The Impact of CIMMYT Wheat Germplasm on Wheat Productivity in China

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WHEAT (http://wheat.org) is a CGIAR Research Program launched in 2012 and led by the International Maize and Wheat Improvement Center (CIMMYT). Coupling advanced science with field-level research and extension in lower- and middle-income countries, WHEAT works to raise wheat productivity, production and affordable availability for 2.5 billion resource-poor consumers who depend on the crop as a staple food. Partners include the Australian Centre for International Agricultural Research (ACIAR), the British Biotechnology and Biological Sciences Research Council (BBSRC), the International Center for Agricultural Research in the Dry Areas (ICARDA), the Indian Council of Agricultural Research (ICAR), and a community of more than 200 public and private organizations worldwide, among them national governments, companies, international centers, regional and local agencies and farmers. Funding for WHEAT comes from CGIAR and generous donors including national governments, foundations, development banks and other public and private agencies.

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Abstract: This study examines the factors that affected wheat total factor productivity (TFP) growth in China, with a focus on China's collaboration with the wheat breeding program of the International Maize and Wheat Improvement Center (CIMMYT) and its free use of CIMMYT improved lines and other genetic resources, collectively termed "germplasm," during 1982-2011. Based on a comprehensive dataset that included planted area, pedigree and agronomic traits by variety for 17 major wheat-growing provinces, both descriptive analyses and quantitative econometric estimates showed that the use of CIMMYT gemplasm had led to an increase in wheat TFP of between 5% to 14% (annual growth of between 0.17% and 0.45%) over that period, depending on the measurement used. This represents from 3.8 million to 10.7 million tons of added grain, worth between US $1.2 billion and US $3.4 billion, based on 2011 prices. Results also showed that China breeders' use of CIMMYT germplasm had increased — CIMMYT contributions were present in more than 26% of all major wheat varieties in China after 2000 — and had significantly enhanced the varieties' performance for important traits including yield potential, processing quality, disease resistance, and early maturity.

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Executive Summary

Wheat is one of the most important crops in China. Farmers cultivate wheat in all provinces except for Hainan (NBSC 1980-2013) but most wheat is produced in the winter wheat regions, particularly in the Huang and Huai River winter wheat regions. Autumn-sown wheat, also called "winter wheat" in Chinese statistics, accounted for 82% of China's wheat area in 1980 and 93% in 2011. Wheat yield and total factor productivity (TFP) have grown rapidly in the past three decades.

This study examines the factors that affect wheat TFP growth in China, with a focus on the contributions of the wheat breeding program of the International Maize and Wheat Improvement Center (CIMMYT) – specifically, improved lines and other genetic resources, collectively termed "germplasm," along with related information – to China's wheat varieties and to their impacts on wheat productivity.

Based on a comprehensive dataset assembled for the study and which included planted area, pedigrees and agronomic traits by variety for 17 major wheat-growing provinces[1] from the past three decades, both descriptive analysis and quantitative econometric estimation consistently show that the role of CIMMYT in China's wheat breeding has increased and that Chinese breeders' use of CIMMYT germplasm has significantly raised wheat productivity in China.

The wheat varietal market in China is extremely dynamic, with an exceptional number of breeding programs producing many improved varieties that are taken up quickly by farmers. Yearly during the past three decades, nearly 300 major[2] wheat varieties have been sown nationwide and the number has exceeded 360 since the late 2000s. 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. Given the significant size and output of the Chinese national wheat program, which comprises many research institutes and universities working on wheat breading, the contribution is substantial; more than 26% of all major wheat varieties released in China after 2000 contain CIMMYT germplasm.

Because CIMMYT works mostly on spring-habit wheat, the largest contribution is in spring wheat production areas, but winter wheat varieties in Yunnan and Sichuan also contain high levels of CIMMYT germplasm.

Varieties containing CIMMYT germplasm often show better agronomic performance: higher yield, higher grain weight, more kernels per spike, shorter growth period, shorter plant height and more crude protein in the grain. Moreover, the varieties with CIMMYT germplasm have better resistance on average to several major diseases of wheat in China.

The contributions of CIMMYT germplasm to wheat TFP in China have been significant and are rising. We estimate that the use of CIMMYT gemplasm has resulted in an increase in TFP of between 5% to 14% in the past three decades, depending on the measurement used.[3] This represents from 3.8 million to 10.7 million tons of added grain,[4] worth between US $1.2 billion and US $3.4 billion, based on 2011 prices.

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1 Provinces that individually accounted for at least 0.5% of China's national wheat area and together made up 98% of that area in 2011.

2 For winter wheat, a variety grown on at least 6,667 hectares (ha) in China in a given year, prior to 2000. From 2000 onward, a variety sown on at least 3,333 ha is considered "major."

3 Three types of breeding products containing CIMMYT germplasm are considered: (1) direct releases of CIMMYT varieties; (2) releases of first-generation products; and (3) releases of second- and higher-generation products.

4 Average annual wheat production in China was 76.6 million tons during 1981-85.

Surprisingly, the greatest impacts have occurred mainly in winter wheat rather than spring wheat regions, a phenomenon which is beyond the scope of this study to explain and requires further research.

Among the important implications of these results for plant breeders and policy makers in China, as well as for international donors, are the following:

- Chinese wheat scientists should strengthen their collaboration with CIMMYT and continue the targeted use of CIMMYT wheat germplasm.
- Given CIMMYT's contributions to wheat productivity in China and the benefits for national food security, the government of China should increase its commitment to international wheat breeding.
- International donors and development agencies should increase investments in CGIAR germplasm improvement programs and partnerships with national agricultural research centers.
- Other countries that have been working closely with CIMMYT and other CGIAR Consortium centers or CGIAR Research Programs should document the achievements and impacts of those efforts.

1. Introduction

Producing over 120 million tons of wheat per year, China is the world's number-one 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 1980-2013). Despite a decrease of 17% in wheat area 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 the 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 yield growth rate 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 (Huang and Rozelle 1996). 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 (Central Committee of the Communist Party of China and the State Council 2014). Given current land and water constraints and high cropping intensity, with 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?

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, reflecting national trends and the distribution of spring and winter wheat. 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 Data Collection

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 frost) 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. Major varieties accounted for nearly 80% of China's total wheat area in the 1980s-90s and 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). This study uses data from the top 17 wheat production provinces, comprising 98% of China's wheat area in 2011.
- Dataset 3 provides detailed pedigree information for most 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 to the point where a non-Chinese (that is, from CIMMYT or the rest of world) parent appeared. We gathered pedigree information for 1,534 Chinese varieties and 59 non-Chinese varieties; that is, varieties introduced to China and directly used in field production during 1982-2011. Despite our best efforts, we were unable to obtain pedigree information 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.[5]
- 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 the 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 because we could not ascertain whether or not the data were available, given the time and budget constraints of this study. We recommend that future research on Chinese wheat varieties improve Dataset 4. 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 those periods.

