Adoption and economic impact of improved wheat varieties in the developing world

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SUMMARY

During the past century wheat breeders have produced a large number of genetically improved wheat lines and varieties. This activity has led to widespread adoption of improved varieties, a steady increase in average wheat yields during the past 4–5 decades and major contributions to food security and poverty reduction. The rate of generation and adoption of improved varieties, and therefore the time lag from varietal release to widespread use, varies across regions. The remarkable success of wheat improvement hinges on the decisions of millions of farmers to adopt, or replace older wheat varieties with superior material. The present paper summarizes studies on the determinants of adoption. Because adoption is a necessary but not sufficient condition for economic impact, the present paper synthesizes key assessments of impact from different farming systems in developing countries.

INTRODUCTION

In a Presidential Address to the British Association in 1898, Sir William Crookes predicted a global shortage of wheat by 1931 (Enfield 1931). During those three decades, global production increased by 60%, driven principally by area expansion, although global average yields did rise by 11% from 0.85 tons/ha to 0.94 tons/ha. Periodic warnings of impending famine stalked the development of the wheat industry during the 20th century, including the World Food Conference in 1973; yet production expanded steadily during the century to the present 630 million tons (FAO 2006).

Reynolds & Borlaug (2006a,b) provide an overview of the international wheat breeding system. Based in part on the 1000 or more improved lines of wheat that the International Maize and Wheat Improvement Center (CIMMYT) distributes each year, National Agricultural Research Systems (NARS) release about 100 new wheat varieties each year (Lantican et al. 2005). Despite the release of nearly 1700 improved wheat varieties in developing countries during the period 1988–2002 (Lantican et al. 2005), only a relatively small number have been adopted on a substantial scale by farmers (Smale et al. 2002). Although comparatively few in number, these adopted varieties made a major contribution to global food security: Lantican et al. (2005) estimate that the annual incremental production from improved wheat varieties amounts to 14–41 million tons, valued at US $2–6 billion.

Wheat productivity increased significantly during the past century through, inter alia, improved varieties, mechanization, more effective pest and disease control, better production practices and improved farm management. Annual yield growth peaked at 2.75% p.a. in the 1980s; the subsequent slowdown has been attributed partly to the dominance of varietal replacement over initial adoption of improved varieties, but perhaps also environmental factors (Heisey 2002) and reduction of agronomic inputs due to smaller profit margins as for example in the Yaqui valley, Mexico (M.P. Reynolds, pers. comm.). Although increased yields have been offset in many farming systems by increased input prices and reduced grain prices, empirical evidence suggests that for every 1% increase in the productivity of wheat...
the extent of poverty has been reduced by 0.5–1.0% (World Bank 2005).

The present paper synthesizes evidence related to the pathway from wheat breeding to adoption to poverty reduction, supplementing the reviews of the international wheat breeding system by Reynolds & Borlaug (2006a,b). This should lead to a better understanding of the contributions of wheat improvement to food security and poverty reduction. The origins and development of the modern international wheat breeding system are briefly introduced in the next section. Regional variation in the adoption of improved varieties is summarized in the third section, followed by a review of the determinants of adoption of improved varieties. Next, the resulting impacts on household food security, farmers' incomes and livelihoods are discussed. The paper covers all types of wheat including bread and durum, as well as winter, facultative and spring wheat. Although references are made to OECD countries, the emphasis is placed on developing countries.

**GROWTH OF BREEDING CAPACITY AND WHEAT PRODUCTIVITY**

**Growth of wheat productivity**

The long run evolution of wheat productivity during 1900 to 2000 is shown in Fig. 1. The growth in average yields barely increased from 1900 until 1930 (in fact from 1800 until 1900 there was no significant yield growth). The first sustained growth in average national wheat yields was recorded in the UK during the 1930s. Growth commenced in other European countries and the USA during the 1940s; and India and Pakistan during the 1960s. Following the initiation of yield growth in the third and fourth decades of the 20th century, average national wheat yields in major wheat producing countries grew steadily during the second half of the century – for example at 110 kg/ha/year in the UK. Considerable year-to-year variability, even at low levels of productivity, is evident from Fig. 1.

Many studies have demonstrated the contribution of genetic improvement of wheat to the growth in productivity (see, for example, Byerlee & Traxler 1995; Pingali & Rajaram 1999; Evenson & Gollin 2003). More specifically, several studies have shown that CIMMYT-related germplasm has made an important contribution to international wheat breeding efforts (Byerlee & Moya 1993; Heisey et al. 2002; Evenson & Gollin 2003; Lantican et al. 2005) and continues to be used extensively by public wheat breeding programmes throughout the developing world. Whilst the growth in wheat breeding capacity in the international research system during the second half of the 20th century is well documented in the literature (e.g. Reynolds & Borlaug 2006a), even in the late 19th century and the early 20th century scientists were selecting improved wheats, for
example in the U.K. at Rothamsted Experimental Station and in Australia by Farrar. Many of their breeding objectives would be recognizable even today, for example, Mexican breeders were selecting for yield, rust resistance and drought tolerance in the first half of the 20th century (Rodriguez 2000). Nevertheless, national average wheat yields stagnated until the 1930s and 1940s.

