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# The effectiveness of regulations and technologies on sustainable use of crop residue in Northeast China

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ABSTRACT

Burning agricultural residue adversely affects air quality and results in a loss of valuable nutrients required to improve soil quality. Sustainable use of crop residue can reduce air pollution from open field burning. In addition to the mandatory regulation on burning crop residue, the Chinese government also promotes the sustainable use of crop residue by subsidizing residue chopper machines and establishing agricultural demonstration sites. This paper documents the trends of crop residue utilization and evaluates the effectiveness of different regulations and technology policies toward the sustainable use of crop residue in Northeast China. Using a unique household level panel dataset, our regression results show that the ban on burning crop residue does not reduce crop residue burning, while increased availability of residue choppers induces farmers to adopt residue retention. Establishing demonstration projects also helps promote the acceptance of residue retention. Given the low level of availability of residue choppers and demonstration projects and their effectiveness, our results recommend further supporting the spread of residue chopper machines through subsidization and establishing demonstration projects. This paper also lends experience to other developing countries that have similar issues.


## 1. Introduction

Air pollution is a global concern for both citizens and policymakers, and China is no exception. Polluted air has negative health consequences, including premature death (Yang et al., 2013; Zhang et al., 2010) and significant reduction in average life expectancy (Chen et al., 2013). It has been criticized as the fourth largest threat to human health, causing 6.5 million reported deaths each year (WHO, 2016a). An estimated loss of 222 million years of life have been attributed to household and outdoor air pollution in 2012, of which China accounts for about 25% (WHO, 2016b).

In agriculture, the illicit burning of residue aggravates air pollution further. China produced about 730 million tons of crop residue in 2010 (Qiu et al., 2014). Using data from 1997 to 2013 for 31 Chinese provinces, Zhang et al. (2016) show that open field burning of crop residue contributed significantly to the particulate matter pollution in many Chinese cities. Further, residue burning has contributed to a sizeable share of $CO_2$ emissions in China (Sun et al., 2016).

Sustainable use of crop residue can effectively reduce air pollutants and improve soil quality. One of the traditional and sustainable uses of crop residue in China was for animal feed. However, as livestock production becomes more industrialized and commercialized, less crop residue has been directly used as animal feed in the livestock sector (Komarek et al., 2015). Due to high costs of transporting and collecting crop residue, its use for bioenergy production has become unappealing (Mitchell et al., 2016). In contrast, residue retention is an efficient way to improve crop yields, as it also enhances soil quality (Wang et al., 2012). As a conservation practice, crop residue retention can lead to reduced soil erosion and a considerable improvement in soil quality (Karlen et al., 1994; Mann et al., 2002; Pratt et al., 2014).

Despite the sound benefits, farmers lack incentives to adopt crop residue retention, partly due to the high costs of purchasing residue chopper machines. To encourage farmers and entrepreneurs to sustainably use crop residue, many countries and regions, including those in the European Union and some US states, have introduced bans on illicit burning of crop residue (Searle and Bitnere, 2017; Blank et al., 1993). The Chinese government also introduced a ban against illicit burning of crop residue in many areas in 2008. Local township officials monitor

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farmers' fields or even use remote sensing technologies to ensure the effectiveness of the ban.

However, many scholars have questioned the effectiveness of these burning bans due to farmers' strong resistance and non-compliance behaviors. In Russia, short-term bans were ineffective in changing farmers' behaviors, especially in the absence of credible monitoring and sanctioning of the policy (Theesfeld and Jelinek, 2017). In India, the cooperation of local farmers was also especially low, since they could not identify any way to comply with these regulations (Mohan, 2017). Even in high-income countries like the US, the efficiency of burning bans was not satisfactory due to limited resources for monitoring non-compliance and/or bad outreach to stakeholders (Dhammapala et al., 2011). Little is known about the effectiveness of the burning ban in China, as no published studies have investigated this issue.

In addition to the ban on residue burning, the Chinese government promoted crop residue retention by subsidizing chopper machines and setting up agricultural demonstration sites. Due to high initial investment of chopper machines, the Chinese government provided subsidies to farmers who purchased these machines. It has also promoted the adoption of residue retention technology through agricultural demonstration sites. Given the large amount of resources devoted to the sustainable use of crop residue, the government must determine the efficacy of these policies.