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

3. Overview of Wheat Production in China

Trends in Wheat Production in China

China has the world's second-largest wheat area after India and is the world's number-one 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[6] – and China produced more than 117 million tons annually, representing 17% of world wheat output over the same period (Table 1).

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 (Table 2).

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 3 and Figure 1). Wheat production growth slowed during 1985-97, but was still a brisk 3.2%. Annual wheat imports fell from about

Table 1. Average annual wheat area, yield and production in major wheat-producing countries in 2010-2012.

Country	Area (million ha)	Average yield (t/ha)	Production (million t)
China	24.2	4.8	117.7
India	29.1	3.0	87.5
USA	19.2	3.1	58.7
Russian Federation	22.6	2.0	45.2
World	241.8	3.3	791.0

Source: http://www.faostat.fao.org.

Table 2. Total grain area and shares of rice, wheat, maize and other grains, China, 1980-2012.

Year	Grain area (million ha)	Area shares (%)			
		Rice	Wheat	Maize	Other grains
1980	117.2	28.9	24.6	17.1	29.4
1985	108.8	29.5	26.8	16.3	27.4
1990	113.5	29.1	27.1	18.9	24.9
1995	110.1	27.9	26.2	20.7	25.1
2000	108.5	27.6	24.6	21.3	26.5
2005	104.3	27.7	21.9	25.3	25.2
2010	109.9	27.2	22.1	29.6	21.2
2012	111.2	27.1	21.8	31.5	19.6

Other grains include other cereals (e.g., millet, sorghum, barley), soybean, sweet potato and potato.
Source: NBSC (2013).

Table 3. Wheat area (million ha), yield (t/ha) and production (million t) 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.

[6] 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 2010-12.

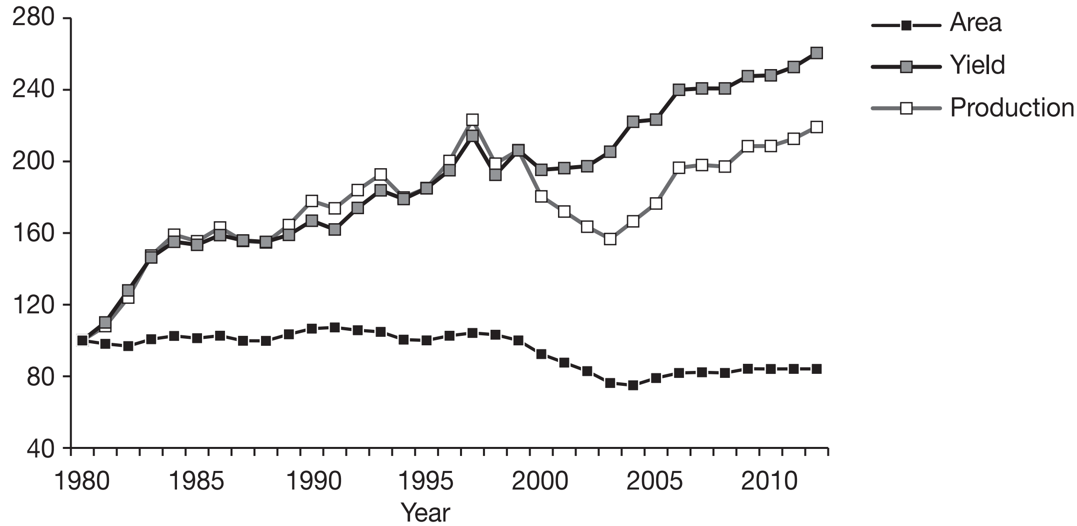


Figure 1. Wheat area, yield and production, 1980-2012 (1980 = 100).
Source: NBSC (2013).

15 million tons in the late 1980s to nearly nothing in the late 1990s, by which time there was an 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* 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, rapid and continual technical advancements in wheat have greatly benefitted farmers 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 use of new varieties, average wheat yields in China nearly doubled during 1980-95, rising from 1.9 to 3.5 t/ha (Table 3). Rozelle and Huang (2000) showed that, in addition to investments in agricultural research and extension, investments in irrigation contributed to the rapid growth of average wheat yields through 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 annual 2.4% growth 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.[7] 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 3 and Figure 2). 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, so the production share of winter

[7] The term "winter wheat" in this report does not imply habit, as in "winter, facultative and spring habit wheats."

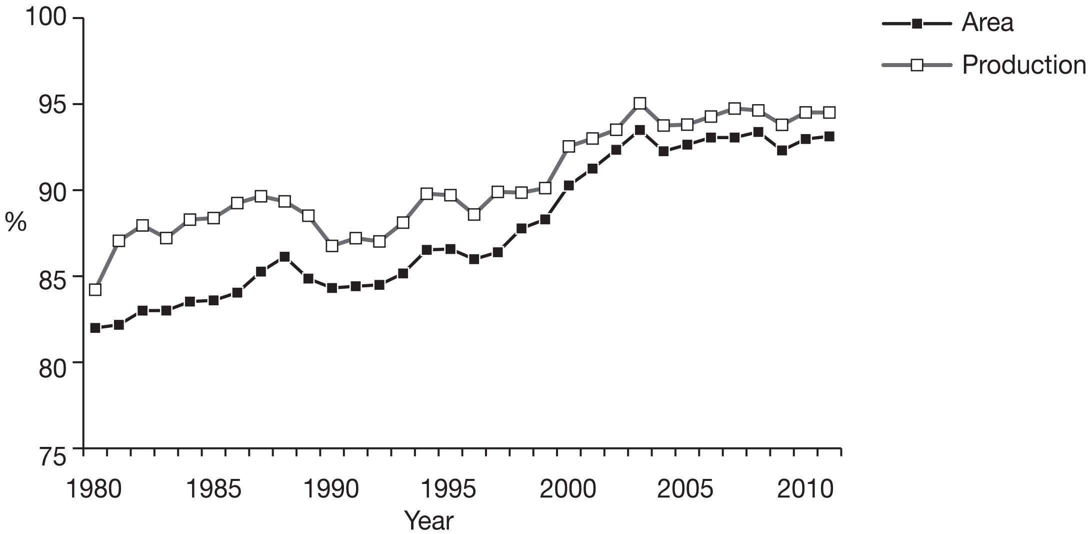


Figure 2. Share of winter wheat area and production in China, 1980-2011.
Source: MOA, various issues from 1980 to 2012.

wheat has increased less than its area share (Figure 2) but winter wheat is higher-yielding than spring wheat (an average 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, as described in the following section.

