Evaluating the impact of adapting CIMMYT wheat germplasm in China: implications for wheat productivity

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Abstract

Wheat is one of the most important crops in China. This study examines the contributions of wheat germplasm from different sources to wheat total factor productivity (TFP). Based on a unique dataset on planted area, pedigree and agronomic traits by variety for 17 major wheat-growing provinces from the past three decades, the results show that wheat TFP has grown steadily in the past three decades. On average, existing varieties are replaced by new ones in less than four years. Chinese wheat breeders have increasingly used CIMMYT breeding stocks to generate new wheat varieties, with CIMMYT germplasm contributing about 7% of the genetic material in Chinese wheat varieties during the past three decades and about 9% in recent years. More than 26% of all major wheat varieties released in China after 2000 contain CIMMYT germplasm. The use of CIMMYT gemplasm has resulted in an increase in TFP of 5% to 14% in the past three decades, depending on the measurement used. This represents from 3.8 million to 10.7 million tons of added grain. The paper concludes with policy implications for plant breeders and policy makers in China, as well as for international donors.

1. Introduction

Producing over 120 million tons of wheat per year, China is the world's largest wheat-growing nation. Wheat is China's second-most-important food crop after rice and the third most important crop overall, after maize and rice (NSBC). Despite wheat area decreasing by 17% during 1978-2012, yield gains drove production increases totaling 125%, over the same period, moving China from a major wheat importer (average annual imports of 11.5 million tons; about 13% of domestic consumption) in 1980s, to a net exporter by 2001. Over the past decade, China's wheat production has supplied from 98% to 102% of domestic demand.

The increase in wheat yields in China has been impressive. The crop had an annual average growth rate in yield of 2.49% during 1978-2012, compared to 1.26% for rice and 1.83% for maize over the same period (NBSC 1980-2013). Despite this, wheat impacts have received scarce attention, as the literature has focused on rice and overall agricultural performance.[1] An exception is Jin et al. (2002), who showed that wheat total factor productivity had grown rapidly, that new technology had accounted for most of this growth during 1980-95 and that genetic material from CGIAR (previously known as the Consultative Group on International Agricultural Research) had contributed to China's wheat productivity prior to the mid-1990s. To our knowledge, there is no rigorous analysis on the sources of wheat productivity growth in China from that period onward.

Understanding wheat productivity growth trends and their sources is of interest both for China's policymakers and, given China's weight in world agriculture and trade, for the governments, foundations, development banks and other public and private agencies that fund CGIAR research on wheat genetic resources and breeding. Ensuring national security for critical food grains such as rice and wheat has long constituted a key aim of China's agricultural policies; an emphasis that has intensified since the global food crisis of 2006-08 and is reflected in China's number-one national policy document of 2014. Given current land and water constraints and high cropping intensity, with the excessive use of agrochemicals, future wheat food security in China will depend largely on sustainably raising productivity.

This raises several important questions: What are the trends and sources for China's wheat productivity growth in recent decades? Have wheat yields in China approached their maximum genetic potential? Is CGIAR germplasm contributing to China's wheat productivity growth since the mid-1990s?

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[1] Huang and Rozelle (1996) showed that technology changes and the increasing availability of water, inorganic fertilizer and other farm chemicals raised rice yields. The successful story of rice, especially hybrid rice, in raising crop yield and improving China's food security is well-documented (Huang and Rozelle 1996; Li et al. 2009). Lin (1992) and Huang and Rozelle (1996) reported that institutional change stimulated agricultural production, particularly in China's early reform period of 1979-94.

This study aims to answer those questions and to provide empirical evidence regarding the impact in China of wheat research by the International Maize and Wheat Improvement Center (CIMMYT), with a focus on China's use of CIMMYT wheat germplasm and associated effects on domestic wheat production and productivity. Section 2 describes the data used, including official statistics and information collected through a survey. Section 3 provides a brief overview of wheat production in China. The contributions of CIMMYT wheat germplasm to Chinese varieties receive attention in Section 4. Section 5 focuses on wheat total factor productivity (TFP) and the impacts of CIMMYT wheat germplasm, based on econometric analysis. Section 6 outlines key conclusions and selected policy implications.

2. Data and Samples

This study used five datasets described below and covering the period from 1982 through 2011, except for Dataset 1, which covers 1980-2012.

Dataset 1 contains provincial and national statistics on wheat production (area, yield and production), irrigation and abiotic constraints (e.g., drought and cold damage) that affect wheat. Sources were China's Statistical Yearbook of the National Bureau of Statistics of China (NBSC, 1980-2013) and the China Agricultural Yearbook of the Ministry of Agriculture (MOA, 1982-2013).

Dataset 2 includes the areas sown to major varieties (a total of 1,873), by province, for each year during 1982-2011[2]. Major varieties accounted for nearly 80% of China's total wheat area in the 1980s-90s and on 88% in the 2000s. The names and areas of the major varieties come from both published and unpublished documents in the "Compilation of Varietal Areas for Major Crops" (MOA 1982-12). For this study, we included data from the top 17 wheat production provinces, which accounted for 98% of China's total wheat area in 2011[3].

Dataset 3 provides detailed pedigree information for most of the varieties listed in Dataset 2. These data resulted from an exhaustive review of published books and papers, on-line materials and unpublished documents, as well as personal interviews. For each variety, we traced the pedigree only to the point where a non-Chinese (that is, from CIMMYT or the rest of world) parent appeared. In the end, we obtained pedigree information for 1,534 Chinese varieties and 59 non-Chinese varieties; that is, varieties that were introduced to China and directly used in field production during 1982-2011. Despite our best efforts, we were unable to obtain pedigree information

[2] A variety grown on at least 6,667 hectares (ha) in China in a given year is considered "major."

[3] The 17 wheat production provinces include Henan, Shandong, Hebei, Anhui, Jiangsu, Sichuan, Shaanxi, Xinjiang, Hubei, Gansu, Shanxi, Inner Mongolia, Yunnan, Heilongjiang, Guizhou, Ningxia and Chongqing (Appendix Table 2). Because Chongqing was a part of Sichuan in the early period, that province was merged with Sichuan in the analysis to produce consistent time-series data; all data presented are for these 16 provinces and henceforth referred to simply as for "China."

for 280 major Chinese wheat varieties — about 15% of the total from Dataset 2. Based on personal interviews, many of these are landraces whose pedigrees would be very difficult to trace; we have classed them as purely Chinese germplasm, with no CIMMYT contribution. Major published sources of information for Dataset 3 included: 1) Chinese Wheat Improvement and Pedigree Analysis (Zhuang 2003); 2) Catalogue of Chinese Wheat Varieties (1983-1993) (Jin 1997); 3) Catalogue of Chinese Wheat Varieties (1962-1982) (Jin 1986); 4) Chinese Wheat Varieties and Their Pedigrees (Jin 1983); 5) The China Crop Variety Query System[4].

