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Combating Stem and Leaf Rust of Wheat

Historical Perspective, Impacts, and Lessons Learned

H.J. Dubin
John P. Brennan

2020 Vision Initiative

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A total of 20 case studies are included in this project, each one based on a synthesis of the peer-reviewed literature, along with other relevant knowledge, that documents an intervention's impact on hunger and malnutrition and the pathways to food security. All these studies were in turn peer reviewed by both the Millions Fed project and IFPRI's independent Publications Review Committee.

AUTHORS

H.J. Dubin
Consultant and former associate director, Wheat Program, CIMMYT
Email: hjdubin@comcast.net

John P. Brennan, Coolamaine Economic Research
Economist
Email: jpjkbrennan@gmail.com

Notices

[1] Effective January 2007, the Discussion Paper series within each division and the Director General's Office of IFPRI were merged into one IFPRI–wide Discussion Paper series. The new series begins with number 00689, reflecting the prior publication of 688 discussion papers within the dispersed series. The earlier series are available on IFPRI's website at www.ifpri.org/pubs/otherpubs.htm#dp.

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ABSTRACT

This case study explores the half century of successful efforts of the international wheat stem and leaf rust resistance programs within the context of the international agricultural research system. The study uses a historical perspective to examine the major factors that underpin the success, and presents the impacts on economic returns, food security, and poverty in developing countries. It concludes that the major reasons for success in research on durable stem and leaf rust resistance rested on the following: symbiotic relationships of the collaborative international and national programs; free exchange of genetic resources and information; human resource development; and long-term donor commitment. Data presented show that the use of durable rust resistance has significant economic returns as well as positive impacts on poverty reduction, nutrition, food security, and the environment. Nevertheless, in recent years, decreased donor support for agriculture and productivity has had negative effects. The recent occurrence of a new strain of stem rust that defeated key durable resistance genes has endangered large wheat areas in developing countries. This highlights the critical need for continuous research and vigilance to keep ahead of the ever changing pathogenic microbes.

Keywords: Millions Fed, Food Security, Wheat Rust, Stem Rust, Leaf Rust Norman Borlaug

ABBREVIATIONS AND ACRONYMS

CBD	The Convention on Biodiversity
CGIAR	Consultative Group on International Agricultural Research
CIDA	Canadian International Development Agency
CIMMYT	International Maize and Wheat Improvement Center
CWANA	Central & West Asia & North Africa
FAO	Food and Agriculture Organization of the United Nations
ha	Hectare
IADB	Inter-American Development Bank
IARC	International Agricultural Research Center
ICARDA	International Center for Agricultural Research in Dry Areas
INIFAP	Instituto Nacional de Investigaciones Forestales, Agrícolas, y Pecuarias, México
IPO-Wageningen	Research Institute for Plant Protection (IPO), Wageningen, The Netherlands
IRRI	International Rice Research Institute
ISWRN	International Spring Wheat Rust Nursery
ISWYN	International Spring Wheat Yield Nursery
ITPGRFA	International Treaty on Plant Genetic Resources for Food and Agriculture
IWIN	International Wheat Improvement Network
IWIS	International Wheat Information System
ME	Mega-environments
MV	Modern varieties (semidwarf wheat)
NARS	National Agricultural Research Systems
ODA	Overseas Development Administration, UK
PBI Cambridge	Plant Breeding Institute, Cambridge, UK
SMTA	Standardized Material Transfer Agreement
SSA	Sub-Saharan Africa
t	tonne
TRIPS	Trade-Related Intellectual Property Rights
Ug99	Strain of stem rust identified in Uganda in 1999
USAID	U.S. Agency for International Development
USDA	U.S. Department of Agriculture

1. INTRODUCTION

Background

Green Revolution successes and impacts have been studied and reviewed in recent years (Byerlee and Moya 1993, Byerlee and Traxler 1995, Evenson 2001, Heisey et al. 2002, 2003, Evenson and Gollin 2003, Lantican et al. 2005). However, individual elements of these impacts have been analyzed only to a lesser extent for their effect on food security and poverty in developing countries.

A major part of the plant breeder's arsenal in producing semidwarf modern wheat varieties (MVs) is breeding for disease resistance. Diseases play a significant role in decreasing yields worldwide and rust diseases have been a major scourge of wheat since biblical times (Kislev 1982). Since the early 1900s, when genetics of breeding for disease resistance began to be understood (Biffin 1905), breeders' efforts focused on disease resistance.

The average time rust resistance had been effective in a wheat variety was five to six years due to the type of resistance breeders used (Kilpatrick 1975). The rust soon evolved and overcame the resistance, causing a "boom and bust" cycle. These rust epidemics caused major imbalances in markets, creating uncertainty of production that affected supply and prices. In the first half of the 20th century these occurred in countries as diverse as India, Pakistan, Russia, Canada, the United States, Mexico, Chile, China, Egypt, and Australia.

In the United States in the early 1900s, an understanding of the genetics of the rust fungi began to emerge, especially at the University of Minnesota (Stakman and Piemeisel 1917). The United States Department of Agriculture (USDA) also was engaged in wheat breeding and one of their scientists produced wheat lines with resistance from European germplasm that had good stem rust resistance (Dyck and Kerber 1985). In the 1930s to 1940s progress was made with rust resistance in the United States and elsewhere. In 1944, N.E. Borlaug[1] began his work in Mexico to control stem rust. He used the resistance from the United States and participated in the formation of the USDA's International Rust Nursery,[2] initiated to develop better rust resistance. Although germplasm exchange was common in these years, this was the first systematic exchange of germplasm that helped catalyze the birth of the international nursery system and networking (Kolmer 2001).

The resistance used in the Mexican wheat varieties like Yaqui 48 and Yaqui 50 contained genes for stem rust and leaf rust resistance that had long lasting effects way beyond the border of Mexico. This was not understood until many years later and will be examined in more detail in this study.

The seeds of the "commons" were thus sown and free exchange of germplasm became a major factor in the success of the Green Revolution wheat with their unique characters including long lasting rust resistance genes (Byerlee and Dubin 2008).

This case study explores the success of the stem and leaf rust resistance program, previous to, and within the context of, the Green Revolution, including international agricultural programs and National Agricultural Research Systems (NARS). It examines the major factors that underpin its success and shows the impacts on economic returns, food security, and poverty in developing countries.

Importance of Wheat Worldwide

Globally, wheat is one of the most significant crops, with total production in 2005 of 607 million tonnes. Production was over 1.0 million tonnes in 48 separate countries (FAOSTAT 2009). Globally, wheat is consumed in 175 countries, with average consumption of 67 kg/per capita in 2003, which represents more than one-third of the minimum food requirements of most adults. Wheat is a significant crop in many of the poorer countries, both in production and consumption. In 2007, 76 developing countries produced wheat, and 52 consumed more than 50 kg per capita. Of the 23 developing countries with income levels

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[1] N.E. Borlaug, winner of the 1970 Nobel Peace Prize for his work on food production in the developing world.

[2] 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.

below US$1,000 per capita per year, 8 were significant wheat producers (more than 0.5 million tonnes) and 9 were significant wheat consumers (more than 50 kg per capita) (FAOSTAT 2009).

Countries in East Africa, North Africa, and the Middle East consume more than 150 percent of their own wheat production and are heavily dependent on wheat imports to meet their food needs (FAOSTAT 2009).

Wheat is a significant food source on a global basis. In 2003, wheat was consumed in 132 developing countries, and supplied a worldwide average of 518 calories per head per day, or approximately 18 percent of total calorie intake (FAOSTAT 2009). The 15g per head per day of protein supplied by wheat represents 20 percent of global intake of protein. For 43 developing countries with a population of 1.75 billion in 2003, wheat provided more than 20 percent of calorie intake, and similar proportions of the global protein intake (Table 1.1). Wheat was not a significant provider of dietary fat, as it provided only 3 percent of the global intake of fat in 2003.

Table 1.1 Importance of wheat consumption in developing country diets, 2003

	No. of developing countries	Population 2003 (millions)
		Wheat calories as % of total calorie intake
> 50%	6	83
40% – 50%	9	229
30% – 40%	9	309
20% – 30%	19	1,131
10% – 20%	41	1,860
< 10%	48	1,451
		Wheat protein as % of total protein intake
> 50%	8	161
40% – 50%	9	157
30% – 40%	5	247
20% – 30%	19	1,198
10% – 20%	48	2,127
< 10%	43	1,173

Source: Derived from FAOSTAT data (FAOSTAT 2009)

Diseases of Wheat

Importance of Diseases, Insects and Weeds to Crop Production

Diseases, insects, and weeds are a major constraint to crop production worldwide. It has been estimated over the years that they can destroy between 31 and 42 percent of all crops annually (Agrios 2005). Approximately 14 percent of these losses are due to diseases which amount to about US$220 billion (2002 dollars) annually (Agrios 2005).

Rust diseases are the most important diseases of cereals. They can cause up to 60 percent loss of yield for leaf or stripe (yellow) rust and 100 percent loss for stem rust (Park et al. 2007). A well documented example was the stem rust epidemic of 1953-54 in Canada, Mexico, and the United States, which caused a loss in production in the United States of about 166 million bushels (4.5 million tonnes) in the two years (USDA-ARS 2009). Today, however, the countries that lose the most are the ones who need the food the most, the emerging nations.

Description of Stem, Leaf, and Stripe Rusts

The rusts are a group of fungi that are among the most destructive plant pathogens in the world. As noted below, they are described in the earliest literature. They are notable, historically, for their severe attacks on cereal grain crops. The diverse species may attack many grass hosts, and it is estimated that cereal rusts reduce total grain yields by about 10 percent annually (Agrios 2005). Under epidemic conditions they have caused famines and even ruined economies. There are more than 5,000 rust species that attack many crops (Agrios 2005).

Three types of rusts infect wheat: stem (black) rust (*Puccinia graminis* Pers. f. sp. *tritici* Eriks. & E. Henn; leaf (brown) rust (*P. triticina* Eriks.); and stripe (yellow) rust *(P. striiformis* Westend f. sp. *tritici*). The life cycles of the different rusts can be quite complex. The most obvious structures seen to the naked eye are the uredinial and telial[3] stages. These are the bases for the common names. In the case of stem or black rust, the telial stage is quite obvious and it is black; leaf or brown rust has a brown uredinial stage; and stripe or yellow rust has a striped uredinial stage (Figure 1.1).

Figure 1.1 Leaf, stem, and stripe rust - uredinial stages

Leaf rust Stem rust Stripe rust

Source: Cereal Disease Laboratory, ARS, USDA

The infections may occur on any of the parts above ground but generally the cereal rusts attack the stem and leaves. The most obvious stage is the uredinial and appears as rusty spots or pustules that contain millions of urediniospores or infective propagules. These occur in the spring and summer in all three rusts and can continually re-infect the wheat crops and hence cause epidemics. Billions of windborne spores may be produced that can be carried thousands of kilometers (km) (Agrios 2005).

Rusts may debilitate or kill young wheat plants but more typically reduce foliage, root growth, and yield by decreasing photosynthesis, increasing respiration rate, and decreasing translocation of carbohydrates. They move the carbohydrates to the areas infected and use them for growth (Agrios 2005).

Rust pathogens have an excellent ability to vary via mutation. Some may also vary through sexual reproduction and thus overcome resistance genes. In the case of stem rust of wheat, the alternate host, barberry (*Berberis vulgaris*)[4], historically played an important role in sexual variability in the United States and other countries. However, the successful eradication of barberry has reduced the influence of the sexual cycle on the disease (Roelfs et al. 1992).

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[3] Uredinia produce the summer rust spores and telia produce the overwintering spores.

[4] An ornamental shrub originally from Europe.

2. HISTORY OF WHEAT RUSTS, EPIDEMICS, AND LOSSES

Pre-Biblical, Biblical and Roman Times

Kislev (1982) published the first note about the existence of stem rust in pre-biblical times in Israel. He found germinating urediniospores, uredinia, and hyphae on fragments of lemmas in a storage jar from the Late Bronze age (ca. 3300 BC). The specimens were charred but well preserved.

Zadoks (2008) indicates that the Bible has several curses that relate to crops "smitten by mildew." Mildew is an old English term for rust, principally stem rust. He cites Lehmann et al. (1937) that old Hebrew texts use terms that indicate blackening or scorching of wheat plants, indications typical of severe stem rust.

In Roman times various authors noted the importance of rust on production of the wheat and barley crops. The Romans considered rust to be a *numen* (a spirit or deity) to be feared. It needed to be appeased with processions, sacrifices and feasts lest their crops be destroyed. Field symptoms described, as well as recent crop and rust phenology, indicate that the main rust was stem rust, though leaf or stripe rust could not be discounted (Zadoks 2008). The grain rusts have co-evolved with their hosts for millennia and continue to do so as we shall see.

Epidemics on Traditional Tall Wheat

Indian Sub-Continent

Rust has been recorded on wheat in India for centuries (Nagarajan and Joshi 1975), with documented evidence from 1786, 1805, 1828-29, 1831-32, 1879, 1887 and 1907. Nagarajan and Joshi (1975) identified 17 notable appearances or epidemics of wheat rusts in India between 1786 and 1956. Howard and Howard (1909) estimated that losses from wheat rusts in parts of India on occasions reached 50 percent or more, and argued that the losses from wheat rusts in India each year exceeded the losses from all other pests combined. In 1946-47, a stem rust epidemic in central India caused losses estimated at nearly 2 million tonnes, or 20 percent of total wheat production (Joshi et al. 1986). However, Nagarajan and Joshi (1975) noted that in India the rust epidemics did not appear to create famines on their own but rather aggravated famines that occurred prior to or after a poor monsoon.

Europe

In 1891 in Prussia, the losses for all cereal crops from rust diseases were estimated to be almost one-third of the total value of the crops (Howard and Howard 1909). In 1932, a severe epidemic of stem rust devastated wheat crops in many East European countries. The epidemic began in Bulgaria, but spread throughout eastern and northern Europe (Zadoks 2008). Its impacts were most severe in Russia. Zadoks (2008) reviewed the evidence on the relationship between this rust epidemic and the Russian famine of 1932-33 in which millions died. Zadoks concluded that the epidemic did not cause the famine, but rather that delays in crop development increased the vulnerability of wheat crops to rust blown in from countries to the southwest.

Stakman and Harrar (1957) quote sources that estimated the losses from a stem rust epidemic in Sweden in 1951 as a 20 percent reduction in winter wheat and a 50 percent reduction in spring wheat.

North America

Stakman and Harrar (1957) reported that a stem rust epidemic in 1916 destroyed approximately 1.6 million tonnes of wheat in the US and Canada. "The epidemic was ruinous, not only to the crop, but also to thousands of farmers who were forced off their farms by despair or bankruptcy."

In 1935, stem rust destroyed approximately 3.7 million tonnes of wheat in the US, or more than 50 percent of the expected production, mostly in the spring wheat area of the Dakotas and Minnesota.

Stakman and Harrar (1957) quote detailed figures on the impact of this epidemic. Farmers lost from 0.06 to 0.54 t/ha of their planted crop area, and then received lower prices for their harvested grain because of low bushel-weights. Further, the loss in purchasing power of farmers affected business in the entire spring-wheat region and far beyond. Another stem rust epidemic followed in 1937, which compounded the regional impacts of the 1935 epidemic.

In 1950, the stem rust race 15B became generally prevalent for the first time in North America. Soon thereafter, stem rust became widespread in spring wheat (both bread and durum wheats). Cornell University (2008) noted that the rust spores produced in fields in Kansas in 1953 were deposited 1,000 km north—in North Dakota and Minnesota—across 100,000 square km of wheat at a rate of more than 8 million spores per hectare. Stakman and Harrar (1957) provide data on the percentage yield losses from stem rust in Minnesota and the Dakotas in 1953 and 1954 (Table 2.1), showing losses up to 35 percent for spring bread wheat and 80 percent for durum. The total US losses in 1953 and 1954 were estimated at 2.5 and 2.1 million tonnes, respectively (USDA-ARS 2009), which would be valued at almost US$700 million in 2006 prices.[5] At that time, when prices were much higher, the losses were equivalent to approximately US$2.6 billion. Stakman and Harrar (1957) note that the almost total destruction of the durum crop in two successive years demonstrated that the rust could become pandemic in years when seasonal conditions favored rust development in the face of ineffective resistance.

Table 2.1 Percentage losses from stem rust, United States, 1953-1954

State	Spring bread wheat		Durum wheat	
	1953	1954	1953	1954
Minnesota	10	15	75	80
North Dakota	35	35	65	80
South Dakota	30	20	80	75

Source: Derived from Stakman and Harrar (1957)

Rupert (1951) reported that the devastating stem rust epidemic in 1947-48 caused approximately 30 percent of the crop to be lost in the Bajio region, at that time the main production region of Mexico. Extensive plantings of wheat in northern Mexico were also destroyed by stem rust in the 1948-49 and 1949-50 seasons. Of the seven common Mexican spring wheat varieties in 1951 listed by Rupert (1951), only one was not susceptible to stem rust, and one other was not susceptible to leaf rust.

Latin America

In 1951 about 40 percent of the wheat crop in Chile, mainly durum, was destroyed by a stem rust epidemic. Stakman and Harrar (1957) quote sources that say that once resistance in the main durum variety broke down, durum was no longer grown in Chile because of the subsequent low yields.

Australia

Several studies have reported losses from wheat stem rust in Australia (Park 2007). The most significant epidemics in the period up to the 1950s occurred in 1889, 1899, and 1947. Each of these epidemics was assessed as having a significant impact on wheat production and the welfare of wheat farmers. Stakman and Harrar (1957) noted that in 1947-48, a stem rust epidemic in New South Wales, Australia, caused losses estimated at 270,000 tonnes, or approximately 12 percent of state production that season.