Several prior studies have analyzed factors that may affect adoption of conservation practices, but no published studies have examined the effectiveness of these policy instruments in promoting the sustainable use of crop residue, especially in the context of China. By reviewing and synthesizing past research, Knowler and Bradshaw (2007) conclude that almost no universal variables can explain the adoption of conservation practices across countries and time periods. For example, Arslan et al. (2014) show that extension service and rainfall variability are the two key determinants of adoption of conservation practices in Zambia. Lalani et al. (2017) show that poor farmers in Mozambique are more likely to adopt conservation practices compared with rich farmers. In China, Wang et al. (2010) show that better extension work promoting conservation tillage (CT) technology can lead to higher adoption of CT technology in China, which can in turn reduce illicit residue burning.

Using a unique panel data set collected from a household survey in 2013, this study analyzes the effectiveness of alternative policy instruments in promoting the sustainable use of crop residue in China. We focus on corn farms in Northeast China, a major corn production region in the country. Illicit burning of residue has contributed to poor air quality not only in this region, but also in other regions through wind.

Our primary finding is that the mandatory burning ban has no effect on reducing illicit burning of crop residue, while increased availability of residue chopper machines and the establishment of demonstration projects promote the adoption of residue retention and reduce crop residue burning. These results are robust to variations in alternative specifications.

The primary contribution of this study to the related literature is that we provide a comprehensive assessment of the effectiveness of various regulation and technology options in promoting the sustainable use of crop residue in China. As noted above, previous studies have primarily focused on identifying factors affecting adoption of conservation practices. To our knowledge, no published studies have analyzed the impacts of alternative regulation and technologies on residue management. Our results indicate that the provision of residue chopper machines and the establishment of demonstration projects can effectively promote more sustainable use of crop residue, especially when using crop residue as a bioenergy source is not commercially viable. These results provide useful information for the Chinese government to design effective policy instruments for the sustainable use of crop residue and optimize their budget allocation accordingly. Our results may be also useful for other countries to tackle similar issues.

The remainder of the paper is organized as follows. Section 2 reviews the policy background. Section 3 describes the data and methodology. Section 4 presents the results. Finally, Section 5 provides the discussion and conclusions.

## 2. Policy review

As the Chinese government realized that burning crop residue not only increases the severity of air pollution, but also wastes valuable biological resources, it started to implement regulations and support the sustainable management of crop residue. The first national policy, *Suggestions on accelerating comprehensive use of crop residue*, was launched by the State Council in the summer of 2008. It aimed to achieve over 80% sustainable use of crop residue by 2015. This policy suggests enhancing the comprehensive use of crop residue by establishing demonstration projects, as well as increasing research and development funding and training. Comprehensive use of crop residue includes using the residue for producing organic fertilizers, biogas, and animal feed, using raw materials for producing edible fungus, and as raw material for the paper industry. It also suggests prohibiting burning crop residue in areas with dense population, including areas near airports, major transportation lines, the four main municipalities, provincial capitals, or the administrative areas of sub-provincial cities. Although the mandatory burning ban is a national top-down policy, the stringency of the actual implementation varies across provinces. The National Development and Reform Commission (NDRC) and the Ministry of Agriculture (2009) issued the *Guidelines for planning of comprehensive use of crop residue* in 2009, and called for efforts and actions from provincial governments.

Because the goal of 80% sustainable use was not fully met by 2015, the NDRC, the Ministry of Finance, the Ministry of Agriculture, and the Ministry of Environmental Protection together issued the *Notifications on further accelerating comprehensive use of crop residue and prohibiting burning* in 2015 and extended the goal to 85%, to be achieved by 2020. In addition to proposing more specific measures, such as using residue choppers for residue retention, these notifications also suggest local governments to budget more funding to prohibit burning crop residue.

The *2015 Air Pollution Prevention Act* provides legal support for local governments to design non-burning zones. It further encourages local governments and agricultural departments to develop new technology options for sustainable use of crop residue. Governments are explicitly suggested to subsidize residue chopper machines and harvest combines, and provide necessary support for collecting, storing, transporting, and utilizing crop residue.

Subsidizing residue chopper machines to promote residue retention is the second pillar of the sustainable residue management policy, the ban on illicit burning of crop residue being the first. Using residue chopper machines is an important stage for residue retention. These machines can collect crop residue from the ground, chop it, and either eject it into an attached trailer or blow it back into the field. The primary goal of providing subsidies to residue chopper machines was to promote further mechanization of Chinese agriculture. In 2008, some provinces started to include residue chopper machines as subsidization objects. Since 2011, residue chopper machines are also part of the national list of subsidized machinery (Ministry of Agriculture, 2011; Ministry of Agriculture and Ministry of Finance, 2015). For the three sample provinces, the subsidy policy started at the same time with the same subsidy levels. Farmers in Heilongjiang, Jilin, and Liaoning were subsidized about RMB 900–2700, depending on the types of chopper machines they purchased.