Dataset 4 includes information on major traits for each variety, collected mainly through an extensive desk survey and interviews, using the same sources as for Dataset 3. We sought to include data on growth habit (spring vs winter), yield potential, growth period, plant height, disease and lodging resistance and cold and drought tolerance, sourcing this information from pre-release varietal evaluation/demonstration trials. Because different regions have different needs, not all of the preceding traits are recorded or reported during varietal testing and registration (see Appendix Table 1). Missing information on specific traits could also be due to a variety having no significant advantage for those traits, or simply because we could not ascertain whether or not the data were available, given the time and budget constraints of this study. Nonetheless, the Dataset contains information on wheat type for 94% of the varieties in Dataset 3, on yield potential for 85% of the varieties and on disease resistance for 100% of the varieties (Appendix Table 1).

Dataset 5 details wheat production inputs and outputs for major wheat-producing provinces. Drawn from the Agricultural Commodity Cost and Revenue Statistics Compilation (NDRC 1980-2012), the data cover quantities and total expenditures, as well as price indices for major agricultural inputs during 1980-2011 from the China Statistical Yearbook (NBSC 1980-2012). NDRC data on chemical fertilizer use per unit land area were not consistent over time, in the NDRC. Specifically, chemical fertilizer use in the 1985-1990 and 2000 compilations was reported as total fertilizer inputs by aggregate weight, rather than in amounts of elemental N, P and K applied, as reported for all other years. We therefore used total expenditures and fertilizer prices to estimate N, P and K applications for 1985-1990 and 2000.

3. Overview of Wheat Production in China

China has the world's second-largest wheat area after India and is the world's largest wheat producer. At 24.2 million ha, China's harvested wheat area accounted for about 11% of the global total during 2010-12. The national average wheat yield is 4.8 tons per ha (t/ha) – well above the global average[5] – and China produced more than 117

[4] Supported by the National Agricultural Technology Extension and Service Center at MOA, this system provides a partial listing of major varieties approved after 2000.

[5] Among the world's four leading wheat producers, China's average wheat yield was 55, 60 and 140% higher than those of the USA, India and Russia, respectively, during 2010-2012.

million tons annually, representing 17% of world wheat output over the same period (FAO).

Prior to 2000, wheat was China's second-most-important grain, accounting for 25 to 27% of the total national area sown to food grains. The rising demand for feed grain has driven a significant expansion of maize area, and wheat is now third after maize and rice but still accounted for nearly 22% of China's grain area in 2012 (NBSC).

Wheat production in China has grown steadily throughout the last several decades, except for a short period of stagnation from the late 1990s to the middle 2000s (Figure 1). In the early reform period (1980-85), wheat production increased more than 50% (Table 1 and Figure 1). Wheat production growth slowed during 1985-97, compared to the early 1980s, but was still a brisk 3.2%. Annual wheat imports fell from about 15 million tons in the late 1980s to nearly nothing in the late 1990s, by which time there was oversupply of wheat in China (NBSC 1990-2000). The resulting expansion in domestic wheat stocks caused wheat prices to fall (Sonntag et al. 2005) and discouraged farmers from growing the crop, largely explaining the diminished wheat area and yields during the late 1990s and early 2000s (Figure 1). After falling during 1998-2003, wheat *production* has resumed its steady growth despite a continuous reduction in wheat *area* since 2004. By 2012, wheat production in China had almost regained the historically-high levels of 1997 (Figure 1).

Expanded wheat production has come mainly from yield growth (Figure 1), which has been the central goal of policies on technology and investment for wheat and other crops. While less dramatic than the well-known story of hybrid rice discovery and expansion, wheat farmers have benefitted from rapid and continual technical advancements in recent decades. Chinese wheat breeders acquired rust resistant, semidwarf varieties from CIMMYT in the late 1960s and incorporated desirable traits from that germplasm into their own varieties. By 1977 farmers were growing semidwarf wheats on about 40% of China's wheat area; by 1984, this number rose to 70% (Rozelle and Huang, 2000) and, as of the 1990s, it would be difficult to find anything other than improved semidwarf varieties in China.

Partly due to the new varieties, average wheat yields in China nearly doubled during 1980-95, rising from 1.9 to 3.5 t/ha (Table 1). Rozelle and Huang (2000) showed that, in addition to investments in agricultural research and extension, investment in irrigation contributed to the rapid growth of average wheat yields to the late 1990s. A short period of stagnation in wheat yield growth at that time (Figure 1) was followed by a rebound to an average 2.4% growth each year during 2001-2012.

Statistics on wheat production by variety and province in China are reported in two categories based on the sowing season. One is "winter wheat," which is sown in autumn and can overwinter.[6] However, The other is “spring wheat,” which is sown in spring. In spring wheat production regions, most of the wheat has spring habit. We use the above definitions throughout this report in referring to winter wheat and spring wheat.

Based on the above, China is dominated by winter wheat (Table 1). Winter wheat accounted for 82% of total wheat area in 1980, 84% in 1990 and more than 90% after 2000. By 2011, winter wheat covered 22.6 million ha and spring wheat 1.7 million ha. The average yield of winter wheat has grown more slowly than that of spring wheat, but winter wheat is higher-yielding than spring wheat (4.9 vs 3.9 t/ha, in 2011).

The large differences in area and yield between winter and spring wheat are associated with the regional distributions of these two types of wheat in China. Wheat production has remained significant in northern China’s maize-wheat region (Figure 2). Wheat area in all provinces except for Anhui, Henan and Jiangsu has gradually decreased during 1980-2010 (Figure 2), and wheat production has increased significantly in major wheat production provinces (Figure 3). The largest growth in wheat production in the past three decades occurred in Henan, Hebei, Shandong and Anhui (Figure 3). Obviously, the increase in wheat yield has been a primary source of production growth.

4. Wheat Varieties and CIMMYT’s Contribution

Number of Varieties and Varietal Turnover

A large number of wheat varieties has been developed and grown in China. On average, wheat farmers grew 295 major varieties each year during 1982-2011 (last row, Table 2). For the provinces studied, the average number of major wheat varieties adopted annually by farmers was 24.

There has been a slight rising trend in the number of varieties over time. Although the rising trend is not linear, the average annual number of new varieties adopted by farmers increased from less than 300 during the 1980s to more than 360 in recent years (column 1, Table 2). This is due largely to a significant increase in the number of varieties released. There was a similar trend at the provincial level (column 2). While no study has examined the reasons behind this rising trend, an improved plant breeding capacity and commercialization by the seed industry may help to explain the observations (Hu et al. 2010).

Annual average varietal turnover[7] for wheat in China was also an impressive 0.28 during 1982-2011 (Table 2), meaning that 28% of varieties planted by farmers each

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[6] Note that the term “winter wheat” in this report does not imply habit, as in “winter, facultative and spring habit wheats.”

[7] The replacement of varieties already grown by newly-introduced ones. It ranges from zero (no new variety replacement) to 1 (all existing varieties were replaces by the new varieties within one year).

year were new varieties. The lack of a clear, changing trend over time may suggest that, despite the increasing number of wheat varieties adopted, wheat farmers in China have grown accustomed to replacing the varieties they use every 3.6 years (1/0.28), on average.[8]

The Contribution of CIMMYT Germplasm to Wheat Varieties in China

We have used two approaches to examine the contribution of CIMMYT germplasm to China's wheat varieties, both based on pedigree analysis for all major wheat varieties identified in this study.