In 1973 (before any adoption of semidwarf wheats in Australia), a stem rust epidemic in southeastern Australia was rated as the most severe in the history of the Australian wheat industry (Park 2007). Northern areas, considered more prone to stem rust, were not severely affected because they were

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[5] FAO producer prices in US dollars (FAOSTAT 2009) were weighted by production to provide a weighted average producer price. In 2006, the most recent prices available from FAOSTAT, that weighted average price was US$148 per tonne.

protected by a concerted effort to grow resistant varieties in those areas. The losses in southeastern Australia were estimated at US$200 to 300 million, or 25 to 35 percent of the value of production in that part of Australia. One outcome of that epidemic was the formation of the National Wheat Rust Control Program to screen breeding lines and introduce resistance genes into leading varieties and elite lines (McIntosh 2007). Another outcome was the rapid adoption of rust-resistant semidwarf varieties that were first released in 1973. Significantly, there have been no subsequent severe epidemics of stem rust in Australia.

Epidemics on Modern Semidwarf Wheats

While the frequency and severity of rust epidemics have been reduced with the widespread use of modern wheat varieties, Saari and Prescott (1985) list 33 rust epidemics that occurred in Africa and Asia between 1970 and 1985 (Table 2.2). However, these were generally less severe than previously, and tended to be localized. This section reviews a number of the key epidemics on modern wheat.

Table 2.2 Number of wheat rust epidemics in Africa and Asia, 1970 to 1985

Region	Stem rust	Leaf rust	Stripe rust	Total
Sub-Saharan Africa	5	1	6	12
Middle East - North Africa	2	3	8	13
Asia	0	4	4	8
- Total	7	8	18	33

Source: Derived from Saari and Prescott (1985)

Pakistan Rust Epidemics 1977-78

Bhatti and Ilyas (1986) estimate that in most years, rust diseases on average caused losses of about 2 percent, but in certain years under favorable conditions of rust development could be 10 to 20 percent. Of the rust diseases, they note that leaf rust was the most important at that time. It causes heavy losses to the crop when moderate temperatures and high humidity prevail for long periods. However, it should be noted that in recent years stripe rust appears to be the most important. In 1972, leaf rust started late in the season but expanded rapidly. In 1973, leaf rust was widespread, with 100 percent infection on susceptible varieties (Bhatti and Ilyas 1986). Though two varieties (Lyallpur 73 and Blue Silver) were resistant, Pakistan authorities were reluctant to push for a change of cultivars. Leaf rust epidemics in 1976 and 1978 had 50 to 80 percent severity on most commercial cultivars, and 30 percent losses were recorded in the Pakistan Punjab (Bhatti and Ilyas 1986) and large losses in Sind.

In 1977 and 1978, a stripe rust epidemic affected the northern regions of Pakistan, particularly northern Punjab and North West Frontier Province. Losses in between 1977 and 1978 from leaf and stripe rust were estimated to be 10.1 percent, or 830,000 tonnes of lost production (Bhatti and Ilyas 1986); in 1978, production was reduced by more than 1 million tonnes (CIMMYT 1978).

Once Pakistani authorities realized the need to change varieties, they imported some 10,000 tonnes of seed of the resistant variety Pavon 76 from Mexico, and a further 5,200 tonnes of seed of resistant varieties from India, as they did not have any seed of resistant varieties available locally (CIMMYT 1978). That seed of Pavon 76 was the basis for good leaf rust resistance for more than 20 years before being replaced by newer resistant varieties with better yields.

The rust epidemic of 1977–78 became the catalyst for the establishment of the Pakistan Agricultural Research Council, which coordinates national research efforts for the major crops (CIMMYT 1989). One of its first steps was to establish a national wheat pathology research system.

Genetic research showed the narrow base of leaf rust resistance in most cultivars in Pakistan (Bhatti and Ilyas 1986), and efforts were made to combine effective genes for seedling and adult plant resistance for future varieties. Bhatti and Ilyas (1986) noted that by the mid-1980s, losses due to stem rust had become negligible because of this resistance and the early maturity of the new varieties. However, in upland Baluchistan, Punjab and North West Frontier Province, old varieties were still grown, resulting in heavy losses due to stem rust.

India

Nagarajan and Joshi (1975) identified six notable appearances or epidemics of wheat rusts in different parts of India between 1970 and 1973. Byerlee (1996) observed that epidemics in India after the Green Revolution began were generally localized rather than widespread. Epidemics of stem and stripe rust caused losses in Punjab, Haryana and western Uttar Pradesh of 0.8 and 1.5 million tonnes in 1971-72 and 1972-73, respectively (Joshi et al. 1986). In 1978-79, stem rust affected the large Narmada Valley in Madhya Pradesh, India, and local varieties Pissi and Malvi Local were heavily attacked (Joshi et al. 1986). It was estimated that yield losses were 60 to 75 percent in some cases, although the epidemic was restricted to the unimproved local varieties (Joshi et al. 1986). The "Sonalika epidemic" of leaf rust that affected all of Uttar Pradesh and part of Bihar in 1980 caused losses of 1 million tonnes. Joshi et al. (1986) reported trials where losses in non-epidemic years in Punjab, North Haryana and western Uttar Pradesh were 7 to15 percent; in the Central Indo-Gangetic plains, the estimated losses were 12 to 17 percent, while in South India losses were much higher.

Joshi et al. (1986) noted that several estimates were made over time on the value of the losses from rusts in India. If the 2006 price of US$148 per tonne were applied to the estimated crop losses, the losses would have been valued at between US$118 and US$222 million (Table 2.3).

Table 2.3 Value of losses from Indian rust epidemics

Years	**Rust**	Losses (million tonnes)	Value of losses (US$ million, 2006 prices)[a]
1945-47	Stem rust	2.0	296
1971-72	Stem & stripe rust	0.8	118
1972-73	Stem & stripe rust	1.5	222
1980	Leaf rust	1.0	148

[a] Using a 2006 price of US$148 per tonne

Source: Derived from Joshi et al. (1986)

Mexico Leaf Rust Epidemic 1976-77

In 1976-77, a leaf rust epidemic developed in northwestern Mexico where more than 70 percent of the country's wheat crop was produced (Hanson et al. 1982). Seasonal conditions favoring disease development coincided with drought, land tenure problems and difficulties with seed production that reduced the seed supply of resistant replacement varieties. "The stage was set for a wheat leaf rust epidemic of catastrophic proportions" (Dubin and Torres 1981, 45). Mexican authorities took two measures of control (Hanson et al. 1982). On the advisement of Mexican authorities farmers with infected crops that had not yet headed ploughed in 15,000 ha of wheat and replaced them with safflower. The remaining crops in the region were treated with an aerial application of fungicides through a government-sponsored program. Dubin and Torres (1981) describe the detailed activities that resulted in 115,200 ha of wheat crops being sprayed with imported systemic fungicides within a 3-week period. While the fungicides did not eradicate the disease, they reduced the losses, to the extent that the yields in 1977 were only reduced by 15 percent from 1976 levels in the Yaqui-Mayo Valleys, compared to more than 40 percent reductions in the nearby Carrizo Valley where no spraying was undertaken. Dubin and Torres (1981) estimate that the spray program prevented yield losses of at least 1.0 t/ha on sprayed fields, and added over 100,000 t of extra wheat production in Sonora in that year. The epidemic reinforced the need for farmers to maintain resistance in the fields and showed the value of the resistance that has been successfully maintained in bread wheat from that time onwards to prevent a similar epidemic developing. Efforts in durum wheat have not been as successful so far.

Ethiopia Stem Rust Epidemic 1993-94

A new race of stem rust with virulence was detected for the then widely planted variety Enkoy, grown on 70 percent of the mid-altitude and 90 percent of the highland wheat fields in Bale and Arsi (the "breadbasket of Ethiopia") in 1992-93 (Kebede et al. 1996), and a severe stem rust epidemic developed in those regions in 1993-94. The epidemic, which developed in December 1993 and spread rapidly throughout the regions where Enkoy was grown, reduced Enkoy yields by 65 to100 percent (Shank 1994). In the highland wheat areas, yields were reduced by an estimated 42 percent by the epidemic. Total susceptibility and 100 percent yield loss due to stem rust was noted in a fungicide experiment conducted on Enkoy at Kulumsa Agricultural Research Center, in the following year (Badebo and Kebede 1996).

Coupled with reduced rainfall in the lowland areas, these reductions contributed to severe food shortages in Ethiopia in 1994, and more than 300,000 people were reported in need of food aid assistance (Shank 1994). In 1994, the malnutrition rate at the Raitu clinic in southern Ethiopia was estimated at 5 percent, with severe malnutrition at 2 percent. Strenuous efforts were made to find resistant replacements for Enkoy, although the limited seed available initially meant that it could not be totally replaced immediately.

Leaf Rust in Southern Cone Since 1996

The use of susceptible wheat varieties in the Southern Cone of South America (Argentina, Bolivia, Brazil, Chile, Paraguay and Uruguay) has allowed leaf rust to develop in the past decade (German et al. 2004). Leaf rust epidemics in Argentina between1999 and 2003 resulted in estimated costs of US$74 million when three popular varieties became susceptible to leaf rust, and evolution in the rust population over the ten years to 2004 have resulted in an estimated loss of US$172 million across the Southern Cone (German et al. 2004).

Summary of Losses Caused by Rust Diseases

Stakman and Harrar (1957) note that leaf and stripe rust generally do not cause the same level of yield damage as stem rust. However, both typically can become as epidemic as stem rust, and each may cause greater annual damage then stem rust in certain areas. Traditionally, stripe rust is likely to be most destructive in cool, moist seasons; stem and leaf rusts are likely to be most destructive in warm, moist seasons. However, this appears to be changing. In recent years new, higher temperature tolerant, aggressive strains of stripe rust are moving into non-traditional, warmer areas (Hovmøller et al. 2008; Milus et al. 2009).

Hanson et al. (1982) provided a summary of the impacts of rust diseases in developing countries and identified the hot spots for each of the rusts. Table 2.4 indicates that stem and stripe rusts are more destructive in an epidemic, but that leaf rust is more significant endemically

Table 2.4 Summary of losses caused by rust diseases in developing countries

Rust	Yield loss (%) in susceptible varieties		Endemic areas as proportion of total wheat areas (%)	Hot spots – areas where disease is most severe
	Average in endemic area	In epidemic		
Stem rust	40%	Up to 100%	50%	Highlands of Kenya and Ethiopia; Parana State, Brazil; South India
Leaf rust	15%-20%	Up to 50%	90%	Mexico, India, Pakistan, Bangladesh, China
Stripe rust	40%	Up to 100%	33%	Highlands of South America and East Africa; North Africa; Middle East; Indo-Gangetic Plains of India and Pakistan

Source: Hanson et al. (1982)

3. HISTORICAL EVOLUTION OF INTERNATIONAL COLLABORATION

A discussion of the long-term international control of stem and leaf rust through durable resistance cannot be made in isolation. It has to be studied in the context of the pre-International Maize and Wheat Improvement Center (CIMMYT[6]) and CIMMYT programs as part of international cooperation. Incorporation of rust resistance was, and continues to be, a key aspect of the international wheat breeding programs, though insufficient support has been given to disease resistance more recently. Breeding for disease resistance is an integral part of most breeding programs and may constitute 30 to 50 percent of the breeding effort. Hence, to present the primary factors that influenced the success of durable stem and leaf rust resistance work, we must observe and understand the key factors to the success of the whole breeding program and to rust resistance efforts.

The Need for International Nurseries

The international germplasm nursery system was born out of the stem rust race 15B epidemic that began in North America in the early 1950s. This rust race was seen for some years before but only in very low amounts while stem rust was quiescent in North America during the 1940s (Stakman and Harrar 1957). However, 15B increased in the United States in the summer of 1950 in the spring wheat areas and then it was seen in Mexico (1950-51). It culminated in the severe epidemics of 1953-54 in all North America (Borlaug 2007).

The USDA and similar agencies in Mexico (Mexico/Rockefeller Foundation program),[7] Canada, and Latin America became very concerned. Although wheat breeding lines had been informally exchanged for some years by many countries, the apprehension was so great that USDA and cooperators held a stem rust conference in St. Paul, Minnesota in November 1950. At that meeting agreement was reached to formalize the screening of wheat germplasm and thus was born the International Spring Wheat Rust Nursery (ISWRN) Program.[8] Initially seven countries participated in the program (Argentina, Chile, Canada, Colombia, Ecuador, Mexico, and the United States). More than 1000 wheat lines were tested annually for rust resistance in each location (Plucknett et al. 1990, Kolmer 2001). This nursery and associated breeding programs were successful in bringing the stem rust under control by the mid-1950s. All germplasm and information was freely shared and made available to the cooperators and others who were interested. The ISWRN was the flagship of rust screening nurseries worldwide until its demise in 1987 due to lack of funding (Kolmer 2001).

In the 1950s, the Mexican-Rockefeller wheat program established a new effort under the leadership of N. E. Borlaug, applying the principles of cooperation in Latin America. This culminated in the Inter-American Nursery Trials initiated in 1960 and the Near East and North Africa Spring Wheat Yield Nursery initiated in 1962. The two nurseries merged in 1964 into the International Spring Wheat Yield Nursery (ISWYN), arguably the first real international wheat nursery. The objectives had evolved to include evaluation for yield, additional diseases, and for exchange of materials among breeding programs worldwide. This truly began the opening of the commons, a free germplasm exchange system and worldwide collaboration. As will be seen later, these international nurseries and the concomitant training helped to standardize data collection and produce reliable information that could be analyzed over time and space (Byerlee and Dubin 2008).

One of the collateral benefits of the nursery program was the expansion of the genetic base of the Mexican program through new germplasm. By the late 1950s, the nurseries grown in Mexico included

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[6] The International Maize and Wheat Improvement Center, known by its Spanish acronym (CIMMYT), is an internationally funded, not-for-profit organization that conducts research and training related to maize and wheat throughout the developing world (www.cimmyt.org).

[7] An international agricultural development program founded in 1943 to help Mexico increase food production.

[8] The international rust nursery program later had spring wheat and winter wheat screening nurseries but we focus primarily on the spring bread wheat here as well as throughout this paper. Spring bread wheat is the major wheat type grown in the developing world.

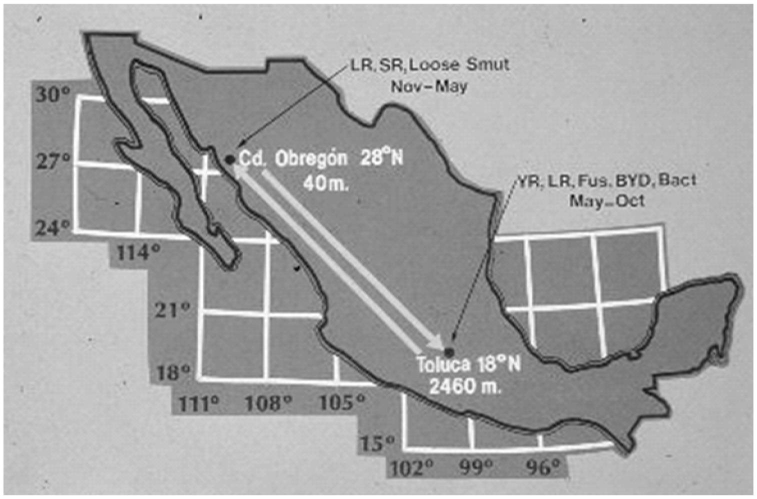
about 50,000 entries. In the meantime American and Canadian wheat research programs asked to plant off-season nurseries in Mexico. This reduced breeding time for them and added to the germplasm exchanges and networking among programs. In the 1960s and 1970s, scientists in other countries asked to plant off-season nurseries in Mexico. In this way, Mexico became an informal center of international germplasm exchange and information in spring wheat (Byerlee and Dubin 2008).

Shuttle Breeding and Semidwarf Genes

In the 1940s in Mexico, the Borlaug breeding program was focusing on increasing production and stem rust resistance with the tall wheat varieties. This was achieved with Supremo and Frontera wheat until the emergence of race 15B (Bickel 1974). Fortuitously, Borlaug had bred resistance to 15B into Kentana 48 with crosses from Kenya wheat and later with Chapingo 52, Chapingo 53, Bajio 53, and others (Kolmer 2001). But how did he achieve this in just a few short years? We have to go back to the mid-1940s when Borlaug realized that Mexico could not be self-sufficient in wheat by depending solely on the traditional highland areas. He heard of new areas in the north of Mexico that had started irrigation like the Yaqui Valley in Sonora state and hoped to produce wheat there (Borlaug 2007). He also saw the opportunity to cut the time in half (from between ten and twelve years to between five and six) to release a rust resistant variety by moving his breeding populations from the Mexico City area to the Yaqui Valley. However, the prevailing dogma of plant breeding said this could not be done, and he was criticized for doing it. He persisted, with the support of E. C. Stakman, his old professor from the University of Minnesota; thus started his program known today as "shuttle breeding." At that time, he did not realize the importance this methodology would have on the lives of millions of people.

How was it done? Borlaug would plant his nurseries in May in the Mexico City area (Chapingo/Toluca) in the highlands and harvest in October, and then plant in the Yaqui Valley in November and harvest in April (Figure 3.1). The summer elevations were 2,200 to 2,600 meters above sea level in a cool wet climate and the winter elevation at sea level in a desert climate. The distance was 1,600 km and 10º latitude apart. He obtained his rust resistant wheat and, as well, bred out the day-length sensitivity, allowing the varieties to be planted over wide latitudes. Furthermore, he bred resistance to the prevalent diseases—including stem rust, leaf rust, stripe rust, and a series of other pathogens—in both areas by selecting only highly resistant materials. In four years, he had promising varieties selected.

Figure 3.1 Shuttle breeding in Mexico



a LR=leaf rust; SR=stem rust; YR=stripe rust; Fus=Fusarium; BYD=Barley yellow dwarf; Bact=bacteria

Source: CIMMYT

Once the new varieties like Yaqui 50 and others that were resistant to stem and leaf rust were released, he continued to look for better yields. He found the tall wheat varieties fell down (lodged) under good fertility and irrigated conditions. Borlaug had heard about dwarf wheat being developed at Washington State University by Orville Vogel (USDA) using Japanese materials. He thought it a good approach for the excellent irrigated growing conditions in northern Mexico. Vogel started work on this in 1949 and had already produced some breeding material called Norin 10-Brevor that he sent to Borlaug in 1953, Borlaug notes: "Our first attempts to incorporate the Norin10-Brevor dwarfness were unsuccessful. A second attempt in 1955 was successful and immediately it became evident that a new type of wheat was forthcoming with higher yield potential" (Dalrymple 1986).

