Original Article

Rising Herbicide Use and Its Driving Forces in China

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Abstract China is one of the developing countries that has experienced rapid growth in herbicide use in the past two decades. However, little information is available on what drive this growing use of herbicides. This study aims for a better understanding of the trend and major factors that affect herbicide use in China. Based on national aggregate data and primary household survey data, this study shows that besides falling herbicide prices, rising wages have been a major driver of this rapid growth since the mid-2000s. Analyses based on household data show that off-farm rural labor employment away from home province contributes to the increasing use of herbicides in wheat and maize production. In addition, irrigation and farmers' education have significant impacts on herbicide use. With increasing wages and off-farm rural labor employment, we expect herbicide use in China to continue rising.

La Chine est un des pays en voie de développement qui a connu une croissance rapide de l'utilisation des herbicides dans les deux dernières décennies. Cependant, il n'y a pas beaucoup d'information sur cette utilisation plus élevée d'herbicides. Cette étude vise à mieux comprendre cette croissance et les autres facteurs qui influencent l'utilisation des herbicides en Chine. Basées sur des données agrégées et des données d'enquête sur les ménages, cette étude démontre que, ainsi que une chute des prix des herbicides, la croissance des salaires a été une cause déterminante de l'utilisation des herbicides à partir de la moitié des années 2000. Analyses basées sur les données des ménages nous indiquent que les travaux rurales non-agricoles loin de la province d'origine des travailleurs contribuent à l'utilisation d'herbicide dans la production de blé e de maïs. En plus, l'irrigation et l'éducation des agriculteurs influencent significativement l'utilisation des herbicides. Avec la croissance continue des salaires et du travail rurale non-agricole, on s'attend une croissance continue de l'utilisation des herbicides en Chine.

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Introduction

Herbicides have played an increasingly important role of weed control in modern agriculture. Initially adopted in the 1940s, herbicide application has expanded significantly in developed countries (Gianessi, 2013). Although herbicide use in crop production began much later in developing countries, its use has dramatically increased in the past two to three decades (Gianessi, 2013).

While herbicide application has raised agricultural production by preventing weed damage (Lichtenberg and Zilberman, 1986), it has also raised several concerns. Reports suggest that the reduction of crop yield caused by weeds reached 10–25 per cent in the Asian-Pacific region (Baki, 2006) and about 12–17 per cent in China (Zhang, 2003). However, substantial use of herbicides also raises concerns of risks to human health and adverse environmental consequences such as soil erosion, underground water toxicity, and the loss of wildlife and biodiversity (Freemark and Boutin, 1995; Dubrovsky *et al*, 2010; Rohr and Mccoy, 2010). Moreover, the growing use of herbicides has resulted in rapid evolution of herbicide-resistant weeds. A recent report estimates that the number of global herbicide-resistant weeds increased from less than 20 in 1975 to more than 400 in 2015 (Heap, 2013). Therefore, there is a tradeoff between growing agricultural output and adverse environmental consequences with increase in use of herbicides (Pingali, 2001; Schreinemachers *et al*, 2010).

Annual herbicide use in China was only 46 thousand metric tons (tons hereafter) in 1995, but reached more than 1 million tons in 2015.[1] Furthermore, China has become one of the most important herbicide exporters in the world in recent years (GACC, 2015).

Despite of the rapid growth in herbicide use in both developed and developing countries, few studies have empirically examined the driving forces behind rising herbicide use. Among the existing literature, Pingali (2001) suggests that higher labor costs, decreasing herbicide price, and the wide adoption of herbicide-resistant GM crops could be potential factors driving the expansion in herbicide use. Beltran *et al* (2013) found that wealthy farmers use more herbicide in the Philippines. However, to our best knowledge, no empirical study examines the growth pattern and the driving forces behind herbicide use in China.

China is an interesting case not only because of its rapid expansion in herbicide production and utilization but also due to its significant rural transformation in recent decades. For example, on the supply side, the domestic production of herbicide increased from a negligible level in the early 1990s to more than 1.8 million tons in 2015 (MCIC, 1990–1992, 1993–2015). Consequently, the real price of herbicide dropped by 69 per cent over the same period (authors' estimate based on the trade data). On the demand side, after more than two decades of slow growth in unskilled labor wage, it has increased rapidly since the mid-2000s and is expected to continue rising (Cai and Du, 2011; Li *et al*, 2012). Meanwhile, off-farm employment of rural labor has expanded substantially (Wang *et al*, 2011). However, to what extent have the above changes affected herbicide use in China in the past? Will the rapid growth in herbicides continue?

The overall objective of this study is to have a better understanding of the trend and major driving forces of herbicide use in China. Specifically, we examine the trends of herbicide supply and demand and major factors affecting herbicide use at the national level since 1990. Then we examine herbicide adoption behaviors of farmers producing wheat and maize in Northeast and North China. We select these crops because of their importance in crop production and data availability. Wheat and maize are two of the top three crops (maize, rice, and wheat) in China and the dominant crops in Northern China. Together, they accounted for 37 per cent (maize, 22.4 per cent and wheat, 14.6 per cent) of total crop area in China in 2014 (NBSC, 1991–2015).