The first approach was to determine whether or not a variety contains CIMMYT germplasm, using available pedigree data. The variable created in this way is an indicative or dummy variable (yes or no) and we call it an "extensive" measure of CIMMYT's germplasm contribution. As a refinement, we divided all major wheat varieties (1,873) into four categories (Table 3): (i) varieties developed by CIMMYT and used directly by Chinese farmers; (ii) varieties with a CIMMYT parent, known as "first-generation" CIMMYT varieties; (iii) varieties with a grandparent or earlier parent from CIMMYT germplasm, known as second- or higher-generation CIMMYT varieties; and (iv) varieties that contain no CIMMYT germplasm. These groups are exclusive and their shares add up to 100% of all major wheat varieties in China. The approach focuses on the number of varieties but does not account for area coverage.

In the second approach, which we term an "intensive" measure, we calculated the genetic contribution of CIMMYT germplasm to each major Chinese wheat variety using the coefficient of parentage (COP) and considered the area sown to the variety, for each year during 1982-2011. Based on pedigree data and assigning a COP in a continuous range of [0,1], we gave geometric weights to parents (0.50/parent), grandparents (0.25/grandparent) and so on. Direct introductions from CIMMYT were assigned a COP of 1. We assumed that the parental genetic contribution to posterity was additive. We then weighted the COP for each variety based on the area sown. The area-weighted contributions of CIMMYT germplasm to each variety were measured at the provincial, regional and national levels.

Based on the above two approaches, Table 3 presents the sources of germplasm of major wheat varieties in the past three decades at the national aggregate level. We divide the sources of germplasm of the major wheat varieties into two groups, CIMMYT and non-CIMMYT. The later includes those from both China and other countries. Therefore, the sum of the sources from CIMMYT and non-CIMMYT equals 100%.

In general, the contribution of CIMMYT's germplasm to China's wheat varieties is significant. In the past three decades, based on the extensive measure, the proportion

[8] Leading varieties are often grown much longer than this.

of major wheat varieties that had CIMMYT's germplasm was 17% (column 1, Table 3). Among the major wheat varieties planted in the past three decades in China, approximately 2% constituted direct use of CIMMYT lines by Chinese farmers (column 2, Table 3). Chinese wheat varieties with a first of higher generation CIMMYT parent accounted respectively for 5% and 10% of all major wheat varieties grown in China over the past three decades (columns 3 and 4, Table 3). Based on the intensive measure, our results show that CIMMYT contributed about 7% of China's wheat germplasm, weighted by area sown to each variety, in the past three decades (column 6, Table 3). To state this another way, CIMMYT was the source of 7% of all germplasm for all seed of 1,873 major wheat varieties used by Chinese farmers during 1982-2011.

Furthermore, the contribution of CIMMYT's germplasm to China's wheat varieties has grown over time (Table 3). Based on the extensive measure, the proportion of varieties with CIMMYT's germplasm increased from less than 10% in the early 1980s to nearly 25% by 2011 (column 1, Table 3).

The pathway of CIMMYT's impact on China's wheat has also changed. In the early 1980s, CIMMYT germplasm reached farmers mainly in either of two ways: 1) direct introductions, which accounted for more than 4% of Chinese wheat varieties in that period; or 2) use of CIMMYT germplasm as first-generation parents by Chinese breeders. More recently, direct introduction of CIMMYT lines has declined, whereas use of CIMMYT germplasm in Chinese breeding programs has steadily increased. The proportion of China's major wheat varieties with the CIMMYT's germplasm through this channel had increased from 5.04 (4.32+0.72, row 1, Table 3) in 1982-1985 to 23.44 (4.41+19.03) in 2006-2011. In addition, based on the intensive measure, CIMMYT's germplasm contribution to Chinese wheat varieties has more than doubled in the last three decades (column 6, Table 3).

There are several explanations for the changing pathways and intensity of CIMMYT's contributions to Chinese wheat varieties. In the early 1980s, China's wheat breeding program was in its infancy and its capacity was not strong (Huang and Hu 2008). Average wheat yields were low (Table 1) and wheat varieties suffered seriously from rust diseases, especially stripe rust (*Puccinia striiformis* f.sp. *tritici*). During the 1970-80s, CIMMYT developed numerous high-yielding, rust-resistant semidwarf wheat varieties (e.g., Mexipak 65, Mexipak 66, Cajeme F71, Siete Cerros), which were directly introduced for use mainly in China's northern spring-winter mixed and southwestern winter wheat regions (Zhuang 2003).

By the late 1980s, the capacity of China's crop plant breeding programs had improved significantly and, as a result of the Open-Door Policy, academic exchanges with CIMMYT and the rest of world expanded and accelerated. The number of Chinese researchers participating in CIMMYT visits, training activities and collaborative research programs increased rapidly after the early 1990s (see Huang et al. 2014). In

1997 CIMMYT opened an office in Beijing to further collaboration, help provide new scientific information and technology to Chinese researchers and facilitate the international exchange of wheat seed and genetic resources.

With heightened collaboration in wheat research and the greater use by Chinese breeders of new CIMMYT varieties, it was only a matter of time before CIMMYT germplasm made its presence felt in Chinese wheat varieties.

CIMMYT Germplasm Contributions to Traits

To assess the contributions of CIMMYT's germplasm to major traits of China's wheat varieties, we analyzed Dataset 4 and grouped results either as quantitative or qualitative / category-type traits. The results for quantitative traits in varieties with CIMMYT germplasm are impressive, with statistically significant superiority for all traits except wet gluten, wet gluten content and test weight (Table 4). For example, the average yield during 1982-2011of varieties with CIMMYT germplasm was 5,887 kg/ha, compared to 5,484 kg/ha in varieties without CIMMYT germplasm. The varieties with CIMMYT germplasm also had shorter growth period and plant height, as well as more crude protein content, higher grain weight and more grains per spike. The most marked trait advantages occurred in varieties derived from China x CIMMYT crosses (columns 3 and 4), rather than in direct releases of CIMMYT germplasm (column 2). In general, varieties with CIMMYT contributions also showed better disease resistance but less resistance to lodging or tolerance to drought and cold (Table 5). For example, 33% of the varieties with CIMMYT germplasm were highly-resistant to stripe rust, China's number-one wheat disease, compared to 29% for non-CIMMYT varieties. Findings for leaf rust (*Puccinia triticina*) and powdery mildew (*Blumeria graminis f.* sp. *Tritici*) were similar.