Origins of national wheat breeding
The following vignettes of early wheat breeding illustrate the diverse sources of early germplasm and the ways in which breeding programmes were established. In the USA, hard red winter wheat has been grown on the Great Plains for roughly 130 years after being introduced from Russia around 1873. The Russian varieties performed well on the Great Plains of America because of their winter hardiness, drought resistance and early maturity, and they were able to produce fairly high yields under the variable climate on the Plains (Reitz & Salmon 1959). Many separate lots of hard red winter wheat had been imported by 1900, and thousands of selections from those had been tested in Federal and State agricultural experiment stations by the 1920s. By 1919, roughly one-third of the wheat crop in the USA was of the Crimean type, popularly referred to as ‘Turkey’. The original home of the Turkey germplasm is north of the Black Sea and the Caucasus, where the soil and climate conditions are similar to the southern Great Plains. Before the turn of the century, workers at experimental stations in the USDA soon realized that the Crimean wheat varieties were deficient in many ways and began making efforts to improve them. In the early 1900s early strains among the rather mixed introductions were isolated by pedigree selection, and several improved varieties were developed and distributed for commercial growing. When it became apparent that progress from selection alone was limited, crossbreeding of selected varieties for superior traits began in the early 1900s paving the way for the modern American wheat breeding industry.

In 1928, a conference was held in Manhattan, Kansas, USA on the coordination of interstate wheat breeding. This interstate coordination proved highly advantageous for testing and maintaining various improved varieties (Reitz & Salmon 1959). From 1900–10 to 1941–50, US wheat yield increased by roughly 5% per decade, compared with the expansion of wheat area by 9% per decade over the same time period. Today most major land grant universities (state universities with agricultural programmes) have established experimental stations, both rainfed and irrigated, with the breeding objectives of enhanced yield and yield stability. For example, Kansas State University alone operates 19 such stations throughout the state (the largest wheat-producing state in the USA) and runs performance tests on varieties that Kansas State University has released and is testing, as well as other public and private varieties.

At about the same time that Russian varieties were introduced into the USA, Mexican farmers were introducing improved varieties from Western and Southern Europe. Recognizing the importance of agricultural research, during the first decade of the 20th century the Mexican Government planned to establish experimental stations across the country (Rodriguez 2000). The first, the San Jacinto Experimental Station, was established in 1908 with the objective of, inter alia, selecting improved wheat for tropical environments (Barkin & Suarez 1983). French researchers were hired for San Jacinto but the Mexican Revolution delayed the establishment of wheat breeding. During the 1930s wheat landraces were being collected in the Yaqui Valley, Sonora, and evaluated for yield, maturity and drought resistance. These early selection activities resulted in the development of improved spring and durum wheat varieties for Central Mexico; and spring, winter and facultative wheats for the northern part of the country (N. E. Borlaug, unpublished). By 1948 seed multiplication from improved Mexican varieties had commenced. The well-known cooperative programme for wheat improvement between the Mexican Agriculture and Livestock Secretariat and the Rockefeller Foundation was launched in 1944 at a time when yields averaged about 500 kg/ha/year and imports provided one half of national consumption.

In Europe at the start of the 20th century, France was the largest wheat producer, with average yields in the range 1.2–2.0 tons/ha/year (Lecouteux 1883). At this time Europe produced three times more wheat than the USA. According to Bassi (1936), by the 1930s wheat production in the Mediterranean Basin had expanded considerably, attributable to a large extent to plant breeding and better crop management. However, the scarcity of wheat and increased bread prices during the 1930s in Italy led to civil strife. Hence the priority assigned by Italian governments to the creation of wheat research institutions for increasing and stabilizing wheat yields and consequent prices (Segre’ 1982). Italian germplasm spread to South America in the 1920s and 1930s and was used in breeding programmes in Tunisia, USA, Canada, Mexico, Russia, Eastern Europe and especially in China, where more than 10 Italian varieties had been widely grown since 1938.

Establishment of the international wheat breeding system
Following the Second World War, global leaders recognized the importance of food security to
maintain peace and therefore invested in global agricultural R&D organizations such as the Food and Agricultural Organization and in cereal crop improvement. Another factor that stimulated investments in wheat breeding was the 1950s stem rust epidemic. This caused heavy losses in North America (losses in the USA were about 60% in 1953 and 75% in 1954). Collective efforts, including international screening nurseries were supported by the Office for Special Studies and the US Department of Agriculture. Seven nations (Mexico, Colombia, Ecuador, Peru, Chile, Argentina and Canada) joined forces in screening 1000 lines selected from the world-wide wheat collection. The results of the First International Stem Rust Trial exceeded all expectations. New sources of resistance were found, some of which have persisted in popular varieties until today. An added benefit of this trial was the creation of a network through which lines and introductions could be tested and distributed to developing countries.

In response to the expressed interest of many wheat-producing countries around the world, in 1964 the Office for Special Studies (which became CIMMYT in 1966) created the International Spring Wheat Yield Nursery (ISWYN) that included lines adapted to high and low latitudes. Countries that already had wheat improvement programmes reorganized and expanded them, and countries without wheat research programmes began to develop them. The pace of interchange of wheat germplasm between NARS and CIMMYT and among NARS accelerated (Heisey 2002). Every year CIMMYT makes thousands of wheat crosses and generates around 1000 or so advanced lines, which are distributed to national programmes by way of international nursery systems: since 1966 in excess of 25000 advanced lines have been distributed, of which approximately one half were spring and facultative wheat and the balance winter and durum wheat. Multiple nurseries consisting of advanced yield trials, screening nurseries, and F2 segregating populations are distributed annually to a network of over 200 wheat research cooperators around the world who evaluate the germplasm and incorporate it in various ways into their own breeding programmes (Skovmand et al. 1997) see Table 1. Data from many of these nursery trials are then returned to CIMMYT, catalogued, analysed and made available to the global wheat improvement community. The dominance of CIMMYT crosses of wheat is stated by Byerlee (1992) who, however, also points out that there is a distinction between spring bread wheats, for which large national programmes use CIMMYT materials more often as parents in their crossing programmes, whereas in durum wheat CIMMYT germplasm is often released directly.

The contribution of the private sector to international plant breeding efforts varies not only between countries and regions, but also depending on the type of wheat. Private sector releases are observed in OECD countries, Eastern and Southern Africa, Latin America and, to a lesser extent, in Western Asia and North Africa (WANA). Elsewhere, the private sector accounted for few varietal releases (Lantican et al. 2005). Thus, a continued focus on both national and international public sector wheat improvement programmes as well as private sector firms is required (Heisey 2002).