The results show that the most rapid rise in herbicide use has occurred since the mid-2000s. At the national level, although falling prices due to increased supply contributed to the increasing use of herbicides, the rising wage has become a major driver in the rapid growth of herbicide use since the mid-2000s. The analyses based on rural household data show that off-farm employment away from home, type of crop, and household characteristics impact herbicide use in crop production.

This paper is structured as follows. The next section describes the data used in this study. "An Overview of China's Herbicide Supply and Demand" section provides an overview of the supply and demand in China's herbicide industry in the past three decades. "Econometric Analysis of Aggregate Demand and Household Use of Herbicides" section presents econometric models on herbicide utilization at the national and household levels, as well as the estimation methods. "Estimation Results" section presents the results and the final section concludes this study.

Data

We use both national aggregate data and primary household survey data. The national aggregate data cover 1990–2015 and we use it to estimate the aggregate herbicide demand function. The primary household data are from surveys conducted by the Center for Chinese Agricultural Policy (CCAP), Chinese Academy of Sciences, in Northeast and North China in 2013. We use this dataset to examine factors that affect herbicide use in wheat and maize production.

The national level dataset includes production, trade, utilization, and price of herbicides, crop-sown areas, and wages for off-farm employment of rural labor. Since data by type of herbicides are not available on herbicide production, consumption, and trade, we use aggregate number in this study. Based on our interviews with the industry and local market, currently major herbicides used in China include glyphosate, paraquat, acetochlor, quizalofop-P-ethyl, and nicosulfuron (Zhang, 2013). Data for herbicide production are from Ministry of Chemical Industry of China (MCIC, 1990–1992, 1993–2015). Herbicide import and export data are from the General Administration of Customs of China (GACC) (1990–2015). Because annual actual utilization and stocks of herbicides are unavailable, we calculate the apparent national herbicide consumption based on production and trade data. To reduce the difference between estimated apparent annual consumption and actual herbicide utilization due to changes in end-year stocks, we generate annual herbicide utilization by the five-year moving average of herbicide apparent consumption. With this method, we missed annual data for the initial 2 years (1990 and 1991) and the last 2 years (2014 and 2015). As there was nearly no end-year stock in the initial years of production in the early 1990s, we use annual apparent consumption as actual herbicide use in 1990–1991. For annual herbicide utilization in 2014 and 2015, we estimate them based on annual apparent consumption and our estimation of stock changes.

While the average domestic herbicide prices are not available, because the herbicide market has been largely liberalized in our study period, we use the unit export prices of herbicides as a proxy for the domestic prices in 1990–2015.[2] The data on total crop-sown area are from the National Bureau of Statistics of China (NBSC, 1991–2015). Rural labor off-farm wages are from NBSC (2001–2015), except those in 1990–2000, which are from Lu (2012), as NBSC did not publish these data before 2001. Nominal wages are reported in Appendix Table A1. Data on crop output procurement price index are from NBSC (2015). Real herbicide price, crop output procurement price index, and wages are deflated by consumer price index (CPI) and normalized at 2015 ($CPI_{2015} = 1$).

The household survey conducted by the CCAP in 2013 covers six provinces in Northeast China (Heilongjiang, Jilin, and Liaoning) and North China (Hebei, Shandong, and Henan). Both Northeast and North China are major maize producing regions, and the latter is also a major wheat production region. In Northeast China, we randomly selected two major maize producing counties from each of the three provinces. In North China, we randomly selected three counties from each of the studied provinces where maize and wheat are major crops. Within each county, the CCAP followed the following stratified random sampling approach to select townships, villages, and households. First, all townships were divided into two groups: with above and below the average levels of farm size. We randomly selected one township from each group in each county. Second, following the same approach, we randomly selected one village with more than average and one with less than average farm size from each township. Finally, we selected 10 households as follows: dividing all households in each village into two groups of small and large farms, and randomly selecting seven households from the small-farm group and three households from the large farm group. As the average farm size differs among provinces, the largest farms have more than 100 mu (15 mu = 1 ha) of land in Heilongjiang and Jilin provinces and more than 50 mu of land in the other four provinces. If the total number (n) of large farm households was less than three in a village, we surveyed these households (1 or 2) and then randomly selected ($10 - n$) households from the small-farm household groups for a total of 10 from each village. Subsequently, two plots were randomly selected from each household for the production input survey, including herbicide use measured in expenditure,[3] and the output. Finally, we had a valid sample of 1,733 plots that planted wheat (646) or maize (1,087) from 592 households in 60 villages of 15 counties in Northeast and North China.[4] We interviewed the local market and experienced farmers to collect information on the types of herbicides used in our study areas.