Regional Distribution of Wheat Production in China

Farmers cultivate wheat in nearly every province of China, although related cropping systems and the intensity and importance of wheat vary by region (Figure 3). Except for the single-season spring wheat region (Heilongjiang, Inner Mongolia,

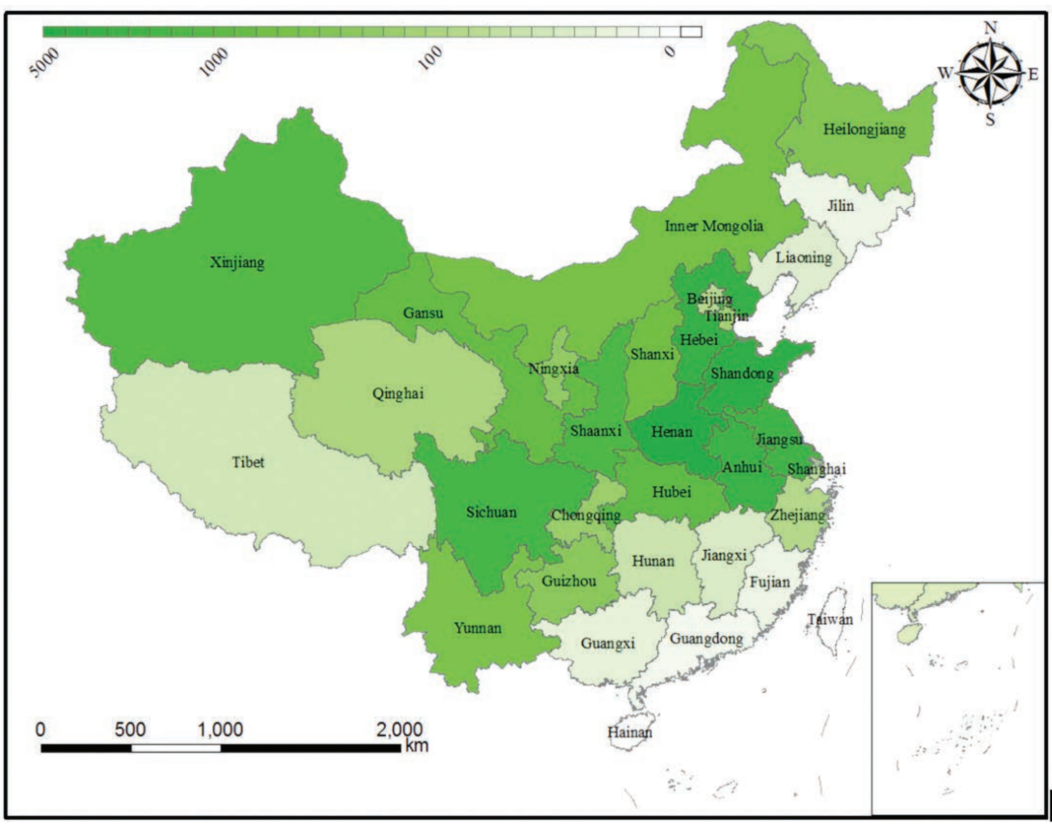


Figure 3. Wheat area ('000 hectares) distribution in China by province in 2010.
Source: NSBC (2011).

Jilin, Liaoning and Qinghai provinces) and the single-season spring-winter mixed region (Gansu, Ningxia and Xinjiang provinces), farmers in the northernmost provinces grow wheat in intensive, multiple-crop rotations. Farmers in winter wheat provinces (Auhui, Hebei, Henan, Jiangsu, Shaanxi, Shandong and Shanxi) commonly plant wheat in rotations with maize or cotton. Yangtze Valley farmers – especially north of the Yangtze River in areas where it is not possible to grow two rice crops per year – sow facultative, over-wintering wheat in rotation with single-season rice.

Wheat production has remained significant in northern China's maize-wheat region (Figure 4). The top-five winter wheat production provinces (Anhui, Hebei, Henan, Jiangsu and Shandong) accounted for some two-thirds of China's total wheat area (Table 4). Wheat area in all provinces except for Anhui, Henan and Jiangsu has gradually decreased during 1980-2010 (Figure 4), with the most notable reductions occurring in Heilongjiang (spring wheat, northeastern China) and Sichuan (winter wheat, southwestern China). Over the same period, wheat area increased from 3.9 to 5.3 million ha in Henan, China's number-one wheat-producing province.

Table 4. Wheat area, winter wheat share, and average wheat yield by province, China, 2011.

Province	Area share (%) Share in China	Winter wheat share	Average yield (t/ha)
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).

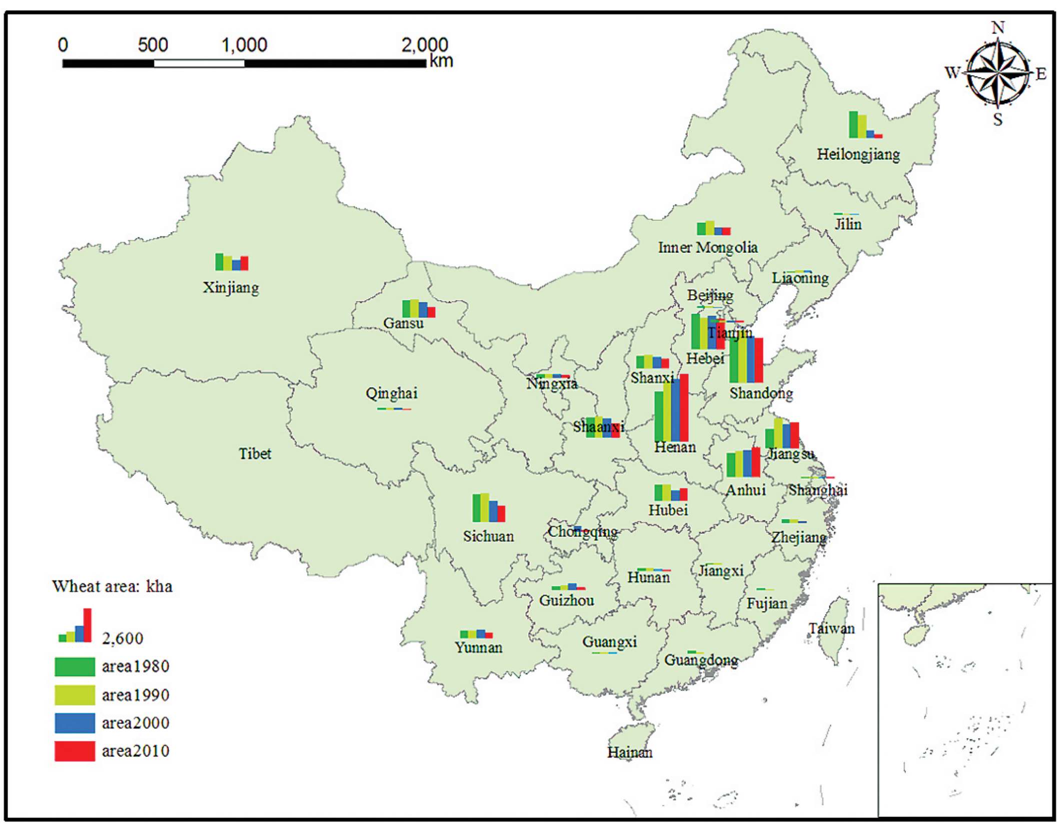


Figure 4. Wheat area ('000 hectares) in China by province in 1980, 1990, 2000 and 2010.
Source: NSBC (2013).