### Table 1. Proportion of releases of improved wheat varieties by region

<table>
<thead>
<tr>
<th>Region</th>
<th>Number of varieties released</th>
<th>1966–2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-Saharan Africa (SSA)</td>
<td>191</td>
<td>0.09</td>
</tr>
<tr>
<td>West Asia and North Africa (WANA)</td>
<td>459</td>
<td>0.17</td>
</tr>
<tr>
<td>South Asia</td>
<td>369</td>
<td>0.18</td>
</tr>
<tr>
<td>East &amp; Southeast Asia (E&amp;SEA)</td>
<td>293</td>
<td>0.14</td>
</tr>
<tr>
<td>Latin America (LAC)</td>
<td>872</td>
<td>0.42</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2184</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Source: Byerlee & Moya 1993; Lantican et al. 2005

### Adoption of improved varieties

#### Variation by regions

The adoption of many technologies and improved cultivars occurs in distinct waves or phases. In relation to the adoption of improved cereal cultivars, Gollin et al. (2005) set forth three phases: the Green Revolution, based on input-responsive improved varieties; the Post Green Revolution input intensification phase with increased allocative efficiency and strong yield gains; and an input efficiency phase as input costs rose whilst prices of grain reduced. There is evidence that a fourth phase, a management revolution, is emerging, in which knowledge and management substitute for material inputs (see Dixon et al. in press), for which improved varieties, including those with specific characteristics demanded by the market, will still be required.

Building on the rapid adoption of improved wheat varieties in South Asia and Mexico in the 1960s and 1970s, successive generations of improved varieties spread over extensive areas. Improved varieties of wheat have spread more widely and quickly than any other technological innovation in the history of agriculture in developing countries (Dalrymple 1985). By 1982–83 some 0.42 of the wheat area in developing countries was sown to improved spring, facultative...
and winter varieties, including 0.43 in India, 0.16 in Argentina and 0.0 in Turkey – the proportions are much higher for spring wheat alone. By 1990, improved varieties were sown on practically all high and medium crop potential land world-wide. Figure 2 contrasts the speed of adoption and coverage by region and illustrates how quickly a majority of farmers adopted improved varieties in high potential areas, e.g. in the well-watered areas of South Asia.

It is also possible to estimate the current adoption of improved varieties by wheat environment (Trethowan et al. 2005) or, potentially, by farming system (Dixon et al. 2001). Based on the 12 distinct wheat mega-environments (ME) first proposed in 1992 by Braun et al. (as zones with similar growing conditions) and modified later by Rajaram et al. (1994) and Trethowan et al. (2005), Table 2 shows the estimated level of adoption of improved wheat by ME.

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**Table 2. Wheat varietal distribution (%) by production mega-environments, region, and wheat type, 1998–2002**

<table>
<thead>
<tr>
<th>Wheat type*</th>
<th>ME1</th>
<th>ME2</th>
<th>ME3</th>
<th>ME4</th>
<th>ME5</th>
<th>ME6</th>
<th>ME7</th>
<th>ME8</th>
<th>ME9</th>
<th>ME10</th>
<th>ME11</th>
<th>ME12</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSA</td>
<td>35</td>
<td>41</td>
<td>6</td>
<td>18</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>WANA</td>
<td>33</td>
<td>2</td>
<td>0</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>9</td>
<td>6</td>
<td>12</td>
<td>2</td>
<td>17</td>
<td>100</td>
</tr>
<tr>
<td>S&amp;EA</td>
<td>28</td>
<td>5</td>
<td>0</td>
<td>16</td>
<td>2</td>
<td>5</td>
<td>37</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>100</td>
</tr>
<tr>
<td>LAC</td>
<td>7</td>
<td>33</td>
<td>28</td>
<td>17</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>EE&amp;FSU</td>
<td>1</td>
<td>6</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>3</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>77</td>
<td>3</td>
<td>100</td>
</tr>
<tr>
<td>All bread wheat</td>
<td>16·4</td>
<td>12·4</td>
<td>5·6</td>
<td>11·8</td>
<td>1·7</td>
<td>2·3</td>
<td>12·6</td>
<td>2·3</td>
<td>2·5</td>
<td>2·7</td>
<td>25·4</td>
<td>3·9</td>
<td>100</td>
</tr>
<tr>
<td>All durum wheat</td>
<td>42·9</td>
<td>8·6</td>
<td>0·0</td>
<td>22·9</td>
<td>0·0</td>
<td>2·9</td>
<td>5·7</td>
<td>0·0</td>
<td>17·1</td>
<td>0·0</td>
<td>0·0</td>
<td>0·0</td>
<td>100</td>
</tr>
<tr>
<td>All wheat</td>
<td>18·2</td>
<td>12·2</td>
<td>5·3</td>
<td>12·5</td>
<td>1·6</td>
<td>2·4</td>
<td>12·2</td>
<td>2·2</td>
<td>3·5</td>
<td>2·5</td>
<td>23·8</td>
<td>3·6</td>
<td>100</td>
</tr>
</tbody>
</table>

* SSA – sub-Saharan Africa; WANA – West Asia and North Africa; S&EA – South & East Asia; LAC – Latin America & Caribbean; EE&FSU – Eastern Europe & the former Soviet Union.
As farmers were adopting the first generation of semi-dwarf varieties in South Asia, breeders were releasing improved, second generation, varieties. In comparison with the early semi-dwarf varieties, the second wave of improved varieties not only offered farmers higher yields but also greater tolerance to biotic stress (Byerlee & Moya 1993). Later waves of improved varieties also offered better quality grain. Thus, for a large proportion of the wheat crop in developing countries the key questions relate not to initial adoption of semi-dwarf varieties but to farmers’ decisions to progressively replace older improved varieties with new and better improved varieties.