The third measure for promoting the adoption of residue retention is the provision of agricultural demonstration sites. While experiments with conservation agriculture began in 1991, the Ministry of Agriculture installed the first conservation tillage demonstration projects in 1993

(Jin et al., 2007). Since 2002, the Chinese government has been actively supporting the extension of conservation tillage on a nationwide basis (Wang et al., 2007). Between 2010 and 2014, RMB 280 million were spent on large-scale demonstration projects in northern China. By 2014, 204 demonstration sites were present across the country (Liang and Che, 2014).

## 3. Data and descriptive analysis

### 3.1. Data

To study the effectiveness of various regulations and technologies, we employ a panel dataset from a survey of Chinese grain farms conducted in 2013. We focus on corn farms in the three Northeastern provinces, that is, Heilongjiang, Jilin, and Liaoning. These three provinces are the major corn-producing areas in China, accounting for about 35% of the total corn production (National Bureau of Statistics of the People's Republic of China, 2017). Crop residue burning is a critical issue in these provinces, as they produce large amounts of residue without alternative use.

A stratified random sampling was used: Two corn and two rice counties were randomly selected from major corn- and rice-producing counties to meet multiple research purposes. In each county, two townships were randomly selected according to the level of land consolidation. Similarly, two villages were randomly selected from each township. In each village, 10 farms, including three large and seven small farms[1] were randomly selected for interviews. In total, the data set includes 480 farm households from 48 villages in 12 counties in the three provinces in Northeast China. For a more detailed description of the dataset, please refer to Huang and Ding (2015). For this study, we employed a subsample of 273 corn farmers.

To obtain the information on farmers' use of corn stover, face-to-face interviews were conducted and farmers were asked about their use of corn stover in percentage for each method of use in 2013, 2008 (five years ago), and 2003 (10 years ago). There were four primary methods of corn stover use, including open field burning, domestic fuel, feeding livestock, and residue retention. Farmers were also asked to report other use as an additional category, but only for 2013 at the plot level. In addition, the household interviews covered the basic information on characteristics of farms and farmers, such as farm size, income level, off-farm jobs, and gender among others.

To collect the information on regulation and technology options for crop residue management, we conducted face-to-face interviews with village leaders. They were enquired about (1) whether and when their villages had started implementing mandatory regulations on burning crop residue; (2) whether and when their villages started to use residue choppers; and (3) whether and when their villages had demonstration projects for conservation practices. The descriptive statistics of these variables are reported in Table A1 in Appendix A.

### 3.2. Trends of corn stover use

Fig. 1 shows the trends of corn stover use over the sample period. Despite a clear declining trend, burning corn stover as domestic fuel remained its dominant use. In Heilongjiang, in 2003, almost two-thirds of corn stover was burned as domestic fuel, declining to 45% in 2013. The share of corn stover used as domestic fuel decreased from 65% to 57% between 2003 and 2013 in Jilin, while the decline was more pronounced in Liaoning: from 63% in 2003 to 40% in 2013. Open field burning is the second major use of corn stover. Heilongjiang and Jilin both experienced a slight increase between 2003 and 2013: from 20% to 28% in Heilongjiang and from 24% to 30% in Jilin. Liaoning had 20% of corn stover burned in open fields in 2003, and this share dropped to 12% in 2013.

The use of corn stover as a livestock feed declined over the sample period. Between 2003 and 2013, the rate of corn stover used as animal feed dropped from 11% in Heilongjiang and Jilin and 17% in Liaoning to a negligible 2–4%. This could be attributed to increased industrialization in the animal husbandry sector and rising labor costs of using crop residue to feed animals. Residue retention was not a traditional residue management method in the examined regions. Following the promotion of residue retention by national and local governments, we observe an increase in residue retention over the sample period. While residue retention was close to zero in 2003 in three provinces, the share of residue retention in the total use of corn stover increased to about 5% in Jilin and Heilongjiang and 8% in Liaoning in 2013.