5. Impact of CIMMYT on Wheat Productivity in China

Calculating Wheat Total Factor Productivity

We calculated the change in total factor productivity (TFP) for wheat in China using the standard Divisia index methods and applying the Tornquist-Theil index. The Tornquist-Theil index can provide consistent aggregation of inputs and outputs under the assumptions of competitive behavior, constant returns to scale, Hicks-neutral technical change and the separability of input and output. Because current factor prices are used to devise the weights for aggregating the input index, quality improvements in inputs are incorporated (Capalbo and Vo 1998). A similar approach has been used in many other studies: e.g., the productivity analyses for agriculture in South Asia by Rosegrant and Evenson (1992) or for major grains in China by Jin et al. (2002).

Expressed in logarithmic form, the Tornquist-Theil TFP index for each province and the nation as a whole is defined as:

$$\ln(TFP_t/TFP_{t-1}) = \ln(Q_t/Q_{t-1}) - 0.5\cdot\sum_i (S_{it} + S_{it-1})\cdot\ln(X_{it}/X_{it-1}) \qquad (1)$$

where Q_t is the wheat output (yield in kg/ha) in the t^{th} year; S_{it} is the share of the i^{th} input in total cost; X_{it} is the i^{th} input, including labor, seed, fertilizer, pesticide, machinery and equipment, and other inputs (e.g., farm plastic film, animal traction), and other material inputs. Setting TFP in the base year to 100, the time trend of TFP indices for each province or whole China can be estimated by accumulating the changes over time based on equation (1) using Dataset 5.

Results for Wheat Total Factor Productivity

Although we use provincial TFP in the ultimate multivariate analysis of the impact of CIMMYT germplasm, the discussion of aggregate national TFP can provide insights on overall trends in China's wheat productivity. Figure 4 shows the trends of output (or yield), input per hectare and TFP indices for 1982-2011. In general, China has experienced rapid and dramatic growth (more than 200%) in wheat TFP during this period, largely attributable to rising wheat yields and slightly to reduced costs for wheat production inputs (Figure 4). While not presented in Figure 4, our data show as well that the labor inputs decreased by about 60% due rising wages during 1982-2011, accompanied by an increase in capital inputs such as mechanization and chemical inputs.

National wheat TFP growth, however, has fluctuated over the past three decades (Figure 4). The rapid growth in the early 1980s is consistent with previous findings on agricultural productivity growth (Lin 1992; Fan 1991) and on crop specific TFP growth (Huang and Rozell 1996; Jin et al. 2002). The stagnation of wheat TFP growth in the second half of 1980s resulted from a moderate rise in input costs and moderate growth in wheat yield. Wheat TFP restarted its high growth in the early 1990s, except for stagnation during 1998-2003 and 2009-2011 (Figure 4).

Modeling the Impacts of the CIMMYT Germplasm

To examine the impact of CIMMYT germplasm on wheat productivity in China, we used the following multivariate regression model:

$$TFP_{jt} = a + b\cdot CG_{jt} + c\cdot Z_{jt} + e_{jt} \qquad (2)$$

where j denotes province, t indexes time (year), and CG is the contribution of CIMMYT germplasm. The latter was measured in two ways, extensive measure and intensive measure:

1. Extensive measure: in the regression, we use the following two alternatives to define extensive measure. The first is the percentage of major wheat varieties that contain CIMMYT germplasm (row 1, Table 6). The second uses two separated variables: a) the percentage of China major wheat varieties that were released from CIMMYT and directly used in production in China (row 2, Table 6), and b) the percentage of China major wheat varieties that belonged to the first- and higher-generation CIMMYT varieties (row 3, Table 6).
2. Intensive measure: the percentage of the major wheat varieties with CIMMYT germplasm, weighted by area sown to each variety (row 4, Table 6).

In addition to the variable "CG", to explain changes in wheat TFP over time and across provinces, equation (2) includes a set of potentially significant variables (Z) such as the proportion of irrigated cultivated land, the proportion of crop area affected by drought and by frost[9] and time trend, which represents factors — such as technology — that have changed over time. The term e_{it} is the idiosyncratic error term. Marginal effects to be estimated include b and c. A summary of statistics of both dependent and independent variables are presented in Appendix Table 4.
Equation (2) is estimated using ordinary least squares (OLS) based on three alternative measurements for the contribution of CIMMYT germplasm to China's wheat varieties.

Impacts of CIMMYT Germplasm

In general, all models performed well (Tables 6). The R^2 for regressions was about 0.55. Most estimated parameters were statistically significant and the signs of the estimated parameters for four variables of *X* were also as expected. For example, the positive parameters for the proportion of irrigated cultivated area in all specifications of equation (2) implied that wheat TFP increased with irrigated area (row 5, Table 6). Parameters for the two abiotic constraint variables — drought and frost — were negative in most specifications, which suggested that increased incidence of drought and frost reduces TFP, as would also be expected. After controlling for the effects of other variables, the estimated time trend parameter ranges from 2.42 (row 8, Table 6) to 2.90 (row 8, Table 6), with statistically significance at 1%, which means that China's wheat TFP has been growing annually at about 2-3% over 1982-2011, due to technology change and other observable changes.

Of most interest for this study are the estimated parameters for the contribution of CIMMYT germplasm to China's wheat varieties. The striking finding is that all the four parameters for this variable are positive and statistically significant at 1% (row 1-4, Table 6). For example, the parameter is 0.75 (row 1, Table 12), which implies that if the proportion of varieties with CIMMYT germplasm increased by 1%, China's wheat TFP would increase 0.75%. In the past three decades, the proportion of Chinese

[9] Wheat-specific data for drought and frost were not available, so we assumed that recorded occurrences of such nature disasters affected all crops, including wheat.

wheat varieties with CIMMYT germplasm increased by 18.6%, from 7.5% in 1982 to 26.1% in 2011 (Appendix Table 3), which suggests that use of CIMMYT germplasm had increased China's wheat TFP by about 14% (18.6% x 0.75). The results also provide additional information on CIMMYT germplasm impacts, the impacts are statistically significant both for direct releases of CIMMYT germplasm (row 2) and for varieties derived from crosses with CIMMYT germplasm (row 3).
Based on the intensive measure (the proportion of CIMMYT germplasm), Table 6 further confirms CIMMYT's impact on wheat productivity growth in China. The estimated parameter of the proportion of CIMMYT germplasm is 0.92 and statistically significant at 1%. The proportion of genetic material from CIMMYT increased from about 4% in the early 1980s to 9% in recent years (Table 3) and the impact on China's wheat TFP was 4.6% (5% x 0.92). The larger impact (14%) for the extensive measure could result from the approach (whether or not a variety has any CIMMYT germplasm, 1 or 0) overstating the CIMMYT contribution, whereas the intensive measure does not consider the quality or performance of agronomic traits from CIMMYT and other sources and may therefore underestimate the impact of germplasm contributions.

6. Conclusions

On average, Chinese farmers grew nearly 300 major wheat varieties each year over the past three decades and more than 360 yearly as of the late 2000s. Varietal turnover was fast.In general Chinese farmers replace existing wheat varieties with new varieties in less than 4 years.