**Speed of varietal turnover**

Variety replacement ratio is a useful indicator of the rate of farmer adoption of second- and third-generation improved varieties and of farm-level demand for improved germplasm. The rate of varietal replacement is based on the average age of varieties grown by farmers in a given year (measured in years since release), weighted by the area planted to each variety in that year. This measure, $WA_t$, is computed for a given year, $t$, as follows:

$$WA_t = \sum_i p_{it} R_{it}$$

where $p_{it}$ is the proportion of the area sown to variety $i$ in the year $t$; and $R_{it}$ is the number of years (at time $t$) since the release of variety $i$ (Brennan & Byerlee 1991). Genetic resistance to some diseases breaks down over time: replacement of seed with new varieties is, thus, essential to minimize the impacts of diseases such as rust.

Another useful, related, parameter is adoption lag, which refers to the time period required for farmers to adopt newly released varieties. Brennan & Byerlee (1991) identify two points on the adoption curve, 10 and 95% of the ‘full adoption’ for a given variety in a given farming system. The present authors suggest that 10% adoption, termed initial adoption, is largely a function of the availability of improved seed, depending on policies on seed multiplication and distribution, and the existence of innovative farmers. Whereas the time required to reach the 95% level of feasible adoption, referred to as full adoption, is a function of positive varietal characteristics, marginal benefits of adoption, and the effectiveness of the extension and local knowledge systems. During the Green Revolution, semi-dwarf varieties replaced traditional varieties very quickly due to the effectiveness of extension, rapid farmer-to-farmer diffusion and the massive net gains attributed to adoption of the 1960s improved varieties. As shown in Table 3, the speed of varietal or seed turnover today tends to be somewhat slower because the new improved varieties give only modest incremental gains over the previous varieties.

Table 3 illustrates that the developed world reaches full adoption of a new variety, on average, 2·4 years quicker than the developing world. However, it is interesting to note that early innovator farmers in developing countries seem to initiate adoption as fast as if not faster than those in developed countries, but the time up until 95% adoption generally takes longer. The relatively short adoption time in the Yaqui Valley in Mexico indicates that seed multiplication and varietal distribution are quite efficient and that farmers in that area are willing to try and quickly adopt new improved varieties. It is worth noting also that in some areas such as Parana, Brazil, initial adoption takes a relatively long time but once adoption has begun the diffusion to full adoption takes place quickly.

**Determinants of varietal adoption and replacement**

Because farmers decide, ultimately, which varieties are sown, numerous studies have been conducted on the determinants of adoption of improved varieties in less-developed countries (LDCs). Despite considerable diversity between sites (Heisey & Mwangi 1993), empirical evidence points to a number of common factors which influence the adoption of improved varieties in a wide range of farming systems. These factors include the level of education of the farmer, his resource base, the availability of credit and the intensity of demonstrations and extension work.

<table>
<thead>
<tr>
<th>Country/Region</th>
<th>Estimated lags to feasible adoption ceiling (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–10% adoption</td>
</tr>
<tr>
<td>Punjab, Pakistan</td>
<td>3</td>
</tr>
<tr>
<td>Punjab, India</td>
<td>-1·1</td>
</tr>
<tr>
<td>Yaqui Valley, Mexico</td>
<td>1</td>
</tr>
<tr>
<td>Parana, Brazil</td>
<td>4·5</td>
</tr>
<tr>
<td>Region II N, Argentina</td>
<td>-0·4</td>
</tr>
<tr>
<td>Kansas, USA</td>
<td>1·8</td>
</tr>
<tr>
<td>NSW, Australia</td>
<td>1·3</td>
</tr>
<tr>
<td>New Zealand</td>
<td>1·1</td>
</tr>
<tr>
<td>The Netherlands (winter wheat)</td>
<td>-1·2</td>
</tr>
<tr>
<td>Developing Countries</td>
<td>0·8</td>
</tr>
<tr>
<td>Developed Countries</td>
<td>1·5</td>
</tr>
<tr>
<td>Overall</td>
<td>1·1</td>
</tr>
</tbody>
</table>

Note: Negative numbers indicate that some varieties were grown commercially before their official release.

Many studies have shown a positive correlation between farmer education level and the probability of adopting improved varieties across a wide range of farming systems. It should be noted that adoption rates are not solely correlated with formal education but also with informal education and access to knowledge, which could be sourced from neighbouring farmers, membership of a farmer group or producer cooperative, or access to radio broadcasts. To cite a cross-section of the large number of studies, Lin (1990) on Chinese wheat systems, El-Beltagy et al. (2002) on Afghanistani systems, Mussei et al. (2001) on Kenyan systems and Gamba et al. (2002), Kotu et al. (2000) and Zegeye et al. (2001) on Ethiopian systems have shown the strong association of early adoption of improved wheat varieties with the education level of the farmer. Lin (1990) concluded that the education level of the household head has a positive effect on the probability and intensity of adopting new seed technology in China. In the El-Beltagy et al. (2002) study of wheat farmers in Afghanistan, it was found that education was the most important explanatory variable in the decision to adopt new seed technology. Those authors did note, however, the effect of education on the proportion of improved varieties grown and that the proportion seemed to drop over time. In the Mussei et al. (2001) study of wheat farmers in Tanzania, it was found that 0.85 of improved wheat adopters were literate compared to only 0.71 of non-adopters. Heisey et al. (1990) concluded that informal education is the driving force for dissemination of information about new varieties. Informal education may be as important as, and sometimes more important than, formal education in determining the rates of adoption. This is shown by Mussei et al. (2001) who found that information from other farmers was the most influential input for to production or adoption decisions, followed by extension visits.