In 1960 the last tall wheat, Nainari 60, was released by the Mexican wheat program. Soon after, new high yielding semidwarf wheat (modern varieties) were released, including Pitic 62, Penjamo 62, Sonora 64, Lerma Rojo 64, Siete Cerros 66, Inia 66 and others. Several of these were the wheat varieties sent to India and Pakistan that initiated the Green Revolution (Bickel 1974).

Formalization of the International Research System

By 1964, Borlaug's program had instituted the ISWYN nursery which was being sent to collaborators in developing and other countries. In the early 1960s, the training programs and germplasm exchange became more formalized. The Mexican/Rockefeller program was superseded by the Inter-American Food Crop Improvement Program in 1960 and expanded to include maize, wheat, and potatoes.

At the same time, the Ford Foundation and the Rockefeller Foundation helped create the International Rice Research Institute (IRRI) in the Philippines. It was founded as an autonomous international institute and modeled after the Mexican/Rockefeller wheat program, but it was more formal and permanent. Fortuitously, President Adolfo Lopez Mateos of Mexico was on a world tour in 1963 and was impressed by what he saw in Philippines and by the need, worldwide, for these types of institutions. Many countries noted the success of wheat in Mexico and Lopez Mateos told the Rockefeller Foundation that Mexico would support a wheat and maize institute similar to IRRI. The Rockefeller Foundation was interested and an agreement was signed in 1963. Other donors such as USAID, Ford Foundation, and Inter-American Bank signed on as well. By 1966 the facilities for CIMMYT were finished.

A catalyst to the formation of these institutions was the dire situation of food production in developing countries, especially in South Asia where rice and wheat were the main food staples. Famine in these areas was widely predicted. Many economists and biologists were supporting Malthus, and India was considered beyond hope (Paddock and Paddock 1967). It was envisaged that the new centers would help increase rice, wheat, and maize production in these regions.

Based on the early success of IRRI and CIMMYT, there was a desire to continue the model with other crops and technologies. New centers were founded in 1967 and following years. As the number of centers and donors increased, more coordination was needed. The World Bank, in conjunction with key donors like USAID, catalyzed the formation of a loose group of 17 member countries, international organizations, and foundations that coordinated support to the centers. This became known as the Consultative Group on International Agricultural Research (CGIAR), which has grown to 15 centers and 64 members as of 2007.

Organization of the International Wheat Research System

Borlaug had freely exchanged wheat germplasm and information, and trained young scientists informally during the 1940s and 1950s. In the 1960s, as systems were established, there were more formal exchanges in germplasm, information sharing and human resource development. There was an evolution of the system over time based on experimentation, learning, changing problems, and funding.

Germplasm Development, Breeding and Crop Management

We cannot tell the rust resistance story without some further background on germplasm, breeding techniques, and wheat management. For a more detailed picture see Rajaram and Van Ginkel (2001), Singh et al. (2007) and Reynolds and Godinez (2006).

The source of germplasm used by the original Mexico/Rockefeller program and later CIMMYT came from many nations around the world. Free sharing of germplasm was the rule. In this way diversity was maximized. Rasmusson (1996) estimated that nearly half of the progress made by breeders was due to exchange of germplasm. Regrettably, free sharing of germplasm today has decreased due to intellectual property rights issues (Byerlee and Dubin 2008).

As discussed, crosses are made using the shuttle breeding technique in Mexico. Based on the shuttle breeding program, it takes only five to six years from the initial crossing to the international distribution of advanced spring wheat lines to national programs. Over the years the CIMMYT wheat program might make up to 8,000 crosses per year focusing on the diverse mega-environments and their needs. Rajaram and Van Ginkel (2001) note that, since 1945, more than 200,000 crosses have been made in the program and that greater than 4,000 advanced spring wheat lines are tested annually at sites worldwide. This large-scale crossing program of genetically diverse germplasm and the multi-location testing have yielded widely adapted germplasm.

Crosses are made based upon the international testing program's results from around the world. In this way the process may break undesirable linkages and pyramid desired genes for important characters. The recycling of the best genotypes based on the international data is like a large "recurrent selection program." In this way even tolerance or resistance to unknown stresses are incorporated. As genetic information is obtained through molecular genetics and other technology, more precise crosses are being made. Furthermore, changes in breeding methodology also decreased the number of crosses. Thus the efficiency of the breeding program has been significantly increased.

Disease screening focuses on disease "hot spots," for example, Kenya for stem rust and Ecuador for stripe rust. These are areas of high variability for virulence genes of the rusts. The lines that have the lowest levels of rust infection (low average coefficient of infection) at these and all other sites are selected as the most likely to have more durable resistance This is corroborated with genetic studies wherever possible (Rajaram et al. 1988). In addition, breeding nurseries are heavily inoculated with selected races of rusts in Mexico and only the most resistant are used for crossing.

The main traits selected for in the spring wheat program are high and stable yields, resistance to diseases and insects, tolerance to stresses such as heat and drought, and grain quality. Input efficiency has been selected successfully for some years with respect to phosphorus, nitrogen and water. Some new nutritional characteristics being studied are zinc and iron, both commonly deficient in the diets of developing country populations.

Crop management in the early Borlaug program and later at CIMMYT was, and still is, critically important. The best germplasm is useless if the appropriate technology is not used. The Green Revolution in the 1960s would not have been successful without the proper land preparation, weed control, and fertilizer and water application. Borlaug and his team had to work closely with the Indian and Pakistani programs to get these in place (Bickel 1974). From the beginning, training in agronomy went hand in hand with breeding and pathology (Bickel 1974). Significant research in crop management continues to be carried out at CIMMYT today (Reynolds and Godinez 2006).

The CIMMYT program emphasized teamwork in its research. It was important that the breeders and pathologists worked together closely and each understood the others' jobs. In fact many of the breeders had been trained as pathologists, including Borlaug. As well, crop management was an integral part of the program. Teamwork was emphasized in the training programs to ensure that the whole technical package could be brought to the farmer.

One key issue relating to effective resistance in farmers' fields is the infrastructure to enhance seed increase and seed distribution networks. This is crucial where varieties need to be replaced to maintain resistance. Those systems involved extension agents and seed distributors working with scientists from International Agricultural Research Centers (IARCs) and NARS to ensure that good quality seed was available to farmers in a timely manner. Agricultural extension and seed production have often been bottlenecks in replacing old varieties and increasing yield. This was the case in the 1960s and still is in many parts of the developing world.

One example was the failure to replace susceptible varieties in Pakistan in 1977-78, but there have also been many examples of success. Through the period of the Green Revolution, NARS developed efficient systems of seed increase and distribution in many developing countries, facilitating the progress in rust resistance in that period.

The International Nurseries Network

In 1970, the CIMMYT annual report stated the role of international nurseries was to give collaborators:

- 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, and
- a means of evaluating promising breeding materials on a worldwide basis and fostering international cooperation.

Although the basic objectives have remained essentially the same, much more is now included as we shall see. Payne (2004 p.1) states that the International Wheat Improvement Network (IWIN), as it is now called, 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, via 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.”

The range of nurseries has grown and become more sophisticated over the years to serve the needs of the national programs according to their degree of development. These trials range from segregating materials to advanced materials and special nurseries for biotic or abiotic stresses like rust or heat tolerance (Table 3.1).

Table 3.1 Evolution of pre-CIMMYT and CIMMYT nurseries

Decade	Main focus	Main nurseries added
1950s (USDA)	Rusts	International Spring Wheat Rust Nursery for North and South America.
1960s Pre-CIMMYT & 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; International Durum Yield Trial; International Bread Wheat Screening Nursery; International Triticale Yield Trial; International 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 Temperature 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.

Source: Byerlee and Dubin (2008)

As more biotic and climatic data became available via the international information system, some of the nurseries also became more targeted. Thus the ISWYN, the first worldwide yield trial, ceased in 1994. By 1992 the available data allowed CIMMYT to develop the concept of mega-environments , or zones, with similar production constraints and climatic conditions. There are now 12 mega-environments (Trethowan et al. 2005). On this basis the germplasm could be better targeted and thus reduce genotype-by-environment interactions.[9] However, the germplasm still has a high degree of broad adaptation for diverse targeted environments (Trethowan and Crossa 2006).

From 1994 to 2000, CIMMYT shipped 1.2 million samples of wheat seed to more than 100 countries. This is equivalent to 11 tons of wheat, barley and triticale[10] seed shipped annually (Fowler et al. 2001). Figure 3.2 illustrates how the seed is managed over a four-year process from seed multiplication to the return of data from collaborators. IWIS, the International Wheat Information System that CIMMYT uses for analysis and data storage, is freely available to all collaborators (Payne et al. 2002). Before seed is shipped it is washed and treated with fungicide by CIMMYT's Seed Health Unit, ensuring that the seed is free of seed-borne diseases.

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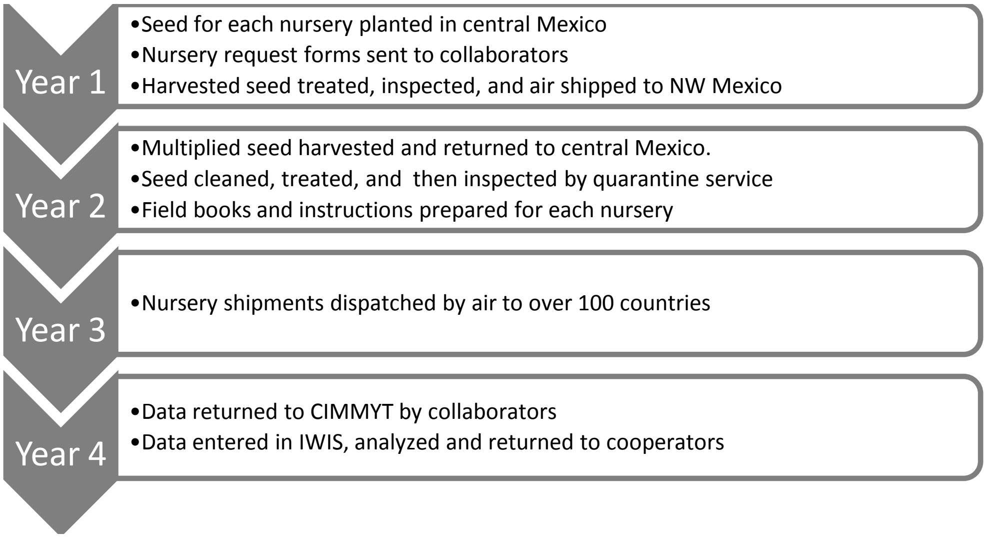
[9] The influence of specific combinations of genetic and environmental factors on a trait that goes beyond the additive action of these factors. This can refer to genes that control sensitivity to the environment or environmental factors that influence gene expression.

[10] Triticale (× Triticosecale) is a hybrid of wheat (Triticum) and rye (Secale).

Figure 3.2 The four-year cycle of the international nurseries



Source: Byerlee and Dubin 2008

Seed produced and shared by CIMMYT has always been considered international public goods. It was a common objective with all to help increase food production in the emerging nations. Because CIMMYT does not name varieties any nation could release the same germplasm under different names and they did. It was important that cooperators had a sense of ownership and CIMMYT was seen as an honest broker regarding the sharing of germplasm and information.

The total number of diverse sets of nurseries shipped to developing countries, from 1973-2006, (Figure 3.3) reached more than 2,000 per year in the late 1980s. This was due to a large increase in young scientists being trained and more countries joining the system.[11] Due to funding shortfalls after 1988 the number of nurseries sent decreased. The discovery of Karnal bunt, a seed-borne disease, in the Yaqui Valley stopped seed shipments from Mexico in 1993. The number of countries receiving nurseries peaked at 116 in 1979. The regional distribution has changed as well. The more developed countries received fewer materials and the more tropical countries of Sub-Saharan Africa that do not traditionally grow wheat did also. It was realized that few countries in these areas had a comparative advantage in wheat production. When the Soviet Union broke up, countries in Central Asia began to receive materials.

For many years CIMMYT and the International Center for Agricultural Research in Dry Areas (ICARDA), its sister center located in Aleppo, Syria, have had cooperative wheat improvement programs, especially for germplasm adapted to the ICARDA region. This cooperation was formalized in 2005, when the ICARDA-CIMMYT Wheat Improvement Program for Central and West Asia and North Africa (CWANA) was established. A range of nurseries is distributed regionally. Breeding for rust resistance is a priority and special emphasis is being given to stripe rust in recent years due to the advent of new, aggressive races in several areas of the developing world (Hovmøller et al. 2008).

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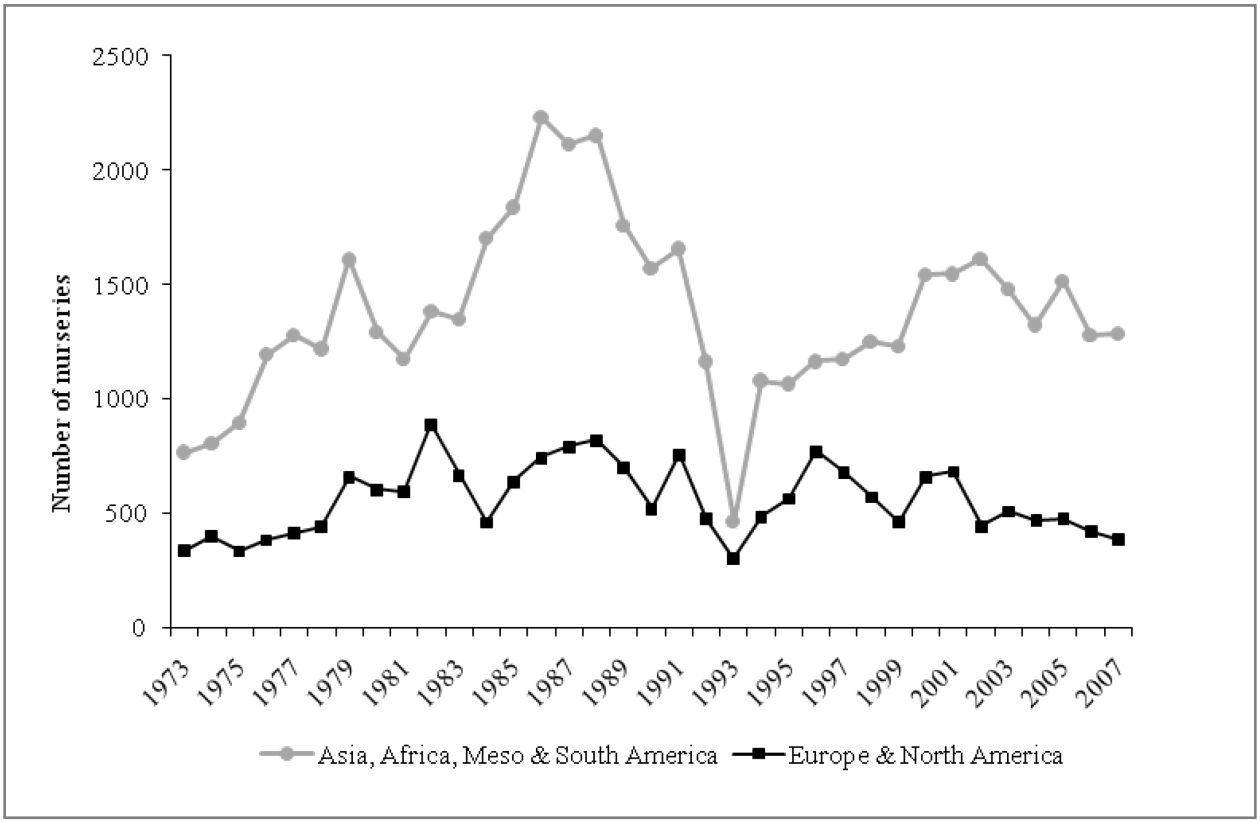
[11] In particular, a program to develop wheat for the more tropical environments brought in a number of non-traditional wheat producing countries.

Figure 3.3 Annual number of CIMMYT wheat nurseries shipped



Source: Byerlee and Dubin (2008)

Information Collection and Sharing

Data on yield, physiological and morphological characters, such as height, days to flowering and maturity, resistance to up to 15 specific diseases and insects, grain quality and associated climatic information are collected at each testing or nursery site. They are annually collated, analyzed, and distributed to collaborators and the public via periodic reports. In general about half of the recipients sent usable data in the early years. By the 1980s, the quality of data improved. The functionality of the system was predicated on getting reliable data and this could only be done by dedicated, well-trained scientists with a sense of responsibility and *esprit de corps*. Regrettably, in recent years the data quality has decreased due to a reduction in support for training and concomitant loss of well-trained scientists (T. Payne 2009, *pers. comm.*).

