia et al. 1996).

Likewise yield variability has significantly decreased since 1965 in major production environments during and after the Green Revolution. This trend is largest in the major irrigated wheat areas of South Asia, and has been statistically related to the area sown to varieties emerging from the international program (Gollin 2006).

Table 5: Trends in yield potential of spring bread wheats by environment, 1979–1999. (Source: Lantican et al. 2001).

	Irrigated	High rainfall	Dry	Hot
Growth rate (%/year)	0.82	1.16	3.48	2.10
Growth (kg/year)	53.5	62.5	87.7	46.1

4.3. Economic impacts

Products of the international collaboration have been widely adopted in the developing world and to some extent in industrial countries as well. In 2002, the last year for which data are available, varieties resulting from direct CIMMYT crosses were sown on 33% of the developing world's spring wheat area (bread and durum), and varieties resulting from further adaptation and selection using at least one CIMMYT line as a parent were sown on another 36%. Largely because of this wide adoption, yields in the developing world have increased at 2.58% annually from 1966 to 2006, double the growth rate of 1.25% per year in the developed world.

Not surprisingly the economic benefits are huge. Byerlee and Traxler (1996) estimated that over the period from 1965 to 1990, wheat research in developing countries generated an annual average economic benefit of $3.2 billion, of which about half was attributed to the international network. This compares with an annual budget of the CIMMYT wheat program averaging < $20 million. Later studies found economic benefits of a similar level of magnitude (Table 6). Depending on assumptions, the benefit–cost ratio for investment in the system ranges from 50:1 to 390:1 (Lantican et al. 2005). These estimates are an underestimate since they do not take account of the *yield loss* to diseases in the absence of the system. The present value of research on just one major disease, leaf rust, is estimated at about $5.4 billion 1990 dollars (Marasas et al. 2004). Impacts of this magnitude have been large enough to substantially impact world wheat prices with major benefits for poor consumers who depend on wheat as a food staple. It has been estimated that wheat prices would have been 19–22% higher in the absence of international research (Evenson and Gollin 2003).

Finally, it is important to note that the impacts of the international wheat improvement network have been even greater in the post Green Revolution era (after 1980) than during the Green Revolution (Byerlee and Traxler

Table 6: Summary of estimates of economic benefits to international wheat breeding research.

Study	Period covered	All breeding	Attributed to CIMMYT-national network
Byerlee and Traxler (1996)	1966–1990	$3.0 billion per year Internal rate of return of 53%	$1.5 billion per year
Heisey et al. (2002) mid-range estimate	1996–1997	$2.4 billion per year	$1.1 billion per year
Lantican et al. (2005) – mid-range estimate	1988–2002	$3.4–4.8 billion per year	$1.0–1.8 billion per year
Marasas et al. (2004) – leaf rust resistance only	1973–2007		$5.4 billion net present value
Evenson and Rosegrant (2002)	1965–2000	With no breeding research: • 9–14% reduction in output • 29–61% increase in price	With no CGIAR • 5–6% reduction in output • 19–22% increase in price

1996). Higher impacts resulted from continued expansion of the area sown to improved varieties as well as replacement of original Green Revolution varieties with higher yielding and more disease resistant varieties adapted to specific environments.

4.4. Impacts beyond wheat

It is clear from the above, that a highly organized and extensive open source system of international breeding evolved from a small beginning in Mexico in the 1940s and 1950s. Although wheat is the oldest of these systems, equivalent networks were established for most other major food staples, spearheaded by the international centers of the CGIAR.

The success rate has been remarkably consistent across commodities. Overall it is estimated that the CGIAR has increased the number of varieties by at least one-third (Evenson and Gollin 2003). The economic returns to international breeding research for rice, the most important food staple in the developing world may be even larger than for wheat (Evenson and Rosegrant 2002; Raitzer 2003). Substantial successes have also been recorded for maize, sorghum, millet, cassava, potatoes, beans and several other legumes (CGIAR 2008).