Despite the decreasing wheat areas in most provinces, wheat production has increased significantly in major wheat production provinces (Figure 5). The largest growth in wheat production in the past three decades occurred in Henan, Hebei, Shandong and Anhui (Figure 5). Obviously, increased wheat yields have been a primary source of production growth.

To examine the changes in wheat yield and productivity and the impacts of CIMMYT's germplasm on China's wheat productivity, we selected 17 wheat production provinces, each accounting for at least 0.5% of national wheat area and together making up 98% of that area in 2011 (Table 4). 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."

Based on the type of wheat, the 16 provinces can be divided into two groups and six specific wheat production regions as follows (Table 5).[8]

Group 1

- Region 1: Northern spring wheat region. This includes the areas where only spring wheat is planted.
- Region 2: Northern spring-winter mixed wheat region. Farmers here grow both spring and winter wheat.

Group 2

- Region 3: Northern winter wheat region. Farmers here have planted winter wheat only in the last decade.
- Region 4: Huang and Huai River winter wheat region. Farmers here have planted winter wheat only in the last decade.
- Region 5: Middle and Lower Yangtze winter wheat region.
- Region 6: Southwestern winter wheat region.

[8] These regional categories may differ from those provided in other publications.

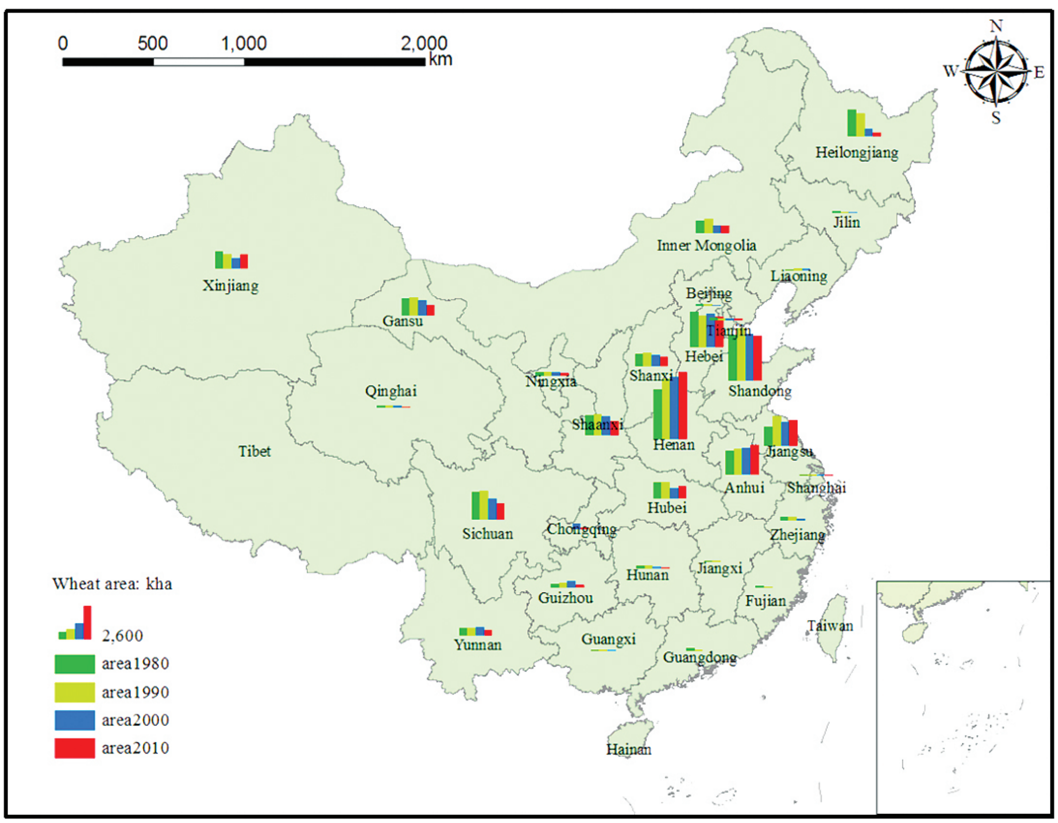


Figure 5. Wheat production ('000 tons) in China by province in 1980, 1990, 2000 and 2010.
Source: NSBC (2013).

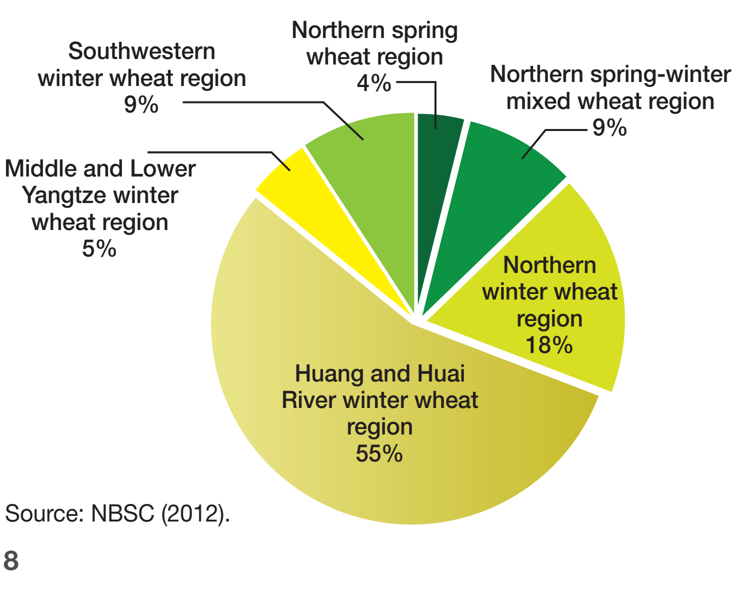
According to official statistics, the Huang and Huai River winter wheat region (55%) and the northern winter wheat region (18%) together accounted for 73% of China's total wheat area in 2011 (Figure 6). The regions with full and partial spring wheat, including the northern spring wheat region (4%) and northern spring-winter mixed wheat region (9%) accounted for only 13% of China's wheat area in 2011.