In relation to other drivers of adoption, a statistically significant relationship between credit and adoption has been shown, indicating that those farmers with good access to credit have a higher probability of adopting improved wheat varieties. A study in Ethiopia concluded that the availability of credit increased the probability of adoption by non-adopters by 84.3% (Kotu et al. 2000). Numerous studies (e.g. Mussei et al. 2001; Kotu et al. 2000) show that many small farmers report a shortage of credit as the major constraint to adopting new technology: this constraint applies to both an embodied technology such as seeds and a disembodied technology such as planting date. Feder et al. (1985) claim that in areas where the adoption of divisible innovations, such as improved wheat varieties, depends on complementary investment, for example irrigation wells, the lack of access to credit can lessen the rate of adoption by smaller farmers.

Extension activity and knowledge dissemination play vital roles in the adoption of improved wheat varieties. Farmers with access to more information, through either demonstrations or extension agents, have been shown to be more likely to adopt improved varieties. For example, Mussei (2001) shows that a higher percentage of adopters of improved wheat technologies in Tanzania participated in on-farm demonstrations than the percentage of non-adopters. Doss (2003), Doss et al. (2003) and Zegeye et al. (2001) point to extension agents and neighbours as the principal sources of information about new wheat technology and that information from these sources determines adoption of improved technologies. Mussei (2001) again illustrates the importance of extension visits and the frequency of these visits in the adoption of improved wheat. Feder & Slade (1984) show that farmers’ access to more information is correlated with their willingness to adopt new technologies. They also claim that there is a threshold level of cumulative information that must be attained before the new technology is adopted.

During the 1990s, however, structural adjustment led to cuts in budgets and the dismemberment of classical agricultural research and extension services to the extent that these services are now unable to address the differing needs of farmers living in complex, diverse and risk-prone environments. Hallsworth (1987) has also reported that despite large number of extension workers worldwide, many farmers in remote areas have little contact with extension services. The architects of structural adjustment expected that fee-based private research and extension would replace the public sector services that were previously supported by government. The challenge is that few resource-poor farmers are able to pay the fees for privately provided extension services. Consequently, privately provided services have generally been directed towards larger commercial farmers (Chapman & Tripp 2003).

Many other factors influence the access to information on wheat varieties. Tiruneh et al. (1999) identified gender as a driver of adoption in the central highlands of Ethiopia. They showed that the proportion of male-headed households that adopted improved wheat varieties (0.30) was significantly higher than of female-headed (de jure) households (0.14). When combining extension visits and gender, Tiruneh et al. (1999) showed that the odds of adopting improved wheat varieties increased by a factor of 22 for male-headed households who had access to extension services disseminating relevant information about improved wheat varieties.

Theoretically, large farms should have no comparative advantage over smaller farms in the adoption of seed-embedded technologies, i.e. new wheat varieties, should be scale neutral. However,
most empirical studies counter this proposition of scale neutrality (e.g. Lin 1990; Kotu et al. 2000; Mussei et al. 2001; Zegeye et al. 2001). In fact, field studies have shown that farm size is often positively correlated with adoption rates of improved wheat. Which could be explained in a number of ways, including the likelihood that large-scale farmers have more opportunities to learn about improved varieties, as well as greater risk-bearing capacity. Another explanation for non-conformity to scale neutrality posited by Feder et al. (1985) is that even some embodied technologies such as high-yield varieties may require significant overhead set-up investments, for instance, in education, search for markets for the new variety, and the training of labour in specific practices. Heisey et al. (1990) explain the violation of scale neutrality by claiming that smaller farmers lag behind in adoption rates, not because they are reluctant to change, but because they are less likely to have full information about the new varieties in the initial stages of adoption given their lower literacy and fewer extension contacts.

In relation to complementary production inputs, Feder et al. (1985) claim that improved varieties will not be adopted unless both seeds and some fertilizers are available because the high yield potential of the improved varieties is generally only realized under conditions where soil nutrients are not a limiting factor. However, experimental evidence suggests that the performance of modern semi-dwarf bread wheat cultivars is at least equal to that of tall cultivars and landraces under conditions of low N fertility (Jain et al. 1975; Fischer 1981; Wall et al. 1984; Entz & Fowler 1989; Austin et al. 1993; Ortiz-Monasterio et al. 1997). Empirical evidence is provided by Ferede et al. (2000), who show that the use of herbicides is positively and significantly correlated with the adoption of improved wheat varieties. They show that with the use of fertilizer the probability of adopting improved varieties increases two fold, making fertilizer availability a key factor in the decision to adopt or not. Irrigation is another complementary input: with a reliable irrigation water supply many improved varieties are more profitable and adoption rates are higher.

Another set of factors influencing the adoption or replacement decision relates to the end use of the crop. Many crop varieties favoured by smallholder farmers have multiple uses (e.g. young leaves as vegetables, dried stalks for fodder or energy, in addition to grain for home consumption or sale). Improved varieties, therefore, are often assessed by farmers not only in terms of grain production per se but also in terms of the productivity and profitability of the by-products. Even if they are high yielding, improved varieties may not be attractive to farmers unless they also possess other characteristics that farmers consider important (Almekinders & Elings 2001). Farmers in marginalized areas with low agricultural potential and heterogeneous agro-ecological conditions often value the particular variety’s adaptation to low soil fertility, resistance to drought, pests and diseases, and storability of grains and seed. Hence, farmers tend to maintain crop diversity (Benin et al. 2004; Brush & Meng 1998). In relation to the adoption of improved bread-wheat varieties in Ethiopia, Jalleta (2004) found that farmers refrained from the adoption of some improved varieties of bread wheat that were promoted by the extension services because the varieties performed poorly under farmers’ particular conditions. His study also showed that farmers have multiple criteria for evaluating the varieties, of which grain yield is but one: Ethiopian farmers identified grain yield and grain quality as the main criteria governing the decision to adopt other or replace current wheat varieties. Farmers’ assessments of improved varieties do not only relate to end uses or products. As noted above, the condition for superior relative productivity of many improved varieties includes minimal abiotic stress, e.g. good soil moisture and fertility, and limited biotic stress. Moreover, the relative returns to land, e.g. yield, may be less important factors in adoption decisions than the returns to other factors of production including labour, water and capital.

