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The role of exotic wheat germplasms in wheat breeding and their impact on wheat yield and production in China

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ABSTRACT

Wheat is the second most important food crop in China and its yield has increased significantly since the early 1980s. While the rise in yield is obviously owed to the adoption of modern varieties and the rising use of inputs, little research has examined the yield gains as a result of the improvement of germplasms through international exchanges in the domestic breeding program. This study aims to understand the uses of exotic germplasms in wheat varieties adopted by farmers and their contributions to wheat yield and production in China. Based on unique data on major wheat varieties adopted by farmers and their pedigree in 17 major wheat production provinces in the period between 1982 and 2014, descriptive analyses show that the varieties with germplasms from CIMMYT (International Maize and Wheat Improvement Center) and other countries (or Others) accounted for 19% and 81%, respectively, in the major varieties adopted by farmers. While the direct adoption of exotic varieties in production has been falling, the use of exotic germplasms in wheat breeding has increased over time. Moreover, the varieties with both, Chinese and exotic germplasms, normally had higher average yields than the varieties with Chinese germplasms alone in most periods studied. The econometric analysis further shows that when compared with the varieties with pure Chinese germplasms, those with exotic germplasms contributed higher yields. Without the germplasms from CIMMYT and Others, the average annual yield would be lowered by 63 kg/ha and 323 kg/ha, respectively, during 1982–2014. The estimated increase in wheat production as a result of using exotic germplasms reached 10.4 million tons annually and has increased over time in the past three decades. The paper concludes with several policy implications for China's plant breeding strategy and for international donors funding the germplasm program.

1. Introduction

Producing over 120 million tons of wheat per year, China is the world's largest wheat producer. Wheat is also the second largest food crop after rice, and the third largest crop overall, after maize and rice, in China (NBSC, 1980-2016). Despite the wheat area decreasing by 17% during the period from 1978 to 2015, production more than doubled over the same period, transforming China from a major wheat importer (average annual imports of 11.5 million tons—about 13% of domestic consumption in the 1980s) to

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near-self-sufficiency since the early 2000s (NBSC, 1980-2016).

The significant rise in wheat yields in China is a successful story of modern technologies at work. While increase in modern inputs such as fertilizers contributed to yield growth in all major crops, Jin, Huang, Hu, and Rozelle (2002) showed that the primary source of wheat yield growth was from the rise of total factor productivity (TFP), which had increased at about 4% annually, during the period between 1979 and 1995. Their study further showed that in addition to overall change in technology, the genetic materials (or germplasms) from the Consultative Group on International Agricultural Research (CGIAR) also contributed to the growth in the TFP of China's wheat prior to the mid-1990s. Huang, Xiang, and Wang (2015) extended the early study to 2011 and found that CIMMYT[2] germplasms had contributed to a total increase in the TFP of wheat in China by a range of 5% to 14% during the period from 1982 to 2011. These results are consistent with the literature reported by many natural scientists who have argued the critical importance of incorporating foreign (or exotic) germplasms in wheat breeding in China (He, Rajaram, Xin, & Huang, 2001; Wang, 2012).

Despite the importance of exotic wheat germplasms in wheat breeding and wheat yield improvement in China, little research has documented the roles of different exotic germplasms by source, and examined their impacts on wheat yields and production. To our knowledge, only three studies had partially analyzed the impacts of germplasms on wheat productivity in China. Jin et al. (2002) examined the impact of CGIAR's germplasms on TFP through its impact on varietal turnover[3] during the period between 1982 and 1995, but they did not explicitly examine its impact on the TFP of wheat and yield. Chan-Kang, Fan, and Qian (2003) estimated the contribution of CIMMYT's germplasms to yield gains based on experimental yield data of adopted wheat varieties in China. Huang et al. (2015) analyzed the direct impact of CIMMYT's germplasms on wheat TFP in China during the period between 1982 and 2011. However, all these studies compared CGIAR's germplasms with the aggregate germplasms that combined those from both, China and other countries. However, past literature shows that China's wheat breeding program has also intensively used germplasms from Italy, the USA, and the former Soviet Union (He et al., 2001; Wang, 2012).

Understanding the roles of breeding programs by incorporating germplasms from different sources is important not only for breeders in their breeding design, but also for policymakers in setting their funding priorities. This study aims to understand the sources of germplasms embodied in wheat varieties as adopted by farmers and their contributions to wheat yields and production in China. To achieve these goals, we examine the following two sets of questions: 1) What roles have exotic germplasms from CIMMYT and other countries played in the wheat breeding program in China in the past three decades? How have they changed over time? 2) What are the impacts of incorporating exotic germplasms in wheat varieties on wheat yield performance in China? What have the contributions of germplasms from CIMMYT and other countries to China's wheat production been?

The rest of this paper is organized as follows. Section 2 introduces the data used in this study. Section 3 documents the contributions of exotic wheat germplasms to Chinese varieties since the early 1980s. Section 4 presents the econometric model, the estimation results on yield, and production impacts of CIMMYT's and other exotic germplasms in China. Section 5 concludes this study with several policy implications.

2. Data and samples

This study uses the following four datasets. Dataset 1 includes the major wheat varieties adopted by farmers and the sown areas by each major variety and by province during the period between 1982 and 2014.[4] Dataset 2 includes detailed information on the pedigree of each major wheat variety included in Dataset 1. Dataset 3 includes variety-specific experimental yields of the major varieties included in Dataset 1. These three datasets are used to document the contributions of exotic wheat germplasms to China's wheat varieties and to estimate their impacts on wheat yields in China. Dataset 4 includes the inputs and yield of wheat production and crop areas affected by natural disasters, segregated by province. These inputs were used to estimate the wheat production function.