We interviewed the heads of households or those responsible for farming activities. This sampling approach created a weight variable based on the following information: the share of household numbers by farm size in total households in the village and actual number of households surveyed in each household group. We use this weight variable to calculate the sample mean in the descriptive analysis and conduct the weighted regression analysis.

An Overview of China's Herbicide Supply and Demand

Herbicide Production, Trade, and Utilization

Before the mid-1990s, the herbicide sector was in its infancy. Annual herbicide production was less than 20 thousand tons in 1990 (Figure 1) and herbicides were mainly produced by state-owned enterprises under the guidelines of the government. To facilitate the development of the chemical pesticide industry, the government established the National Innovation Center for Chemical Pesticide (NICCP) in 1993 (MCIC, 1993). In this early stage of herbicide industry development, the prices were high (Figure 2), and trade and utilization were limited (Figure 1).

The rapid growth of herbicide production occurred only after the late 1990s. With the rising research and development expenditure in domestic herbicides after the launch of NICCP, and the emerging joint ventures with multinational companies such as Ciba Specialty Chemicals, Hosta, and Dupont, since the late 1990s, herbicide production steadily increased from 53 thousand tons in 1995 to 297 million tons in 2005 and into the most rapid growth period thereafter (Figure 1). By 2013, herbicide production reached 1.8 million tons. Indeed, the rapid expansion of the industry has led to excessive production of herbicides and increasing stocks since the late 2000s, particularly in the early 2010s. Due to the over-supply of herbicides in 2012–2013 and the slowdown of herbicide export growth after 2013, herbicide production growth rate reduced significantly in 2014 and 2015 (Figure 1).

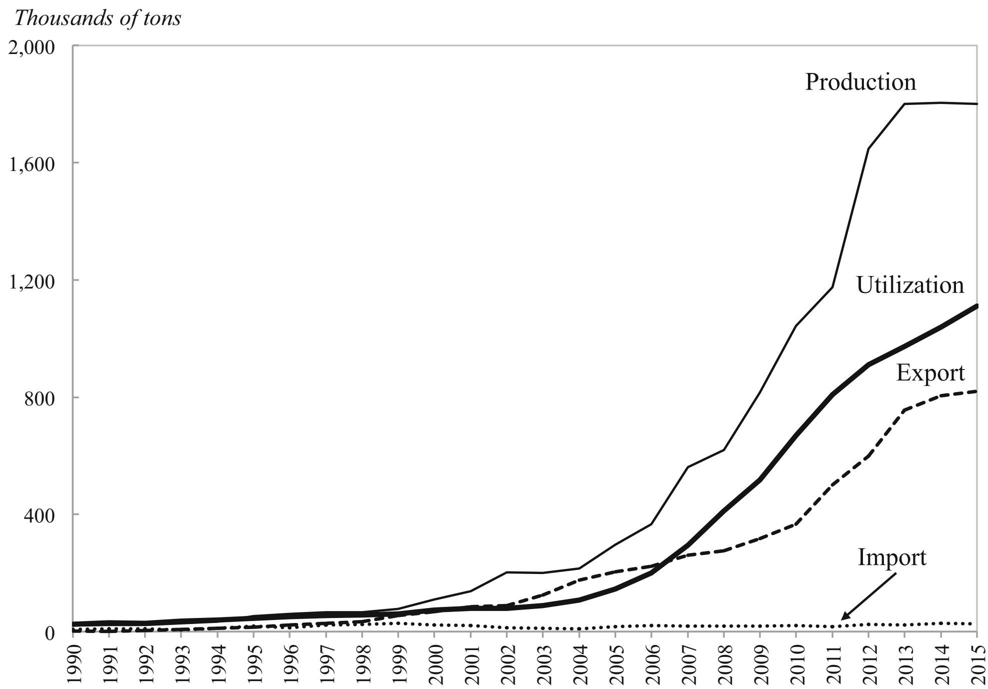

Figure 1: Herbicide production, trade, and utilization in China, 1986–2015.
Sources: Data for herbicide production are from MCIC (1990–1992, 1993–2015). The method to estimate herbicide utilization is discussed in footnote 2 in Table A1. Import and export data are from GACC (1990–2015).

The rapid growth in herbicide production has led to a significant rise in China's herbicide exports (Figure 1). Despite the significant increase in domestic demand for herbicide, the growth of production still far exceeds the domestic demand. Export increased from 16 thousand tons in 1995 to more than 200 thousand tons in 2005 and reached 820 thousand tons in 2015, or nearly half of China's herbicide production (Figure 1).