Nonetheless there are important differences among commodities. National systems, for example, have used international rice nursery materials for further crossing and development much more than for wheat where elite nursery material is often directly selected and released. Rice nurseries have also been used more for exchange of genetic materials among collaborators in national systems – 70% of rice nurseries entries are from national systems and over one-third of released rice varieties contain third country parents (Halewood and Nnadozie 2008). This in part relates to greater location specificity for rice especially with respect to taste.

The system has had least success in sub-Saharan Africa where a wide variety of food crops are grown under heterogeneous rainfed conditions. Nonetheless, there have been recent notable successes in crop improvement. For example, bean varieties from the International Center for Tropical Agriculture based in Colombia have been adopted by 5 million households on half of the area of beans in five countries of East and Southern Africa, with important benefits for food security and poverty reduction (Kalyebara et al. 2008).

In the 1980s and 1990s, improved varieties are estimated to have accounted for as much as 50% of the yield growth in developing countries. Without the international system of crop improvement, cereal prices would have been 18–21% higher in 2000, caloric availability per capita in developing countries would have been 4–7% lower, and 13–15 million more children would have been classified as malnourished (Evenson and Rosegrant 2003). Raitzer (2003) estimates that even using the results of only ten rigorous evaluation studies that have been carried out, and assuming no returns from all other CGIAR research, the internal rate of return on the *whole CGIAR investment* since establishment would be at least 34%.

5. Stress on the commons in the 1990s

In the early to mid-1990s, the germplasm sharing and international breeding programs of the CGIAR that had operated as what were essentially informal open-source programs came under stress from a number of quarters. The first of these was the decline in funding for core operating costs of the networks. Second, private sector breeding and biotechnology programs rapidly expanded in the North with implications for free exchange of germplasm. Third, two international treaties were developed largely outside of the agricultural arena, but which impinged strongly on the incentives and rules of germplasm sharing. These changes affected the freedom to exchange germplasm at different stages in the breeding/seed cycle and led to uncertainty and higher transactions costs in international germplasm exchanges, which in some cases resulted in reduced germplasm flows (Tansey 2008).

5.1. Sustainable funding – tragedy of the international commons[4]

Stable funding over many years is especially important to realize benefits from breeding activities. Funding for the network has always been shared between CIMMYT which pays for crossing and seed shipments and most of the human resource development activities, and the collaborators who pay costs of planting, managing and recording data. This system worked well in the early years especially during the "golden years" of research funding following the Green Revolution, when both CIMMYT and the national research systems saw rapid increases in core research budgets.

This situation changed starting in the late 1980s and became a major source of stress for sustaining the network. Several factors contributed to this decline:

1. A decline in international development assistance to agriculture. In 1980, agriculture accounted for over 20% of official development assistance. By 2005 this share had fallen to 4%, in response to falling international commodity prices, increased competition from support to macroeconomic reforms, debt relief, and social development; and opposition from environmental groups that saw agriculture as a contributor to natural resource destruction (World Bank 2007).
2. Within agriculture, there was a shift from productivity enhancement which fell from 74% of the CGIAR budget in 1972–1975 to only 34% in 2004–2005, as natural resources management and policy research assumed greater priority.
3. There was a dramatic shift in the share of unrestricted funding from over 80% in 1990 to about 45% in 2006 as donors increasingly restricted funds to specific projects to preserve their 'identity'. Many of these projects focused

[4] Pardey et al. 2007.

on short-term development impacts, while many of the key components of the germplasm exchange system require long-term core funding.

4. Increasing complexity and transactions costs within the CGIAR due to growing membership and expanding mandates of the system also contributed to a decline in unrestricted funding as the system lost its strategic focus (CGIAR 2008).

The result of these trends is seen in Figure 5 for the specific case of wheat research at CIMMYT which saw its budget halved in real terms over the period 1980–2002. This is also reflected in the sharp drop in number of nurseries and trainees seen above. Other international breeding networks suffered similar declines and similar trends are apparent in national support to crop breeding research (Morris et al. 2006).