Table 5. Percentage of spring and winter wheat area by region, China, 1980-2011.

	1980-89		1990-99		2000-11	
Region	Spring	Winter	Spring	Winter	Spring	Winter
Regions with spring or spring-winter wheat						
1. Northern spring wheat						
Heilongjiang	100	0	100	0	100	0
Inner Mongolia	100	0	100	0	100	0
2. Northern spring-winter mixed wheat						
Ningxia	82	18	86	14	62	38
Gansu	50	50	46	54	35	65
Xinjiang	39	61	36	64	32	68
Regions with winter wheat						
3. Northern winter wheat						
Hebei	1	99	0	100	0	100
Shanxi	4	96	3	97	0	100
Shaanxi	1	99	1	99	0	100
4. Huang and Huai River winter wheat						
Henan	0	100	0	100	0	100
Shandong	0	100	0	100	0	100
Anhui	0	100	0	100	0	100
Jiangsu	0	100	0	100	0	100
5. Middle and Lower Yangtze winter wheat						
Hubei	0	100	0	100	0	100
6. Southwestern winter wheat						
Sichuan	0	100	0	100	0	100
Yunnan	0	100	2	98	0	100
Guizhou	0	100	0	100	0	100

Source: MOA, various issues from 1980 to 2012.
Wheat areas in Regions 1, 2, 3, 4, 5, and 6 accounted for about 4%, 9%, 18%, 55%, 5% and 9% of national wheat area, respectively, in 2011.

Figure 6. Wheat area share in China by region, 2011.



Source: NBSC (2012).

- The northern spring wheat region includes Inner Mongolia, Heilongjiang, Liaoning and Jilin.
- The northern spring-winter mixed wheat region includes Xinjiang, Gansu, Ningxia and Qinghai.
- The northern winter wheat region includes Hebei, Shaanxi, Shanxi, Tianjin and Beijing.
- The Huang and Huai River winter wheat region includes Henan, Shandong, Anhui and Jiangsu.
- The Middle and Lower Yangtze winter wheat region includes Hubei, Zhejiang, Shanghai, Hunan and Jiangxi.
- The southwestern winter wheat region includes Sichuan, Yunnan, Guizhou and Chongqing.

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 (Table 6). For the 16 provinces studied, the average number of major wheat varieties adopted annually by farmers was 24.

Table 6. 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).

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 6). 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 are contributing factors (Hu et al. 2010).

Annual average varietal turnover[9] for wheat in China was also an impressive 0.28 during 1982-2011 (Table 6), meaning that 28% of varieties planted by farmers each 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.[10]

While the number of wheat varieties differs largely among regions, varietal turnover rates in all regions are comparable (Table 7). During 1982-2011, the number of major wheat varieties ranged from 161 in the northern spring wheat region (the smallest wheat production region) to

[9] 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).

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

Table 7. Number of major wheat varieties adopted by farmers and varietal turnover by region, China, 1982-2011.

Region	Number of varieties	Average annual number of varieties per province	Varietal turnover*
Northern spring wheat region	161	14	0.32
Northern spring-winter mixed wheat region	469	24	0.31
Northern winter wheat region	575	30	0.29
Huang and Huai River winter wheat region	627	33	0.24
Middle and Lower Yangtze winter wheat region	90	13	0.25
Southwestern winter wheat region	270	16	0.30

The total number of major varieties from 16 provinces is 1,873. See data section for the definition of major varieties.
Source: Compilation of varietal area for major crops in China, various issues from 1982 to 2012, MOA.
* It ranges from zero (no new variety replacement) to 1 (all existing varieties were replaces by the new varieties within one year).

627 in the Huang and Huai River winter region (the largest wheat production region). For the average number of varieties planted annually per province, the difference was more than double (Table 7). The variation in the number of varieties among provinces is explained by differences in wheat area and wheat production environments. The similar values for varietal turnover, ranging from 0.24 in Huang and Huai River winter wheat region to 0.32 in the northern spring wheat region, suggest that wheat farmers across China are adopting new varieties quickly and often.

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.

1. 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 8): (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.
2. 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 these two approaches, Table 8 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 China and other countries. The sum of CIMMYT and non-CIMMYT fractions is 100%.

Table 8. Sources (%) of germplasm of major wheat varieties adopted by farmers, China, during 1982-2011.

	Proportion of varieties with and without CIMMYT germplasm					Proportion of germplasm (area weighted)	
Period	Total (1)	Directly adopted varieties (2)	First generation (3)	Second and higher generations (4)	Non-CIMMYT (5)	CIMMYT (6)	Non-CIMMYT (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.

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 of major wheat varieties that had CIMMYT's germplasm was 17% (column 1, Table 8). 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 8). Chinese wheat varieties with a first- or 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 8). 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 8). 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 8). 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 8; Appendix Table 2).

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 increased from 5.04 (4.32+0.72, row 1, Table 8) 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 2; Appendix Table 2).

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 3) 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) that 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 (Huang et al. 2014). In 1997 CIMMYT opened an office in Beijing to foster 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.

The advantages of CIMMYT germplasm for specific traits were significantly greater for some regions than for others and were concentrated in spring wheat production regions (Table 9)[11] — principally in the northern spring wheat and northern spring-winter mixed regions. This outcome clearly derives from CIMMYT's focus on spring-habit wheat. Accordingly, the contribution of CIMMYT germplasm generally decreases as one moves from the spring wheat production regions (northern spring wheat region and northern spring-winter mixed wheat region) to the winter wheat regions (northern, Huang and Huai River, and Middle and

[11] Regarding the numbers in Table 9, consider as well the area share for each region (Figure 6).

Lower Yangtze regions). Based on the extensive measure of genetic contributions, nearly 38% of wheat varieties sown in Heilongjiang and Inner Mongolia in the northern spring wheat region in the past three decades contain CIMMYT germplasm. Even based on the intensive measure of genetic contribution, the average proportion of CIMMYT germplasm in pedigrees was 11% for varieties in Heilongjiang and 24% for those in Inner Mongolia (first two rows, Table 9). Table 9 also shows that CIMMYT wheat lines can be used directly in provinces such as Gansu, Inner Mongolia, Ningxia, Sichuan, Xinjiang and Yunnan.

Interestingly, CIMMYT germplasm also figured significantly (based on the intensive measure, 36% during 1982-2011; Table 9) in varieties grown in the southwest winter wheat region and particularly in Yunnan. Indeed, based on the intensive measure, CIMMYTs average germplasm contribution was higher there (31%) than in any other province. This could be due to the fact that wheat in Yunnan suffers from serious attacks of wheat stripe rust disease and certain CIMMYT varieties and other germplasm are highly-resistant to stripe rust and suited for Yunnan.[12]

Table 9. Sources (%) of germplasm of major wheat varieties adopted by farmers by region, China, 1982-2011.