Most wheat varieties that came to market and were rapidly adopted by farmers had been developed by Chinese wheat breeders. At the same time Chinese breeders used CIMMYT germplasm increasingly to generate new wheat varieties. This study showed that CIMMYT germplasm accounted for about 7% of the genetic makeup of major wheat varieties in China in the past three decades and about 9% in recent years. If measured by the proportion of wheat varieties containing CIMMYT germplasm, the number exceeded 26% after 2000. This relatively high impact is disproportionate to the size of the CIMMYT wheat breeding program[10], which is tiny compared to that of China's national wheat R&D program.

In general, varieties containing CIMMYT germplasm show better agronomic performance and often have higher yield, higher grain weight, more grains per spike, a shorter growth period, shorter plant height and more crude protein content. Moreover, this study showed that, on average, varieties containing CIMMYT germplasm feature improved resistance to several major diseases.

[10] CIMMYT investments in wheat improvement, defined as breeding and including molecular approaches, pathology, physiology and quality but excluding investments in seed production, wide crossing and pre-breeding, have not surpassed US $20 million per year during the last three decades.

This study also examined the impacts on the productivity of China's wheat varieties through the introduction of CIMMYT germplasm or its enhanced traits, examining the effects on wheat TFP. The results were striking, with impacts that were large and rising over time. Compared with non-CIMMYT germplasm, CIMMYT gemplasm brought an increase in China's wheat TFP in the range of 5% to 14% in the past three decades. Considering that the average annual wheat production in China was 76.6 million tons during 1981-85. The above percentages represent added wheat production of from 3.8 to 10.7 million tons.

The results of this study have important implications for plant breeders, policy makers in China and international donors. First, the results provide further motivation for Chinese wheat scientists to strengthen their collaboration with international breeding programs. Second, China's investment in agricultural research has increased significantly since the early 2000s. Given the large contribution of CIMMYT to China's wheat productivity, the government could improve national food security by increasing its commitment to international wheat research. Third, this study provides new evidence of impact and more reason for international donors and development agencies to increase their investment in CGIAR germplasm development programs and collaborative work between CGIAR centers and national agricultural research programs. Following on from China's successful experience as documented in this study, low-income and emerging countries can benefit considerably by heightening their effective collaboration with CIMMYT and other CGIAR centers.

References

Capalbo,S.M.and T.T.Vo. 1998. “A Review of the Evidence on Agricultural Productivity and Aggregate Technology.”Agricultural Productivity:Measurement and Explanation,ed.S.M.Capabo and J.M.Antle.Washington,D.C.:Resource for the Future.

Fan, Shenggen. 1991. "Effects of Technological Change and Institutional Reform on Production Growth in Chinese Agriculture." American Journal of Agricultural Economics (73):266-275.

Hu, Ruifa, Jikun Huang and Cheng Xiang. 2010. China’s Seed Industry: Development, Challenge and Policy, Forum on Science and Technology in China, 12 (2010): 123-128.

Huang, Jikun, and R. Hu. 2008. Development and Reform of National Agricultural Research System: Policy Evaluation and Recommendation (in Chinese). Policy Brief: PB-07-3, CCAP, Chinese Academy of Sciences, Beijing.

Huang, Jikun and Scott Rozelle. 1996. "Technological Change: Rediscovering the Engine of Productivity Growth in China's Agricultural Economy." Journal of Development Economics. 49(July):337-69.

Huang, Jikun, Cheng Xiang and Yanqing Wang. 2014. “Hidden Values of CGIAR’s Training Program on NARS’ Research Capacity: A Case Study of CIMMYT on China’s Wheat R&D Productivity” Working Paper, Center for Chinese Agricultural Policy, Chinese Academy of Sciences.

Jin, Shanbao (ed.). 1983. Chinese Wheat Varieties and Their Pedigrees. Agricultural Publishing House, Beijing.

Jin, Shanbao (ed.). 1986. Catalogue of Chinese Wheat Varieties (1962-1982). Agricultural Publishing House, Beijing.

Jin, Shanbao (ed.). 1997. Catalogue of Chinese Wheat Varieties (1983-1993). Chinese Agricultural Publishing House, Beijing.

Jin, Songqing, Jikun Huang, Ruifa Hu and Scott Rozelle. 2002. “The Creation and Spread of Technology and Total Factor Productivity in China’s Agriculture.” American Journal of Agricultural Economics, 84(4) (November 2002):916-930.

Li, J., Y. Xin, and L. Yuan. 2009. Hybrid Rice Technology Development: Ensuring China’s Food Security. IFPRI Discussion Paper 00918, Washington DC.

Lin, Justin Yifu. 1992. "Rural Reforms and Agricultural Growth in China." American Economic Review, 82:34-51.

MOA (the Ministry of Agriculture), 1982-2013. China Agricultural Yearbook. Beijing: China Agricultural Press.

NBSC (the National Bureau of Statistics of China), 1980-2013. China’s Statistical Yearbook. Beijing: China Statistical Press.

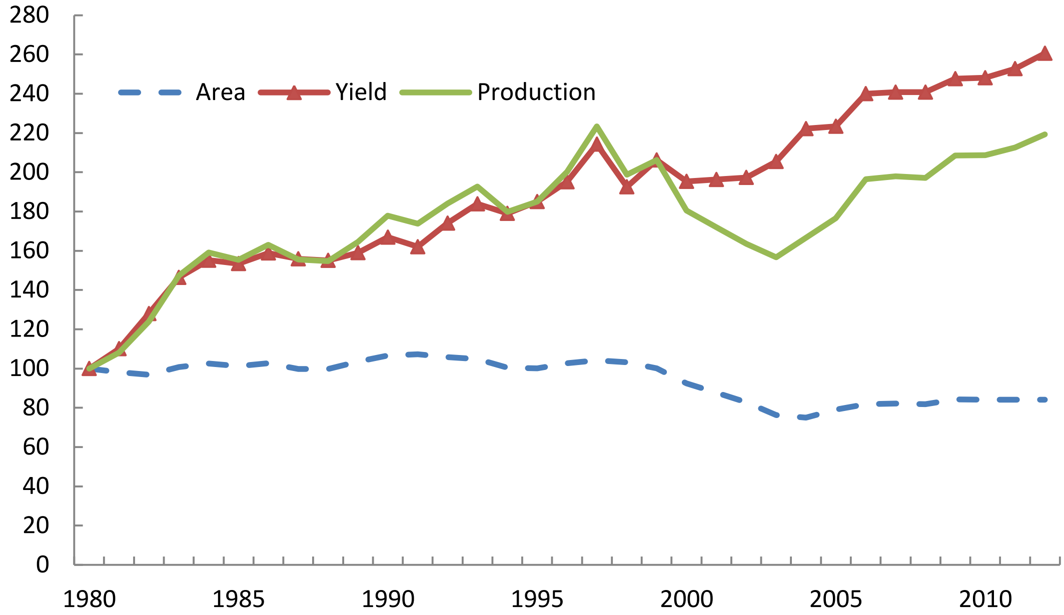
Rosegrant M.W.,and R.E.Evenson.1992."Agricultural Productivity and Sources of Growth in South Asia," American Journal of Agricultural Economics (August 1992):757-761.