Many of the above factors can be summarized under the broad heading of the ‘fit’ of the improved variety to the existing wheat farming system. Besides the more obvious factors such as labour and land shortages, there are a host of more subtle reasons for non-adoption. These include the issue of the rate of change that potential adopters can tolerate at any one time. The rate of change can become so accelerated by the adoption of certain crop varieties that some farmers cannot accommodate the disruptions to their life styles and livelihood systems (Napier 1991; Pretty & Shah 1999). Hence, it may be better to introduce relatively small changes over a longer time frame. Bunch (1982) also points out that the social consequences of a crop failure are high. When a crop is lost, a farmer is often seen as having failed the entire extended family and the farmer’s pride can be severely damaged. Hence, farmers are generally risk-averse and exercise a cautious approach to any substantial change to their farming systems.

IMPACT OF IMPROVED VARIETIES

In the aforementioned Presidential Address to the British Association, Sir William Crookes predicted a global shortage of wheat by 1931. To illustrate how improved varieties of wheat have impacted wheat production in the last century, the story of wheat production in the UK, Sir William’s homeland, is typical. It took nearly 1000 years for wheat yields
to increase from 0.5 tons/ha/yr to 2 tons/ha/yr in the UK but, as testimony to the effectiveness of wheat science, less than 50 years during the 20th century to climb from 2 tons/ha/yr to 6 tons/ha/yr (IFPRI 2002).

The impact from adoption of improved varieties can vary considerably (Pingali 2001). First, improved wheat varieties can generate significant field-level impact on yield and stability. Second, intensification of food crops often leads to the release of land, water and labour resources for on-farm diversification. Third, higher and more stable wheat yields produce people-level impacts on household food security and household income. Fourth, the combination of intensification and diversification creates further people-level impacts on wider dimensions of household livelihoods and poverty reduction, including the off-farm effects on the local economy and in more distant cities (Dixon et al. in press). Food security, livelihoods and poverty reduction can be evaluated at household, national or global levels; and in both the rural and urban settings. Household food security is determined by the multiple dimensions of food availability, including access to food (whether produced or purchased), stability of supply and accessibility, and the nutritional value of the food. The production of food depends on the agro-ecological production potential as well as available production technologies. With the advent of the Green Revolution, there was greater use of improved varieties and complementary material inputs such as fertilizer and knowledge inputs i.e. no-till practices. Thus, household food security and the value of production in developing countries, greatly improved. Morris & Heisey (2003) summarize some key methodological and practical issues, namely estimation of adoption, estimation of impact and the classical problem of attribution, which economists must confront when conducting impact assessments.

Many studies have examined the impact of improved wheat varieties on yield. Whilst recognizing that genetic improvement is only one factor causing yield increases, it is worth examining the growth rates in different regions in which, it transpires, there are great differences. South and East Asia, propelled by the Green Revolution, have benefited from the greatest advancements in yields, viz., an increase of 225% from 1961–64 to 2000–04. While the yields for Sub-Saharan Africa are still low compared with other regions, nevertheless it has seen substantial yield increases of 171% for the same time period.

It is also instructive to examine the variation in the growth of yields by production environment. Actually, the impacts of improved varieties of wheat are quite heterogeneous, corresponding to the diversity of wheat-growing environments: average wheat yields on irrigated land have increased roughly 1% per year between 1965 and 1995 (Lantican et al. 2005). In the first 20 years since the original widely successful improved varieties were released, i.e. by 1990, wheat breeders raised yield potential in irrigated areas by roughly 20% (Byerlee & Moya 1993). However, yield increased faster for the same time period for wheat planted on marginal land at roughly 2–3% in both semi-arid and heat-stressed environments between 1979 and 1995; although, in absolute terms, greater progress was made in irrigated areas because of the higher base yields. Heisey et al. (2002) estimate annual yield growth rates during 1990–97 in various environments as follows: irrigated, 2.04%; high rainfall, 0.07%; acid soils, 4.74%; dry areas, 0.51%; and heat stressed areas, 2.34%.

Whilst yield increases allow for better food security especially food entitlements for farmers through self-provisioning (own production), there has been a significant increase in the gross value of wheat production since 1960. This has arisen from both area expansion and yield increase. As noted above, yield increments can be attributed to, inter alia, genetic improvement and improved crop management including practices, inputs, mechanization and disease control. It can be assumed, therefore, that increases in yield are more closely associated with genetic progress than area expansion. The total economic impact of the benefits of the new wheat varieties released in the Green Revolution period alone, 1966–73, have been estimated at US$ 625 million in 1973, or US$ 2.75 billion (in 2005 US$) (Dalrymple 1985). The value of the incremental yield gain is one indicator of livelihood benefits to wheat producers. South Asia experienced the largest increase in values from 1961–65 to 2000–04 with a 178% increase in value of incremental yield. East Asia also experienced a large increase in production values at roughly a 118% growth in value of production for the same time period. Noting that the average global price of wheat, in real terms, has decreased overall since 1960 (adjusted for inflation, by some 40%) the growth in production values is much less than the growth in production. Because of the price reduction Latin America, which registered early gains, like Asia, in the period 1960–80, suffered a decline in value of production from 1980–2004 of nearly 20%.