Despite their introduction in China in the 1960s, the wide use of herbicides in crop production did not occur until the early 2000s (Figure 1). Scientists first conducted field trials and demonstrations of herbicides in rice fields in the 1960s and on other crops in the 1970s (Zhang, 2003). However, until the early 2000s, herbicide use by farmers in crop production was still not a common practice. Average herbicide use was only 0.41 kg/ha in 2000; however, it increased nearly 15 times to 6.08 kg/ha in 2015 (Appendix Table A1). Total herbicide utilization also increased from 74 thousand tons in 2000 to more than 1 million tons in 2015 (Figure 1). According to the MOAC's report (2015), accumulated crop areas using herbicides reached 107 million ha in 2014, equivalent to approximately 65 per cent of the total crop area in the same year.

Major Driving Forces of Herbicide Demand

Rural labor wages have increased significantly since the mid-2000s. Average farm size remains small in China, despite its increase from 0.58 ha in 2000 to 0.78 ha in 2013 (Huang and Ding,

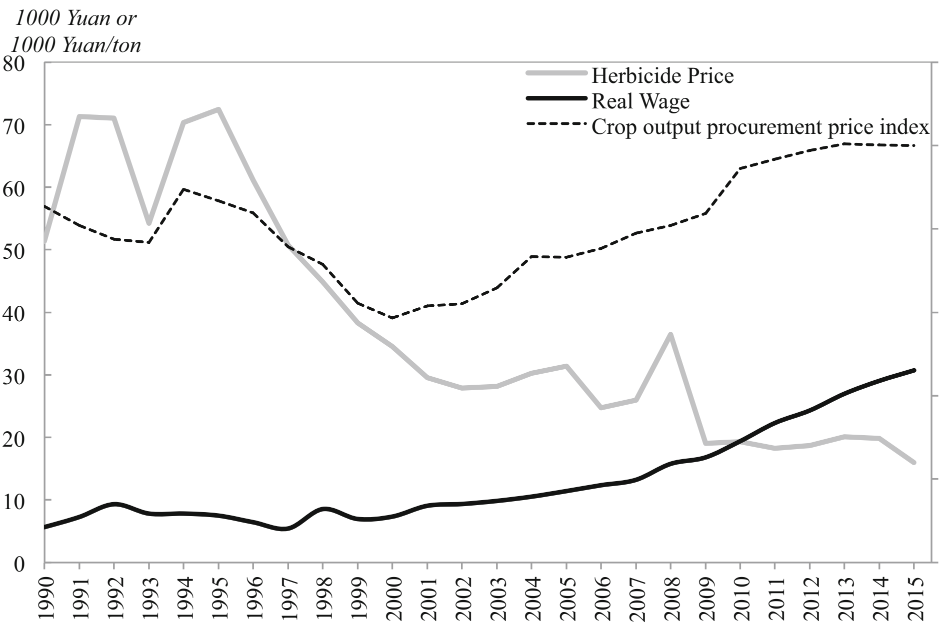

Figure 2: Rural labor off-farm wage (1,000 Yuan/year), herbicide price (1,000 Yuan/ton), and crop output procurement price index in real terms (deflated by consumer price index, CPI, in 2015) in China, 1990–2015. The right hand axis represents the crop output procurement price index.
Source: See the footnotes in Appendix Table A1.

2016). Under the small-farm-dominated household production system, manual weeding was a common weed control method before 2000, when rural wages were low and a large surplus of labor available in rural areas. However, with rapid growth in off-farm employment and the falling growth rate of labor supply since the late 1990s, several studies noted that China reached the Lewis turning point in either the early or mid-2000s (Zhang *et al*, 2010; Cai and Du, 2011; Fleisher *et al*, 2011). Empirical studies also showed that after slow or no growth of wages for off-farm employment before the early 2000s, wage in real term increased at more than 8 per cent annually after the mid-2000s (Li *et al*, 2012; Wang *et al*, 2011). These findings are consistent with the changing trend in off-farm wages for rural labor presented in Figure 2, which suggests that wages for off-farm rural labor were stable with no obvious increases before 2000; however, they doubled during 2000–2007, and nearly tripled in 2007–2015 (Figure 2 and Appendix Table A1). By 2015, the average annual wage for rural labor off-farm employment reached 30,720 Yuan (or US$ 4932).

In addition, increasing off-farm employment away from home may have also contributed to rise in herbicide use by farmers due to lack of labor for manual weeding. Although the development of local township and village enterprises (TVEs) in the 1980s generated off-farm employment, the most significant increase occurred due to migration from rural to urban areas since the mid-1990s (Zhao, 1999; Wang *et al*, 2011; Zhi *et al*, 2013).

A general fall in the price of herbicides over time is another important factor, which has further incentivized farmers in adopting herbicides. As Figure 2 indicates, while there were fluctuations over time, overall, the price of herbicide has been declining in China. The most significant fall occurred in mid-1990s (Figure 2), which is largely consistent with the rapid growth in herbicide production over the same period (Figure 1). The significant growth in herbicide prices in 2007–2008 or during global food crisis was mainly due to the rise in energy prices.