We also observe a growing trend of other uses of corn stover in addition to the four major types mentioned above. Liaoning had the highest percentage (33%) of other uses in 2013, followed by Heilongjiang (20%) and Jilin (8%). A large proportion of the other uses is for sale. According to the plot-level data in Liaoning, about 13% of the total harvested corn stover was sold to either paper mills or animal feed processing industries in 2013.

### 3.3. Policy regulations toward sustainable use of corn stover

Table 1 shows that, in addition to the mandatory regulation on burning crop residue, the Chinese government has also started to provide innovative technology to farmers to achieve the sustainable use of crop residue. In 2003, about 21.5% of the sample village leaders reported that their villages had banned burning crop residue. This number almost doubled in 2008, which may be associated with the 2008 Olympic Summer Games. The share continued to increase to 53.7% in 2013. All the three provinces show the growing trends in the coverage of the mandatory regulation, with Liaoning having the highest coverage level across the three provinces.

Meanwhile, residue choppers and demonstration projects of conservation practices emerged in 2008, with about 4% of the sample villages having access to both. In 2013, the percentage of villages with residue choppers increased to 10% and those with demonstration projects increased to 7.4%. Again, the percentage of the villages with access to both differed across provinces. None of the villages in Heilongjiang reported that they had residue choppers and demonstration projects of conservation practices during the sample period. The percentage of villages in Jilin with residue choppers increased from 8.5% in 2008 to 16.2% in 2013. Residue choppers first appeared in Liaoning in 2013: about 12.7% of the surveyed villages reported having them. The demonstration projects of conservation practices in Jilin started in 2013 with a coverage of 9%, while it started in 2008 in Liaoning with a coverage of 13%.

The villages with the mandatory regulation on burning crop residue have a significantly lower percentage of burning either in open fields or at homes in all the three years (Table 2). Over 80% of corn stover was burned in both 2003 and 2008, while the percentage decreased to 65% in the villages with mandatory regulation and 81% in those without. In 2013, the percentage of open field burning was 24% for villages with mandatory regulation, and 25% for those without the regulation. The percentage of corn stover burned as domestic fuel in 2013 for those with mandatory regulation is slightly lower than those without (40.8% vs. 55.8%). Table 2 also shows that, relative to the villages without burning regulation, the percentage of farmers using residue retention in the villages with mandatory regulation was considerably higher. We also observed a higher percentage of other uses for villages with mandatory regulation in all the three years.

Table 3 shows that farmers in villages with residue choppers had a higher percentage of residue retention in 2013 than those in villages without residue choppers (27.6% vs. 14.1%). Meanwhile, the percentage of other uses is also high for villages with residue choppers, in both 2008

[1] In Heilongjiang and Jilin provinces, a large farm is defined as one whose size is larger than or equal to 100 mu (about 6.67 ha); otherwise, it is defined as small. In Liaoning, the threshold is 50 mu (about 3.34 ha).