Dataset 1 on the major wheat varieties comprises data from both, published and unpublished documents, in the “Compilation of Varietal Areas for Major Crops” (MOA, 1983-2015b). Wheat has been planted in 30 out of 31 provinces in mainland China, but the top 17 wheat-producing provinces accounted for 98% of China's total wheat area in 2014. These 17 provinces are selected as our samples in this study. For these provinces, there were a total of 1979 major varieties during the period between 1982 and 2014. These major varieties accounted for about 80% of China's total wheat area in the 1980s and 1990s, and nearly 90% in the 2000s.

Dataset 2 on the pedigree of each variety comprises data drawn after an exhaustive review of published books and papers, online materials, and unpublished documents, as well as personal interviews. Major published books include several publications on Chinese wheat varieties (Jin, 1983, 1986, 1997; Jin & Liu, 1964; Zhuang, 2003), which catalog wheat varieties that were mainly used by Chinese farmers in the 20th century. Published papers mainly offer information on pre-release varietal evaluation or demonstration trials. The China Crop Variety Query System is the major online source, which is supported by the National Agricultural Technology Extension and Service Center and provides a partial listing of major varieties approved after 2000. For each variety, we trace the pedigree to the point where a non-Chinese (that is, from other countries or international institutions) parent appeared. Finally, we obtain pedigree information for 1660 Chinese varieties and 57 non-Chinese varieties (i.e., varieties introduced to China, and directly used in field production during the period between 1982 and 2014). Despite our best efforts, we are unable to obtain pedigree

[2] The International Maize and Wheat Improvement Center (CIMMYT) is one of the 15 independent, international, non-profit agricultural research organizations that make up the CGIAR, and leads the CGIAR Research Programs on Maize and Wheat.

[3] Variety turnover is a measure of how fast varieties that first appear in the field are able to replace the older varieties.

[4] A “major” variety is defined as a variety that has sown area of at least 100,000 mu (or 6667 ha, 15 mu = 1 ha) within one year in China.

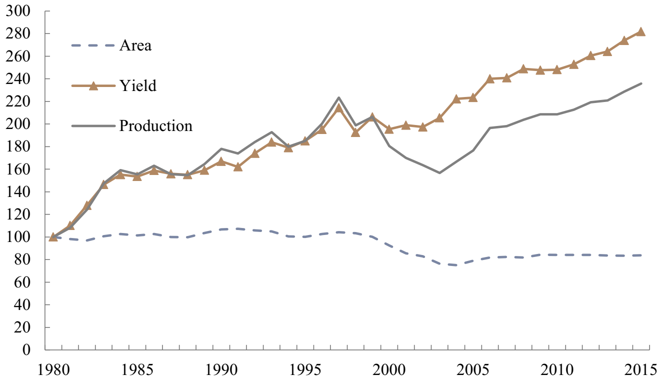

Fig. 1. Trends in wheat area, yield, and production in China, 1980–2015 (1980 = 100).
Source: NBSC (1980-2016).

information for 262 Chinese wheat varieties, many of which are local or traditional varieties and were adopted in the early period, accounting for about 12% of the total from Dataset 1.

Dataset 3 comprises data from the same sources as in Dataset 2. The experimental yields are mainly from pre-release varietal evaluation or demonstration trials conducted across main wheat production regions in China. For landraces, and some varieties bred before the 1980s, the data is replaced by actual yields in production, as no regional tests had been conducted before the varietal release of these varieties. With our best efforts, we were able to obtain variety-specific yield information for 1613 major wheat varieties, accounting for about 82% of the total from Dataset 1.

Data on the inputs and output of wheat production and crop areas affected by natural disasters in Dataset 4 are sourced from the National Development and Reform Commission (NDRC, 1984–2015) and the Ministry of Agriculture (MOA, 1984-2015a) respectively. NDRC published detailed inputs and yield by crop in all major production provinces, including wheat in the 17 major provinces selected in this study. Inputs include labor, fertilizer, pesticide, machinery and equipment, and other input material (e.g., seed, farm plastic film, etc.), measured in per unit area (mu, 15 mu = 1 ha). The MOA (1984-2015a) reported that the total crop areas affected by natural disasters such as droughts, cold weather, floods, and hailstorms. The data are presented by province and by year, but are not crop-specific. Since all provinces selected in this study are major wheat production provinces where wheat is an important crop, we use total crop areas affected by natural disasters as a proxy for wheat. Drought and cold weather are considered as major natural disasters that impact wheat. Thus, the proportion of crop areas affected by drought and frost is used in estimating the wheat production function.

3. Wheat production: the major varieties and sources of germplasms

3.1. Trends in wheat production and major varieties

Wheat production in China has grown steadily over the last several decades. An exception occurred during a short period of falling production in the period between 2000 and 2003, which was mainly due to the decrease in area rather than yield (Fig. 1). Over the entire period of time from 1980 to 2015, despite a decrease in wheat area by 16%, yield increased by 152%, which resulted in an increase in wheat production by 136% (Fig. 1). China's wheat yield is among the highest in the world. The average wheat yield reached 5.1 ton/ha during the period between 2010 and 2016—well above the global average (3.2 ton/ha) (FAO, 2017).[5]

While the literature has documented the roles of hybrid rice and its impact on rice yields (Fan, Chan-Kang, Qian, & Krishnaiah, 2005; Huang & Rozelle, 1996; Lin, 1991; Shi & Hu, 2017), the role of wheat breeding in generating high-yield varieties is even more impressive. Indeed, yield increase in wheat has been much higher than in other major crops, including rice and maize, in China. For example, the average annual growth of wheat yield was 2.43% during the period between 1978 and 2015, as against 1.18% for rice and 1.76% for maize over the same period (NBSC, 1980-2016).[6] The wheat breeding program is believed to have played a very important role in increasing wheat yield (Qin et al., 2015).