Farmers' Herbicide Application in Wheat and Maize Production

The discussions below are based on household surveys conducted in Northeast and North China in 2013 as we mentioned earlier. On average, cultivated land per household was 1.1 ha (Table 1), more than half the national average (0.78). This is due to the relative abundance of cultivated land in Northern China than in Southern China. The average age of household heads was 51 years. Table 1 summarizes other characteristics of households and herbicide application for all samples and by wheat and maize production. As Table 1 shows, for wheat and maize farming households, among the 63 per cent of household labor that worked only in farming, 37 per cent had off-farm employment, 7.9 per cent worked outside their provinces, and the remaining 29 per cent worked in their local provinces. The average household had 0.9 ha for wheat production and 1.5 ha for maize production (row 6, Table 1). The sown area for wheat is because all wheat production samples were from North China, while maize samples came from both North and Northeast China. Wheat is a highly irrigated crop that irrigates 2.4 times per crop season, while maize irrigation, on average, requires less than 1 time (0.7) (Table 1).

Nearly all households in our sample used herbicides to control weeds in wheat and maize production in 2013. Based on our interviews with local markets and experienced farmers, in our study areas, the major herbicides used to control weed in maize fields include nicosulfuron, ametryn, acetochlor, flumetsula, and 2,4-D butyiate, and the major herbicides used to control weed in wheat fields include 2,4-D butyiate, MCPA, and fluroxypyr. On average, farmers spent 185.7 Yuan/ha on herbicides per crop season (Table 1), ranging from 0 (only two households) to 746.3 Yuan/ha. In general, farmers used more herbicides on maize (204.9) than wheat (149.6) production. Herbicide use was mainly by men having an average age of nearly 53 years and with approximately 8 years of education.

Table 1: Characteristics of household and the herbicide applicant by crop in Northeast and North China in 2013

	All samples	*Wheat*	*Maize*
Herbicide use (Yuan/kg)	185.7	149.6	204.9
Number of household labor	3.2	3.3	3.1
Share of off-farm employment labor worked outside own province (%)	7.9	8.9	6.9
Share of off-farm employment labor worked within own province (%)	28.9	30.0	27.8
Share of farming labor (%)	63.2	61.1	65.3
Area of wheat and/or maize (ha)	1.1	0.9	1.5
Frequency of irrigation (times)	1.4	2.4	0.7
Fertilizer use (kg/ha)	443.2	487.3	424.4
Age of herbicide applicant (year)	52.8	53.2	52.5
Gender of herbicide applicant (1 = M; 0 = F)	0.9	0.9	0.9
Education of herbicide applicant (year)	7.9	8.0	7.7

Econometric Analysis of Aggregate Demand and Household Use of Herbicides

The National Aggregate Demand Model

To examine herbicide utilization or demand at the national level and check the robustness of the results, we specify the key variable of interest: wage of rural labor off-farm employment (W, measured in 1,000 Yuan/year) in the linear (W_t) form in the empirical models as follows:

$$q_t = a_0 + a_1 W_t + a_2 P_{Ht} + a_3 P_{C(t-1)} + a_4 T + e_t, \quad (1)$$

where q_t refers to herbicide use per hectare (kg/ha) in year t, P_{Ht} is the real price of herbicide (Yuan/kg) in year t, and $P_{C(t-1)}$ represents the one-year lagged crop output procurement price index. We use the one-year lagged crop price index because farmers' decisions on input use are based on the anticipated output price (Braulke, 1982) and the current input prices (Griliches, 1958). The above equation has two alternative specifications, that is, with and without time trend variable, T. The time trend variable is included to capture the impact of other variables that are not explicitly considered and change with time, such as the possible presence of weed resistance to herbicides over time.

Given the time-series data used to estimate equation (1), it is necessary to test whether each time series is stationary. To do this, we apply the Augmented Dickey-Fuller (ADF) test to examine if all variables of interest are stationary process. The results show that the herbicide use time series is integrated of order two process, that is, $I(2)$, and all other independent variables are integrated of order one process, that is, $I(1)$. Therefore, equation (1) is estimated by the first difference model. With the first difference of all variables, we do not find any series correlation among variables. For comparison, Table 2 presents the results for both the OLS and the first difference models.

Empirical Model of Herbicide Use in Wheat and Maize Production

In modeling farmer's herbicide use, we are particularly interested in the relationship between the availability of household labor and herbicide use in wheat and maize production. As the

Table 2: OLS and first difference regression of herbicide use per hectare (kg/ha) in China, 1990–2015

	OLS		*First difference model*	
	(1)	*(2)*	*(3)*	*(4)*
W_t	0.20***	0.20***	0.16***	0.12***
	(0.02)	(0.02)	(0.03)	(0.04)
PHt	−0.02***	−0.02**	−0.01***	−0.01***
	(0.01)	(0.01)	(0.00)	(0.00)
PC(t−1)	0.04***	0.04***	0.03***	0.03**
	(0.01)	(0.01)	(0.01)	(0.01)
T		0.01		
		(0.03)		
Constant	−3.34***	−23.49		0.11**
	(0.37)	(53.05)		(0.05)
Adj-R^2	0.99	0.99	0.69	0.74

Note: Standard errors are in parentheses. *,**, and *** are statistically significant at 10, 5, and 1 per cent level, respectively. The number of sample is 26.