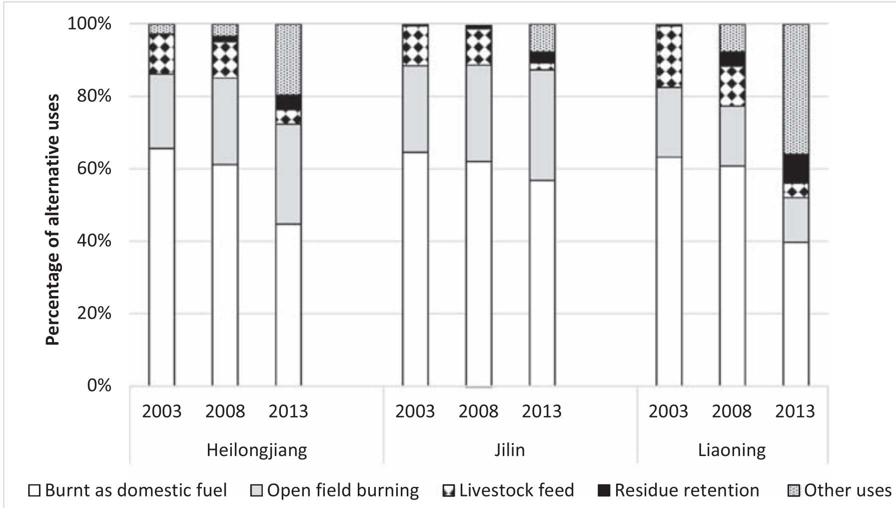


**Fig. 1.** Corn stover use by province in 2003, 2008, and 2013.

and 2013. Not surprisingly, a lower percentage of corn stover was burned in open fields and as domestic fuel in villages with residue choppers, both in 2008 and in 2013. About 78% was burned in open fields or at homes in villages with residue choppers in 2008, while it was 85% for those without residue choppers. In 2013, this difference was even larger, that is, 73.7% in villages with residue choppers and 59.2% in those without. Table 4 shows that farmers in villages with demonstration projects of conservation practices had a higher percentage of residue retention and other uses, but a lower percentage of burning in 2013, while it was the opposite in 2008. In 2013, about 40% of farmers in the villages with demonstration projects of conservation practices used residue retention, while it was only 13.6% in those without demonstration projects. The percentage of other uses in the villages with demonstration of conservation project was almost double as in those without the project, that is, 52.4% against 25.7%, respectively. The percentage of burning corn stover was close to 50% in 2013 in the villages with demonstration projects, while it was as high as 74% in those without.

## 4. Empirical models

To rigorously examine the effects of different policy instruments in influencing farmers' decisions regarding crop residue use, we first develop a fixed effects model, following Chen et al. (2006), Démurger and Fournier (2011), and Zhang and Kotani (2012). The mathematical form of the model is

$$M_{ivt} = \beta_0 + \beta_1 R_{vt} + \beta_2 A_{vt} + \beta_3 D_{vt} + \boldsymbol{\delta Z_{ivt}} + u_i + PT_{jt} + \varepsilon_{ivt}, \quad (1)$$

where $M_{ivt}$ is the percentage of one particular use of corn stover by farmer $i$ in village $v$ in year $t$. We consider three different types of crop residue uses, including open field burning, domestic fuel, and residue retention. $R_{vt}$ is a policy dummy variable, indicating whether village $v$ in year $t$ was prohibited from burning crop residue in open fields. $A_{vt}$ is a dummy variable denoting whether village $v$ had residue choppers in year $t$. $D_{vt}$ is also a dummy variable, indicating whether village $v$ had demonstration projects of conservation practices in year $t$. $\mathbf{Z}ivt$ is a vector of other explanatory variables that may affect farmer $i$'s decisions regarding crop residue uses, including off-farm jobs, age, wealth, and farm size. $u_i$ denotes the time-invariant farmer fixed effects. We also add province × year fixed effects, denoted by $PT_{jt}$, as additional explanatory variables to account for common shocks occurring in province $j$ in a given year that had the same effects on crop residue uses for all farmers in that province in that year. With the inclusion of the province × year fixed effects, the actual effects of policy instruments may be underestimated, since $PT_{jt}$ may absorb some of the policy effects. We therefore report the estimation results from the model with year fixed effects in the robustness check section. $\varepsilon_{ivt}$ are the error terms. We control for the heteroskedasticity of the error terms and cluster the standard errors within farmers to account for autocorrelation of the error terms within each farmer.

To further check the robustness of the results from the above fixed effect model, we set up a difference-in-difference (DID) model, which

**Table 1**
Government policies to prohibit burning crop residue and promote residue retention (%).

| | 2003 | 2008 | 2013 |
|---|---|---|---|
| Mandatory regulation on burning crop residue (1 = yes; 0 = no) | | | |
| All | 21.5 | 40.2 | 53.7 |
| Heilongjiang | 0 | 13.6 | 48.8 |
| Jilin | 21.4 | 31.1 | 41.4 |
| Liaoning | 39.0 | 75.3 | 75.9 |
| Availability of residue choppers at village (1 = yes; 0 = no) | | | |
| All | 0 | 3.6 | 10.3 |
| Heilongjiang | 0 | 0 | 0 |
| Jilin | 0 | 8.5 | 16.2 |
| Liaoning | 0 | 0 | 12.7 |
| Demonstration of conservation projects at the village (1 = yes; 0 = no) | | | |
| All | 0 | 4.0 | 7.4 |
| Heilongjiang | 0 | 0 | 0 |
| Jilin | 0 | 0 | 9.0 |
| Liaoning | 0 | 13.0 | 12.7 |

**Table 2**
Crop residue management and regulation on burning crop residue.

| | With mandatory regulation on burning crop residue | | | Without mandatory regulation on burning crop residue | | |
|---|---|---|---|---|---|---|
| | 2003 | 2008 | 2013 | 2003 | 2008 | 2013 |
| Open field burning and domestic fuel | 81.8 | 80.3 | 64.8 | 87.2 | 87.0 | 80.8 |
| Open field burning | 24.4 | 20.5 | 24.0 | 21.4 | 25.3 | 25.1 |
| Burnt as domestic fuel | 57.4 | 59.9 | 40.8 | 65.9 | 61.7 | 55.8 |
| Residue retention | 4.7 | 7.4 | 26.4 | 2.3 | 1.6 | 2.9 |
| Other uses | 18.2 | 19.7 | 35.2 | 12.7 | 13.0 | 19.2 |

Source: Authors' survey.