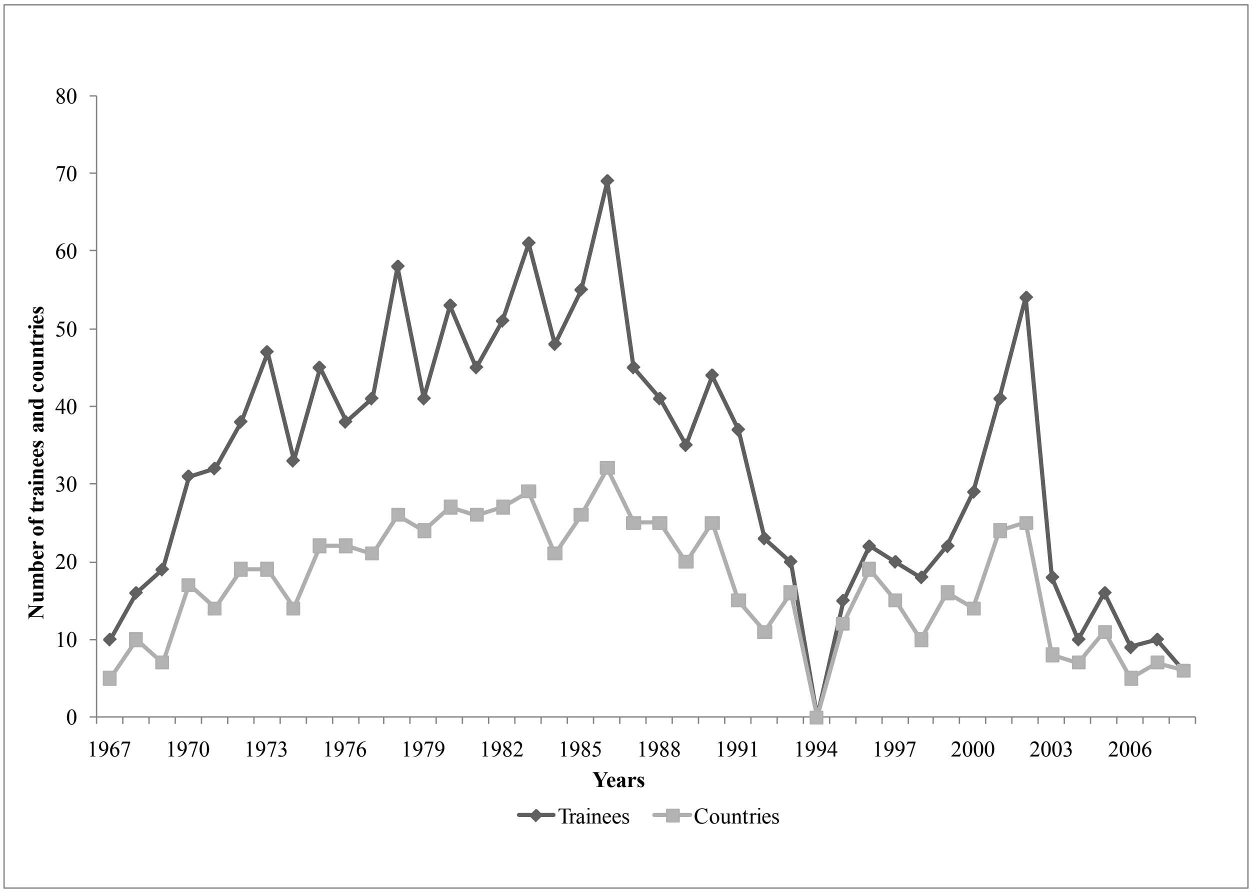
The IWIS, noted above, was designed to computerize the nursery information into user friendly databases. It has two major sections: Wheat Pedigree Management System, which assigns and maintains unique identifiers and genealogies, and the Wheat Data Management System, which manages the results from field and laboratory trials and data on known genes (Payne 2004).

Human Resource Development

At CIMMYT, human resource development was understood to be of equal importance to germplasm development. Without the trained scientists willing to work long hours in the field, Borlaug knew there would not be the favorable yield and resistance outcomes he knew were possible with the modern wheat (Bickel 1974). This set the stage for training at CIMMYT. The basic training courses at CIMMYT, for many years, were in breeding, pathology, agronomy, and grain quality. Later on there was a course in experiment station management. These were practical, hands on, field training courses with ample theory as well. They were for BSc-level scientists. The six-month training course produced the cadre of young scientists who continue to produce the wheat varieties and quality data that are shared by all today. This shared commitment to the common goal of increasing food production and to working in the field, very often under difficult conditions, was paramount in establishing the *esprit de corps*. This spirit inspired the scientists to share germplasm and information with their colleagues worldwide, irrespective of nationalities, politics, or other issues. Over time, more specialized and short courses were introduced, depending on demand and availability of resources.

More than 1,360 young scientists from 90 countries have attended these courses. Similar to the international nurseries, enrollments increased steadily from 1967 to the mid 1980s, peaking in 1986 with 69 trainees from 32 countries. The numbers then dropped largely due to funding constraints, but also as some programs matured (Figure 3.4). There was a modest recovery in the late 1990s to 2002 with increase focus on Afghanistan and Central Asia. The basic traditional training courses ended in 2002.

Figure 3.4 Annual number of CIMMYT wheat trainees and countries of origin



Source: Byerlee and Dubin (2008)

Table 3.2 indicates the number of scientists that worked at CIMMYT for shorter periods than the in-service trainees. These amounted to 1,866 professionals, mostly senior scientists, who spent from several days to several months on germplasm collection, working on special research projects, or updating their methodologies in wheat science. More than 800 graduate students from 76 countries and 176 institutions have also worked with the CIMMYT wheat program (Woolston 2008).

Table 3.2 Number of visiting scientists to CIMMYT

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

Source: Villareal (2001)

Regional Programs and Networking

CIMMYT senior scientific staff members were based in key wheat regions as a part of a regional program to give close support to the NARS. At times, they were placed in specific countries as part of a unique country program. The purpose was to work with national staff to strengthen the national programs, increase regional cooperation, and improve the quality of data generated. This close contact in the field, laboratory, and office was invaluable in producing good working relationships, strengthening the network, and producing high quality results. At the same time the international presence helped accelerate the movement of new, resistant germplasm into the national programs.

Symposia and workshops were an important part of the networking. CIMMYT helped organize a unique type of seminar called the traveling seminar. Scientists from a country or around the region traveled together during the wheat season to meet other scientists, extension agents, and farmers. They observed the crops and discussed common issues. The exchange of ideas and information was instructive and broadened the horizons of the participants.

Gene Banks and Intellectual Property Rights

Gene banks operating on an open source system significantly supported the international breeding efforts. The availability of this germplasm augments the introgression of new genes into the breeding gene pool.

Specifically, the wheat gene bank at CIMMYT, founded in the late 1980s, has been extremely useful to the breeding programs. It is one of the largest wheat collections in the world with ca. 150,000 accessions of wheat and related species. These materials are freely available to all legitimate requesters. From 1992 to 1996, an average of 7,000 samples was sent to requesters, including the private sector (Pardey et al. 1998). The free exchange of genetic materials in CGIAR gene banks was formalized in 1983 via the International Undertaking on Plant Genetic Resources within the auspices of the FAO. This agreement recognized the genetic resources in these banks as the common “heritage of mankind.” Material Transfer Agreements were instituted in the early 1990s to protect this heritage.

However, the environment for germplasm sharing started to change in the early 1990s as a result of declines in funding for the germplasm networks and the increasing role of private sector breeding and biotechnology programs. In addition, two international treaties signed in 1993 affected the freedom to exchange germplasm: *Trade-Related Intellectual Property Rights* (TRIPS) and *The Convention on Biodiversity* (CBD). The international community has attempted to address the impacts of these agreements, in part through the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA), which is a compromise on farmers’ rights, sovereign rights, and benefit sharing. Also, germplasm exchange is now based on a Standardized Material Transfer Agreement (SMTA) that all parties in the treaty have agreed on.

4. SCIENTIFIC IMPACTS OF RUST RESISTANCE BREEDING

Wheat scientists have been quite successful in the past 40 to 50 years in controlling stem and leaf rust. This section presents the scientific bases and background of the resistance used to achieve this, albeit with some setbacks as we shall later see.

A little more history will help provide context for the development of rust science over the centuries. In 1767, Felice Fontana was the first to recognize that the rust fungus was a parasite of the wheat plant. He published a clear description of the stem rust fungus, detailed its structures, and hypothesized that incalculable numbers of microscopic plants infect the wheat and extract nutrients, thus harming wheat yields (Fontana 1767).

After Mendel's data on inheritance were rediscovered in the early 20th century, Biffin (1905) in England published a paper showing that the inheritance of resistance to wheat stripe rust was determined in a Mendelian fashion. Close on Biffin's work, Stakman and colleagues in the United States were working on the genetic specificity of the stem rust fungus (Stakman and Piemeisel 1917). They showed that stable genetic variants of the pathogen, sometimes called races, biotypes, or pathotypes occurred. A great deal of progress was made in rust genetics and pathology in the early to middle part of the 20th century, especially in the United States, Canada, and Australia.

H.H. Flor's pioneering work on flax rust genetics and the gene for gene concept (Flor 1956) set the stage for a fundamental understanding of rust genetics. It states that for each gene in the host that conditions resistance, there is a matching gene in the fungus for avirulence. This relationship applies to many disease and pest relationships. Ultimately the theory forms the basic model for research in both conventional and molecular genetics of the cereal rusts (McIntosh et al. 1995).

Types of Rust Resistance Used in Wheat Breeding

The genetic basis of the various types of rust resistance used over the years is not fully understood even today, and the use of different names to describe rust resistance tends to be confusing. This will probably continue until the molecular genetics and biochemical basis for resistance is fully understood, and that day is approaching.

The genetic resistance to the cereal rusts is often presented as two basic types:

- Race specific resistance, also known as specific, major gene, or seedling resistance, among others. This type is clearly conditioned by the interaction of specific genes in the host with those in the pathogen. There is an obvious differential reaction and races can be determined (Dyck and Kerber 1985).
- Non-race specific resistance, also known as partial, general, minor gene, nonspecific, adult plant, slow rusting, among others. This type is characterized by a non-differential interaction. It is not possible to discern races and it generally allows some sporulation of the rust (Parlevliet 1985).

Data from a worldwide survey (Kilpatrick 1975) suggest that resistance to stem, leaf and stripe rusts averaged 5.3, 5.6 and 5.5 years, respectively, with a range of from 1 to 15 years. However, there is no indication of how many genes were involved in these resistances. Data from the Yaqui Valley in Mexico showed that single leaf rust genes have an average life of two to three years in that environment (Smale et al. 1998).

Many pathologists or breeders have thought that nonspecific rust resistance would be polygenic and long lasting, whereas specific resistance would be a single gene and short lived. This has been shown not necessarily to be the case (Dyck and Kerber 1985). Due to confusion about these issues and inadequate genetic information, Johnson (1981) proposed the term "durable resistance." He defined it as resistance that had been used over a large area, for a long time, had been exposed to a wide spectrum of the pathogen, and remained resistant. In this way the discussion about the genetic basis was avoided until more information was known. Thus there could be a single major gene such as *Sr26* for stem rust that could be durable or long lasting.

It should be emphasized that durable type resistance does not last forever. Parlevliet (1985) noted that no resistance is truly durable in an evolutionary sense. The need to evolve is a natural imperative for survival in biology. Nothing is static in nature.

Box 1. Maintenance breeding

Maintenance research is the research effort needed to ensure that productivity gains achieved are maintained and do not deteriorate over time, and the term maintenance breeding refers to those efforts in relation to plant breeding. Maintenance breeding is that which is aimed to maintaining current yields (based on past productivity increases) in the face of evolving pathogens and changing abiotic constraints. Maintenance research (eg, see Plucknett and Smith 1986) is difficult to value in economic analysis, as it does not lead to measurable increases in output, but rather prevents declines in productivity over time.

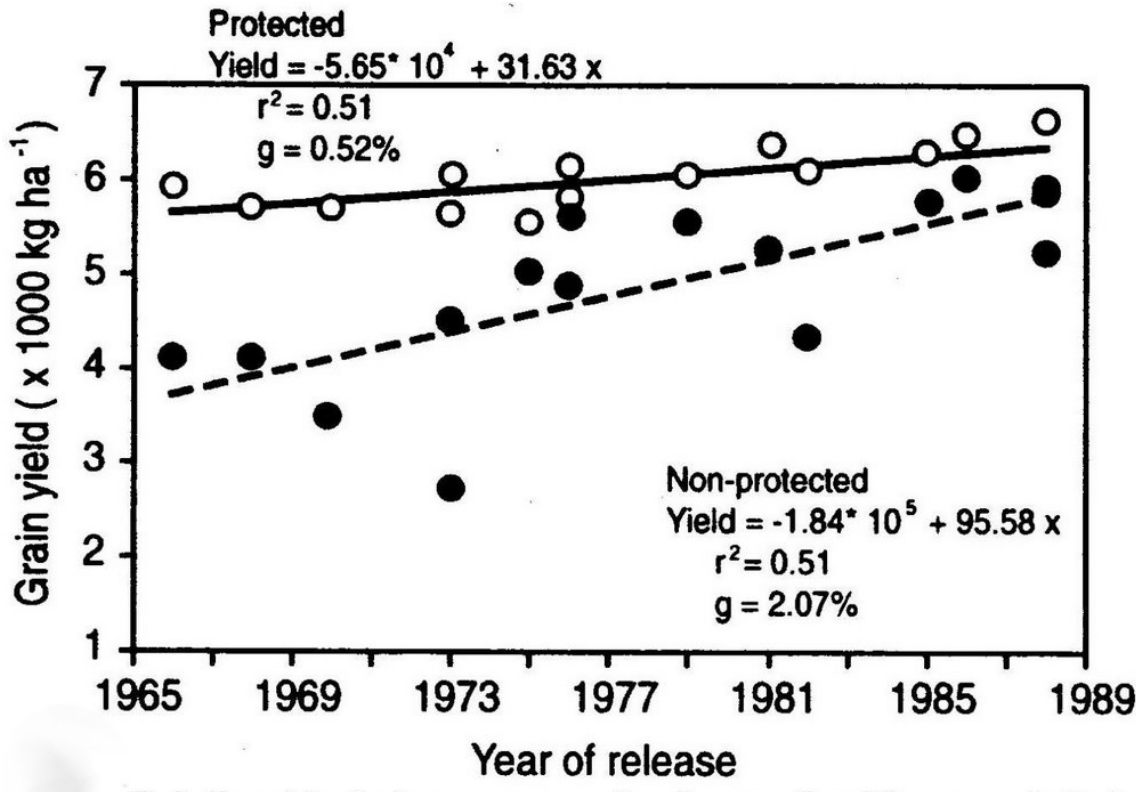
Once resistance to a disease has been developed, strenuous efforts are needed to maintain that resistance. In race-specific resistance, new genes need to be identified and incorporated into suitable varieties to enable the farmers to keep ahead of the evolving pathogen. The end results of such efforts, while they remain successful, can be the maintenance of yields over time, rather than any measurable increase in yields or productivity. The key element of any economic valuation of maintenance breeding is to identify the decline that would have occurred in the absence of the breeding efforts.

The development of durable resistances rather than race-specific resistance is a significant form of maintenance breeding that has proved very effective for rust resistance.

Experimental Evidence for Benefits of Rust Resistance on Yield

Experiments in Mexico indicate that more significant protection of yield progress can often be due to greater rust resistance rather than increases in yield potential *per se* (Sayre et al. 1998). Figure 4.1 shows the results of one these trials with 15 populations of CIMMYT-derived varieties released between 1966 and 1988 in Northwest Mexico. Varieties were yield tested with and without fungicide protection for leaf rust over four seasons. The genetic progress noted for the protected treatment was 0.52 percent and the unprotected 2.07 percent. The results show that good genetic yield progress was made over 20 years, but that the benefit in protecting the yield progress with leaf rust resistance was three times greater than the genetic yield progress. Similar results have been obtained with different planting dates and other localities (Sayre et al. 1998).

Figure 4.1 Relationship between year of release of varieties and their grain yield under fungicide protected and unprotected conditions for normal planting (g=annual genetic progress).



Source: Sayre et al. (1998)

This shows that a major component of the measured yield gains is the development and maintenance of rust resistance (Dixon et al. 2006). The development of disease-resistant varieties is considered one of the major impacts resulting from the wheat breeding activities. Byerlee and Moya (1993) classified genetic gains in wheat into three distinct categories: (1) gains in yield potential; (2) improvement in disease resistance; and (3) maintenance of disease resistance. Byerlee and Moya (1993) suggest that the largest impact from wheat breeding in the period 1960 to 1990 was maintenance of disease resistance, in the sense that breeders developed newer varieties that incorporated newer sources of resistance against evolving races of the three rust pathogens.

CIMMYT Methodology for Rust Resistance Breeding

In the Mexico/Rockefeller program, the search for stem rust and leaf rust resistance used materials from the United States, Kenya and South America, where resistance was known to exist. Roelfs et al. (1992) note the following durable resistance lines from those years: for stem rust, Hope and Thatcher; for leaf rust, Americano 25, Americano 44D, Surpreza, Frontana, and Fronteira; and for stripe rust, Wilhelmina, Capelle Deprez, Manella, Juliana and Carstens VI. Most of these lines were used in the pre-CIMMYT and CIMMYT program. In the earlier years, specific and nonspecific resistance was used. If the specific genes can be combined, or pyramided, that can be quite effective as well.

However, the breakdown of specific resistance—causing the "boom and bust" cycles in wheat production—accelerated the search for more long-lasting types of resistance. In the 1950s Stakman and Harrar (1957) noted that there was a general type of resistance where the adult plant and sometimes seedlings showed a resistance to penetration. At a specific time in the field some plants have much less rust development although the time of, and type of infection, is a susceptible reaction. This leads to a general resistance, where it takes more inoculum, a longer time, and more favorable conditions for rust development on some varieties than on others. This is a description of slow rusting type of (general) resistance that appeared to be longer lasting than others. Typical traits of the nonspecific type of slow rusting resistance include susceptible rust reaction in seedling and adult plant, low receptivity (lower initial infection than the susceptible control plant when first inoculated), and longer latent period (the time from infection to the first pustules produced). The slow rusting genes are generally observed in the adult plant and often associated with "minor" genes of small, additive effects that can be built up to high levels of resistance. The so-called minor genes are difficult to detect but play a major role in enhancing the level of slow rusting.

Niederhauser et al. (1954), working with late blight of potatoes, had observed rate limiting resistance and espoused its virtues. Then Borlaug (1966) and Caldwell (1968) saw its promise with respect to the rusts. When S. Rajaram became head of the CIMMYT bread wheat breeding program in the mid-1970s, he intensified the search for this type of resistance. In 1975, R.M. Caldwell made an extended visit to CIMMYT and he stimulated the search for slow rusting of leaf rust. In that year, and thereafter, replicated experiments were conducted to determine the levels of leaf rust slow rusting resistance present in pre-CIMMYT and CIMMYT materials, especially released varieties. These would be used directly in the breeding program. Varieties such as Yaqui 50, Bonza 55, Torim 73, and Kalyansona-Bluebird, among others, showed good resistance (Dubin 1975, CIMMYT 1976). The first three were later shown to have *Lr34* plus minor genes and the last one probably has *Lr46* plus additional ones (Singh 1992, R. P. Singh 2009, *pers. comm.*)

The decision to select strongly for slow rusting type resistance in the spring wheat germplasm led to the release of several cultivars like Pavon 76 and Nacozari 76 in Mexico and elsewhere. The heavy use of the best slow rusting lines resulted in the wide distribution of slow rusting resistance genes within the CIMMYT spring wheat germplasm (Singh et al. 2004).