China has developed a strong wheat breeding program that has used various sources of germplasms from both local and foreign countries. Chinese wheat breeders acquired high yielding, disease resistant, and semi-dwarf varieties from Italy, the USA, the former Soviet Union, and other countries, aside of CIMMYT, and incorporated desirable traits from these germplasms into their own varieties (He et al., 2001). By 1977, farmers were growing semi-dwarf wheat varieties on about 40% of wheat area in China. By 1984, this number rose to 70% (Rozelle & Huang, 2000). During the 1990s, it was difficult to find anything other than improved semi-dwarf varieties in China.

[5] Among the world's four leading wheat producers, China's average wheat yield was 64%, 69%, and 126% higher than that of the USA, India, and Russia, respectively, during 2010–2016 (FAO, 2017).

[6] Yields of rice, wheat and maize in 1978 were 3978 kg/ha, 1845 kg/ha, and 2803 kg/ha, respectively (NBSC, 1980).

Table 1
Number of major wheat varieties adopted by farmers by period in China, 1982–2014.
Source: Authors' calculation based on Datasets 1 and 2 discussed in section 2.

	Annual number	Total number	Developed in China	Developed outside China		
				Subtotal	CIMMYT	Others
1982–1985	245	417	385	32	17	15
1986–1990	291	520	494	26	16	10
1991–1995	284	561	539	22	14	8
1996–2000	268	532	516	16	6	10
2001–2005	277	524	514	10	6	4
2006–2010	329	581	572	9	5	4
2011–2014	381	594	586	8	4	4
1982–2014	295	1979	1922	57	36	21

Note: Others include Italy, the USA, the former Soviet Union, Romania, Bulgaria, Australia, Canada, the UK, and so on.

Table 2
Shares of major wheat varieties by sources of germplasms in different periods, based on counts of varieties grown in the period between 1982 and 2014 (%).
Source: Authors' calculation based on Datasets 1 and 2 discussed in Section 2.

	1982–1985	1986–1990	1991–1995	1996–2000	2001–2005	2006–2010	2011–2014	1982–2014
1. Varieties with Chinese germplasms only	14.1	13.8	19.3	24.2	24.6	22.2	26.1	16.2
2. Varieties with exotic germplasms only	28.3	19.8	12.8	8.8	6.3	4.5	2.9	12.1
CIMMYT only	4.1	3.1	2.5	1.1	1.2	0.9	0.7	1.8
Others only	21.6	14.2	8.0	6.2	3.2	2.6	1.5	8.6
CIMMYT & Others	2.6	2.5	2.3	1.5	1.9	1.0	0.7	1.7
3. Varieties with both Chinese and exotic germplasms	57.6	66.4	67.9	67.0	69.1	73.3	71.0	71.7
CIMMYT & China	0.0	0.4	0.7	0.8	1.7	3.1	2.7	1.5
Others & China	54.9	60.6	57.4	51.7	51.5	49.2	46.4	56.7
CIMMYT, China & Others	2.7	5.4	9.8	14.5	15.8	21.0	21.9	13.5

A large number of wheat varieties have been developed and adopted by farmers in the past several decades. On average, wheat farmers grew 295 major varieties each year during the period between 1982 and 2014 (column 1, Table 1). The number of varieties has shown a general rising trend over time. The average annual number increased from 245 in the early 1980s (1982–1985) to 381 in the early 2010s (2011–2014) (column 1, Table 1). This is largely because of a significant increase in the number of varieties released. Although no study has examined the reasons behind this rising trend, the improved plant breeding capacity and seed industry commercialization may help explain the observations (Hu, Huang, & Xiang, 2010).

Despite having directly introduced foreign varieties in production, most varieties adopted were developed by Chinese scientists. Of the 1979 major wheat varieties used by farmers during the period between 1982 and 2014, only 57 varieties came from outside China, and were mainly planted by farmers in the early periods (column 4, Table 1). In the early 1980s, 8% (32/417) of the major wheat varieties were exotic varieties, and the proportion dropped to only 1% (8/594) in the period between 2011 and 2014. More than half the adopted foreign varieties were from CIMMYT, others were from Italy, the USA, the former Soviet Union, Romania, Bulgaria, Australia, Canada, the UK, and so on (Others, henceforth).

3.2. Contribution of exotic germplasms to wheat varieties in China

To measure the contribution of exotic germplasms to China's wheat varieties, we apply the “any ancestor” rule that has been used widely in the literature (Chan-Kang et al., 2003; Evenson & Gollin, 2003; Pardey, Alston, Christian, & Fan, 1996). That is, we examine whether a variety has germplasms from a specific source that is interesting to our study (e.g., CIMMYT and Others) based on the available pedigree data. Then, we group all varieties into the following categories (Table 2):

1) the varieties with Chinese germplasms only;
2) the varieties with CIMMYT's germplasms only;
3) the varieties with germplasms from Others only;
4) the varieties with germplasms from both CIMMYT and Others;
5) the varieties with Chinese and CIMMYT's germplasms only;
6) the varieties with germplasms from both China and Others; and
7) the varieties with germplasms from China, CIMMYT, and Others.

These groups are exclusive, and their shares add up to 100% of all major wheat varieties in China. With Datasets 1 and 2, we calculate the sources of germplasms of major wheat varieties in each year at the provincial and national aggregate levels. Table 2 presents the share of major wheat varieties by sources of germplasms in different periods at the national level. Since the area of each variety adopted by farmers differs largely, to account for actual uses of varieties at the farm level by different sources of germplasms, we also calculate the area-weighted shares of major varieties, which are presented in the Appendix under Table A1.