**Table 3**
Crop residue management and availability of residue choppers.

| | With residue choppers | | | Without residue choppers | | |
|---|---|---|---|---|---|---|
| | 2003 | 2008 | 2013 | 2003 | 2008 | 2013 |
| Open field burning and domestic fuel | na | 78.5 | 59.2 | 86.1 | 84.5 | 73.7 |
| Open field burning | na | 48.8 | 25.7 | 22.1 | 22.4 | 24.4 |
| Burnt as domestic fuel | na | 29.7 | 33.5 | 64.0 | 62.1 | 49.4 |
| Residue retention | na | 0.0 | 27.6 | 2.8 | 4.1 | 14.1 |
| Other uses | na | 21.5 | 40.8 | 13.9 | 15.5 | 26.3 |

Source: Authors' survey.

is similar to the model specification used by Beck et al. (2010). The mathematical form of the regression is

$$M_{ivt} = u_i + \lambda_t + \alpha_1 Policy_{vt} + \alpha_2 \boldsymbol{Z_{ivt}} + \epsilon_{ivt}. \quad (2)$$

We define the villages without any policy implementation during our sample period as a control group, while those with the policy in either 2008 or 2013 as a treatment group. In Eq. (2), $M_{ivt}$ and $\boldsymbol{Z_{ivt}}$ are the same as stated above. $u_i$ and $\lambda_t$ are farmer and year dummy variables, respectively, and account for farmer and year fixed effects. The variable of interest here is $Policy_{vt}$, which is a dummy variable that equals one in years after village $v$ implemented a policy and zero otherwise. The coefficient $\alpha_1$ indicates the impact of the policy on crop residue use. We conducted the DID analysis to examine the impacts of these policies one at a time.

## 5. Results

### 5.1. Basic regression results

Before reporting the main regression results from the fixed effect model, we first test the correlations of various policy instruments with lagged residue use. The results in Table A2 in Appendix A show that current policies do not correlate with crop residue use in previous periods, which ensures unbiased causal policy effects from the regression model. For example, the implementation of the mandatory regulation in 2008 (or 2013) does not correlate with the use of crop residue in 2003 (or 2008).

Table 5 reports the baseline regression results by estimating Eq. (1). The variance inflation factor (VIF) values are <3 for all models, suggesting that multicollinearity is not a major issue in the model specifications.

The coefficient estimates of the mandatory regulation variable are small and statistically insignificant in the three models, which indicates that the implementation of the mandatory regulation did not affect crop residue use, which is consistent with our expectations based on the field experiment. There are two possible reasons for

**Table 4**
Crop residue management and demonstration projects of conservation practices.
Source: Authors' survey.

| | With demonstration projects | | | Without demonstration projects | | |
|---|---|---|---|---|---|---|
| | 2003 | 2008 | 2013 | 2003 | 2008 | 2013 |
| Residue retention | na | 0.0 | 39.5 | 2.8 | 4.1 | 13.6 |
| Other uses | na | 9.0 | 52.4 | 13.9 | 16.0 | 25.8 |
| Burning in fields and as domestic fuel | na | 91.0 | 47.6 | 86.1 | 84.0 | 74.2 |
| Open field burning | na | 9.0 | 32.0 | 22.1 | 23.9 | 23.9 |
| Burnt as domestic fuel | na | 82.0 | 15.6 | 64.0 | 60.1 | 50.3 |