Diverse sources of rust resistance and resistance to other diseases have been used in the crossing program; diversity is critical. The major sources of these disease resistant lines have been the following (Rajaram and Van Ginkel 2001):

- proven resistant germplasm from national programs from around the world
- advanced CIMMYT lines carrying desired minor resistance genes
- germplasm received from CIMMYT's and other gene banks
- material developed in CIMMYT's wide crossing program

The strategy with the cereal rusts has been, and continues to be, to breed for slow rusting (nonspecific) resistance based on historically proven stable resistance genes. The additional minor genes for resistance and combinations of them with different genes may provide a degree of diversity to further strengthen the nonspecific resistance (Rajaram and Van Ginkel 2001).

Breeding for nonspecific rust resistance was proving successful. However, scientists still sought a better genetic understanding of the genes being dealt with. In the early 1980s, R. P. Singh joined the CIMMYT program as a rust geneticist, and he made significant progress in understanding the genes involved with slow rusting and how to use them more efficiently (Singh et al. 2008).

Currently, the use of key slow rusting genes for leaf rust (*Lr34, Lr46*) and stem rust (*Sr2*), coupled with the minor, additive, slow rusting genes, is believed to give the highest level of durable resistance. Accumulation of four to five of these minor genes coupled with the key gene may give "near immunity" (Singh et al. 2008).

Key Durable Stem and Leaf Rust Resistance Genes and their Role in CIMMYT Germplasm

The *Sr2* stem rust resistance gene has been in pre-CIMMYT and CIMMYT materials for more than 50 years. It was selected by McFadden in the 1920s from Yaraslav emmer wheat (Kolmer 2001). The resistance was included in Borlaug's early crosses with varieties such as Yaqui 50. It is associated with a morphological marker, false black chaff, which makes selection fairly easy. Many wheat programs worldwide have used this resistance and associated minor genes with great success, though it was partially overcome in the North American epidemic of race 15B in the early 1950s (Dyck and Kerber 1985). However, it continued to be useful for many more years, though it appears to be at least partially overcome again with the advent of race Ug99.

Thatcher resistance, derived from Iumillo durum wheat, is another durable stem rust resistance that has functioned well, especially in conjunction with *Sr2*, for more than 50 years (Kolmer 2001). The genes have never been completely identified but run through much of the CIMMYT germplasm.

Sr 31 is a major seedling resistance gene obtained from a spring by winter wheat cross with the Russian variety Kavkaz. The gene is unique in that it comes from a rye translocation in Kavkaz and therefore is not a wheat gene. CIMMYT used this gene, considered durable based on the definition, in crosses since the late 1970s. It was linked to high yield, broad adaptation, and leaf rust, stripe rust, and mildew resistance. It became common in the spring wheat crosses for some years despite its negative effects on bread making quality. It conditioned a high degree of resistance but has been defeated recently by Ug99. Surprisingly, it lasted some 25 years, uncommon for a single major gene. In conjunction with other genes, this gene likely helped contain stem rust to a low level for many years (Singh et al. 2008).

Lr34 goes back to the 1940s and came from Brazil. The early Borlaug program used the variety Frontana, and it was one of the best sources of durable resistance to leaf rust. Genetic analysis on Frontana and several CIMMYT wheat varieties having the Frontana slow rusting resistance show that they have *Lr34* and two to three additive minor resistance genes (Singh et al. 2004). As indicated earlier, the resistance improves as minor, additive, genes are combined. Recent studies indicate that at least 10-12 slow rusting genes are present in CIMMYT spring wheat germplasm. As with *Sr2*, this gene is linked to another morphological character, leaf tip necrosis, and can be easily selected based on the pedigree (Singh 1992). As far as it is known the *Lr34* and minor gene combinations have not been overcome in more than 50 years. A better understanding of the molecular genetics of the rust pathogen host interaction will help us to better use these genes. Recently history was made when *Lr34* was cloned and the mode of action hypothesized (Krattinger et al. 2009). It is a new type of resistance gene that controls the response to several diseases including leaf rust, stripe rust, and powdery mildew, as well as the tip necrosis of the leaves. It also allows a gene-based molecular marker to be developed.

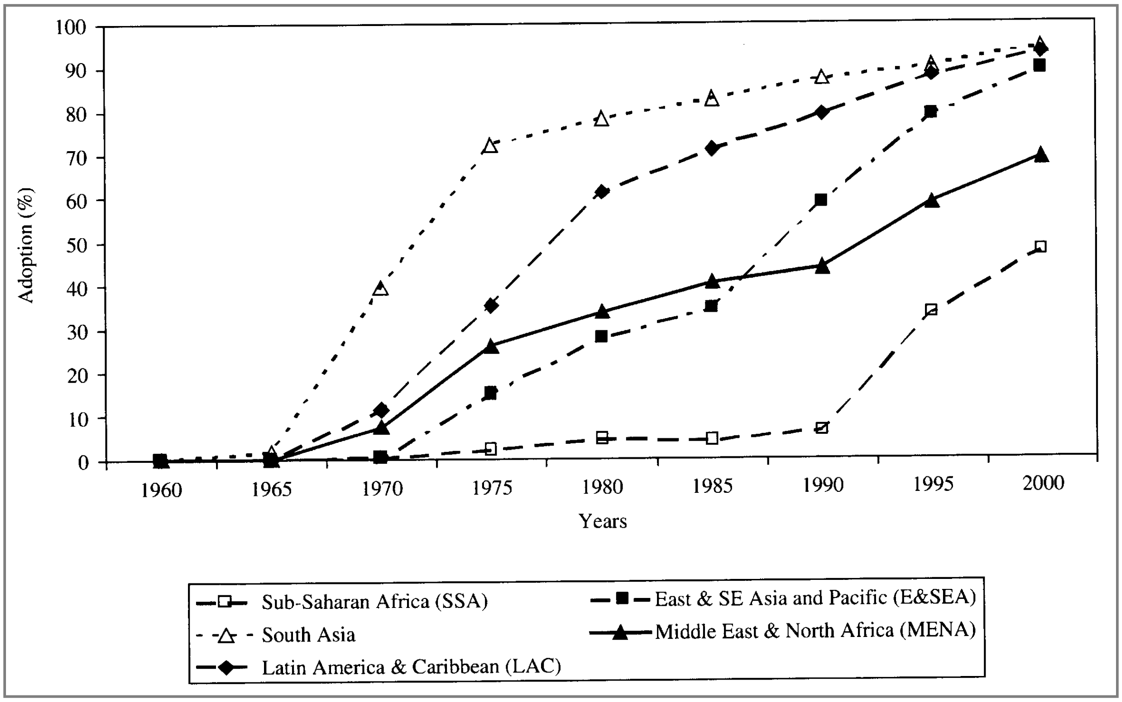
Lr46, the Pavon gene, is the most recently named slow rusting leaf rust gene (Singh et al. 1998). *Lr46* can be traced back to crosses made in the 1970s. The exact source is unknown, though it likely came from Latin America to the Borlaug program and then to CIMMYT. It appears to be widespread in world wheat germplasm. Once the gene is cloned, gene-based markers will allow the determination of origin and distribution (R. P. Singh 2009 *pers. comm.*). Similar relationships with minor additive genes and *Lr46* exist as with *Lr34*. This gene appears to still be effective worldwide after at least 30 years of use.

Deployment of Resistant Varieties

Extent of Use of Resistant Varieties

The adoption of modern varieties that yielded improved rust resistances was rapid and widespread, and has been well documented (see Figure 4.2). While the first wave of varieties focused on maximizing yield gain, the second wave not only attempted to increase yield but also to maintain those higher yields as wheat faced evolving attacks from rusts and other diseases and pests (see Box 1 on maintenance research). By 2002, nearly 95 percent of the developing world's wheat consisted of modern varieties (Lantican et al. 2005).

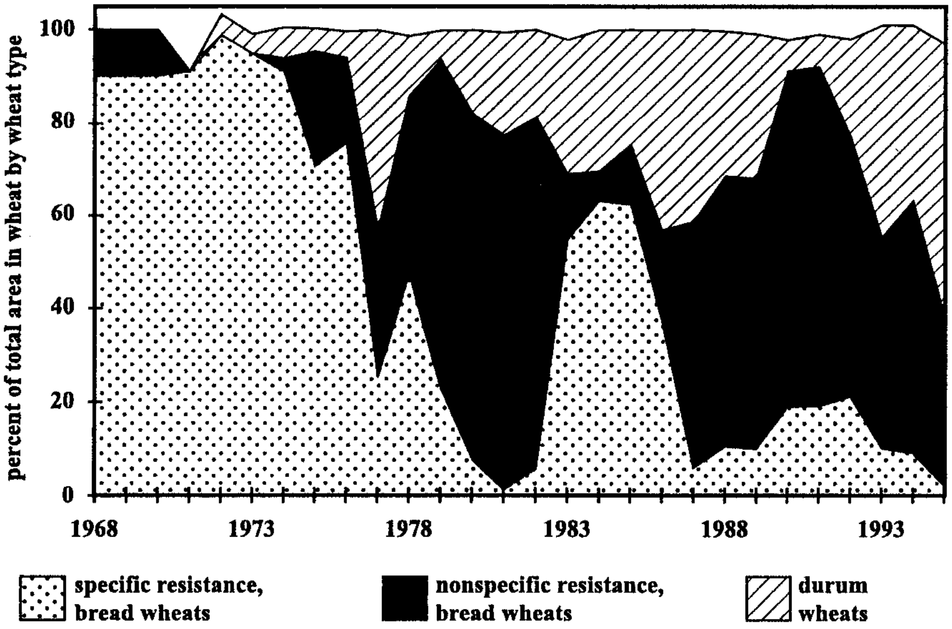
Figure 4.2 Adoption of improved wheat varieties by region



Source: Evenson and Gollin (2003)

Over time, the nature of the resistance incorporated into those modern varieties changed, as outlined in the previous section. An illustration of the nature of that change is given in Figure 4.3. The initial deployment of race-specific resistance in the 1960s was replaced during the 1970s by nonspecific resistance (Smale et al. 1998). Despite a resurgence of race-specific resistance in the 1980s, by 1995 the resistance deployed in bread wheats was almost entirely nonspecific resistance.

Figure 4.3 Type of rust resistance deployed, Yaqui Valley, Mexico, 1967 to 1995



Source: Smale et al. (1998)

Result of Successful Deployment of Rust Resistance

The widespread use of resistant cultivars worldwide has reduced all three rusts as significant factors in wheat production in recent decades. "Although changes in pathogen virulence have rendered some resistances ineffective, resistant cultivars have generally been developed ahead of significant damage" (Expert Panel 2005, p.3). Prolonged use of resistance then led to a decline in levels of inoculum both locally and particularly in areas that were considered "hot spots" and had previously been sources of wind-blown inoculum to other regions.

Large stem rust epidemics have not been a feature of global wheat production for many years. In each of 12 main global wheat production regions, stem rust was listed as of major importance historically (that is, there would be severe losses without the cultivation of resistant varieties) (Expert Panel 2005). In only one of these 12 regions (East Africa) was stem rust of major importance in 2005 (because of the Ug99 strain; see following section). In a further 8 regions, it was listed as minor (that is, it often occurs but is of little significance), while in the remaining 3 regions it was listed as "local" (that is, it only occurs in a small part of the region, although losses can be occasionally severe if susceptible cultivars are grown).

Recent Breakdown of Durable Resistance: A Reality Check

We have described an international breeding system evolving over many years that has been quite successful. However, maintenance of diversity is very important in the system: It is likely that the longer a resistance gene remains effective, the more the breeding community will depend on it for continued protection. This may lead to complacency and excessive use arising from the assumption that the original problem had been solved, ultimately resulting in genetic vulnerability (Expert Panel 2005). At the same time scientific and policy issues may play a significant role. All of these probably affected the advent of the new stem rust race, Ug99, identified in 1998 in Uganda by William Wagoire, and rendered previously resistant lines susceptible to stem rust (Pretorius et al. 2000).

Due to various reasons, which will be discussed later in this paper, support to work on this new danger was small until N.E. Borlaug intervened and funding was obtained for a workshop in Kenya in 2005 (Stokstad 2009). The outcome of that meeting was a concerted international effort to fund the necessary work to identify effective stem rust resistance, incorporate it into acceptable new varieties, and get them to the farmers' fields as soon as possible (Expert Panel 2005). Many countries and organizations are involved in the battle against what has been called the "shifty enemy" by E. C. Stakman (Cornell University 2008).

At this time, major genes and slow rusting genes have been identified and are being incorporated into germplasm. The germplasm is being evaluated through multilocation testing in many key areas, including Kenya and Ethiopia, where Ug99 and some of its descendents are now endemic (Singh et al. 2008). However, there is no time to lose; the new race is mutating and spreading as feared. It recently was observed in Yemen in 2006 and then Iran in 2007 (Nazari et al. 2009).

An expert panel report (Expert Panel 2005) declared Ug99 to be a threat to world wheat production, as it was predicted to migrate across the Red Sea to Yemen, then to the Middle East and subsequently to Central and South Asia. Those areas, with a population of one billion people, produce 19 percent of the world's wheat. The report predicts that either wind currents or inadvertent transport would eventually carry Ug99 to North Africa, Europe, West Asia, China, Australia, and the Americas (Cornell University 2008). Once Ug99 and its derivatives have established themselves in North Africa, the Middle East and South Asia, annual losses could reach US$3 billion in any given year (Cornell University 2008).

Box 2. Issues related to impacts of stem rust strain Ug99 in East Africa

- 86 percent of the Ethiopian population of 70 million is rural; 80 percent of Kenya's population of 30 million is rural
- 56 percent of Kenyan people live below the poverty line; 80 percent of those live in rural areas
- Many rural households are both producers and consumers of wheat in Ethiopia
- In Kenya, most wheat is produced on farms that are net sellers of wheat
- Per capita consumption is over 30 kg/year in Ethiopia, 27 kg/year in Kenya
- The poorest regions in Ethiopia also produce the majority of the wheat
- Households earn income from one or two cereals
- Large-scale farmers produce 80 percent of Kenya's wheat
- Wheat provides 12 percent of their income in Ethiopia
- Subsistence farming remains the main livelihood in Ethiopia
- In Ethiopia, wheat is consumed in 32 percent of rural households and 39 percent of urban households
- Ethiopian households spend 12 percent–26 percent (rural households) and 5 percent–16 percent (urban) on cereals
- Kenya imports over 50 percent of its wheat needs
- Ethiopia receives more food aid than any other country (typically 5–15 percent of total annual cereal production)
- Large-scale farmers can apply fungicides for rust control, and therefore do not have to suffer severe losses in the event of an epidemic
- Small-scale farmers (who would not be able to afford fungicides) have to suffer severe losses in the event of an epidemic.

Drawn from Expert Panel (2005)

5. ECONOMIC AND SOCIAL IMPACTS OF RUST RESISTANCE BREEDING

To assess the impacts of rust resistance, the rate of return on investment in rust resistance can be calculated by estimating the cost of developing and delivering resistance to farmers, the benefits of that resistance to farmers, and the impact on global wheat prices. Resistance also has wider social impacts on poverty, nutrition, and food security, which are also explored below.

Costs of Rust Resistance

Costs of Rust Resistance to Farmers

Rust resistance, because it is embedded in the seed, has no specific additional cost for the individual farmer. Instead, the costs are absorbed by the funders of the research and breeding programs that developed the varieties with the resistance, although some costs are being passed on to farmers in developed countries through the price of seed or through a levy on production. For wheat growers in developing countries, however, those direct costs have mostly been zero or close to zero.

The true economic cost to farmers of effective resistance to rust is the yield reduction they might have to incur in years of no disease to grow the varieties with the highest levels of resistance. Where the resistances have been incorporated into well-adapted high-yielding varieties, then that resistance is effectively free to farmers. The widespread success of the international research system in incorporating the highest levels of resistance into well-adapted high-yielding backgrounds in the Green Revolution and post-Green Revolution periods has meant that the economic costs to farmers of using the resistances have been minimal.

If varieties become susceptible, national programs require appropriate seed production and distribution infrastructure to replace those cultivars as quickly as possible. During the period of replacement, the economic cost of resistance to farmers can be substantial, as they may have to grow lower-yielding varieties to get effective resistance. This can lead to increased use of fungicides to control the disease in higher-yielding but susceptible varieties, or to increased risk-taking by farmers where fungicides are not a realistic option.

Costs of Rust Resistance to Research Organizations

For most developing countries, the cost of the development of rust resistance has been met by public sector agencies, whether IARCs or NARS. In developed countries, increasingly private sector breeders meet the cost. Because incorporating rust resistance is an inherent part of the breeding operation, it is difficult to define the cost of resistance as distinct from the rest of the breeding activities. Also, because of the high level of international cooperation and collaboration on disease resistance, and the generally public availability of resistance genes and parental materials developed, the costs of development of resistance in particular production environments are difficult to identify separately.

Because of the difficulty of separating rust resistance costs from the other genetic improvement activities, in evaluating leaf rust resistance breeding at CIMMYT, Marasas et al. (2004) included the full cost of CIMMYT's wheat genetic improvement, thus overestimating the costs of the resistance activities. An alternative is to take a proportion of the total investment in breeding as the cost of rust resistance, in which case total global costs of wheat improvement research must be estimated first.

Heisey et al. (2002) provide detailed estimates of total expenditure on wheat genetic improvement investments for developing countries from both NARS and CGIAR centers (CIMMYT and ICARDA) from 1965 to 1990 (Table 5.1). In 1990 that estimate was US$112 million (1990 PPP). Since that time, NARS investment is estimated to have increased steadily in real terms. Heisey et al. (2002) indicated that CIMMYT's investment in wheat improvement research declined between 1990 and 2000, while ICARDA's was estimated to have remained at US$1 million per year. Projecting those same levels from

2000 to 2005 and converting that to 2006 dollars, for consistency with the benefit estimates, gives annual costs of investment in rust resistance research of approximately US$196 million in 2005.