Rozelle, Scott and Jikun Huang. 2000. "Transition, Development and the Supply of Wheat in China," Australian Journal of Agricultural Economics, 44(2000):543-571.

Rozelle, Scott, Erika Meng, Songqing Jin, Ruifa Hu, and Jikun Huang. 2000. "Genetic Diversity and Total Factor Productivity: the Case of Wheat in China," Working Paper WP-00-E9, Center for Chinese Agricultural Policy, Chinese Academy of Sciences.

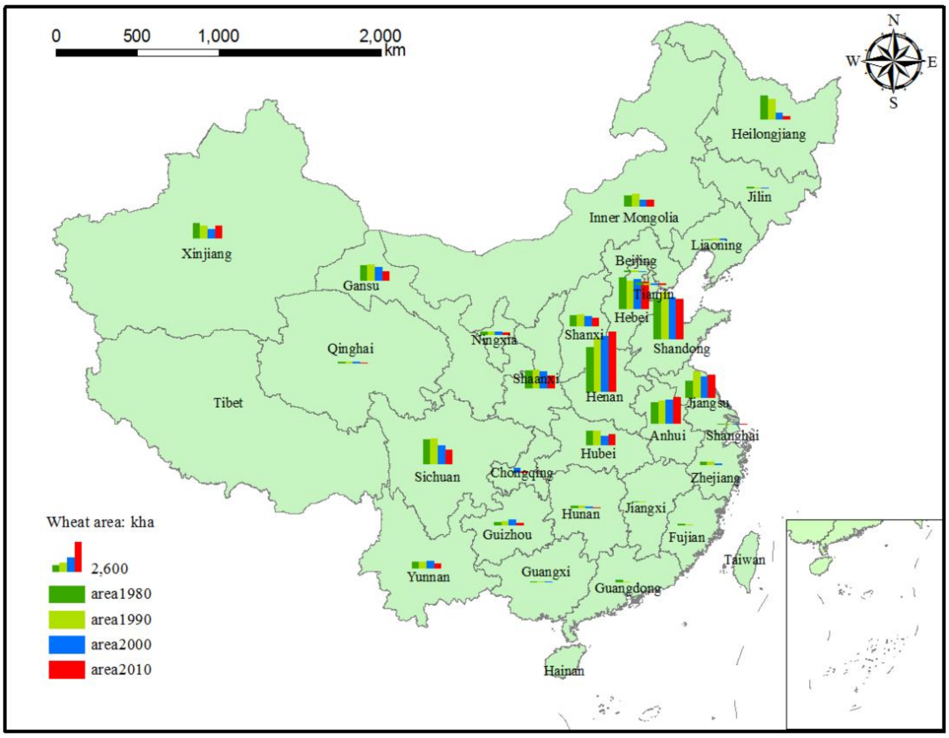
Sonntag, Bernard H., Jikun Huang, Scott Rozelle and John H. Skerritt. 2005. CCICED Task Force, China’s Agricultural and Rural Development in the Early 21st Century, Australian Government, Australian Centre for International Agricultural Research, 2005.

Zhuang, Qiaosheng (ed.). 2003. Chinese Wheat Improvement and Pedigree Analysis. Chinese Agricultural Publishing House, Beijing.



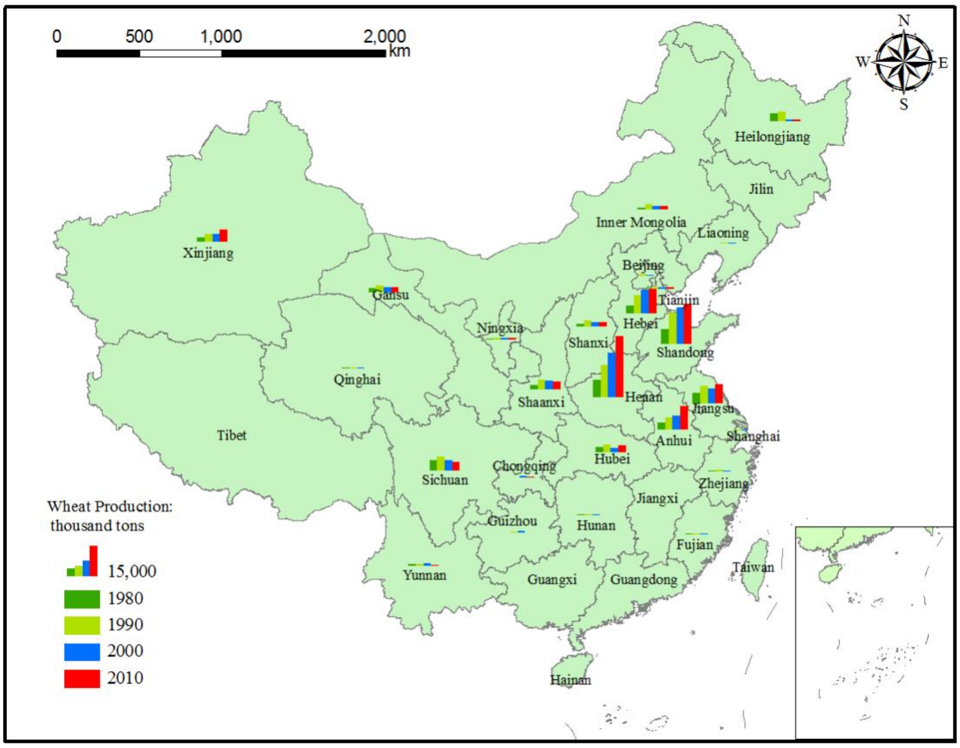
Source: NBSC (2013).

Figure 1. Wheat area, yield and production in 1980-2012 (1980 = 100).



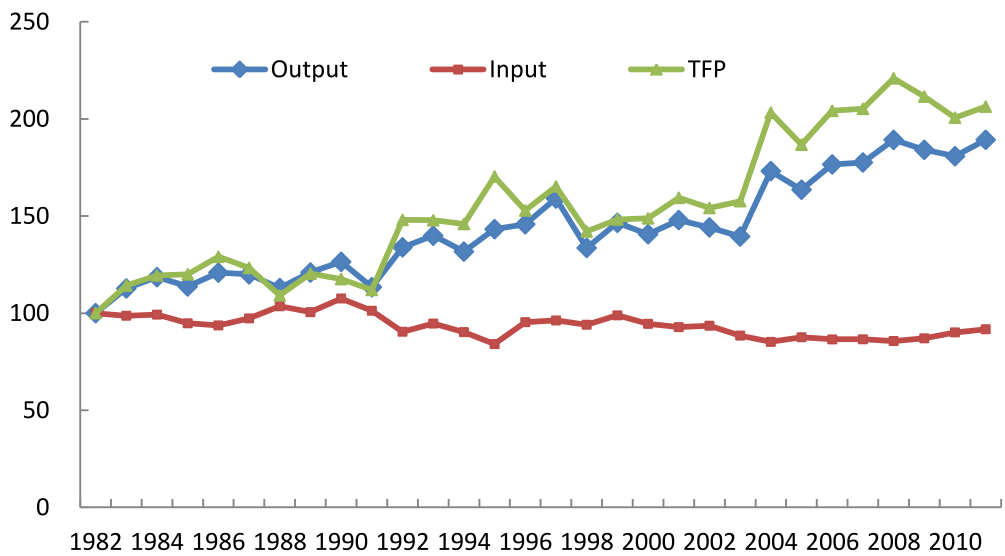
Source: NSBC (2013).