	Proportion of varieties with and without CIMMYT germplasm					Proportion of germplasm (area weighted)	
Region	Total (1)	Direct releases (2)	First generation (3)	Second and higher generations (4)	Non-CIMMYT (5)	CIMMYT (6)	Non-CIMMYT (7)
Northern spring wheat region							
Heilongjiang	37.7	0.0	6.5	31.2	62.3	10.5	89.5
Inner Mongolia	37.6	6.4	12.8	18.4	62.4	23.7	76.3
Northern spring-winter mixed region							
Ningxia	20.3	1.5	7.3	11.6	79.7	26.4	73.6
Gansu	15.6	2.4	5.1	8.1	84.4	11.1	89.0
Xinjiang	23.1	6.4	9.6	7.1	76.9	14.9	85.1
Northern winter wheat region							
Hebei	9.9	0.4	1.4	8.1	90.1	3.7	96.3
Shanxi	14.2	0.6	3.6	10.1	85.8	2.3	97.7
Shaanxi	12.9	0.0	2.5	10.5	87.1	0.6	99.4
Huang and Huai River winter wheat region							
Henan	24.0	0.0	0.8	23.2	76.1	3.2	96.8
Shandong	7.0	0.0	0.9	6.1	93.0	2.8	97.2
Anhui	15.9	0.0	1.6	14.3	84.1	2.0	98.0
Jiangsu	13.5	0.6	1.1	11.8	86.5	1.2	98.8
Middle and Lower Yangtze winter wheat region							
Hubei	10.0	0.0	1.1	8.9	90.0	2.0	98.0
Southwestern winter wheat region							
Sichuan	22.6	0.6	9.4	12.0	78.0	9.0	91.0
Yunnan	35.9	21.8	9.0	5.1	64.1	30.7	69.4
Guizhou	17.3	0.0	1.3	16.0	82.7	3.3	96.7

Source: Authors' survey.

[12] Since the 1980s, the CIMMYT global wheat program has classified production regions into mega-environments (MEs), based on growing conditions and climatic, edaphic, and biotic constraints. Yunnan's wheat-growing regions are similar to those of Mexico's Central Highlands, and can be classified as irrigated (Mega-environment 1) and rainfed (Mega-environment 4), as in Mexico.

CIMMYT germplasm has also contributed uniquely to wheat varieties in the other three winter wheat regions (northern winter wheat region, Huang and Huai River winter wheat region, and Middle and Lower Yangtze winter wheat region, which together accounted for 72% of China's 2011 wheat area). The share of CIMMYT germplasm (mostly spring-habit) in wheat varieties in those regions is low (Table 9) but has afforded improved yield potential, disease resistance and processing quality (Zhuang 2003).

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 traits. The quantitative traits examined include wheat yield, growth period, plant height, crude protein content, grain weight, spike number, grain number per spike, wet gluten content and test weight (Table 10). The qualitative traits examined included type of wheat (spring-habit, winter-habit, facultative wheat), disease resistance, lodging resistance, cold tolerance and drought tolerance (Table 11). For each trait, we compared varieties with and without CIMMYT germplasm contributions, applying the T-test to determine the statistical significance of any differences.

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 10). 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 periods 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 11). 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.

Table 10. Agronomic traits for major wheat varieties with or without CIMMYT germplasm, China, 1982-2011.

	Varieties with CIMMYT germplasm				
	Total (1)	Direct releases (2)	First generation (3)	Second and higher generations (4)	Non-CIMMYT (5)
Yield (kg/ha)	5,887*** (90)	5,565 (58)	5,427 (87)	6,081*** (97)	5,484 (77)
Growth period (days)	165*** (78)	133*** (56)	145*** (80)	177*** (81)	211 (67)
Plant height (cm)	86*** (90)	89 (72)	89 (87)	85*** (94)	89 (78)
Crude protein content (%)	14.5*** (81)	13.5 (50)	14.1 (71)	14.7*** (90)	14.0 (67)
1,000-grain weight (g)	42.6*** (90)	39.9 (69)	43.3*** (86)	42.8*** (95)	40.9 (78)
Spike number (10,000/mu)	36.0 (39)	41.1 (8)	30.2*** (20)	36.7 (51)	36.9 (25)
Grain number per spike	37.1*** (80)	36.5 (58)	37.9** (80)	36.8** (84)	35.6 (69)
Wet gluten content (%)	32.3 (63)	33.1 (17)	31.2 (45)	32.5 (79)	31.9 (42)
Test weight (g/L)	790 (64)	795 (25)	795 (54)	789 (75)	791 (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 11. Type of wheat and disease resistance for varieties with or without CIMMYT germplasm, China, 1982-2011.

	Varieties with CIMMYT germplasm				
	Total	Directly adopted varieties	First generation	Second and higher generations	Non-CIMMYT
	(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

Figures in the parentheses are the percentage of non-missing values (%).
Source: Authors' survey.

5. Impact of CIMMYT Germplasm 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:

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

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., plastic sheeting, animal traction), and other material inputs. Setting TFP in the base year to 100, the time trend of TFP indices for each province or all 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 7 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, in particular labor (Figure 7). While not presented in Figure 7, our data show as well that the labor inputs decreased by about 60% due to rising wages during 1982-2011, accompanied by an increase in capital inputs such as mechanization and agro-chemicals.

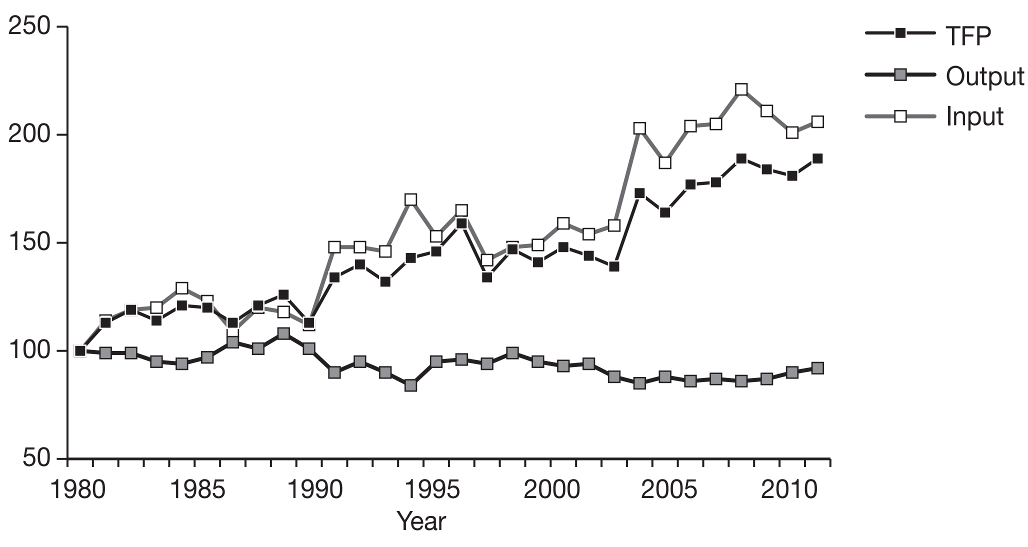


Figure 7. Output, input and total factor productivity (TFP) indices (area sown, weighted average) for wheat in China, 1982-2011 (1980 = 100).
Source: Authors' calculation based on the Divisia-Tornquist Formula.