Table 3: The weighted OLS regression of herbicide use (Yuan/ha) in Northeast and North China in 2013

	All samples	*Wheat*	*Maize*
Number of household labor	−2.58	0.49	−6.33
	(2.71)	(3.16)	(4.44)
Share of off-farm employment labor worked outside own province (%)	0.43***	0.36*	0.51*
	(0.17)	(0.21)	(0.31)
Share of off-farm employment labor worked within own province (%)	0.04	−0.15	0.22
	(0.12)	(0.16)	(0.20)
Area of wheat and/or maize (ha)	−3.31**	−2.04	−4.34
	(1.54)	(1.24)	(3.22)
Frequency of irrigation (times)	7.73**	14.61***	−1.42
	(3.62)	(4.84)	(8.93)
Fertilizer use (kg/ha)	0.04	0.04	0.04
	(0.02)	(0.03)	(0.04)
Age of herbicide applicant (year)	−0.70	−0.61	−0.30
	(0.43)	(0.55)	(0.62)
Gender of herbicide applicant (1 = M; 0 = F)	0.91	5.03	1.08
	(10.13)	(13.04)	(14.65)
Education of herbicide applicant (year)	−2.56**	−0.58	−4.70**
	(1.26)	(1.45)	(2.28)
Maize (1 = Maize; 0 = Wheat)	51.09***		
	(7.59)		
Village dummies	Included but not report		
Constant	119.85**	215.35***	173.31***
	(51.04)	(55.73)	(66.38)
Observations	1,733	646	1,087
Adj-R^2	0.31	0.24	0.33

Note: Robust standard errors are in parentheses; ***,**,* indicate statistically significant at the 1, 5, 10 per cent, respectively.

data used in this study are from cross-sectional household surveys, village dummies can capture the herbicide price variation. We specify the econometrics model as

$$Y_{ijh} = a_0 + a_1L_h + a_2M_h + a_3E_h + a_4A_h + a_5F_{ij} + a_6H_{ij} + a_7D + u_{ijh}, \quad (2)$$

where Y_{ijh} represents herbicide use (Yuan/ha) in the ith plot of the jth crop by the hth household. We include three variables to represent the availability of household labor, the number of household labor (L), the share of off-farm employment labor working outside their provinces in total household labor or labor migrated to other provinces (M), and the share of off-farm employment labor working within home provinces in total household labor (E). If a household has more laborers working off-farm far from home, it is costlier for them to return home, we expect that such household may use more herbicides to substitute for labor in weed control. To test whether the herbicide use per hectare is associated with farm size, we include the crop area (A, ha) in the model. We also include the following types of control variables in equation (2). (1) F represents plot level variables, including frequency of irrigation (times per crop season) and fertilizer use (kg/ha); (2) H is the characteristics of herbicide applicant, including his/her age (year), gender (1 = male, 0 = female), and education (years); and (3) D is a set of village dummy variables to control for non-time varying unobservable regional difference. u_{ijh} is the error term and is assumed to be subjected to independent identical distribution. All variables are in 2013 except for M and E that are lagged 2 years in 2011 to avoid the endogeneity of off-farm employment in explaining herbicide use. Table 1 summarizes the means of all variables used in the regression.

The OLS regression with the village fixed effect model is used to estimate equation (2) for each crop and pooled data of wheat and maize. When data from wheat and maize are pooled together, we add a dummy variable for maize in the regression. As the household survey uses the stratified sampling approach, we apply weighted OLS regression. Table 3 presents the estimation results.

Estimation Results

Results Based on the National Aggregate Demand Models

In general, the national aggregate demand models perform well (Table 2). The first two columns report the results based on the OLS estimation. For the first difference model, column 3 presents the results excluding the time trend variable (or without the constant) and column 4 presents the results with time trend (or with the constant). All of the estimated coefficients are statistically significant. The estimated adjusted R^2 ranges from 0.69 to 0.74 (last row, Table 2), which suggests that herbicide utilization in China can be largely explained by the off-farm rural labor wage, herbicide price, and crop output prices. Comparing the results from two estimations, all estimated parameters of the first difference estimation are slightly smaller than the OLS estimates. The differences between these two models indicate the estimation bias if not using the first difference model. In the remaining discussion, we focus on the results in columns 3 and 4.