Table 5.1 Total investment in wheat genetic improvement (US$ millions)

	1965	1970	1975	1980	1985	1990	1995	2000	2005
Expenditures, 1990 dollars									
Developing countries NARS	30	41	56	74	87	98	105[a]	113[a]	118[a]
Total CGIAR Centers	1	7	9	13	14	14	11[a]	11[a]	11[a]
- Total for Developing Countries	31	48	65	87	101	112	116	124	129
- Total in 2006 dollars	*47*	*73*	*99*	*132*	*153*	*169*	*176*	*189*	*196*
Rust resistance (2006 dollars)									
30% of genetic improvement	14	22	30	40	46	51	53	57	59
50% of genetic improvement	23	37	49	66	77	85	88	94	98

[a] Estimated; includes estimated expenditure on wheat research at both CIMMYT and ICARDA.

Source: Drawn from Heisey et al. (2002)

A significant proportion of breeders' efforts are related to disease resistance. For example, Adusei and Norton (1990) found that 41 percent of wheat research at US research stations was dedicated to maintenance research; most of that maintenance research for wheat would be strongly related to wheat disease resistance, particularly rust resistance. Given that 30 to 50 percent of breeders' efforts are related to disease resistance, the total annual cost of rust resistance for developing countries is estimated at US$59 to US$98 million, in 2006 dollars (equivalent to US$0.50 to US$0.84 per ha of wheat across all developing countries).

Costs of Making Resistance Available

One cost of having effective resistance available in farmers' fields is the cost of infrastructure to enhance seed increase and the seed distribution networks where varieties need to be replaced to maintain resistance. Those systems require dedicated extension agents and seed distributors working with scientists from IARCs and NARS to ensure that good quality seed is available to farmers in a timely manner. However, no estimates are available of the resources required for these activities over recent decades

Valuing the Benefits of Rust Resistance

Alternatives to Resistance

In assessing the economic benefits of resistance, it is appropriate first to consider the alternatives to resistance and the options available to farmers if resistance were not available. When farmers are faced with wheat diseases for which there is no effective genetic resistance available, they can decide to "live with" the disease, and accept the losses that will occur. That will entail looking to other crops that can be grown in place of wheat and accepting the losses that will occur regularly or intermittently in the wheat crop. Such situations occur for many crops, but can be particularly costly options for a staple crop such as wheat when there are few alternatives in production or consumption for the farmers.

Fungicides can be used to help control rusts. While large-scale farmers can and do use fungicides to control rusts (even in developing countries such as Ethiopia and Kenya), small-scale farmers are not able to consider using fungicides to control rusts because of their unavailability or their high costs in local markets (Expert Panel 2005). In developing countries, and in lower-yielding environments elsewhere, growing resistant varieties remains the main control method for rusts, because most farmers cannot afford to use fungicides on wheat.

Murray and Brennan (2009) have recently assessed the costs of fungicides in Australia in 2008 and found the total costs to farmers of a foliar application for disease control was equivalent to approximately US$8/ha,[12] plus application costs. Even if costs were lower in developing countries, the fungicide cost would be markedly higher than resistance, which is essentially free to farmers and costs US$0.44 to US$0.74 per ha to develop. In addition, there are significant environmental and health advantages in not having large quantities of fungicides applied to wheat crops globally.

Approach to Valuing Benefits of Resistance

Assessment of the economic and social impacts of wheat rusts, and therefore of the value of their control through resistance, is complex. It is difficult to distinguish the impact of the development of disease resistance from the impact of modern semidwarf varieties and the Green Revolution; all are intrinsically intertwined. As modern semidwarf varieties were spread and taken up by farmers, they incorporated different levels of rust resistance.

When disease occurrence is recorded, it is seldom accompanied by data on yield losses or the relationship to wheat prices, output levels, or imports (Marasas et al. 2004). Losses of less than 10 percent are generally difficult to identify and measure. Therefore, losses are measured accurately only when disease development is severe, and even then it is difficult to disaggregate losses due to rust from those due to other biotic and abiotic stresses (Marasas et al. 2004).

However, a number of positive impacts of rust resistance at the local level can be identified:

- Varieties with improved rust resistance have resulted in higher yields over time than would have occurred without that resistance.
- Farmers have experienced increased yield stability with rust resistance, as the epidemics that would have occurred in seasons that favored the rusts were reduced or prevented.
- The quality of the grain would have been lower without resistance, as rust epidemics can cause smaller, pinched grains, resulting in lower prices for marketed grain.
- With increased yields and possibly increased local prices, farmers operating in a market economy would receive higher incomes from disease resistant varieties than from varieties without that resistance.

There are no direct estimates of the global value of wheat rust resistance. However, a number of studies have estimated the benefits of particular resistances to particular countries or groups of countries. Three sources of estimates of the value of rust resistance can be examined:

1. Studies of the value of leaf rust resistance breeding for developing countries
2. Estimates of the costs of the new strain of stem rust Ug99 that provide an equivalent estimate of the value of maintaining the resistance before it was overcome
3. Direct estimates of the value of wheat rust resistance for Australia, India and Pakistan

In addition, several studies have estimated the benefits of the development of modern semidwarf varieties and the Green Revolution. Given that rust resistance is part of that genetic improvement, those estimates provide a context for the value of rust resistance and allow separate estimates to be made of the value, depending on the proportion of total breeding benefits that can be attributed to rust resistance.

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[12] The cost was Aus$12/ha, with an exchange rate of US$0.70 per Aus$1.00.

Studies of the Value of Leaf Rust Resistance in Developing Countries

The first study to measure the impact of durable rust resistance was Smale et al. (1998), who assessed the benefits of nonspecific rust resistance in the Yaqui Valley in Mexico. In a detailed study of the varieties grown in the Yaqui Valley between 1970 and 1990 and the different sources of leaf rust resistance in each variety, they estimated the benefits over that period at US$17 million (in 1994 dollars). This was equivalent to US$0.85 million per year for the average of 150,000 ha of wheat in the Yaqui Valley at that time (or US$5.67 per ha, equivalent to $7.71 per ha in 2006 dollars). Smale et al. (1998) consider the issues in extrapolating these benefits to the other developing countries where the nonspecific leaf rust resistance was relevant and concluded that the benefits may well be higher in other areas. However, if the same value per ha were projected to the total wheat area in developing countries, the benefits would be approximately US$902 million per year in 2006 values (Table 5.2).

Table 5.2 Estimated benefits of resistance in developing countries (2006 US dollars)

Study	**Country/region**	**Rust**	Value of resistance	All developing countries[a]
			$/ha	$ million
Smale et al. (1998)	Yaqui Valley, Mexico	Leaf rust	$7.71	$902
Marasas et al. (2004)	Spring bread wheat, developing countries	Leaf rust	$7.83	$917
Hodson et al. (2005)	East Africa, Middle East, South Asia	Stem rust	$21.58	$2,527
Brennan & Quade (2004)	India, Pakistan	Stem rust	$1.53	$180
	India, Pakistan	Leaf rust	$2.53	$297
	Mean	Stem rust	$11.56	$1,353
	Mean	Leaf rust	$6.03	$705

[a] Based on 117 million ha in developing countries in 2006

Marasas et al. (2004) assessed the economic impact of CIMMYT's efforts to breed leaf rust resistant spring bread wheat varieties since 1973. They estimated the yield losses avoided by having resistant rather than susceptible varieties across developing countries, and valued those benefits. They identified losses to susceptible varieties across mega-environments (MEs) along with the percent area affected by leaf rust in each ME (Table 5.3). They estimated losses for race-nonspecific and race-specific resistance separately, as well as another minor category of "almost susceptible" benefits. Over the 25-year period, total gross benefits were estimated at US$7.46 billion (in 1990 dollars). Overwhelmingly, the benefits were obtained in ME1 (Irrigated temperate) for race-nonspecific resistance, accounting for 79 percent of the total benefits, although there were also significant benefits from race-specific resistance and in some other MEs (see Table 5.3).

Table 5.3 Leaf rust losses, by CIMMYT spring wheat mega-environment

Mega-environment	Area in 2000 (m.ha)	% yield lost to leaf rust by susceptible varieties	% area affected by leaf rust	Gross benefits of genetic leaf rust resistance, by resistance type (US$ million, 1990 dollars)				Gross benefits per year (US$, 1990 dollars)	
				Race nonspecific	Race specific	Almost susceptible	Total	Total *($million)*	*($/ha)*
Irrigated	31.9	6.0	96	5,913	357	121	6,392	256	8.02
High rainfall	7.5	3.0	92	140	109	0	249	10	1.33
Acid soil	1.7	3.0	100	4	21	0	25	1	0.60
Semi-arid, Mediterranean	5.4	2.0	45	5	2	0	7	0	0.05
Semi-arid, Southern Cone	3.1	1.0	100	0	18	0	19	1	0.24
Semi-arid, Sub-continent	4.3	1.0	69	7	0	0	7	0	0.06
Hot, humid	3.9	6.0	100	724	23	16	762	30	7.84
All mega-environments	57.8	4.5	89	6,793	530	138	7,461	298	5.16

Source: Derived from Marasas et al. (2004)

These estimated benefits from Marasas et al. (2004) for leaf rust in spring wheat can be extrapolated to all wheat in developing countries on the basis that the same benefits per hectare apply to other regions. The annual benefits over the period 1973 to 1997 averaged US$298 million per year (in 1990 dollars), or US$5.16 per ha using the 61 million ha of spring wheat sown in those MEs in 1990 (Table 5.3). Converting to 2006 values, the benefits are US$7.83 per ha. Applying that benefit to all wheat in developing countries in 2006 gives estimated total benefits valued at of US$917 million per year in 2006 prices.

Estimates from the Losses from Ug99

Estimates of the losses likely to occur from the stem rust strain Ug99 help provide an estimate of the value of the resistance that was in place prior to the development of that strain. Hodson et al. (2005) examined the potential impact of the Ug99 race if it were to spread, as expected, across East Africa and the Nile valley, the Middle East as far north as Southern Turkey, and the entire Indo-Gangetic plains. They defined “best” and “worst” cases, based on 10 percent and 70 percent production losses, respectively, on susceptible varieties. The area of susceptible varieties was estimated for each affected country. Based on the lower estimated losses, the potential aggregate losses were estimated as 8.3 million tonnes across 57 million ha (Table 5.4). Using the 2006 weighted average price of US$148 per tonne, those losses would be valued at US$1.2 billion, or $21.58 per ha across the potentially affected regions (Table 5.4). This provides another estimate of the value of stem rust resistance in these regions, which produce 19 percent of the world’s wheat. If the same value per ha were applied to all wheat in developing countries, the value of the resistance would be US$2.5 billion (Table 5.2). Cornell University (2008) also estimated that if Ug99 and its derivatives were to establish themselves in North Africa, the Middle East and South Asia, annual losses could reach US$3 billion in any given year.

Table 5.4 Summary of estimated potential losses from Ug99[a]

	Area	**Ug99 losses**	Value of losses (2006 dollars)	
	(million ha)	(million t.)	($ million)	($/ha)
East Africa				
Ethiopia	1.57	0.15	$22	$14.14
Kenya	0.16	0.02	$3	$18.62
- Total East Africa	*1.73*	*0.17*	*$25*	*$14.55*
Middle East				
Turkey	9.25	0.24	$36	$3.84
Iraq	2.55	0.22	$33	$12.77
Egypt	1.25	0.38	$56	$44.85
Yemen	0.09	0.11	$16	$189.30
Iran	6.95	0.35	$52	$7.45
- Total Middle East	*20.09*	*1.3*	*$192*	*$9.58*
South Asia				
India	26.38	5.2	$770	$29.17
Pakistan	8.36	1.5	$222	$26.56
Bangladesh	0.56	0.16	$24	$42.44
- Total South Asia	*35.30*	*6.86*	*$1,015*	*$28.76*
Region total	57.12	8.33	$1,233	$21.58

[a]Valued at US$148 per tonne

Source: Derived from Hodson, et al. (2005)

Estimated Value of Wheat Disease Resistance: India and Pakistan

Brennan and Quade (2004), in a study of research capacity building, prepared some estimates of the value of rust resistance in India and Pakistan using the same methodology as Brennan and Murray (1989, 1998). They estimated the potential losses from rusts without any controls, as well as the present losses with the current levels of resistance that are employed. The difference between the potential and present costs provides an estimate of the value of the controls. The proportion of the disease control provided by genetic resistance is combined with these figures to give an estimate of the value of resistance for each rust. The percentage of control through resistance was close to 100 percent for India and Pakistan. Converting the findings to 2006 US dollars (Table 5.5), the estimated value of rust resistance for India and Pakistan, respectively, is $35 million and $18 million for stem rust, and $32 million and $55 million for leaf rust. For both countries, this is equivalent to US$1.53 per hectare for stem rust and US$2.53 per hectare, respectively, which is lower than what was found in other country studies (Table 5.2). These values for resistance are lower because the potential losses if there were no resistance were assessed as considerably lower than in other studies.[13]

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[13] Murray and Brennan (2009) found that the value of rust resistance in wheat in Australia was US$272 million for stem rust and US$94 million for leaf rust (in 2006 dollars), equivalent to US$22.81 and US$7.89 per hectare, respectively. These estimates

Table 5.5 Value of rust resistance in India and Pakistan US$, 2006 dollars, using weighted average producer price of $148/t

	Potential loss with no control *($ million)*	Present loss with current controls *($ million)*	Value of control *($ million)*	% of control provided by resistance	Value of resistance *($ million)*	Value of resistance *($/ha)*
India						
Stem rust	35	0	35	100%	35	1.33
Leaf rust	37	3	34	95%	32	1.22
Pakistan						
Stem rust	18	0	18	100%	18	2.16
Leaf rust	59	1	58	95%	55	6.69
Total: India and Pakistan						
Stem rust	53	0	53	100%	53	1.53
Leaf rust	96	4	92	95%	87	2.53

Source: Derived from Brennan & Quade (2004).

Murray and Brennan (2009) warn that it is not appropriate to sum the benefits of the resistances measured in this way because the estimates of losses on which they are based assume that there is no interaction between diseases. However, if one rust were left uncontrolled in an epidemic, the losses for the other rusts would not be independent because many of the host plants would have already been destroyed by the first rust. Thus, it is only appropriate to consider the value of resistance for each rust separately.

Other Estimates

Studies of the value of wheat breeding achievements have generally focused on the overall benefits from the development of modern semidwarf varieties or the contribution of CIMMYT to those improvements (for example, see Byerlee and Moya 1993, Heisey et al. 2002, Lantican et al. 2005). The findings of a selection of these studies are shown in Table 5.6. For example, Lantican et al. (2005) found that additional production as a result of the new varieties from international wheat breeding research is valued at between US$2.0 and US$6.1 billion in 2002, depending on the scenario definition. This represents US$2.24 and US$6.34 billion in 2006 dollars (Table 5.6).

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are more consistent with the other estimates for developing countries in Table 5.2 than those of Brennan and Quade (2004).

Table 5.6 Summary of estimated benefits from international wheat improvement research

Source	Region/level	Total benefits of modern semidwarf wheat varieties		Value at 2006 prices ($ billion)	Benefits attributable to rust resistance[a] ($ billion)
Byerlee and Moya (1994)	Spring wheat, developing countries, 1977-90	15.34	million t.	$2.27	$0.68
Byerlee & Traxler (1995)		$2.5 billion	1990 dollars	$3.79	$1.14
Heisey et al. (1998)	Wheat, developing countries	$1.6 - $6.0 billion	1990 dollars	$2.43 - $9.15	$0.73 - $2.73
Evenson (2000)		$3.4 - $6.3 billion	1990 dollars	$5.16 - $9.56	$1.55 - $2.87
Lantican et al. (2005)	Wheat, developing countries	$2.0 - $6.1 billion	2002 dollars	$2.24 - $6.84	$0.67 - $2.05
All studies				$2.24 - $9.56	$0.67 - $2.87

[a] Based on 30% of total benefits from modern semidwarf wheats

Only a proportion of the benefits of international wheat breeding improvement can be attributed to rust resistance research. As previously discussed (see costs of rust resistance to research organizations), some 30 to 50 percent of the wheat improvement effort could be attributed to development and maintenance of rust resistance. In Table 5.7, the benefits of rust resistance measured in this way would range from US$0.67 to US$2.87 billion per year (in 2006 dollars) using 30 percent of total benefits (Table 5.6). These estimates are broadly consistent with the range of the more direct estimates developed above from studies of rust resistance.

Evenson and Gollin (2003) reported on a detailed study on the impacts of crop genetic improvement across all crops from 1960 to 2000 on world production, prices, and food intake. In one scenario, drawn from Evenson and Rosegrant (2003), they found that the modern semidwarf varieties led to approximately 17 percent higher production in developing countries, with a subsequent significant reduction in average prices (Table 5.7). While these benefits cannot be attributed to rust resistance in wheat, if the same benefits here for all crops were ascribed to wheat and 30 percent of wheat benefits were attributed to rust resistance, then wheat rust resistance would provide significant achievements (Table 5.7).

Table 5.7 Impacts of modern semidwarf varieties in developing countries on key global parameters, 1960 to 2000

	Increase/decrease due to semidwarf varieties	**Increase/decrease attributable to rust resistance[a]**
Crop production in developing countries	15.9% to 18.6%	5.2%
Crop prices, all countries	-35% to -66%	-15.2%
Imports by developing countries	-27% to -30%	-8.6%
% percent of children malnourished in developing countries	-6.1% to -7.9%	-2.1%
Calorie consumption per capita in developing countries	13.3% to 14.4%	4.2%

[a] Based on 30% of mid-point of range

Source: Evenson and Gollin (2003)

Impact on Global Wheat Prices

Diseases can affect grain quality, so a reduction in diseases can lead to a higher local price for individual farmers. However, at the broader market level, large changes in production can change the market price for all wheat. For example, large crop losses from disease may imply price increases that are passed on to consumers, or unforeseen imports purchased at world market prices that may be unfavorable (Marasas et al. 2004). A recent parallel has been the increase in grain prices as more grain has been used for ethanol production. Whenever large quantities of grain are not available, whether through disease losses or through diversion to other uses, prices increase significantly.