**Table 5**
Regression results from fixed effects models for residue use.

| Variables | (1) Open field burning | (2) Domestic fuel | (3) Residue retention |
|---|---|---|---|
| Mandatory regulation on burning crop residue at village level (yes = 1; no = 0) | 2.937 | −6.329 | 4.011 |
| | (3.486) | (4.606) | (2.985) |
| Availability of residue choppers at village level (yes = 1; no = 0) | −7.817* | −14.933** | 19.899*** |
| | (4.236) | (7.456) | (7.567) |
| Demonstration projects of conservation practices at village level (yes = 1; no = 0) | −5.695 | 1.592 | 7.784** |
| | (6.942) | (6.237) | (3.359) |
| Family members with off-farm jobs (yes = 1; no = 0) | 0.504 | 1.804 | −0.863 |
| | (2.520) | (3.711) | (3.686) |
| Farm size (ha) | −0.604* | 0.029 | 0.571*** |
| | (0.348) | (0.218) | (0.209) |
| Wealth level (thousand RMB) | 0.110 | −0.081 | −0.033 |
| | (0.101) | (0.107) | (0.030) |
| Constant | 10.747 | 72.623*** | 4.879 |
| | (12.029) | (12.435) | (3.675) |
| Observations | 761 | 761 | 761 |
| $R^2$ | 0.902 | 0.895 | 0.735 |
| Number of households | 270 | 270 | 270 |

This table shows the effects of various policy instruments on use of crop residue and the results are obtained by estimating Eq. (1) and including province × year fixed effects. Dependent variable = percentage of respective residue management method (0–100). Standard errors, shown in parentheses, are clustered within households.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

this finding. First, monitoring illicit burning of crop residue and penalizing farmers were costly and not strictly implemented. Second, except for burning residue, farmers lacked appropriate alternative methods to deal with the large amount of crop residue generated. Our data show that only about 40% of the villages with mandatory regulation monitored famers' illicit burning of crop residue. In these villages, only 7% of the farmers with illicit burning behaviors were fined, while the remaining only received verbal warnings. In addition to such loose regulations, the lack of alternative methods of using crop residue provided strong incentive to farmers to burn residue either in open fields or as domestic fuel in order to clean the field for next year's planting.

In contrast, we find that the availability of residue choppers not only increased the percentage of residue retention, but also reduced the burning percentage. The coefficient of the availability of residue choppers variable is positive and statistically significant at the 1% level in the third column. This implies that the percentage of residue retention is 19.9% higher for the villages with residue choppers than for those without. The coefficients of the same variable are negative and statistically significant in the first and second columns, suggesting that the percentages of open field burning and domestic fuel are about 7.8% and 15%, respectively lower for the villages with residue choppers than for those without. The increased availability of residue choppers makes residue retention possible in the examined area because corn stover cannot decay naturally owing to low temperatures after crop harvest in the three northeastern provinces.

The coefficient of the demonstration project variable is positive and statistically significant at the 5% level in the third column, but insignificant for the other two models. This suggests that having demonstration projects on conservation practices effectively induced farmers to use residue retention. The percentage of using residue retention is 7.8% higher for villages with demonstration projects than for those without. In our interviews with the corn farmers, most expressed their concerns about the uncertainties of using residue retention. Farmers told our enumerators of worries regarding the new technology possibly reducing corn yields in the following year and hence they preferred to avoid potential risks. The provision of demonstration projects not only trained farmers how to use residue choppers, but also greatly reduced farmers' concerns about potential yield reduction.

Large and small farms have different preferences in using crop residue. The coefficient of the farm size variable is negative and statistically significant at the 10% level in the first column, but positive and statistically significant in the third column. If farm size increases by 1 ha, the percentage of open field burning decreases by 0.6%, while the percentage of residue retention increases by 0.57%. On one hand, larger farms are more likely to be monitored under the mandatory ban, making them less likely to burn crop residue in open fields, but adopting residue retention. On the other hand, it makes economic sense to make alternative uses of the considerable amount of crop residue produced by large farms, such as selling it to paper industries.

### 5.2. Robustness check

We conduct several robustness checks to examine the sensitivity of our results. We first consider an alternative model specification that controls for the year fixed effect only, rather than the province × year fixed effects considered in the baseline specification. The results reported in Table A3 in Appendix A show that these estimates are broadly consistent with our baseline estimates. In the second robustness check, we include individual policies one at a time to further address the issue of multicollinearity of the three policies. The results, reported in Table A4 in Appendix A, show great consistency with our baseline estimates as well.

In the final robustness check, we assess the sensitivity of our results by employing an alternative identification strategy, where we test in a DID setting whether increased availability of residue choppers and the establishment of demonstration projects induced sustainable use of crop residue. Before running the DID model, we test the differences in the key socio-economic variables between our treatment group (villages with policies) and our control group (villages without policies). The results in Table A5 in Appendix A show that there are no significant differences in the key socio-economics variables between the two groups, except age. These results provide reassurance that our control and treatment groups are similar and comparable in 2003 before residue choppers were provided and demonstration projects were established.