In general, the contribution of exotic germplasms to China's wheat breeding has been significant in the past three decades. On average, the varieties that contained exotic germplasms accounted for 84% (12.1 + 71.7) of all major varieties during the period between 1982 and 2014 (last column, Table 2). Of this lot, the varieties with CIMMYT's and Others' germplasms accounted for 18.5% (1.8 + 1.7 + 1.5 + 13.5) and 80.5% (8.6 + 1.7 + 56.7 + 13.5), respectively, over the same period.

While the direct use of exotic varieties in production as discussed above (Table 1) and using exotic germplasms alone in wheat breeding (rows 2–5, Table 2) have significantly decreased, there is a rising trend of using exotic germplasms in wheat breeding in China. In the early 1980s, the varieties with exotic germplasms alone reached as high as 28.3% of the total, 21.6% were either directly used varieties or the varieties fully generated from Others' germplasms (column 1, Table 2). By early 2010s, the varieties with exotic germplasms alone reduced to less than 3% (row 2). On the other hand, the share of varieties with both, Chinese and exotic germplasms, had increased from 57.6% in the period between 1982 and 1985 to 73.3% in the period between 2006 and 2010 though there was a moderate fall in recent years (row 6, Table 2). Specifically, despite starting from a low share, the varieties with germplasms from both CIMMYT and China (rows 7 and 8) had increased from less than 3% to (0 + 2.7) to 24.6% (2.7 + 21.9) in the period between 2011 and 2014. Over the same period, the varieties with germplasms from both, Others and China (rows 8 and 9), had also increased from 57.6% (54.9 + 2.7) to 68.3% (46.4 + 21.9). Meanwhile, Chinese breeders have also increasingly used their own country's germplasms. As much as 72% (14.1 + 57.6) of varieties with Chinese germplasms (rows 1 and 6) existed in the period between 1982 and 1985. The number rose to 97% (26.1 + 71.0) in the period between 2011 and 2014.

The area-weighted shares of varieties by sources of germplasms show similar trends in the contribution of exotic germplasms to wheat varieties in China, but with additional information (see Table A1 in the Appendix). On an average, varieties with exotic germplasms had higher market shares (or planted areas by farmers). The pure Chinese varieties accounted for 16.2% of total varieties in the period between 1982 and 2014 (row 1, Table 2), but their area-weighted share was only 10% over the same period of time (row 1, Table 3). Over time, the area-weighted shares of varieties with exotic germplasms (Table 3) increased more than those without area-weighted ones, particularly before the mid-2000s, (Table 2).

There are several explanations for the rising use of exotic germplasms in Chinese wheat breeding, and for the expansion of their contribution to wheat areas in China. In the early 1980s, China's modern wheat breeding program was at its initial stages (Huang & Hu, 2008). Local Chinese varieties were rather tall, low yielding, and often susceptible to prevailing diseases. During the 1980s, exotic varieties were introduced either to improve them or for direct use by farmers. In the meantime, some major varieties were generated entirely based on the germplasms from CIMMYT and Others. After the late 1980s, there has been significant improvement in the capacity of China's plant breeding and the academic exchanges with the plant breeding scientists in many other countries, including exchanges of wheat seeds and genetic resources. In the meantime, China has also enhanced its collaborations with international organizations, such as CIMMYT. China officially joined the CGIAR in 1984. In 1997, CIMMYT opened an office in Beijing to provide new scientific information and technologies to Chinese researchers, and to facilitate the international exchange of genetic resources (Huang, Xiang, & Wang, 2016; Wang, 2012). Increasing uses of some exotic germplasms in wheat breeding in China is also due to their comparative advantage in major wheat traits, particularly yield.

3.3. Sources of germplasms and wheat yield performance

To understand the contributions of exotic germplasms to varietal yield improvement, we first examine the trend of experimental

Table 3
Average experimental yields (kg/ha) of major wheat varieties by sources of germplasms in different periods, between 1982 and 2014.
Source: Authors' calculation based on Datasets 1, 2, and 3 as discussed in Section 2.

	1982–1985	1986–1990	1991–1995	1996–2000	2001–2005	2006–2010	2011–2014	1982–2014
1. Varieties with Chinese germplasms only[a]	3024	3521	4257	4838	5910	5840	6389	5628
2. Varieties with exotic germplasms only	4883***	4978***	5075***	5433***	5932	6068	5916**	5188***
CIMMYT only	4647***	4811***	5359***	5815*	5610	5681	6363	5247**
Others only	4874***	4943***	4952***	5059	5099***	5009***	4898***	4939***
CIMMYT & others	5421***	5349***	5451***	6000***	6881***	7044***	6691	6158***
3. Varieties with both Chinese and exotic germplasms	5054***	5012***	5343***	5620***	5976	6392***	6858***	5869***
CIMMYT & China		5837***	5757*	6359***	6274	6129*	6422	6249***
Others & China	5064***	5040***	5419***	5620***	5962	6303***	6776***	5769***
CIMMYT, China and others	4726***	4607***	4917***	5584***	5980	6647***	7080***	6190***

Notes: *, **, and *** represent statistical significance of the mean difference from varieties with Chinese germplasms alone at 10%, 5%, and 1% levels, respectively.

[a] As shown in Table 2, for varieties with Chinese germplasms alone (row 1), the number of samples in the period between 2011 and 2014 was the largest for the entire period; while the varieties with exotic germplasms alone (row 2) were distributed more in the early periods. Since there were higher yields in later periods, the yield in the entire period (1982–2014) was lower in row 2 than in row 1.

yields by the varieties with different sources of germplasms, and then compare the experimental yields between varieties with and without the exotic germplasms based on Dataset 3. The results are presented in Table 3. The mean yield difference in each period is examined using a simple *t*-test.

The results show several interesting observations. First, the yield of pure Chinese varieties has increased significantly over time. The average experimental yield of the varieties with local germplasms alone had increased from 3024 kg/ha in the period between 1982 and 1985 to 6389 kg/ha in the period between 2011 and 2104 (row 1, Table 3). While there are several sources of land productivity growth, improvement in wheat breeding, including enlarging uses of wider germplasms from all of China, is also believed to have contributed to the significant rise in wheat yield in China (Wang, 2012).