Figure 2. Wheat area ('000 hectares) in China by province in 1980, 1990, 2000 and 2010.



Source: NSBC (2013).

Figure 3. Wheat production ('000 tons) in China by province in 1980, 1990, 2000 and 2010.



Source: Authors' calculation based on the Divisia-Tornquist Formula.

Figure 4. Output, input and total factor productivity indices (area sown, weighted average) for wheat in China, 1982-2011.

Table 1. Wheat area (million hectares), yield (tons/ha) and production (million tons) for winter and spring wheat, China, 1980-2011.

Year	Total			Winter wheat			Spring wheat		
	Area	Yield	Production	Area	Yield	Production	Area	Yield	Production
1980	28.8	1.9	55.2	23.7	2.0	46.5	5.2	1.7	8.7
1985	29.2	2.9	85.8	24.4	3.1	75.8	4.8	2.1	10.0
1990	30.8	3.2	98.2	25.9	3.3	85.2	4.8	2.7	13.0
1995	28.9	3.5	102.2	25.0	3.7	91.7	3.9	2.7	10.5
2000	26.7	3.7	99.6	24.1	3.8	92.2	2.6	2.9	7.4
2005	22.8	4.3	97.4	21.1	4.3	91.4	1.7	3.6	6.0
2010	24.3	4.7	115.2	22.6	4.8	108.9	1.7	3.7	6.3
2011	24.3	4.8	117.4	22.6	4.9	111.0	1.7	3.9	6.4

Source: MOA, various issues from 1980 to 2012.

Table 2. Average annual numbers of major wheat varieties adopted by farmers and varietal turnover, China, 1982-2011.

Period	Average annual number of varieties	Average annual number of varieties per province	Varietal turnover *
1982-1986	251	20	0.30
1987-1991	296	24	0.24
1992-1996	263	22	0.27
1997-2001	304	24	0.33
2002-2006	296	23	0.30
2007-2011	363	31	0.27
1982-2011	295	24	0.28

Source: Compilation of varietal area for major crops in China, various issues from 1982 to 2012, MOA.

Note: The total number of major varieties from 16 provinces is 1,873. See data section for the definition of major varieties.

* It ranges from zero (no new variety replacement) to 1 (all existing varieties were replaces by the new varieties within one year).

Table 3. Sources (%) of germplasm of major wheat varieties adopted by farmers, China, during 1982-2011.

Period	Proportion of varieties with and without CIMMYT germplasm					Proportion of germplasm (area weighted)	
	Total	Directly adopted varieties	First generation	Second and higher generations	Non-CIMMYT	CIMMYT	Non-CIMMYT
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
1982-1985	9.1	4.1	4.3	0.7	90.9	4.1	96.0
1986-1990	11.4	2.9	4.8	3.7	88.6	5.6	94.5
1991-1995	15.7	2.5	4.6	8.6	84.3	6.8	93.2
1996-2000	16.6	1.1	4.2	11.3	83.4	8.0	92.0
2001-2005	19.4	1.1	4.6	13.7	80.6	7.9	92.1
2006-2011	24.5	1.1	4.4	19.0	75.5	8.8	91.2
1982-2011	17.2	2.0	5.0	10.3	82.8	6.9	93.1

Details for data by year are presented in Appendix Table 2.

Source: Authors' survey.

Table 4. Agronomic traits for major wheat varieties with or without CIMMYT germplasm, China, 1982-2011.

	Varieties with CIMMYT germplasm				Non-CIMMYT
	Total	Direct releases	First generation	Second and higher generations	
	(1)	(2)	(3)	(4)	(5)
Yield (kg/ha)	5,887***	5,565	5,427	6,081***	5,484
	(90)	(58)	(87)	(97)	(77)
Growth period (days)	165***	133***	145***	177***	211
	(78)	(56)	(80)	(81)	(67)
Plant height (cm)	86***	89	89	85***	89
	(90)	(72)	(87)	(94)	(78)
Crude protein content (%)	14.5***	13.5	14.1	14.7***	14.0
	(81)	(50)	(71)	(90)	(67)
1,000-grain weight (g)	42.6***	39.9	43.3***	42.8***	40.9
	(90)	(69)	(86)	(95)	(78)
Spike number (10,000/mu)	36.0	41.1	30.2***	36.7	36.9
	(39)	(8)	(20)	(51)	(25)
Grain number per spike	37.1***	36.5	37.9**	36.8**	35.6
	(80)	(58)	(80)	(84)	(69)
Wet gluten content (%)	32.3	33.1	31.2	32.5	31.9
	(63)	(17)	(45)	(79)	(42)
Test weight (g/L)	790	795	795	789	791
	(64)	(25)	(54)	(75)	(47)

- A T-test was conducted for differences between columns 5 and 1 or 2, 3 or 4.
- *** and ** represent statistically significance at the 1% and 5% levels, respectively.
- Figures in parentheses are percentages of non-missing values.

Source: Authors' survey.

Table 5. Type of wheat and disease resistance for varieties with or without CIMMYT germplasm, China, 1982-2011.

	Varieties with CIMMYT germplasm				Non-CIMMYT
	Total	Directly adopted varieties	First generation	Second and higher generations	
	(1)	(2)	(3)	(4)	(5)
Wheat type (%)	(99)	(100)	(96)	(100)	(91)
Spring-habit	54	81	71	43	30
Winter-habit	15	19	14	14	40
Facultative wheat	31	0	15	43	30
Stripe rust (%)	(81)	(64)	(79)	(84)	(68)
Highly susceptible	4	0	0	5	3
Susceptible	9	4	12	8	12
Intermediate	29	13	23	34	28
Resistant	25	48	35	19	29
Highly resistant	33	35	30	34	29
Leaf rust (%)	(77)	(61)	(71)	(82)	(58)
Highly susceptible	11	0	4	14	5
Susceptible	11	18	13	10	23
Intermediate	36	32	41	35	39
Resistant	25	36	26	24	20
Highly resistant	16	14	17	17	12
Powdery mildew (%)	(78)	(58)	(71)	(84)	(60)
Highly susceptible	12	5	6	14	6
Susceptible	14	43	13	10	19
Intermediate	52	33	52	54	49
Resistant	12	0	22	10	15
Highly resistant	11	19	7	11	11
Scab (%)	(48)	(19)	(43)	(55)	(39)
Highly susceptible	18	0	6	23	8
Susceptible	30	86	64	16	38
Intermediate	41	14	27	46	40
Resistant	9	0	3	12	12
Highly resistant	2	0	0	3	2
Lodging resistance (%)	(65)	(31)	(57)	(75)	(54)
Weak	3	0	0	5	5
Intermediate	26	9	23	28	27
Strong	71	91	77	68	68
Cold tolerance (%)	(38)	(14)	(21)	(49)	(41)
Weak	5	0	13	4	8
Intermediate	31	20	38	30	26
Strong	64	80	50	66	67
Drought tolerance (%)	(21)	(3)	(21)	(24)	(26)
Weak	5	0	6	4	5
Intermediate	22	0	31	19	20
Strong	74	100	63	77	75

Note: Figures in the parentheses are percentage of non-missing values (%).