5.2. Plant breeding in an era of privatization

The private sector has had long involvement in plant breeding in the North. Trade secrets had been used to protect intellectual property for hybrid crops, especially maize, leading to private domination of hybrid seed industries by 1950. Intellectual property rights (IPRs) on plants and biological processes date from the 1930s, but only became more widespread in the 1960s when special IPR regimes in the form of plant variety rights (PVRs) were adopted in Europe, with the signing of the UPOV (the International Union for the Protection of New Varieties of Plants) in 1961. IPRs assumed much greater importance when utility patents were extended to plants and biological process in 1981 in the USA. This combined with the rise of molecular tools and techniques in biological research stimulated a sharp increase in private investment in genetic improvement, the rise of 'life science' companies, a growing concentration in the plant breeding and seed industries and a trend to patent plant varieties and processes (see Figure 6). This trend was

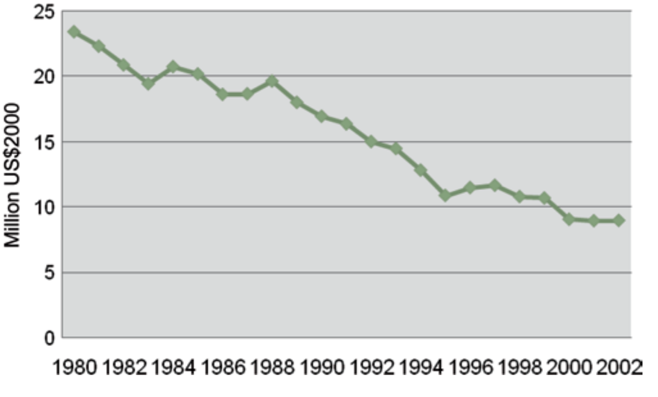
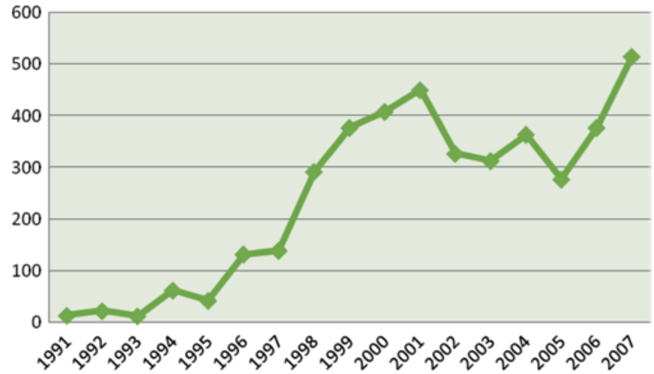


Figure 5: Trends in Real Budget of CIMMYT's Wheat Program, 1980–2002.



Source: Heisey, P. W. (personal communication).

Figure 6: Number of patents issued annually on varieties and research tools and processes for major crops in the USA.

further accelerated by ideologically-driven programs of privatization of public sector programs, such as the 1985 sale of the Plant Breeding Institute in the UK (Murphy 2007). The shift from public to private breeding is evident in Figure 7. By 1994, it was estimated that 66% of plant breeders in the US were working in the private sector (Heisey et al. 2001).

PVRs and patenting affect germplasm flows at different points in the breeding cycle (Figure 8) although their full impact has not been quantitatively assessed. On the one hand, PVRs were explicitly designed to allow other breeder's to use protected varieties in their breeding programs. However, patenting does not provide this freedom to operate, and is more likely to have negatively affected the exchange of information and materials. Furthermore, the sheer size and concentration of the private sector in the North has also reduced the amount of