Second, for the entire period between 1982 and 2014, when compared with the average yield of the varieties without the exotic germplasms (5628 kg/ha), the varieties with both, Chinese and exotic germplasms (5869 kg/ha), had significantly higher yield, but the varieties with exotic germplasms alone (5188 kg/ha) had significantly lower yield (last column, Table 3). The above observations may explain why the varieties with both Chinese and exotic germplasms dominated and the varieties with single exotic sources accounted for only small parts of wheat varieties that were bred (Table 2) and adopted (Appendix Table A1) in the past three decades in China.

Third, over time, when compared with the varieties with Chinese germplasms alone, the yield advantage of combining both, exotic germplasms and Chinese germplasms in breeding has been continued in nearly every sub-period though the more significant gains occurred in the early period than in the later period (Table 3). Exceptions were made for the varieties with Others' germplasms alone that has statistically lower yield than the varieties with Chinese germplasms alone since the early 2000s. Since the base of the above comparison is the set of varieties with Chinese germplasms alone and their average yield has more than doubled in the past three decades (row 1, Table 3), the lower yield gains from using exotic germplasms in the recent years than in the early years only implies that there has been more progress in improving domestic germplasms in China but the advantage of incorporating exotic germplasms with Chinese germplasms to improve wheat yield still continues.

4. Impact of exotic germplasms on wheat production in China

4.1. Econometric model and estimation method

To rigorously quantify the impact of exotic germplasms on actual wheat yield performance at the farm level, an econometric model is needed to analyze the specific impact of exotic germplasms after controlling for the impacts of other factors such as inputs and other technologies that have also changed over time. To consider the technical inefficiency issue further, this study uses the stochastic frontier production function and assumes that the introduction of exotic germplasms mainly contributes to the shift in the wheat yield frontier. Using the translog form of the Cobb–Douglas yield function, the empirical specification is defined as follows:

$$ln\, y_{it} = a_i + \sum_j b_j\, ln\, x_{jit} + cT + \frac{1}{2}\sum_j\sum_k d_{jk}\, ln\, x_{jit}\, ln\, x_{kit} + \frac{1}{2}hT^2 + \sum_j \beta_j\, ln\, x_{jit}\, T + \delta G_{it} + v_{it} - u_{it} \tag{1}$$

where y_{it} represents the wheat yield (kg/ha) in the i^{th} province in year t; x_j is a vector of conventional inputs, including per hectare labor input (day/ha), fertilizer use (yuan/ha, which is deflated by the fertilizer price index), and other inputs (mainly including seed, pesticide, machinery, equipment, farm plastic film, and animal traction) (yuan/ha, which is deflated by agricultural input price index).[7] T is a linear time trend to capture technological progress other than the adoption of varieties with exotic germplasms. G is the area-weighted share of the varieties with exotic germplasms, which reflects the contributions of exotic germplasms, and the base for comparison is the area-weighted share of the varieties with Chinese germplasms alone. G is measured in two alternative ways to check the robustness of the results. The first is based on the three categories of the major wheat varieties, and uses two separate variables: a) area-weighted share of varieties with exotic germplasms alone, and b) that of varieties with both Chinese and exotic germplasms. The second is based on further division of the major varieties with seven categories as discussed in Section 3.2, and uses six separate variables to compare with the category of varieties with Chinese germplasms alone. Thus, the coefficients of G reflect the impacts of the varieties with exotic germplasms on additional yield change from the improvement of the varieties with pure Chinese germplasms. The values of G variables all range from 0 to 1. v_{it} is assumed to be an iid N(0, σ_v^2) random variable, independently distributed of the u_{it}. u_{it} is a non-negative random variable with $u_{it} \sim N^+(0, \sigma_u^2)$, which reflects technical inefficiency. The heteroscedasticity in u_{it} is allowed, and the scale parameter is a function of the proportion of crop area affected by drought and frost.[8] Table 4 presents a summary of statistics of all the dependent and independent variables used in this study.

To estimate the above yield equation model, we perform a stochastic frontier analysis using the true fixed-effects model (TFE–SFA). Among studies that used the SFA method, the most frequently used methods are proposed by Battese and Coelli (1992, 1995), which ignores firm heterogeneity, and captures time-invariant unobservable factors into the efficiency term (Belotti & Ilardi, 2012; Belotti, Daidone, Ilardi & Atella, 2012 Greene, 2005a, 2005b; Kumbhakar, Lien, & Hardaker, 2012; Sun, Luo, Huang, & Ouyang, 2017). The TFE–SFA model proposed by Greene (2005b) allows disentangling time-varying inefficiency from unit specific

[7] Fertilizers, seeds, and other inputs are recorded in yuan/ha. We deflated them using the agricultural input price index to convert these monetary observations into implicit physical quantities.

[8] Wheat-specific data for drought and frost were not available; because all 17 provinces studied are major wheat production provinces where wheat is also an important crop, we use crop areas affected by drought and frost as proxies for wheat.

Table 4
Statistics of all variables used in regression analyses.