The direct results of improved varieties are best known for their effect on quantity of output, but they can also enhance the quality of the wheat. One of the major impacts of improved varieties in wheat is rust resistance. Norman Borlaug took up research in rust resistant varieties in 1945 and by 1949 four new rust-resistant varieties were developed and subsequently widely planted (Dalrymple 1977). By the early 1950s, Mexico released the first wheat varieties carrying stem rust resistance. In mid-decade, the first crosses were made with semi-dwarf germplasm that came to
Mexico from Japan by way of the USA. By the early 1960s, the first high-yielding, input responsive semi-dwarf wheats were released. By the late 1960s, the major wheat-producing countries of South Asia became self sufficient in wheat, thanks in part to adoption of semi-dwarf varieties (Rajaram et al. 1998).

It is generally accepted that wheat breeding initially focused solely on increasing yield and has evolved throughout the last century to focus more on disease resistance. So while the first wave of improved varieties focused on maximizing yield gain (research oriented to productivity increase), the second wave of improved varieties not only attempted to increase yield but also to maintain these higher yields as wheat faced evolving attacks from disease and insects (so-called maintenance research). This was empirically proven during the Green Revolution when most wheat farmers replaced varieties at least twice (Dalrymple 1977). Farmers replaced varieties so as to defend yield gains in the face of disease threats, or to gain a little more yield. Breeding improved varieties that are resistant to insects and disease and tolerant to environmental stress has significantly decreased the year-to-year variation in yield and has stabilized household food security. The economic benefits of maintenance research are also reported as large. For instance, Marasas et al. (2003) indicate that while productivity enhancement is often estimated in terms of yield gains and increased supply, productivity maintenance is measured in terms of the yield losses avoided. The same author indicates that the internal rate of return on CIMMYT’s research investments in breeding for leaf rust resistant spring bread wheat was estimated at 41% and the net present value (discounted at 5%) at US $ 5.36 billion (at 1990 dollars), with a benefit-cost ratio of 27:1.

While farmers benefit from the total increased productivity, net of augmented costs, as discussed above, a major component within yield gains is the development and then implementation of new and durable varieties of wheat that are disease resistant, particularly to rust. The development of disease-resistant varieties is considered one of the major impacts accredited to improved wheat breeding. Byerlee & Moya (1993) classify genetic yield gains in wheat into three distinct categories: gains in yield potential, improvement in disease resistance, and maintenance of disease resistance. Byerlee & Moya (1993) suggest that the largest impact to wheat breeding from 1960–90 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. A summary of pure genetic yield gains is illustrated in Table 4. This disaggregates yield gains between agronomic and genetic and simply shows the contribution of international wheat breeding, attributed to genetics, in bread wheat in developing countries.

Table 4. Rates of genetic gain in bread wheat grain yield in developing countries*

<table>
<thead>
<tr>
<th>Environment/location</th>
<th>Period</th>
<th>Rate of gain (%/year)</th>
<th>Environment/location</th>
<th>Period</th>
<th>Rate of gain (%/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring Habit Wheat</td>
<td></td>
<td></td>
<td>Rainfed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irrigated Sonora, Mexico</td>
<td>1962–75a</td>
<td>1.1</td>
<td>Ethiopia</td>
<td>1967–94</td>
<td>1.45</td>
</tr>
<tr>
<td></td>
<td>1962–83a</td>
<td>1.1</td>
<td>Uruguay</td>
<td>1966–95a</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>1962–81a</td>
<td>0.9</td>
<td>Parana, Brazil</td>
<td>1978–94</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>1962–85a</td>
<td>0.6</td>
<td>(non acid)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1962–88a</td>
<td>0.9</td>
<td>Argentina</td>
<td>1912–80</td>
<td>0.4</td>
</tr>
<tr>
<td>Nepal</td>
<td>1978–88a</td>
<td>1.3</td>
<td>1966–89</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>1911–54</td>
<td>0.6</td>
<td>1971–89a</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1967–79</td>
<td>1.2</td>
<td>1988–97a</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1989–99</td>
<td>1.9</td>
<td>1988–97a</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>Northwest India</td>
<td>1966–91a</td>
<td>1.0</td>
<td>Paraguay</td>
<td>1972–90</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>1985–95a</td>
<td>0.9</td>
<td>1979–92a</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Pakistan</td>
<td>1965–82a</td>
<td>0.8</td>
<td>Bolivia</td>
<td>1986–96a</td>
<td>1.0</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>1967–85a</td>
<td>1.0</td>
<td>Central India</td>
<td>1966–91</td>
<td>0.27</td>
</tr>
<tr>
<td>Hot (irrigated)</td>
<td></td>
<td></td>
<td>Acid Soils (rainfed)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sudan</td>
<td>1967–87a</td>
<td>0.9</td>
<td>Rio Grande</td>
<td>1976–89</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>do Sul, Brazil</td>
<td>1970–90</td>
<td>3.6</td>
</tr>
<tr>
<td>Facultative/Winter</td>
<td>1930–40</td>
<td>1.4</td>
<td>Parana, Brazil</td>
<td>1969–89</td>
<td>2.2</td>
</tr>
<tr>
<td>Habit Wheat</td>
<td></td>
<td></td>
<td>RSA</td>
<td>1970–96</td>
<td>0.2</td>
</tr>
<tr>
<td>Rainfed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Each estimate is from an independent study; please refer to source for in-depth details.

a Semidwarfs only.

In a celebrated recent assessment of the Green Revolution, Evenson & Gollin (2003) found that 0.17 of the food production increase in the early Green Revolution 1960–1980 was attributable to genetic gain but an astounding 0.40 of the production increase in the period 1980–2000 was attributable to genetic progress.