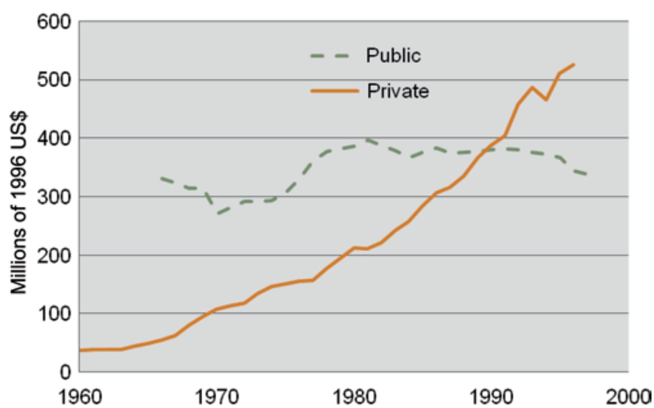


Figure 7: Real Public and Private Sector Expenditures on Plant Breeding, USA.

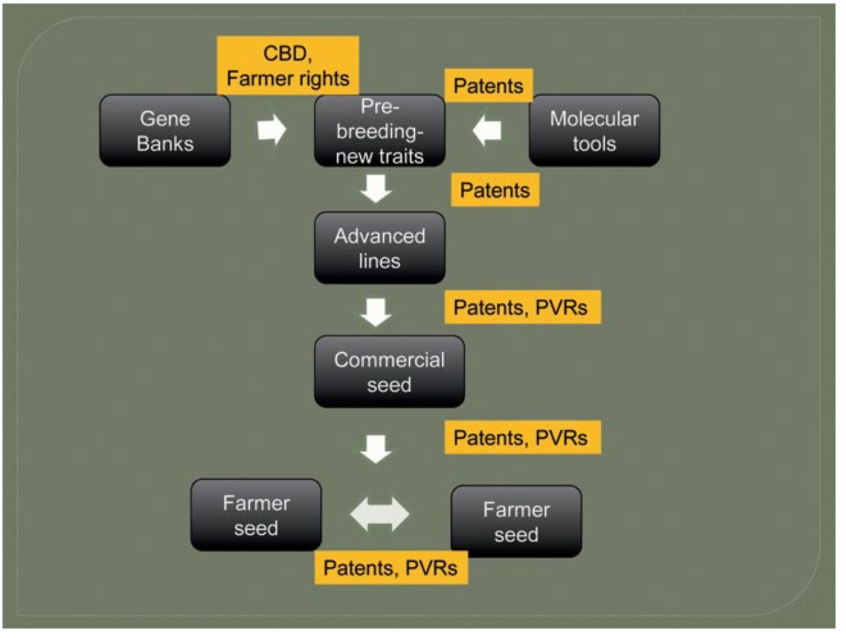


Figure 8: Impacts of 'New Rules' of the Game on Germplasm Flows.

germplasm sharing with breeding programs in the South, where most programs for food staples are in the public sector. Five companies now control one-third of global seed sales and 38% of agricultural biotechnology patents (World Bank 2007). These impacts have been greater for some crops, such as maize, than for wheat, where biotechnological tools are less widely used, and public breeding continues to be important.[5]

5.3. International treaties that sowed the "seeds of confusion"[6]

5.3.1. Trade-related intellectual property rights (TRIPS)

Up to 1993, intellectual property rights relating to plants and biological processes had largely been applied in developed countries and some middle-income countries. However, pushed by private interests in these countries, the 1993 TRIPS agreement required all member countries of the WTO to provide for IPRs on microorganisms and plant varieties. Developing countries are currently at various stages in implementing this agreement using a variety of *sui generis* systems. The impact is seen in the growing share of protected varieties in middle-income countries (Pardey et al. 2007).

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[5] One company has as much as 90% of the market for the seed of some transgenic crops (soybean). By contrast, patents on wheat accounted for only 250 of the total of just over 4000 issued by 2007.
[6] Louwaars 2007.