	Mean	Standard deviation
Yield (kg/ha)	4067	1199
Varieties with exotic germplasms only:	0.16	0.20
CIMMYT only	0.02	0.07
Others only	0.08	0.15
CIMMYT & Others	0.06	0.15
Varieties with both Chinese and exotic germplasms:	0.72	0.22
CIMMYT & China	0.01	0.04
Others & China	0.56	0.24
CIMMYT, China & others	0.15	0.17
Labor (day/ha)	159	80
Fertilizer (yuan/ha)	797	324
Other inputs (yuan/ha)	1660	659
Time	16	9
Crop area affected by drought (%)	9	9
Crop area affected by frost (%)	1	2

time-invariant unobserved heterogeneity. We choose the TFE–SFA model for the following reasons. First, owing to the diversified agro-ecological environment in China, heterogeneity does exist among different wheat production zones that do not change in the short term, unrelated to the production process, but affecting the output. Second, this study focuses on the contribution of exotic germplasms to the yield frontier, which may relate to individual unobservable heterogeneity. Third, the model estimation uses the maximum likelihood dummy variable (MLDV) method that is appropriate when the length of the panel is sufficiently large, but the number of individuals is not large (Belotti & Ilardi, 2012). In this study, we use provincial panel data from 17 provinces over 32 years from 1983 to 2014,[9] which is justified for using the MLDV estimation.

4.2. Empirical results

Table 5 reports the estimation results. In general, the models perform well and are robust. The ratio of σ_u over σ_v, reflecting the contribution of the non-efficiency to the random error, can thus measure the validity of the stochastic frontier estimation. According to the regression results, the values of the ratio for the model's two specifications are 2.73 (0.156/0.057) and 2.89 (0.159/0.055), respectively, indicating that it is appropriate to use the stochastic frontier function with the TFE model.

The estimation results of all the controlled variables are robust under the two alternative measurements of G (Table 5). The estimated output elasticities of fertilizer are 0.05 and 0.06, respectively, with statistical significance at the 5% level (Appendix Table A2). The estimated output elasticities of other inputs are 0.12 with statistical significance at the 1% level. The estimated elasticity of labor is insignificant, and this may be due to the large labor surplus in rural China in most years covered in this study (Cook, 1999). The log derivative of the yield frontier with respect to time trend is 0.012 with statistical significance at the 1% level, implying other technological progress except the introduction of exotic germplasms has contributed to wheat yield growth at 1.2% annually. Parameters for the proportion of crop area affected by drought and frost are positive and significant, which suggests that the higher incidences of both, drought and frost, result in the higher technical inefficiency (or lower technical efficiency) of wheat production.

Of greatest interest are the estimated parameters for the varieties with exotic germplasms. All the estimated parameters of eight variables are positive, and six of them are statistically significant (rows 1–8, Table 5). These results are largely consistent with those of the comparison of wheat yield between the varieties with and without exotic germplasms that are based on the experimental station yield data as discussed in Section 3.3.

On average, when compared with the varieties with Chinese germplasms alone, while all varieties with exotic germplasms perform better in wheat yields, the positive yield impact of the varieties with both, Chinese and exotic germplasms, is higher for those with exotic germplasms alone (column 1, Table 5). The coefficient for the varieties with exotic germplasms alone is 0.173 with statistical significance at the 10% level (row 1, Table 5), implying that compared with the varieties with local materials alone, 1% point increase in the share of varieties with exotic germplasms alone raised wheat yields by 0.173%. The estimated coefficient for the varieties with both Chinese and exotic germplasms is much bigger (0.273) and with statistical significance at the 1% level (row 5, Table 5).

If exotic germplasms are separated by CIMMYT and Others, we find that the impacts on wheat yields differ among various categories (column 2, Table 5). Among six categories of the varieties with exotic germplasms, compared with the varieties with Chinese germplasms alone, four of them had statistically significant positive impacts, the estimated coefficients ranging from 0.191 for “CIMMYT & Others” to 0.235 for “Others & China,” 0.264 for “CIMMYT, China & Others,” and 0.281 for “CIMMYT only.” The estimated coefficients for the varieties with the other two categories, “Others only” and “CIMMYT & China,” are positive but not

[9] The data used in regression start from 1983 rather than 1982, because some right-hand side variables are available only after 1983. Since 98% of production teams had adopted the household-based farming system (HRS) by the end of 1983 (Lin, 1992). Thus, HRS is considered to have been fully implemented in China since then.

Table 5
Estimation results of wheat yield function based on the TFE–SFA model.

	(1)	(2)
Frontier		
Varieties with exotic germplasms only:	0.173* (0.105)	
CIMMYT only		0.281* 0.170)
Others only		0.125 (0.122)
CIMMYT & Others		0.191* (0.107)
Varieties with both Chinese and exotic germplasms:	0.273*** (0.094)	
CIMMYT & China		0.039 (0.149)
Others & China		0.235** (0.093)
CIMMYT, China & Others		0.264*** 0.088)
Labor	−0.058 (0.076)	−0.052 (0.075)
Fertilizer	0.057 (0.080)	0.053 (0.081)
Other input	0.123** (0.051)	0.119** (0.051)
Labor^2	−0.046 (0.098)	−0.043 (0.094)
Labor*fertilizer	0.049 (0.079)	0.053 (0.078)
Labor*Other inputs	−0.005 (0.089)	−0.007(0.089)
Fertilizer^2	−0.263*** (0.089)	−0.272*** (0.091)
Fertilizer*Other inputs	0.188 (0.122)	0.195* (0.108)
Other inputs^2	−0.150 (0.190)	−0.158 (0.184)
Time	0.012*** (0.004)	0.012*** (0.004)
Time ^{2}	−0.001 (0.001)	−0.001 (0.001)
Time *Labor	−0.011* (0.007)	−0.011 (0.007)
Time *Fertilizer	0.007 (0.007)	0.008 (0.007)
Time *Other inputs	−0.005 (0.004)	−0.005 (0.004)
Usigma		
Proportion of crop area affected by drought (%)	0.028* (0.016)	0.028*(0.015)
Proportion of crop area affected by frost (%)	0.125** (0.050)	0.125** (0.048)
Constant	−4.173*** (0.514)	−4.132*** (0.491)
Vsigma		
Constant	−5.714*** (0.380)	−5.811*** (0.439)
E(σ_u)	0.156	0.159
σ_v	0.057*** (0.011)	0.055*** (0.012)
N	495	495
Log likelihood	27.371	27.467