Source: Authors' Survey.

Table 6. Estimated total factor productivity (TFP) of wheat in China, 1982-2011.

	TFP		
	(1)	(2)	(3)
Proportion of varieties with CIMMYT germplasm (%)	0.75*** (6.19)[a]		
Directly releases (%)		1.09*** (5.01)[a]	
First- and higher-generation crosses (%)		0.65*** (5.04)	
Proportion of germplasm from CIMMYT (%)			0.92*** (4.60)[a]
Proportion of irrigated cultivated land (%)	0.49*** (6.64)	0.47*** (6.32)	0.42*** (5.55)
Proportion of crop area affected by drought (%)	-0.39*** (4.26)	-0.38*** (4.17)	-0.41*** (4.35)
Proportion of crop area affected by frozen (%)	-0.68*** (2.90)	-0.72*** (3.08)	-0.71*** (2.96)
Time trend (year)	2.42*** (12.96)	2.56*** (12.78)	2.90*** (17.34)
Dummy for major winter wheat region (Yes=1; No=0)	36.21*** (8.65)	35.50*** (8.46)	32.70*** (7.64)
Dummy for southwestern winter wheat region (Yes=1; No=0)	29.39*** (7.04)	26.25*** (5.85)	25.63*** (6.10)
Constant	60.38*** (10.07)	60.93*** (10.18)	66.80*** (11.34)
N	465	465	465
R^2	0.553	0.556	0.537

[a] The figures in the parentheses are absolute t ratios of estimates.
*** represent the statistical significance at 1% (there is no case with statistical significance at 5% or 10%).

Appendix Table 1. Availability of variety trait information for 1,873 wheat varieties grown in China during 1982-2011.

	Available (%)	Not available (%)
Wheat type	94	6
Yield potential	85	15
Growth period	75	25
Plant height	85	15
Disease resistance	100	0
Stripe rust	77	23
Leaf rust	69	31
Powdery mildew	71	29
Scab	48	52
Lodging resistance	64	36
Cold resistance	48	52
Drought resistance	28	72

Source: Authors' survey.

Appendix Table 2. Wheat area, winter wheat share, and wheat yield by province, China, 2011.

Province	Area share (%)		Average yield (t/ha)
	Share in China	Winter wheat share	
Major provinces	**98**	**93**	**4.9**
Henan	22	100	5.9
Shandong	15	100	5.9
Hebei	10	100	5.3
Anhui	10	100	5.1
Jiangsu	9	100	4.8
Sichuan	5	99	3.5
Shaanxi	5	100	3.6
Xinjiang	4	72	5.4
Hubei	4	100	3.4
Gansu	4	69	2.9
Shanxi	3	100	3.4
Inner Mongolia	2	0	3.0
Yunnan	2	100	2.3
Heilongjiang	1	0	3.5
Guizhou	1	100	2.0
Ningxia	0.8	53	3.1
Chongqing	0.6	100	3.1
Other provinces	**2**	**76**	**4.2**
National	**100**	**93**	**4.8**

Source: NBSC (2012).

Appendix Table 3. Sources (%) of germplasm of wheat varieties adopted by farmers by year, China, 1982-2011.

Year	Proportion of varieties with or without CIMMYT's germplasm					Proportion of germplasm (area weighted):	
	Total	Directly adopted varieties	First generation	Second and higher generations	Non-CIMMYT	CIMMYT	Non-CIMMYT
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
1982	7.5	4.3	2.7	0.5	92.5	3.1	96.9
1983	7.4	4.1	2.9	0.4	92.6	4.1	95.9
1984	7.4	3.3	4.1	0.0	92.6	3.8	96.2
1985	9.3	4.3	4.3	0.7	90.7	4.8	95.2
1986	9.6	3.9	4.3	1.4	90.4	4.5	95.5
1987	10.2	2.8	6.3	1.1	89.8	5.5	94.5
1988	12.1	2.5	6.0	3.6	87.9	5.1	94.9
1989	11.9	2.9	5.1	3.9	88.1	6.5	93.5
1990	11.6	2.4	4.1	5.1	88.4	6.0	94.0
1991	14.6	3.2	5.5	5.8	85.4	6.4	93.6
1992	16.0	3.3	5.1	7.6	84.0	7.8	92.2
1993	16.7	2.2	4.7	9.8	83.3	6.6	93.5
1994	17.4	2.3	5.3	9.9	82.6	6.4	93.6
1995	17.9	1.6	4.8	11.5	82.1	7.0	93.0
1996	17.7	1.6	4.4	11.7	82.3	6.4	93.7
1997	19.8	1.3	5.9	12.2	80.6	9.5	90.5
1998	18.6	2.1	4.5	12.1	81.4	8.3	91.7
1999	21.1	1.4	6.0	13.7	79.0	8.0	92.0
2000	18.6	0.7	5.5	12.4	81.4	8.1	91.9
2001	20.6	1.1	5.2	14.3	79.4	8.1	91.9
2002	19.3	0.6	5.4	13.3	80.7	7.2	92.8
2003	18.2	0.7	5.6	11.9	81.9	8.0	92.0
2004	18.7	0.4	4.0	14.4	81.3	7.3	92.8
2005	23.1	1.1	5.3	16.7	76.9	9.1	90.9
2006	23.0	0.3	6.3	16.3	77.0	8.7	91.3
2007	24.6	0.0	5.8	18.8	75.4	9.3	90.7
2008	26.2	1.2	5.5	19.5	73.8	9.3	90.7
2009	25.4	1.10	5.3	19.1	74.6	9.2	90.8
2010	26.2	1.23	5.2	19.8	73.8	8.4	91.6
2011	26.1	1.07	5.1	20.0	73.9	7.9	92.1

Source: Authors' survey.

Appendix Table 4. Descriptive statistics for variables used in the regression analysis.

	Mean	Std. Dev.
Total factor productivity (TFP)	147	43.99
Proportion of varieties with CIMMYT germplasm (%)	20	16.46
Direct CIMMYT releases (%)	2	7.39
First- and higher-generation crosses with CIMMYT germplasm (%)	18	15.85
Proportion of germplasm from CIMMYT (%)	8	9.39
Proportion of irrigated cultivated land (%)	45	21.44
Proportion of crop area affected by drought (%)	23	16.01
Proportion of crop area affected by frozen (%)	3	6.13
Time trend (year)	15.5	8.67
Dummy for major winter wheat region (Yes=1; No=0)	0.5	0.50
Dummy for Southwestern wheat region (Yes=1; No=0)	0.2	0.39