As in the rich countries, the rising use of PVRs in developing countries should not have a big impact on germplasm flows given the breeders' exemption. Even for downstream germplasm flows from breeders to farmers and among farmers, impacts have probably not been significant for small farmers to date (Tripp et al. 2007). Indeed, the private sector accounted for about 20% of wheat varieties released in developing countries over the period, 1988–2002, with 50–80% of them having CIMMYT parentage. However, widespread misunderstanding of the extent and implications of PVRs and the adoption of more restrictive UPOV 1991 rules on seed saving and breeders' exemptions have increased transactions costs and uncertainty.[7]

The increase in use of patenting, especially for molecular tools and genetic constructs has, however, been much more restrictive on germplasm flows and greatly increased transactions costs. For many countries, the fact that a gene or molecular tool is protected in rich countries may not be a problem, as IPRs are relevant only in the country awarding the patent (unless a product derived from the gene or tool is exported to a country holding the IPR). Since many small countries and the least-developed countries are not attractive commercial markets for private companies, few patents are taken out in those countries. Scientists within these countries may unilaterally decide to use a particular gene or tool if they can physically obtain it (e.g. by obtaining seed with a desired gene).

Patent protection is more common for the rapidly emerging and larger developing countries such as Brazil, China and India. For all countries, timely access to new tools and technologies, as well as the tacit knowledge required to use them effectively, increases the value of a formal agreement to obtain access.

Short of a generic agreement on humanitarian licensing signed by all parties, public and private, the only way to legally access materials patented in a country is through case-by-case negotiated licenses. Since many materials are protected by a "thicket" of patents with many different owners, this can be a very costly process (Pardey et al. 2008). For example, the humanitarian licenses for vitamin A enhanced transgenic rice involved up to 71 patents held by 31 different organizations (Kryder et al. 2000). Further, proliferation of utility patents in the public sector only adds to these transactions costs.

5.3.2. The Convention on Biodiversity (CBD)

The CBD was initiated by environmental interests with strong support from developing countries. It was in part a reaction to the privatization of research and development (R&D), bioprospecting and growing use of IPRs, which was seen as 'biopiracy' and an unequal exchange, given that the majority of biodiversity exists in the South.

[7] UPOV 1991, revised the original UPOV treaty to allow restrictions on farmers' seed saving and varieties 'essentially derived' from protected varieties.

The CBD formalized in 1993 overruled the principle of genetic resources as the heritage of mankind formally established through the International Undertaking on Plant Genetic Resources in 1983, and recognized national sovereignty over genetic resources. Although germplasm flows for food and agricultural uses were largely to and among developing countries, some countries such as Peru and India used the CBD to invoke restrictions on exports of their agricultural plant genetic resources. There was also evidence of a slowdown in flows from gene banks (Visser et al. 2000). In any event, the implementation of TRIPs and CBD is leading to 'hyperownership' among private rights and sovereign rights that is still being resolved (Louwaars 2007).

6. Repairing the commons in the 21st Century

6.1. Sharing plant genetic resources through a new international treaty

Given the risk of significantly restricting the beneficial flows of plant genetic resources under TRIPS and CBD, there have been a number of repair efforts to try to protect the commons. The most significant of these has been the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) which is a compromise between sovereign rights, farmers' collective rights and benefit sharing. Under this agreement, countries place germplasm into a pool which can be shared under certain conditions. In particular, IPRs cannot be issued on the original materials, but products of the materials can be protected, provided benefits are shared through an international fund aimed at conserving genetic resources. Germplasm exchange is now through a standardized MTA which went into effect for all parties in the treaty including the whole CGIAR system in January, 2007.

It is still too early to evaluate the impacts of the ITPGRFA but it is far from comprehensive and details of implementation are still being worked out. It excludes several important food and agricultural crops, newly collected materials can be excluded, and it only covers food uses. The treaty is also less than clear on how it will resolve conflicts between private rights, communal rights and sovereign rights (Louwaars 2007; Halewood and Nnadozie 2008).

6.2. Efforts to get around patents

The growing use of patents has also led to innovative approaches to acquire proprietary science and expand the commons for molecular tools and constructs – or at least reduce the transaction costs of doing so – for the benefit of small farmers in the developing world. These include the following:

- *Market segmentation and humanitarian licenses* recognize that many technologies may benefit poor farmers who are not an attractive market for private firms. Golden Rice is an example: patents have been negotiated for humanitarian use for farmers in the developing world with incomes under $10,000 a year. Likewise the African Agricultural Technology Foundation brokers the acquisition of intellectual property for smallholders in Africa, case-by-case, on a humanitarian basis.