The most important finding of this study is that the coefficient of wage for off-farm rural labor is statistically significant in all estimated models. In both models, with and without the time trend variable (columns 3 and 4, Table 2), the estimated coefficients of rural labor off-farm wage (W) are 0.16 and 0.12, respectively, and statistically significant at the 1 per cent level. This suggests that if wage increased by one unit (or 1,000 Yuan, or 7.6 per cent at the sample mean), the average per hectare herbicide use could increase by 0.16 kg (or 8 per cent at the sample mean, 0.16/1.895) in model (3), *ceteris paribus*, and 0.12 kg in model (4). Given the rise of annual wage from 5.63 thousand Yuan in 1990 to 30.72 in 2015 (Figure 2), the estimated results show that the increase in wage raised per hectare herbicide use by 4.01 kg/ha [0.16 × (30.72–5.63)] and 3.01 kg/ha [0.12 × (30.72–5.63)] in models (3) and (4), respectively, which accounted for about 61 and 46 per cent of the total increase in herbicide use in 1990–2015 (6.70–0.17 = 6.53, column 2, Appendix Table A1). Estimated at the sample means, the average elasticity of demand for herbicides with respect to wage is 1.14 [0.16/(1.895/13.122)] and 0.86 [0.12/(1.895/13.122)] in models (3) and (4), respectively.

The coefficient of herbicide price is negative and statistically significant in all models. The estimated coefficient is −0.01 (columns 3–4, Table 2), indicating that one unit increase in herbicide price (or 1/37.915 = 2.6 per cent at the sample mean) can reduce herbicide use by 0.01 kg/ha. Figure 2 shows that herbicide price has decreased by about 40 Yuan/kg since the early 1990s, which implies that it has raised herbicide use by more than 0.4 kg/ha or about 6 per cent (0.4/6.53) of the total increased herbicide use over the same period.

The estimated coefficient of crop output price is positive and statistically significant in all models. The crop output price experienced fell in the 1990s but steadily rose thereafter (Figure 2). Therefore, the increase in crop output price also contributed to the increase in herbicide use since the early 2000s, although its impact was much less than that of wages and herbicide prices over the same period.

Results Based on Farmer's Herbicide Use Models

Table 3 presents the estimates of farmers' herbicide use in wheat and maize production based on the village fixed effect estimation. The first column shows the regression results based on pooling wheat and maize data; the second and third columns are the estimates by crop. About half of the estimated coefficients are statistically significant. Here, we highlight several key findings.

The most important result is that the availability of household labor for farming has a significant impact on herbicide use. We find that the estimated coefficient of the share of off-farm employment labor working outside their province (*M*) is positive and statistically significant for all models (row 2, Table 3). That is, the farther the off-farm employment from home, the more herbicide is used to substitute for labor in weed control. Holding all other variables constant, the estimated coefficient also suggests that an increase of 1 per cent in the share of off-farm employment outside the home province can increase herbicide expenses by 0.36 Yuan/ha in wheat and 0.51 Yuan/ha in maize production (row 2). However, the estimated coefficients of both number of household labor and share of off-farm employment within home province are statistically insignificant (rows 1 and 3).

This study also found that the frequency of irrigation has a positive relationship with herbicide use in wheat, but not in maize production. One more time irrigation for wheat can increase herbicide expenditure by 14.61 Yuan/ha (row 5). This result might not be surprising because irrigation also helps in growth of weed. However, it is surprising to find no evidence of a similar impact in maize production, which is an issue requiring further study.

Among the three variables of herbicide use, only education is found to have a significant impact on herbicide use in maize production (rows 7–9, Table 3). The negative coefficient (−4.70) of education suggests that educated farmers apply less herbicides than farmers with less education do. An insignificant coefficient of gender implies that herbicide use is neutral to men and women.

Concluding Remarks

While herbicide production was negligible in the 1990s, China has become one of the most important herbicide producers and exporters in the world since the early 2000s. Meanwhile, the domestic utilization of herbicide in crop production has dramatically increased, especially after the mid-2000s.

This study examines the major driving forces behind the rapid growth in use of herbicides in China. Based on national aggregate time-series data, the econometric results show that wage for off-farm rural labor is the most important factor driving the increasing use of herbicides. Moreover, declining herbicide prices have also stimulated farmers to substitute manual weed control practices with chemical herbicides. Furthermore, the household data analysis shows that off-farm employment of household labor, especially those who work far from home, has a significant impact on farmers' herbicide application in crop production. Farmers use much more herbicide in maize than in wheat production. The rising levels of irrigation have a positive impact on herbicide use in wheat production. The more educated farmers use less herbicide than less educated farmers do in maize production.

Given the above findings, we expect herbicide use in crop production to continue rising in China. After reaching the Lewis turning point in the mid-2000s, wages have been growing significantly and we expect them to rise more rapidly in the coming years. Urbanization will continue to stimulate rural labor migration and reduce agricultural labor forces, which will facilitate herbicide use. Although farmers that are more educated may reduce herbicide use, this study found that their impact is far less than the rising wages and off-farm employment of rural labor.