The use of improved varieties not only has the potential to increase yields but can free up resources for other uses as well. This has been observed where improved varieties have allowed smaller farms, which were once dependent on the less profitable cropping patterns which would always provide the minimum quantity of sustainable staple crops such as wheat, to switch to improved varieties of wheat on less acreage. This helped and maintain the subsistence level of staple crops while allowing the remaining land to be devoted to high value/profit crops to be sent to market, thus enhancing farmers’ incomes in lower income countries. Another indirect impact that improved varieties are having is the advent of double cropping in certain areas. In Asia, adoption of improved varieties has become synonymous with double cropping where in some cases the improved varieties’ yields were not superior to local varieties but were adopted none the less because of their shorter growing period.

Who benefited
Byerlee & Moya (1993) found that the largest share of the benefits derived from wheat breeding, roughly 0.70, has flowed to farmers in irrigated areas. This is an important point because about one half of the world’s population living in poverty is located in the large irrigated tracts of South Asia alone. It is not just large-scale farmers who are reaping these benefits; small-scale farmers, many of whom have less that one hectare of land, are also widely adopting improved varieties. This notion is supported by Lipton & Longhurst (1989) and confirms that both large- and small-scale farmers have adopted improved varieties. 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 size farms.

Lantican et al. (2005) have shown that marginal areas have benefited substantially from improved wheat germplasm, contrary to some impressions. While initial gains came from the crossover of varieties from favourable environments, targeted breeding efforts have contributed significantly to more recent productivity growth in marginal environments. Increased production from marginal environments accounted for around 0.25 of the total wheat production increase in 1997. These findings show greater progress in wheat research and the huge potential for improving wheat productivity in unfavourable environments. However, there remain many factors that account for the slow adoption of improved wheat germplasm.

Though farmers are the primary beneficiaries of improved wheat varieties through increased yield and reduced variance, it should be evident that improved varieties also impact consumers as well, primarily through lower food prices which improve overall household food security. For example, the real wheat price in India paid by consumers decreased by roughly 2% p.a. from 1970–95, benefiting the rural and urban poor, where in some regions (like the Punjab) people spend roughly 20% of their income on wheat products (Harris et al. 1995). It should be noted that throughout the world a large number of small-scale wheat farmers actually purchase more wheat than they sell. When analysed as such, wheat farmers in marginal areas have captured some of the impact of the technological change in high-yielding areas.

The impact of higher yields directly affects the rural poor who reap the benefits of higher yields and also indirectly affects the urban poor who are consumers. Ravallion & Datt (1995) illustrate that it is not simply the rural poor who benefit from higher yields but also the urban poor, and they show that in India short-run poverty levels are inversely correlated with average cereal yields. They found that a range of absolute poverty measures responded in the short run to changes in agricultural wages as well as to average farm yields, which showed that wages responded to farm yields, presumably through higher labour demand, due to multiple cropping. Higher yields thus helped reduce absolute poverty through indirect wage effects, as well as through the more direct channels, including effects on both employment and on-farm productivity. According to the authors the bulk of the consumption gains to poor people since roughly 1970 are attributed to the direct and indirect impacts of agricultural growth. That being said, increased wheat yields attributed to improved varieties help reduce the poverty rate amongst the rural poor who are directly affected through higher income due to increased yields. These higher yields also help the urban poor who have to spend less of a proportion of their income, due to lower agricultural prices, on staple crops leaving more disposable income for other goods.

Improved wheat varieties not only have the potential to increase yields but also to increase grain and end-product quality. They also have the potential to lower consumer prices, and lessen environmental degradation. In their study Lantican et al. (2005) show that using 2002 adoption data, the additional amount of wheat attributed to international wheat breeding research, that developing countries produced was estimated from 14 million tons p.a. to 41 million tons p.a. The terms of financial production
gains that would be attributed to international wheat breeding research would range from 2.13 to 6.5 billion (2005 US$) for the 2002 calendar year alone. The estimated benefit-to-cost ratio for all investments in wheat breeding ranges from 16:1 to 21:1 (Heisey et al. 2002). When analysing the overall contribution of CIMMYT to improved wheat varieties around the world, Lantican et al. (2005) show that CIMMYT varieties generate between US $ 0.53 and 4.2 billion (2005 US$) per year with a benefit-cost ratio between 50:1 and 390:1. While the estimates of the impacts of international wheat breeding are difficult to precisely estimate, what is clear is that wheat breeding continues to generate massive benefits in developing countries.

In conclusion, researchers took on the challenge of the genetic improvement of wheat more than a century ago, initially in Europe, North America and Australia. This contributed to the steady increase in wheat yields witnessed in the majority of major wheat producing areas during the second half of the 20th century, and to global food security and poverty reduction. Breeders have generated a large number of improved lines and released varieties, yet only a small number of these are adopted by farmers on a large scale.

Wheat yields barely increased until the 1930s and 1940s in Western Europe and North America, and until the 1960s and 1970s in many developing countries. Growth in annual yield peaked at 2-7.5% p.a. in the 1980s, but has slowed since, partly because varietal replacement is now more important than initial adoption, but perhaps also because of environmental factors. More than a century of wheat breeding has made substantial contributions to the growth in productivity of wheat, albeit with a long lag time.

Building on the rapid adoption of improved wheat varieties in South Asia and Mexico in the 1960s and 1970s, successive generations of improved varieties have spread and now dominate the irrigated and rainfed wheat areas of the world. However, there is considerable variation across regions in the speed of adoption. The determinants of adoption of improved varieties include farmers’ education levels, the availability of credit, the farm size, and improved wheat variety demonstrations and extension activity. Though farmers are the primary beneficiaries of improved varieties of wheat through increased yield, reduced instability, increased diversification, improved household food security and income, improved varieties also impact consumers as well, primarily through lower food prices. Thus, wheat breeding can, in principle, contribute to the first Millennium Development Goal (MDG) of halving hunger and poverty reduction by 2015, and to several other MDGs, although progress to date has been slow.

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