Note: Standard errors are given in parentheses. ***, **, and * represent statistically significance at the 1%, 5%, and 10%, respectively.

statistically significant, which indicates that the yield of these varieties are similar to the varieties with Chinese germplasms alone. The implications of the above results for breeders is seen when they select the germplasms from the local and various exotic sources.[10]

4.3. Impacts of different exotic germplasms on wheat yield in the past three decades

To further investigate the impacts of exotic germplasms from CIMMYT and Others on wheat yields in the past three decades, we use the estimated coefficients presented in column 2 of Table 5. To do so, we only use the estimated coefficients that are statistically significant. That is, we only use the coefficients for the following four groups of varieties with: "CIMMYT only," "CIMMYT & Others," "Others & China," and "CIMMYT, China & Others." Then, we estimate the total impacts of each of CIMMYT's and Others' germplasms based on the following assumption: for varieties with two or three sources of germplasm, we assign the same weight to each source,[11] that is, 1/2 each for those with two sources and 1/3 each for those with three sources. Then, the impacts on annual wheat yield and production from exotic germplasms in the past three decades and by each sub-period are estimated. Since the estimated coefficients for all variables with exotic germplasms are their differences from that of the varieties with Chinese germplasms alone, in conducting this analysis on additional wheat yield gains (and production) from exotic germplasms, we use the difference between with and without exotic germplasms to estimate the impacts based on the following formula: $\Delta y_t = y_t - y_t/(1 + \delta G_t)$, where y_t represents the actual wheat yield in year t, and δ is a vector of the estimated coefficients for G_t in the column 2 in Table 5.

[10] We have tried to divide the 17 provinces into three wheat producing zones according to He et al.'s (2001) classification and include a set of interaction terms of G with the two region dummy variables in the model to capture the regional differences in the impacts of exotic germplasms. However, the estimation results did not show significant regional differences. Future research is needed to examine the reasons for it. Thus, we do not report these results here.

[11] In fact, for varieties with two or three germplasm sources, it is difficult to justify the exact contributions of each source of germplasms. In order to calculate the approximate value of the contribution, for varieties with two or three sources of germplasms, we assume the weight of each source is the same. Although this approach might lead to over-estimating the contribution of germplasms from the domestic (or exotic) source for some varieties, it might also under-estimate the contribution of germplasms from the domestic (or exotic) source for the other varieties, which suggests that over-estimation or under-estimation of sources of germplasms might not be a big problem.

Table 6
When compared to Chinese germplasms, the contributions of exotic germplasms to annual wheat production in China, during the period between 1982 and 2014.

	1982–1985	1986–1990	1991–1995	1996–2000	2001–2005	2006–2010	2011–2014	1982–2014
Average annual area (million ha)[a]	28.95	29.56	29.90	28.99	23.00	23.90	24.18	26.95
Average annual yield (kg/ha)[b]	2891	3161	3623	3919	4332	5544	5903	4184
Contribution to annual yield (kg/ha)[c]								
1. Varieties with exotic germplasms only								
CIMMYT only	6.5	5.3	6.1	2.2	1.2	1.6	1.7	4.4
CIMMYT & Others	2.8	8.4	10.4	17.1	12.4	17.9	15.7	11.9
2. Varieties with both local and exotic germplasms								
Others & China	371.8	465.6	523.1	517.2	543.1	570.4	571.3	528.8
CIMMYT, China & Others	8.4	28.1	96.8	194.7	209.0	330.3	372.3	157.9
Total contributions to annual yield (kg/ha)[d]								
CIMMYT	11	19	44	76	77	121	134	63
Others	190	246	299	332	347	404	418	323
Total contributions to annual production (million ton)[e]								
CIMMYT	0.31	0.56	1.30	2.19	1.77	2.88	3.23	1.70
Others	5.50	7.28	8.94	9.63	7.99	9.66	10.10	8.70

[a] Wheat area is from NBSC (1983–2015).
[b] Wheat yield is from NDRC (1983–2015).
[c] Contribution to yield is obtained by $[y_t \text{ -} y_t/(1+\delta G_t)]$, where y_t is wheat yield in year t, and G_t is area-weighted shares as those presented in Appendix Table A1. δ is from column 2 of Table 6, and only variables with significant coefficients are included.
[d] For varieties with two or three sources of germplasms, the same weight (e.g., 1/2 or 1/3) is assigned to each source.
[e] Contribution to wheat production is calculated by multiplying the contribution to yield (rows 7–8) by wheat area (row 1).

The results of the impact of exotic germplasms on wheat yields and production in the past three decades are summarized in Table 6. During the period between 1982 and 2014, the estimated results show that annual average contributions of CIMMYT's and Others' germplasms to actual yields were 63 kg/ha (row 7, Table 6) and 323 kg/ha (row 8, Table 6), respectively. With the average annual wheat area of 26.95 million ha, the estimated average impact on annual wheat production reached 1.70 (26.95*63/1000) million tons from CIMMYT's germplasms, and 8.70 (26.95*323/1000) million tons from Others' germplasms in the past three decades (column 8, Table 6). The accumulated contributions of CIMMYT's and Others' germplasms to wheat production in China amounted to 56 million tons (1.7*33 years) and 287 million tons (8.7*33), respectively, during the period between 1982 and 2014.

Table 6 also shows the contributions of CIMMYT's and Others' germplasms to China's wheat yield and production by sub-period. In general, the contributions of CIMMYT and Others' germplasms to China's wheat yield have gradually increased over time (rows 7 and 8). For example, for CIMMYT's germplasms, its contribution to yield increased from 11 kg/ha in the period between 1982 and 1985 to 134 kg/ha in the period between 2011 and 2014 (row 7, Table 6), implying that it increased by more than 11 times. The contribution of Others' germplasms has more than doubled, having increased from 190 kg/ha to 418 kg/ha over the same period (row 8, Table 6).