Conversely, an increase in production resulting from improved rust resistance is likely to lead to lower prices over time (Alston et al. 1995). For example, the real price of wheat in India paid by consumers decreased by approximately 2 percent per year from 1970 to 1995 (Dixon et al. 2006).

Evenson and Gollin (2003) estimated that the price would have fallen 35 to 66 percent because of modern semidwarf varieties (Table 5.7). If 30 percent of the production increases were the result of improved rust resistance, then a price reduction of the order of 10 to 20 percent would be attributable to the increased production resulting from the improved rust resistance.

Estimated Returns on Investment in Rust Resistance

While the data obtained here do not enable a precise estimate of the returns on investment in wheat rust resistance, some broadly indicative estimates can be developed from the above analysis and discussion:

- The global investment in the development, deployment, and maintenance of rust resistance in wheat in developing countries is likely to be US$60 – US$100 million per year, in 2006 dollars.
- The value of individual epidemics avoided or reduced by the resistance is likely to be up to US$300 million, in 2006 dollars.
- Apart from major epidemics, improved rust resistance has significantly reduced annual losses from rust diseases in many, possibly most, production environments.
- Based on extrapolation from studies of the value of rust resistance in particular countries or regions, the estimated benefits of rust resistance in developing countries, in 2006 dollars, is between US$0.2 and US$2.5 billion per year for the individual rusts.
- Based on a partition of the benefits from modern semidwarf wheat varieties, and taking 30 percent of the total benefits for rust resistance, gives a separate estimate of the benefits of rust resistance at US$0.7 to US$2.9 billion per year in 2006 dollars, broadly consistent with the extrapolation from direct studies of the value of resistance.
- On that basis, the estimated total benefits of rust resistance globally are approximately US$0.4 to US$2.0 billion per year, in 2006 dollars.

Using conservative estimates of benefits of US$0.4, US$0.8, and US$1.2 billion per year and lags between investment and returns of five, seven, and ten years, the internal rate of return on the expenditure on rust resistance between 1960 and 2006 has been assessed (Table 5.8). Benefits have been estimated by linear interpolation between the first benefits and 2000, with a constant benefit since 2000. The estimated internal rate of return is between 19 percent and 66 percent, depending on lags and level of impact. With benefits of $0.8 billion per year and seven-year lags, the internal rate of return is estimated at 38 percent per year. This indicates a successful outcome from the development of improved rust resistance.

Table 5.8 Estimated internal rate of return from investment in rust resistance

Lags	Benefits US$ billion per year, 2006		
(years)	0.4	0.8	1.2
5	35%	54%	66%
7	26%	38%	46%
10	19%	27%	32%

Source: Calculated by authors

Impacts on Poverty, Nutrition, and Food Security

Poverty and Nutrition

Agricultural research that generates broad-based productivity increases is an effective means of reducing poverty through income generation and rural employment. Developing country populations can realize significant benefits from having effective resistance to rust. Many of these farmers and societies rely extensively on the wheat crop for their livelihood and nutrition, and because large-scale fungicide treatment is not feasible for them, improved rust resistance has a direct influence on both poverty alleviation and nutrition.

Given that rust resistance is incorporated into the seed, the marginal costs of improved resistance are minimal for poor farmers. Rust resistance inherently favors low-income and/or small-scale farmers, in the sense that more resource-rich farmers can use fungicides to control rust diseases, which generally are prohibitively expensive for small-scale farmers (Expert Panel 2005). Large-scale farmers have an option for alternative means of disease control; small-scale farmers do not have that option.

Both large-scale and small-scale farmers have adopted the improved varieties (Lipton and Longhurst 1989), although in many regions smaller-scale (and poorer) farmers may not have achieved the same level of productivity improvement as larger-scale farms (Dixon et al. 2006). Byerlee and Moya (1993) and Marasas et al. (2004) found that farmers in irrigated areas received the largest share of benefits from wheat breeding, and Dixon et al. (2006) noted that about half of the world's population living in poverty is located in the large irrigated areas of South Asia alone. Dixon et al. (2006, p. 499) argued "improved varieties were designed for, and are now being utilized by, farmers both rich and poor, on both marginal and superior land, and for big and small farms."

Though farmers are the primary beneficiaries of improved wheat varieties through increased yields and reduced variability, for poor producers, lower prices resulting from increased production can offset the advantages of higher yields, and the benefits of increased yields and reduced variability can be further offset if accompanied by increased levels and prices of inputs (Dixon et al. 2006). Whether producers are better off will depend on their environment, the level of yield gains in that environment and the extent to which they market their production. Some producers, particularly those in areas not favoring modern semidwarf varieties, will be worse off from these developments. Studies, such as Evenson and Gollin (2003), show that the overall net effect has been a significant gain for producers. Thus, it is likely that most producers are better off, while only a minority is worse off. The relative size of that minority is not clear.

On the other hand, all consumers will benefit from any price reduction. Such price changes resulting from rust resistance research would lead to an overall shift in welfare from producers to consumers (see Alston et al. 1995). There is evidence that urban poor as well as rural poor have made significant gains through the modern semidwarf varieties (Harris et al. 1995; Ravallion and Datt 1995). In addition, higher production can reduce absolute poverty in rural areas through increased demand for harvest and post-harvest labor. There have also been down-stream benefits to the economy if that increased production found its way into a marketing chain (Lipton and Longhurst 1989).

Where production was consumed on farm rather than traded, the families could expect to have improved nutrition from the larger harvests. One benefit of modern semi-dwarf varieties incorporating rust resistance is the gain in calorie consumption per capita in developing countries, and the reduction in the percentage of malnourished children (see Table 5.7). Calorie consumption per capita in developing countries significantly increased by approximately 13 to 14 percent between 1960 and 2000. That improvement led to corresponding gains in health and life expectancy, so that the extent of children malnourished fell by about 7 percent, or more than 30 million children (Evenson and Gollin 2003). If rust resistance was responsible for 30 percent of the increase in global wheat production, then it has made a significant impact on nutrition.

The increased availability and lower prices for food are especially beneficial to the poor, who spend a large share of their income on food. Expert Panel (2005) notes that in countries where wheat is an important staple, low-income households tend to spend a larger proportion of their income on wheat than higher-income households. Price falls are beneficial to both urban and rural consumers who will have more disposable income for other goods (Dixon et al. 2006).

World Bank (2005) found that the empirical evidence suggested that for every 1 percent increase in the productivity of wheat the extent of poverty has been reduced by 0.5-1.0 percent. This reduction in poverty is likely to apply whether the productivity improvement comes through yield increases or through yield losses avoided through resistant varieties. Thus, the increases in wheat productivity, to which rust resistance has contributed significantly, are likely to have reduced global poverty markedly. If Evenson and Gollin (2003) figures from Table 5.7 were used, for example, the 5.2 percent increase in productivity would have reduced poverty by between 2.6 percent and 5.2 percent across all developing countries.

Nagarajan and Joshi (1975) discussed the extent to which rust epidemics in India in the past have led to famines. They concluded that the failure of the monsoons and the associated "Kharif" summer season crops are the main cause of past famines. As a result, they argued "rust epidemics or pandemics can aggravate famine conditions, if occurring prior to, or after a poor monsoon" (Nagarajan and Joshi 1975, p. 32).

Therefore, improvements in rust resistance are an effective way to provide benefits to the poor, though they only receive benefits in proportion to their production and consumption. While rust resistance is an effective (and low cost) way to benefit poor farmers, it is not a targeted way to direct benefits to the poor farmers rather than to the wealthier farmers.

Food Security

Rust resistance has clearly enhanced food security in many developing countries by eliminating, or at least reducing the frequency of, serious epidemics. The availability of effective rust resistance in developing countries, especially those with food deficits, has precluded the need for a number of strategies that would have been needed to improve food security. For example, the additional food security resulting from the improved rust resistance has allowed a reduced emphasis on food aid imports for many countries. Expert Panel (2005) notes that where effective resistance against stem rust is not available, farmers need to consider whether they should develop alternative crop systems that reduce the reliance on wheat, or even alternative livelihood systems for some of the people involved.

Farmers have experienced increased yield stability with improved rust resistance, as the epidemics that would have occurred in seasons that favored the rusts were reduced or prevented by the level of resistance deployed. Gollin (2006) has shown that the absolute magnitude of yield variability for wheat in developing countries declined with the spread of modern semidwarf wheat varieties, even after adjusting for expanded use of irrigation and other inputs. The value of the increased yield stability is equivalent to yield increases worth US$143 million per year (Gollin 2006). Rust resistance can clearly claim a significant proportion of these benefits through its contribution to that improvement in stability of yields.

The increased stability of yields lead to a more stable and cohesive society with greater food security than if the harvests were subject to regular, or even occasional, destructive epidemics inducing famine. At the household level, for example, Bunch (1982) found that the social consequences of a crop failure are high. When a crop is lost, a farmer can be seen as having failed the entire extended family and the farmer's pride can be severely damaged. Farmers (particularly poor farmers) are generally risk-averse (Dixon et al. 2006), so the contribution of rust resistance to yield stability is significant in terms of social consequences as well as economic advantages.

Overview of Impacts

A summary of outcomes from resistance to stem and leaf rusts over the past 50 years is shown in Table 5.9. A wide range of economic and social indicators show that the development and deployment of resistance to stem and leaf rusts in developing countries have brought about positive outcomes. Across some 60-120 million households, wheat yields and returns have increased, bringing about significant increases in aggregate wheat production. Those increased wheat supplies have also resulted in improvements in nutrition (Table 5.9) for consumers across developing countries.

Table 5.9 Summary of Outcomes from Rust Resistance

Measure of impact	Size of impact
Total wheat area affected[a]	117 million ha
Estimated number of households affected[b]	60-120 million
Changes in wheat yields:	
- Value of benefits per hectare of wheat[c]	US$6–US$12
- Equivalent average annual yield increase[d]	4% –8%
- Equivalent average annual yield increase[e]	108–216 kg/ha
Estimated increase in wheat production in developing countries[f]	5.2%
Estimated reduction in % of children malnourished[f]	2.1%
Estimated increase in calorie consumption in developing countries[f]	4.2%

a FAOSTAT data for 2006
b Assuming average farming size of approximately 1-2 ha in developing countries
c See Table 5.2
d Valuing per hectare benefits at 2006 price of US$148 per tonne
e Assuming average yields in developing countries of 2.7 t/ha
f See Table 5.7

Sources: FAOSTAT 2009; authors' calculations.

6. POSITIVE AND NEGATIVE FACTORS THAT INFLUENCED THE RUST RESISTANCE PROGRAM

In previous sections we have tried to paint the panorama of the 50 or so years that led to the discovery, incorporation and use of durable types of stem and leaf rust resistance in the international wheat breeding programs. We have told the story with CIMMYT as the main actor in the program. However, the NARS and several governmental or university programs also have played major roles in the development of the durable type of stem and leaf rust resistance and its use in developing countries. Principal among them were the USDA, University of Minnesota, Agriculture and Agri-Food Canada, University of Saskatchewan, PBI-Cambridge, IPO-Wageningen, and University of Sydney.

Now we will try to discern the critical factors that helped the program succeed within the context of the international wheat breeding effort.

Factors that Contributed to Long Term Success of Breeding for Durable Wheat Rust Resistance

The overarching action that shaped the success of the international breeding effort was a true cooperation or collaboration among the parties. Most of the other pillars that helped produce the success of breeding for durable rust resistance fall under this heading. Others were related to social situations or individual and institutional policy.

Free Exchange of Germplasm

The informal, free exchange of germplasm before the advent of the ISWRN and henceforth with IWIN adhered to the classic definition of "open-source" collaboration, whereby all cooperated and all benefited. This collaboration, coupled with CIMMYT training of young scientists from the NARS, produced the basic tools to achieve the goals of the programs. Because CIMMYT did not release varieties directly, countries were able to select and give their own names to new releases and thus have a sense of ownership in the breeding process and the release as well. This produced a sense of pride and showed CIMMYT as an honest broker in its activities. The value of the unbiased position by the CGIAR centers cannot be over-emphasized. Many times they have been able to help diverse countries move germplasm and scientists for the common good that ordinarily would not be possible. A key example was during the Pakistan leaf rust epidemic of 1977 and 1978. When seed of resistant varieties was not available, the president of Pakistan asked CIMMYT to intercede with the prime minister of India to sell seed of leaf rust resistant varieties. A letter was hand carried to India and they agreed to sell the seed (M. McMahon 2009, *pers. comm.*).

International Nursery System and Information Sharing

The birth of the international nursery system out of the stem rust epidemic of the early 1950s started the collaboration and set the tone for the Borlaug program in Mexico, then Latin America, and finally on to South Asia and the rest of the world. Without the free exchange of germplasm, and the nursery system as the vehicle, the incorporation and distribution of the durable rust resistance worldwide would likely not have happened.

Information sharing based on the data generated and reported, via the IWIS and its predecessors over the years, was a major factor in helping disseminate the information on rust resistance and the ultimate release of the resistant varieties. The open source system that had been so successful historically in crop improvement to help the poor is more relevant than ever in today's changing world. However, as related earlier, this has suffered as intellectual property rights have come into the picture.

Multilocation Testing System

This system, starting with the shuttle breeding in Mexico and then testing at more than 100 sites around the world, has continually broadened the gene pool of the wheat program. These are sites where wheat may be a major or minor crop and represent many different environments with unique biotic and abiotic stresses. The key, as noted in section 3, is the cycling of the best germplasm based upon the multi-site/multi-year testing results. The method is of paramount importance, in conjunction with "hotspot" testing, for the rapid incorporation of the best disease resistance. In this way, advanced lines are available to the NARS for crossing, selection of segregating populations, advanced lines, and possible rapid release after local yield trials.

Within the multilocation testing program, specific "hotspot" sites that have high variability in virulence for specific diseases, like the rusts, are selected for testing the germplasm. This method helps to increase the chances of pyramiding rust resistance genes. This technique has been confirmed as effective in increasing the probability of durable resistance, as genetic studies have shown certain resistance genes associated with durability present in the majority of released varieties (Rajaram et al. 1988). The use of hotspot testing for rusts has been an important factor in introgressing long-lasting rust resistance into CIMMYT materials.

Human Resource Development

Trained scientific personnel were as necessary as the germplasm for the national programs over the years. It is worth repeating that the young scientists' commitment and dedication were crucial. They went the extra mile to get out the germplasm and the information. As seen in Figure 3.4, human resource development was a major activity, though as the budgets decreased, so did the training. In recent discussions with international scientists and NARS scientists, it has been stated that there is a shortage of newly minted scientists who can work in the field, identify diseases, and work with breeders or vice versa. Several scientists voiced the need to emphasize that the field is where varieties are made. While not downplaying the laboratory, greenhouse, or new technology, there is clearly a scarcity of well-trained scientists who are field- oriented. Monsanto has recently announced a scholarship program in honor of Henry Beachell and N. E. Borlaug for crop breeders, because so few are being trained. They agree not to hire them but to allow them to work in the public sector (Monsanto 2009). Although CIMMYT has various training courses, the basic six-month training course that produced well rounded scientists at the B.Sc. level was the course most desired. At the same time, CIMMYT has supported many graduate students' theses work and this level of training is urgently needed as well.

Standardized data taking and quality was an important focus in the training courses. This contributed to producing reliable data that were returned for analysis and then used in the broad breeding program.

Regional Programs and Networking

In a peripheral way, regional programs had a significant effect on the use of durable type of resistance. The fact that international staff lived in the wheat-growing regions and interacted often with national staff allowed them to participate in the selection process of national and international germplasm. In areas of South America and East Africa (Kenya and Ethiopia) regional programs distributed nurseries that monitored for the rusts. Lamentably, these nurseries were discontinued in the mid-1980s.

Food Shortages

The international breeding initiative in the 1940s was born out of necessity. Mexico had severe food shortages and the government requested help from the United States. The success of the Rockefeller program into the late 1950s to early 1960s gave birth to the larger international effort in wheat and rice that arose in response to the severe food shortages in the Indian sub-continent (Paddock and Paddock

1967). Food production could not keep up with the population increase at that time and the international community responded effectively. The Green Revolution was the result.

Clear Focus on Food Production

The Borlaug program had a clear focus on food production in Mexico and its major limiting factor in wheat—stem rust. He had to battle to keep that focus throughout his career, especially in the early years (Bickel 1974). In later years, Borlaug and R. G. Anderson would tell their staff, "Don't worry about budgets or other things, your job is to get the best germplasm possible out to the farmers" (N. E. Borlaug 2009, *pers. comm.*). A persistent theme in CIMMYT was to "keep your eye on the ball"—producing food for the poor—and as Norman Borlaug recently said, "A will to win" (N. E. Borlaug 2009, *pers. comm.*).

Long Term Commitments – Funds and Staff

The Rockefeller Foundation deserves special commendation for its foresight and long lasting support of agricultural research in developing countries. Its support of the Mexican *Oficina de Estudios Especiales* headed by J. G. Harrar and the Borlaug wheat research effort, among others, allowed the program to thrive. Furthermore, the foundation was the first to sign on in support of the founding of CIMMYT. After approximately 40 years of support in Mexico and elsewhere, the Rockefeller Foundation began to phase out core funding support for agriculture, although they still supported specific projects at CIMMYT and elsewhere. Other donors such as USAID, World Bank, IADB, CIDA, ODA, and others continued to support the work that allowed the dissemination of durable resistance throughout the wheat world. The long-term commitment was and continues to be essential for agriculture research and development. In recent years, funding has decreased and become restricted to the point where the international wheat effort has been severely constrained. This will be discussed below.

An additional factor for success was the dedication of the international staff involved over the years in the CIMMYT Wheat Program. The fact that many were able to make a career of breeding, pathology, agronomy, and related disciplines meant that a cadre of experienced and knowledgeable scientists were available to produce the resistance and train the national staff necessary to get the product into the farmer's field.