- *Public Intellectual Property Resource for Agriculture* is a consortium of public R&D organizations largely in the USA that encourages reciprocal intellectual property sharing among members from the public sector and provides licenses for humanitarian use in the developing world, provided that derived materials are licensed under the same conditions.
- *CAMBIA BiOS* fosters collaborative "open source" development of key enabling technologies, such as tools for genetic transformation that will be made freely available to developing countries (Jefferson 2007). It is also a clearinghouse for databases on patents issued, to reduce transaction costs in acquiring intellectual property.

All of these initiatives depend on a humanitarian license which involves considerable transactions costs in drawing up MTAs. It may be possible to develop a common understanding and a standardized MTA among major IPR owners in the private and public sectors to reduce these transactions costs – an agreement that would define 'humanitarian', assign liability, and specify rules on licensing of derived products.

6.3. Sustainable funding

Long-term sustainable funding was critical to the success of the international wheat and other CGIAR programs. The CGIAR recognizes the fragility of funding of core activities and is currently conducting a wide ranging reform process to strengthen the research agenda, funding and governance.

A range of innovations will be needed along with renewed commitment from development agencies and developing countries themselves to fund international agricultural research with strong international public good elements. One initiative is the Crop Diversity Trust, which has raised most of its target endowment of US$150 million to fund the maintenance and characterization of germplasm resources in perpetuity. This concept could be extended to cover some of the costs of running networks and nurseries.

Likewise there have been a number of institutional innovations to put the breeding networks on a more sustainable footing. The most notable example is the conversion of the Latin America rice program into the Latin American Fund for Irrigated Rice (FLAR) owned, managed and financed by members, including the core breeding program. While this has achieved some success, it raises similar issues of IPRs and germplasm sharing as privatization of research even within member countries (Binenbaum et al. 2007). Also the model may not be replicable to less commercially-oriented crops of importance to the poor.

7. Conclusion

This review of the open sources system used by the CGIAR for crop improvement research, and of wheat research in particular, leads to four main conclusions.

First, open source approaches can be highly effective in biological research and have huge impacts both in terms of scientific achievements but also humanitarian impacts in improving the lives of billions. Although the CGIAR is best known for its contribution to the Green Revolution of the 1970s, its impacts have continued to deepen and widen until today. And the success with wheat and rice has been replicated for other commodities, and increasingly for other types of research.

Second, open source approaches are more than agreements on sharing of materials and information. It is essential that the networks created have a common and widely shared goal – in this case, for increasing food production in the developing world, later refocused on global poverty reduction. People are also essential components and finding ways to build social capital and trust among participants is critical to success. Strong central leadership was also needed to establish the networks.

Third, approaches must continuously evolve in response to new challenges and new science, but also new institutional ‘rules of the game’ under which such networks operate. International crop improvement networks have faced considerable challenges especially new international agreements on intellectual property rights and conserving biodiversity. While good progress has been made in adapting to many recent changes, the most intractable challenge to a continued open access system remains the increasing use of patents on biological processes and tools in both the public and private sector, and the greatly increased transactions costs of obtaining freedom to operate as patents proliferate into complex and intertwined “thickets” (Boettiger and Wright 2007; Pardey et al. 2008).

Finally, sustainable funding is central to overall success, especially for core activities of germplasm collection, pre-breeding, and distribution of materials. Reduced funding has been the Achilles heel of the international crop improvement efforts. The irony of the wheat success story discussed in this paper is that the problem that gave rise to the system in the 1940s and 1950s, stem rust, has recently re-emerged as a threat to wheat production and food security in developing countries. New sources of funding from private philanthropic foundations and farmer interest groups may head off serious losses but these could have been avoided with more sustained longer-term support.

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