National wheat TFP growth, however, has fluctuated over the past three decades (Figure 7). 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 7).

When we calculated TFP by wheat production region,[13] all regions showed a rising trend, though growth rates differed among regions (Figure 8). The highest growth occurred in winter wheat regions 3-5. The lowest growth occurred in spring wheat regions 2 and 3. Wheat TFP depends on multiple factors, including technology change and technology efficiency, irrigation infrastructure and local weather, but a key question examined in the next section of this study is whether or not CIMMYT germplasm had contributed to wheat TFP growth in different regions of China.

Modeling the Impact of CIMMYT Germplasm

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

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

where *j* denotes province, t indexes time (year), and CG is the contribution of CIMMYT germplasm. The latter was assessed using the extensive and intensive measures:

- Extensive measure: in the regression, we used the following two alternatives to define extensive measure. The first is the percentage of major wheat varieties that contain CIMMYT germplasm (row 1, Table 12). The second uses two separate variables: a) the percentage of China major wheat varieties that were released from CIMMYT and directly used in production in China (row 1, Table 13), and b) the percentage of China major wheat varieties that belonged to the first- and higher-generation CIMMYT varieties (row 2, Table 13).
- Intensive measure: the percentage of the major wheat varieties with CIMMYT germplasm, weighted by area sown to each variety (row 1, Table 14).

[13] We divided wheat production regions into three categories: spring or spring-winter wheat regions (including regions 1 and 2), major winter wheat regions (including regions 3, 4 and 5), and the southwestern wheat region (region 6).

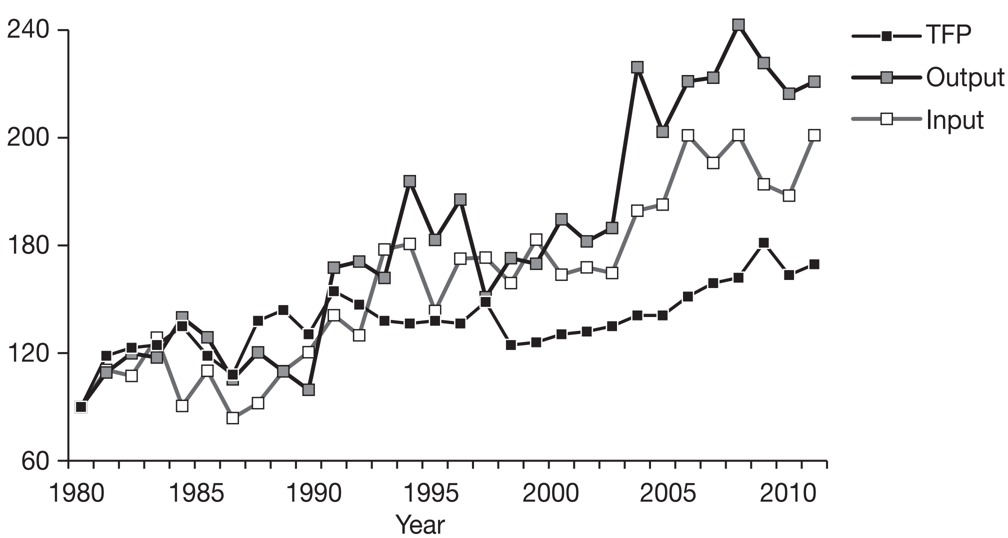


Figure 8. Total factor productivity indices (area sown, weighted average) for wheat in China by region, 1982-2011 (1980 = 100).
Source: Authors' calculation based on the Divisia-Tornquist Formula.

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[14] 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 3.

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. In each alternative measurement, equation (2) is first estimated for all provinces studied and then for three groups of regions. So we have 12 specifications (3 x 4). The three groups of regions are: 1) spring wheat regions, including the northern spring wheat and northern spring-winter mixed regions; 2) the major winter wheat regions, including the northern, Huang and Huai River and Middle and Lower Yangtze winter wheat regions; 3) the southwestern winter wheat region. We designed the model by major regions because we expected that the impacts of CIMMYT germplasm would differ by region.

Impact of CIMMYT Germplasm

In general, all models performed well (Tables 12-14). The R^2 for regressions with the full dataset (all regions) was about 0.55. The R^2 values for the three regional groupings were also high (from about 0.42 to 0.68). 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 2, Tables 12-14). Parameters for the two abiotic constraint variables — drought and frost — were negative in most specifications, which suggested

[14] Wheat-specific data for drought and frost were not available, so we assumed that recorded occurrences of such phenomena applied to all crops, including wheat.

Table 12. Estimated total factor productivity (TFP) of wheat in China, 1982-2011: ordinary least squares estimates based on the proportion of major wheat varieties that contain CIMMYT germplasm.

	All regions (1)	Spring and spring-winter wheat regions (2)	Major winter wheat regions (3)	Southwestern winter wheat region (4)
Proportion of varieties with CIMMYT germplasm (%)	0.75*** (6.19)[a]	0.18 (1.36)	1.48*** (5.49)	1.01*** (5.34)
Proportion of irrigated cultivated land (%)	0.49*** (6.64)	0.44*** (5.49)	0.65*** (5.27)	0.46 (1.54)
Proportion of crop area affected by drought (%)	-0.39*** (4.26)	-0.44*** (2.96)	-0.15 (1.22)	-0.07 (0.36)
Proportion of crop area affected by frost (%)	-0.68*** (2.90)	-0.24 (0.57)	-0.84*** (2.92)	-1.05 (1.57)
Time trend (year)	2.42*** (12.96)	1.19*** (4.94)	2.81*** (8.53)	2.77*** (7.71)
Dummy for major winter wheat region (Yes = 1; No = 0)	36.21*** (8.65)			
Dummy for southwestern winter wheat region (Yes = 1; No = 0)	29.39*** (7.04)			
Constant	60.38*** (10.07)	98.85*** (15.00)	68.94*** (7.06)	74.00*** (5.43)
N	465	147	237	81
R^2	0.553	0.417	0.619	0.656