Impact Assessment

Economic assessments of wheat breeding efforts have been a powerful tool to support the breeding programs over the years. Critical appraisal has created an awareness of key data in assessing contributions. This has helped focus the research effort at CIMMYT and make the center's intervention more effective. The ongoing economic assessment of how well the program was meeting its targets meant that the scientists involved were continually challenged by economists to justify their progress and achievements. In the early 1990s, the first assessment of the wheat breeding effort was made by the pioneering work of Byerlee and Moya (1993). This was followed by assessments by Heisey et al. (2002) and Lantican et al. (2005). Specific studies on rust resistance such as Smale et al. (1998) and Marasas et al. (2004) allowed for continuous feedback to scientists on the extent and value of their achievement vis a vis rust resistance.

Negative Factors that Affected the Process

Long-term support is needed to get a good return on investment in agriculture research and development. This is especially so in crop breeding. The funding for the international wheat research system had been long term and the payoffs have been excellent. The funding not only was international; the NARS supported the activity by covering the human resources, costs of planting, management, and data collection, as well as significant scientific resources in countries such as India and Brazil.

In 1980, agriculture accounted for about 20 percent of official international development support and by 2005 it had fallen to 4 percent. Several reasons were responsible:

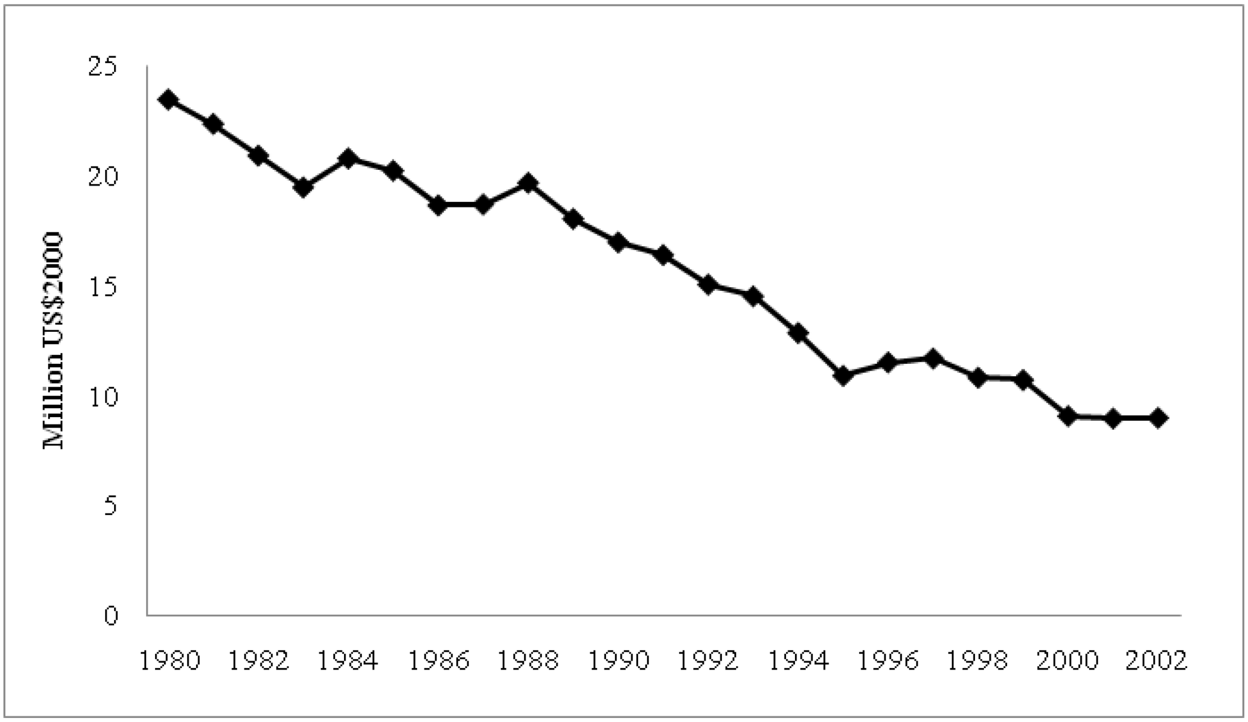
- Decreased international commodity prices
- Increased competition from support for macroeconomic reforms
- Debt relief and social development
- Opposition from environmental groups that accused agriculture of contributing to natural resource degradation (World Bank 2007)

Not only did support for agriculture decrease but there was a move away from improvement of productivity toward natural resources management and policy research.

Budget decreases, restricted flexibility and short-term focus

As the overall international agricultural development budget decreased, so did the CIMMYT wheat budget (Figure 6.1), which, in real terms, was cut more than half from 1980 to 2002 (Byerlee and Dubin 2008). The effect was seen in section 3, which describes adverse impacts on nursery shipments and training.

Figure 6.1 Trends in real budget of CIMMYT's wheat program, 1980-2002



Source: Byerlee and Dubin (2008)

Also, the share of budget allocated to unrestricted core funding fell from over 80 percent in 1990 to around 45 percent in 2006 and has fallen even further by 2008. Donors restricted funds to specific projects, very often short term, to preserve the identity of the funds. As described above, the main components of breeding and international germplasm exchange need long term core funding.

Effects of Funding Reductions on Rust Research

As the international development community reduced support to commodity research programs this had repercussions throughout all programs at CIMMYT and other CGIAR centers. During this period, CIMMYT was going through a transition phase that ultimately eliminated the wheat program as such. In 2006 the wheat program was re-established as CIMMYT went through another restructuring.

In 1988, CIMMYT wheat program had 16 pathologists (pre-doctoral fellows, post doctoral fellows and senior staff) working on diverse projects. Five were working at least part-time on rusts at CIMMYT's base and in the regions. In 1999, there were six pathologists, with two working on rusts: one CIMMYT staff and one seconded from INIFAP (CIMMYT 1988, 1999). In 1987, the USDA discontinued the ISWRN due to funding issues. From the mid-1980s to about 1990, CIMMYT decreased its pathology support in East Africa. The last CIMMYT regional pathologist/breeder left in 1989. In addition, the International Disease Trap Nursery and the Latin American Rust Nursery were discontinued due to changes in the program. Finally, in the mid-to-late 1990s, two key international rust programs that collaborated closely with CIMMYT were curtailed due to staff retirements.

It is probable that Ug99 would have been discovered several years earlier with an increased lead time for resistance breeding if these events had not occurred. With the discovery of Ug99 in Uganda, CIMMYT conducted additional germplasm screening in Uganda and Kenya between 1999 and 2005. When Ug99 appeared in Kenya in 2002, resistance data were obtained and crosses were made for this resistance at that time (R.P. Singh 2009, *pers comm.)*

Controversial Aspects of the International Wheat Breeding Efforts

High Inputs for Modern Varieties

The Green Revolution initially occurred in the irrigated environments, and additional fertilizers accompanied the new semidwarf wheat varieties. In addition, the short stature of the new wheats made them less competitive against some grass weeds, so that herbicides were more likely to be needed than with taller wheats. Therefore, in the initial period up to 1980, modern varieties (and the associated rust resistance) were related to high inputs.

However, from around 1980, the expansion in the area under modern semidwarf varieties of wheat occurred in rainfed areas, "beginning first with wetter areas and proceeding gradually to drier areas" (Byerlee 1996, p. 699). By the mid-1980s, more than 50 percent of the area sown to wheat in rainfed areas in developing countries was planted to semidwarf varieties. In India, for example, three-quarters of the 20 million ha increase in wheat from 1975 to 1995 was in rainfed agriculture (Byerlee 1996). Thus the association between modern semidwarf varieties and high inputs diminished in the post-Green Revolution period.

Furthermore, the CIMMYT wheat breeding program has been selecting wheat germplasm efficient in input use for many years. Compared to tall varieties CIMMYT germplasm requires less nitrogen and phosphorus inputs and concomitantly less land to produce the same amount of wheat (Ortiz-Monasterio et al. 1997; I. Ortiz-Monasterio 2009, *pers comm.*)

To the extent that the rust resistance was an integral part of the modern varieties, resistance was associated with the initial move to higher-input agriculture. It was not directly related because, by its nature, it obviated the use of fungicides as a regular input of wheat in modern farming systems in developing countries.

Genetic Diversity in Modern Semidwarf Varieties

Indirectly related to the use of durable resistance is the genotypic background into to which it is placed. While there have been claims that the Green Revolution reduced genetic diversity, Byerlee (1996) argued that the evidence is mixed. Although diversity was reduced in the early stages of the Green Revolution, recent works (Smale and McBride 1996, Smale et al. 2002, Lantican et al. 2005, Warburton et al. 2006) have shown that the genetic base of the CIMMYT spring bread wheat germplasm continues to broaden with the continued introgression of new sources of wheat germplasm from gene banks, land races, spring x winter wheat crosses, durum x bread wheat, synthetic hexaploid wheat, wild wheat progenitors, and alien species.

Thus while the genetic diversity of varieties generally increased in the 1980s and 1990s, the diversity of rust resistance was not so broad-based. In relation to the spectrum of durable stem and leaf rust resistance genes, we see that the arsenal at this stage is not as great as desired, although the group of resistance genes has lasted for 30 to 50 years with only limited failures. Furthermore, the immunity imparted by *Sr31* was such that it precluded detecting other genes (a masking effect) without morphological or molecular markers once the *Sr31* was present. However, the reliance on the *Sr31* complex for varieties in East Africa, Middle East, and South Asia led to vulnerability to the Ug99 strain of stem rust. It is significant that Ug99 and recent mutations of this strain attack a broad array of resistance genes. Scientists have worked to develop diverse sets of genes and forms of resistance (for example see McIntosh et al. 1995). Research is ongoing to obtain molecular markers for other stem and leaf rust resistance genes both of the major and durable, slow rusters with additive minor genes. New candidate durable type resistance genes are being studied as well as strengthening of the *Sr2* complex for stem rust and more minor genes of additive effects for both rusts (Singh et al. 2008). Critical to this work will be continued funding in the long term.

Sustainability

Financial

The development of rust resistance and its deployment in developing countries has provided a high rate of return on the investment involved. However, the success of the intervention has allowed donor fatigue and a realignment of immediate priorities for funding away from maintenance of rust resistance in some areas over time. Thus the world wheat crop was more vulnerable to the Ug99 threat as IARC funding declined over time. The financial sustainability of the development of rust resistance has been uncertain because of the shortage of funds. At the farm level, the financial returns have come at close to zero cost, and will be readily sustained if the resistance can be maintained in well-adapted varieties.

When farmers replace varieties rapidly, they are able to achieve rust resistance with the highest-yielding varieties. However, Byerlee (1996) argues that the development of durable resistance can have an economic cost if farmers replace varieties less frequently, thereby failing to realize genetic gains in yield potential in new varieties.

Environmental

There has been considerable controversy on the environmental impacts of modern varieties and the Green Revolution. However, the role of wheat rust resistance is less controversial. The use of durable stem and leaf rust resistance over the decades has been the most environmentally sensible way to control the diseases. The increased yields as a result of improved rust resistance means production can take place on smaller cropped areas, decreasing demand on marginal or stressed land for crop production to meet global food demands.

Moreover the reduction in fungicide use is helpful to the environment and is beneficial to the health of the farmer and community. Hundreds of millions of liters of fungicides would need to be applied to wheat crops around the world if the rust resistance had not been developed and deployed. Rust resistance also precludes the misuse of fungicides in the farming environment that would be a constant threat if fungicide use were widespread globally.

Critics of the Green Revolution (e.g., Griffin 1974) have questioned the sustainability of intensive cultivation, noting concerns such as the environmental consequences of soil degradation, chemical pollution, aquifer depletion and soil salinity. Evenson and Gollin (2003) note that, while they are valid criticisms, it is unclear that alternative scenarios would have allowed developing countries to meet, with lower environmental impact, the human needs of their expanding population.

Social and Political

The superior rust resistance of modern wheat varieties is reflected in the increased stability of wheat yields in more recent times (Singh and Byerlee 1990). That improved stability has been a major social benefit for farmers and consumers in developing countries.

The increased income and social benefits have been available to both large and small farmers; and indeed since the small farmers could not have afforded to use fungicides for rust control, the essence of resistance is that it benefits the poorer farmers relatively more than larger farmers. Consumers have benefited from reduced prices from the additional production. In addition, the increased yield stability with improved rust resistance has led to more stable and cohesive societies, and households, than if harvests were subject to more frequent destructive epidemics.

Without rust resistance, farmers may well have needed to consider whether they should develop alternative crop systems that reduce the reliance on wheat, or even alternative livelihood systems for some of the people involved. Such alternatives could have been extremely socially disruptive, perhaps involving internal migration or urbanization for poor farmers and their families.

While there were some political issues relating to the Green Revolution and the change to higher-input wheat production associated with it, there is nothing intrinsically political in the development of durable rust resistance—there were no “victims,” and neither the technology itself nor the process directly disadvantaged anyone. At times, the push from CIMMYT scientists and their colleagues was seen by some countries’ leaders as unnecessary interference in their seed production and distribution, as was perceived in Pakistan in the period immediately prior to the leaf rust epidemic in 1977-78. However, the free provision by CIMMYT of the seed for release by the NARS themselves meant that they had ownership of the varieties, so that any such attitudes tended to be short-lived. The future impediments to continuing successful deployment of rust resistance appear likely to be related to funding rather than any inherent political issues associated with the process.

7. LESSONS LEARNED AND CONCLUSIONS

Key Lessons Learned for Replicating the Success of Rust Resistance

The experience from the efforts to develop and maintain rust resistance has several lessons for any attempts to replicate that success in other situations. There are several key factors that need to be put into place to ensure success for any future efforts to bring about successful international agricultural programs.

Clear Focus and Adequate Resources

One lesson from the success of the implementation of rust resistance is that strong leadership is needed to ensure that a clear focus on the objective is maintained and that no-one gets sidetracked. That involves long-term funding and staffing to ensure that goals are met and achievements are maintained. As a result, donors and administrators must carefully analyze where the payoffs have been and maintain support to those programs; continuous assessment of progress towards the objective is required. New technology should be supported when it can provide advantages, but clearly they should not "throw out the baby with the bath water" in the sense of giving up a successful approach to seek improvements based on new technologies. For example, biotechnology provides a good opportunity to repeat and improve progress so far, though its role needs to be assessed carefully.

International Collaboration and Training

The success in rust resistance demonstrates clearly that a collegial approach is required, involving close collaboration between NARS, CGIAR and other international scientists. One key component of that collaborative approach is the ready exchange of genetic materials among those involved. A continuous stream of diverse germplasm is needed if initial successes are to be maintained over time. If the technology loses its effectiveness (as where the resistance breaks down), scientists must have the replacement technology available and ready to adopt. The rust resistance experience also clearly shows that human resource development is as important as the germplasm effort.

Infrastructure to Maintain Progress

When facing an evolving threat such as plant diseases, eternal vigilance and surveillance of the pathogen and host are needed. This might include, among others, an international early warning system, trap nurseries, and rust population monitoring. As discussed in section 4, no form of resistance lasts forever. *All resistances will break down sometime, and we must prepare for that eventuality*. Therefore, there can be no complacency when working with nature. For example, over time, the successful role of the IARCs in developing the global strategy for rust resistances allowed some NARS to become complacent about the threats posed. That is now evident in countries threatened by the Ug99 stem rust strain, where resources will need to be increased across a range of research skills and infrastructure to manage the rust infections and the response to them (Expert Panel 2005). While countries such as India have the resources and infrastructure to prepare for and respond to the Ug99 threat (ICAR 2008), many poorer countries need considerable external resources to meet those needs now without encountering bottlenecks (Expert Panel 2005). To ensure that such unintended consequences do not arise, anticipatory thinking is needed.

Emphasis on Generating Effective Impacts

In assessing its level of impacts, the technology had maximum impact where it addressed a significant issue for the maximum number of farmers, and where it was broadly adaptable and durable. The low or zero cost to poor farmers meant that those who most needed it could readily adopt the new technology. In particular, technology embedded in seed is likely to lead to effective outcomes, as it requires little investment by farmers to receive the benefits. It is also clear that programs to enhance the adoption of the improved technology produced significant benefits.

Free Exchange of Germplasm and Accommodation of IPR Issues

Despite its significant contribution to the success of rust resistance, the free exchange of germplasm has come under pressure within the CGIAR since the early 1990s. Declining core funding that reduced operating funds for the germplasm networks and the increased role of private sector breeding and biotechnology programs in developed countries both worked towards reducing the free exchange of germplasm. In addition, the TRIPS and CBD agreements were both signed in 1993. These all led to uncertainties and higher transaction costs with respect to international germplasm exchanges. In some cases, it has resulted in diminished germplasm movement (Byerlee and Dubin 2008). The International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) and the Standardized Material Transfer Agreement (SMTA) for all germplasm exchange are responses to the possible consequences of the agreements. Nevertheless, it will be essential to mitigate the effects of IPR to ensure free exchange of materials if similar programs are to succeed in the future.

Practical Technologies

In the future, regardless of the technologies and programs involved, it is imperative that scientists who work in the field and not only the laboratory produce the varieties and seed for the farmer. This is to ensure that the technology is directly relevant to farmers and so that the scientists can respond immediately and practically to future problems that arise.

Conclusions

In conclusion, the successful efforts of the international wheat stem and leaf rust resistance programs over the past half-century have had significant economic returns as well as positive impacts on poverty reduction, nutrition, food security and the environment. Nevertheless, decreased donor support for the programs in recent years has had negative effects, and the recent occurrence of a new strain of stem rust that defeated key durable resistance genes has put large wheat areas in developing countries at risk. It is clear that there is a critical need for continuous research and vigilance to keep ahead of the ever-changing pathogens to maintain the progress that has been made.

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2033 K Street, NW
Washington, DC 20006-1002 USA
Tel.: +1-202-862-5600
Fax: +1-202-467-4439
Email: ifpri@cgiar.org

IFPRI ADDIS ABABA

P. O. Box 5689
Addis Ababa, Ethiopia
Tel.: +251 11 6463215
Fax: +251 11 6462927
Email: ifpri-addisababa@cgiar.org

IFPRI NEW DELHI

CG Block, NASC Complex, PUSA
New Delhi 110-012 India
Tel.: 91 11 2584-6565
Fax: 91 11 2584-8008 / 2584-6572
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