5. Conclusions

Despite the gradual fall in wheat area, wheat production has increased significantly due to the rapid growth of its yield in China since the early 1980s. The growth of wheat production is a successful story of increasing productivity through the use of modern technologies. The rise in yield is obviously owed to both, adoption of modern varieties and modern inputs, such as chemical fertilizers and irrigation. Despite the importance of modern varieties, little research has examined the yield gains from the wheat breeding program through the improvement of germplasms.

Based on unique data with nearly 2000 major wheat varieties adopted by farmers and their pedigrees in all major wheat production provinces in China in the past three decades, the descriptive analyses observes several interesting findings. First, the number of major wheat varieties adopted by farmers (with an annual area of more than 6667 ha) has been gradually increasing over time. Second, exotic germplasms constituted a significant part, while varieties with germplasms from CIMMYT and other countries accounted for 19% and 81%, respectively, out of the total number of the major varieties in the past three decades. While the direct uses of foreign wheat varieties in production has been falling because of significant improvements in the capacity of China's wheat breeding programs, there is a rising trend in breeding practices of combining exotic germplasms with Chinese local germplasms and this has become a major breeding strategy in China. Third, data based on the experimental stations show that although the yield of the varieties with Chinese germplasms alone more than doubled during the period between 1982 and 2014, varieties with exotic germplasms normally had even higher yield potential, particularly for those with both, local and exotic germplasms. This helps explain the fact that Chinese breeders have tended to use more exotic germplasms in their wheat breeding.

Econometric analyses further confirm that the varieties with exotic germplasms have contributed higher yields than the varieties with Chinese germplasms alone. When compared with the varieties with Chinese germplasms alone, on average, 1% point increase in the share of the varieties with exotic germplasms alone can raise the wheat yields by nearly 0.2%, and the number increases to nearly

0.3% for varieties with both, Chinese and exotic germplasms. Despite the less intensive use of CIMMYT's germplasms, when compared to the use of Others' germplasms in China's wheat program, the additional use of CIMMYT's germplasms can lead to a moderate rise in yield than the use of Others' germplasms can. Based on the econometric results and data on the uses of exotic germplasms, we estimate that the average annual contributions of CIMMYT's and Others' germplasms to China's wheat yields were 63 kg/ha and 323 kg/ha, respectively in the past three decades. These are sustainable because they are on the top of the yield gains from the varieties with Chinese germplasms alone. The latter have also improved their yields significantly over time. In addition to the gain in wheat production from the varieties with Chinese germplasms alone, the estimated average additional increase in annual wheat production reached 10.4 million tons from the use of exotic germplasms in the past three decades. The accumulated contributions of exotic germplasms to wheat production in China are estimated to be about 343 million tons during the period between 1982 and 2014, which is about 10% of the total wheat production over the same period of time, or 501% (or 272%) of annual wheat production in 1982 (or 2014).

The results of this study have important implications for plant breeders, policy makers in China, and international donors. First, while the wheat breeders have increasingly used exotic germplasms together with Chinese germplasms to generate new varieties, the varieties with Chinese germplasms alone have also been rising in the past three decades. Given the significant contribution of exotic germplasms to China's wheat production, higher yields would be obtained if the breeders could use more exotic germplasms in their breeding program in the future. Second, the results provide further motivation for Chinese wheat scientists to strengthen their collaboration with international research institutions (e.g., CIMMYT) and other countries in general, pertaining to wheat germplasms in particular. Third, China's investment in agricultural research has increased significantly since the early 2000s. Given the large contribution of exotic germplasms to China's wheat productivity, the government could improve national food security by increasing its commitment to international wheat research. Fourth, this study provides additional evidence of impacts of germplasms on crop yield, and provides further reason for international donors and development agencies to increase their investment in programs and collaborative work for the development of international germplasms between CGIAR centers and national agricultural research programs. Finally, following China's successful experience, as documented in this study, low-income and emerging countries can benefit considerably by increasing their effective collaboration with CIMMYT and other CGIAR centers.

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Appendix A. Appendix

Table A1
Area-weighted shares of major wheat varieties by sources of germplasms in different periods, 1982–2014 (%).
Source: Authors' calculation based on Datasets 1 and 2 discussed in Section 2.

	1982–1985	1986–1990	1991–1995	1996–2000	2001–2005	2006–2010	2011–2014	1982–2014
1. Varieties with Chinese germplasms only	2.9	2.7	4.5	5.5	13.0	19.2	23.8	10.0
2. Varieties with exotic germplasms only	33.2	20.3	13.2	9.7	4.1	3.1	2.0	12.0
CIMMYT only	0.8	0.6	0.6	0.2	0.1	0.1	0.1	0.4
Others only	31.9	18.3	11.1	7.2	2.5	1.3	0.5	10.1
CIMMYT & Others	0.5	1.4	1.5	2.3	1.5	1.7	1.4	1.5
3. Varieties with both Chinese and exotic germplasms	63.9	77.0	82.3	84.8	82.9	77.7	74.2	78.0
CIMMYT & China	0	0.1	0.1	0.3	2.7	4.9	3.1	1.9
Others & China	62.8	73.5	71.8	64.7	61.0	48.8	45.6	61.6
CIMMYT, China & Others	1.1	3.4	10.4	19.8	19.2	24.0	25.5	14.9

Table A2
Average output elasticities of major inputs.

	Model (1)	Model (2)
Output elasticities of inputs		
Labor	−0.058	−0.052
Fertilizer	0.057***	0.053**
Other inputs	0.123***	0.119***
Other technology change	0.012***	0.012***

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