It is noteworthy that given data availability, this study has several limitations that need further examination in future. First, the aggregate analysis of herbicide demand is based on the limited observations at the national level (26 years). A possible extension of the analysis is to use time-series and cross-provincial data if these data would be available in future. Second, more efforts should be made to collect herbicide use data by type and ingredient at both the industrial and farm levels. Finally, while our aggregate analysis using a simple time trend variable does not find evidence of weed resistance, it remains an important issue among other environmental implications of increasing use of herbicides.

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Notes

1. Authors' calculation based on data from MCIC (1993–2015) and GACC (1990–2015).
2. Time-series data for the retail or wholesale prices of herbicide in China are not available. However, as the types of exported herbicide products are similar to those sold in the domestic market, and there was no significant restriction on herbicide exports in the past three decades, the changing trend of unit export prices should be highly equivalent to that of domestic prices. Data on herbicide exports are not available before 1990.
3. Although we attempted to collect herbicide use data by type and in quantity (e.g., kg) during the pre-test of survey questionnaires, we found that farmers can provide accurate information of only the cost of herbicide and not on the type and quantity because herbicides are sold under different names and in different forms (e.g., powder or liquid).
4. Eight households either planted non-cereals (e.g., soybean) or did not have a complete record of herbicide use, and therefore, we exclude them from our analysis.

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Appendix

See Table A1.

Table A1: Herbicide utilization and prices, crop output procurement price index, rural labor off-farm wage, and CPI in China in 1990–2015

Year	*Herbicide availability per hectare*[1] *(kg/ha)*	*Estimated herbicide use per hectare*[2] *(kg/ha)*	*Herbicide export price*[3] *(Yuan/kg)*	*Crop output procurement price index*[4] *(2015 = 100)*	*Rural labor off-farm wage*[5] *(1,000 Yuan/ year)*	*CPI*[6] *(2015 = 100)*
1990	0.17	0.17	17.35	28.84	1.90	33.76
1991	0.20	0.20	24.77	28.07	2.53	34.74
1992	0.19	0.19	26.02	28.39	3.41	36.61
1993	0.18	0.24	22.48	31.81	3.24	41.43
1994	0.23	0.26	35.44	45.14	3.94	50.42
1995	0.37	0.31	46.74	55.95	4.84	64.52
1996	0.33	0.34	42.70	58.58	4.50	69.88
1997	0.40	0.36	36.41	54.37	3.90	71.83
1998	0.36	0.36	31.99	50.91	6.09	71.26
1999	0.32	0.39	26.88	43.66	4.89	70.25
2000	0.41	0.47	24.34	41.32	5.18	70.55
2001	0.47	0.51	21.02	43.66	6.44	71.03
2002	0.82	0.52	19.67	43.68	6.59	70.47
2003	0.57	0.59	20.06	46.92	7.02	71.31
2004	0.32	0.70	22.44	54.36	7.80	74.09
2005	0.71	0.94	23.66	55.20	8.61	75.42
2006	1.08	1.32	18.91	57.68	9.46	76.56
2007	2.08	1.92	20.83	63.35	10.60	80.23
2008	2.32	2.63	30.97	68.69	13.40	84.97
2009	3.26	3.26	16.04	70.67	14.17	84.36
2010	4.33	4.16	16.86	82.38	16.90	87.14
2011	4.26	4.98	16.73	88.83	20.49	91.84
2012	6.57	5.57	17.64	93.09	22.90	94.23
2013	6.48	5.91	19.45	97.05	26.09	96.68
2014	6.21	6.28	19.56	98.78	28.64	98.62
2015	6.08	6.70	15.96	100.00	30.72	100.00

[1]Herbicide availability is defined as total domestic production plus the net import, which is divided by total crop-sown area to obtain herbicide availability per hectare. Herbicide production data are from MCIC (1990–1992 and 1993–2015); crop-sown area data are from NBSC (1991–2015); and herbicide trade data are from GACC (1990–2015).
[2]Because the year-end stock of herbicide might fluctuate significantly over time and we do not have annual stock data, we estimate herbicide use per hectare in 1990–2013 based on the five-year moving average of herbicide availability per hectare. With this method, we missed annual data for the initial 2 years (1990 and 1991) and the last 2 years (2014 and 2015). Because there was nearly no end-year stock in the initial of production in the early 1990s, we use annual apparent consumption as actual herbicide uses in 1990–1991. For annual herbicide utilization in 2014 and 2015, we estimated them based on annual apparent consumption and our estimation on stock changes.
[3]Herbicide export price is the unit value of exported herbicide. The export value and quantity data are from GACC (1990–2015).
[4]Crop output procurement price index data are from NBSC (2015).
[5]Rural labor off-farm wages are from NBSC (2001–2015) except those in 1990–2000; the latter are from Lu (2012) because NBSC did not publish these data before 2001.
[6]CPI is from NBSC (1991–2015).