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

that increased incidence of drought and frost reduced TFP, as would also be expected. After controlling for the effects of other variables, the estimated time trend parameter ranged from 2.42 (row 5, Table 12) to 2.90 (row 5, Table 14), with statistical 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 8 of 12 parameters for this variable are positive and statistically significant at 1% (row 1, Tables 12-14). For the nation as a whole, 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 wheat varieties with CIMMYT germplasm increased by 18.6%, from 7.5% in 1982 to 26.1% in 2011 (Appendix Table 2), which suggests that use of CIMMYT germplasm increased China's wheat TFP by about 14% (18.6% x 0.75). The impacts are most significant in China's major winter wheat regions (column 3, Table 12) and the southwestern winter wheat region (column 4). Though denominated in China as "winter wheat regions" based on when the crop is sown, predominant wheat types there are facultative- and spring-habit wheats. It is thus logical that wheat from CIMMYT's breeding programs, which focus on spring-habit types, has had the highest impact in the above two regions. On the other hand, we did not find a statistically significant difference in impact from CIMMYT germplasm or germplasm from other sources in spring and spring-winter mixed wheat regions, based on the estimated parameter (column 2).

Table 13. Estimated total factor productivity (TFP) of wheat in China during 1982-2011: ordinary least squares estimates based on the proportion of major wheat varieties that contain CIMMYT germplasm and grouped either as direct releases of CIMMYT germplasm or use of CIMMYT germplasm in varietal breeding.

	All regions (1)	Spring and spring-winter wheat regions (2)	Major winter wheat regions (3)	Southwestern winter wheat region (4)
Proportion of varieties with CIMMYT germplasm (%)				
Directly releases (%)	1.09*** (5.01) [a]	0.10 (0.23)	6.05 (1.28)	1.27*** (5.99)
First- and higher-generation crosses (%)	0.65*** (5.04)	0.19 (1.37)	1.47*** (5.46)	0.60** (2.38)
Proportion of irrigated cultivated land (%)	0.47*** (6.32)	0.45*** (5.20)	0.64*** (5.24)	0.23 (0.76)
Proportion of crop area affected by drought (%)	-0.38*** (4.17)	-0.44*** (2.94)	-0.16 (1.26)	0.02 (0.09)
Proportion of crop area affected by frozen (%)	-0.72*** (3.08)	-0.24 (0.57)	-0.84*** (2.90)	-1.44** (2.16)
Time trend (year)	2.56*** (12.78)	1.18*** (4.50)	2.83*** (8.58)	3.36*** (7.93)
Dummy for major winter wheat region (Yes = 1; No = 0)	35.50*** (8.46)			
Dummy for Southwestern winter wheat region (Yes = 1; No = 0)	26.25*** (5.85)			
Constant	60.93*** (10.18)	99.00*** (14.86)	68.68*** (7.03)	77.61*** (5.84)
N	465	147	237	81
R^2	0.556	0.417	0.621	0.682

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

One explanation could be that being of spring- or winter-habit does not matter; that particular wheat type is independent of the advanced agronomic traits conveyed by CIMMYT germplasm (Tables 10 and 11).

The results presented in Table 13 provide additional information on CIMMYT germplasm impacts. For the regression including all regions (column 1), the impacts are statistically significant both for direct releases of CIMMYT germplasm (row 1) and for varieties derived from crosses with CIMMYT germplasm (row 2). The impact from use of direct releases is evident mainly in the southwest winter wheat region (column 4), whereas impacts through use of CIMMYT germplasm in crosses appear in both the major winter wheat regions (column 3) and the southwest winter wheat region.

Based on the intensive measure (the proportion of CIMMYT germplasm), Table 14 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 8) and the impact on China's wheat TFP was 4.6%. The larger impact (14%) for the extensive measure (Table 12) 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.

Table 14. Estimated total factor productivity (TFP) of wheat in China during 1982-2011: ordinary least squares model based on the proportion of major wheat varieties that contain CIMMYT germplasm, weighted by area sown.

	All regions (1)	Spring and spring-winter wheat regions (2)	Major winter wheat regions (3)	Southwestern winter wheat region (4)
Proportion of germplasm from CIMMYT (%)	0.92*** (4.60) [a]	-0.08 (0.27)	7.30*** (5.41)	1.20*** (6.14)
Proportion of irrigated cultivated land (%)	0.42*** (5.55)	0.44*** (5.18)	0.68*** (5.55)	0.05 (0.17)
Proportion of crop area affected by drought (%)	-0.41*** (4.35)	-0.42*** (2.79)	-0.19 (1.52)	0.08 (0.39)
Proportion of crop area affected by frozen (%)	-0.71*** (2.96)	-0.27 (0.65)	-0.70** (2.41)	-1.49** (2.25)
Time trend (Year)	2.90*** (17.34)	1.32*** (5.84)	3.05*** (10.08)	3.41*** (10.46)
Dummy for major winter wheat region (Yes = 1; No = 0)	32.70*** (7.64)			
Dummy for Southwestern winter wheat region (Yes = 1; No = 0)	25.63*** (6.10)			
Constant	66.80*** (11.34)	103.67*** (15.95)	63.41*** (6.46)	86.69*** (6.99)
N [b]	465	147	237	81
R^2	0.537	0.410	0.618	0.684

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

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. With slight differences among regions and provinces, in general Chinese farmers replaced 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,[15] which is tiny compared to that of China's national wheat R&D program.

The contribution of CIMMYT germplasm to China's wheat varieties varies across regions and time. As one would expect, CIMMYT's contribution has been mainly in the spring wheat production regions such as Inner Mongolia, Heilongjiang and Ningxia. However, Yunnan in the southwest winter wheat region also had a high proportion of wheat varieties with CIMMYT germplasm. CIMMYT's germplasm contribution to China's wheat varieties in the major winter wheat regions has been relatively small, but it has made a special contribution to major wheat varieties in those regions, in the form of breeding stocks with higher yields and enhanced resistance to stripe rust and other diseases.

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.

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.

Also, CIMMYT wheat germplasm has had the greatest impact in areas defined as winter wheat — rather than spring wheat — regions. Future research is needed to examine the reasons behind the varied impacts among regions.

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 CIMMYT in general and on wheat germplasm in particular. Second, China's investment in agricultural research has increased significantly

[15] 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.

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.

7. References

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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. 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 (1)	Directly adopted varieties (2)	First generation (3)	Second and higher generations (4)	Non-CIMMYT (5)	CIMMYT (6)	Non-CIMMYT (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 3. 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 frost (%)	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

Source: Authors' survey.

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