**Table 6**
Regression results from difference-in-difference models for residue use.

| | Open field burning | Domestic fuel | Residue retention |
|---|---|---|---|
| Mandatory regulation | 1.631 | −7.203 | 5.083*** |
| | (3.458) | (4.441) | (3.324) |
| $R^2$ | 0.898 | 0.886 | 0.672 |
| Observations | 761 | 761 | 761 |
| Availability of residue choppers | −8.773* | −13.925 | 22.207** |
| | (4.582) | (9.182) | (10.434) |
| $R^2$ | 0.899 | 0.887 | 0.686 |
| Observations | 761 | 761 | 761 |
| Demonstration projects of conservation practice | −7.170 | −1.671 | 12.739* |
| | (7.567) | (7.801) | (6.950) |
| $R^2$ | 0.899 | 0.884 | 0.674 |
| Observations | 761 | 761 | 761 |

This table reports the impacts of these policies one at a time using DID analysis.
Dependent variable = percentage of respective residue management method (0–100).
Standard errors, shown in parentheses, are clustered within households.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

Our DID results reported in Table 6 show that the percentage of residue burning in open fields is 8.8% lower in villages with residue choppers than those without residue choppers, which is similar to the estimate obtained from the baseline model (7.8% in Table 5). Table 6 also shows that the provision of residue choppers reduced the percentage of burning at home, although the estimate is insignificant. In line with our baseline estimate, our DID result shows that the percentage of residue retention is 22.2% higher in the villages with residue choppers than those without residue choppers, which is also comparable with our baseline estimate reported in Table 5 (19.9%). Table 6 also confirms that establishing demonstration projects of conservation practices can greatly increase the percentage of using residue retention (12.7%).

## 6. Conclusions and discussion

This paper documented the trends of corn stover use in Northeast China over the past 10 years and examined the effectiveness of different regulation and technology policies on farmers' crop residue management. Burning either in open fields or at home is still the dominant form of handling corn stover, although it has been declining over the past 10 years. Over 70% of the corn stover was still burned in all the three provinces, except in Liaoning in 2013. Meanwhile, residue retention and other sustainable uses show a slow, increasing trend. The government first employed mandatory regulation to ban burning of crop residue and in the following started to support sustainable management of crop residue by providing technology subsidy and demonstration.

Our empirical results show that mandatory regulations of prohibiting the burning of crop residue were ineffective in reducing burning. In contrast, providing technology support, such as subsidizing residue choppers and providing conservation demonstration, is effective in promoting the sustainable use of crop residue. Given the low level of availability of residue choppers and demonstration projects and their effectiveness, we highly recommend further support for the spread of residue choppers by subsidizing machines and providing demonstrations.

Based on our results, we carefully raise the following policy recommendations. First, providing alternative methods to deal with crop residue is critical to its sustainable use. Without efficient alternatives offered to farmers to prepare their fields for next year's planting, a stand-alone mandatory regulation is unlikely to be effective. Many farmers circumvented the ban by burning crop residue in the off season when the detection risk was low (Qu et al., 2012).

Second, enhancing technology demonstration can help increase farmers' adoption. Farmers were unfamiliar with the new technology related to residue retention, making them question the yield and profit effects, as well as production risk. Farmers may also have little knowledge on how to use this new technology. Establishing demonstration projects not only provides training to farmers, but also reveals the yield and profit effects and associated risks.

Third, promoting off-farm work and improving farm size may also reduce burning of crop residue and increase the adoption of residue retention technology. As the off-farm wage increases, more agricultural workers take off-farm jobs, leaving fewer workers to collect and transport crop residue for cooking and heating purposes. Higher off-farm wages also improve farmers' living standards through the use of clean energy rather than crop residue. Larger farms have incentives to make use of crop residue instead of burning them in open fields due to the opportunity cost and their willingness to accept labor-saving technologies.

The primary caveat of our work is that we cannot conduct a full cost-benefit analysis to assess the cost-effectiveness of these policies. It is difficult to estimate the costs of individual policies and the benefits from reduced emissions due to the implementation of these policies. First, estimating the costs requires information on the adoption rate of the whole population, which is difficult to obtain. Second, estimating the benefits requires estimating the relationship between air quality and residue burning, and the associated benefits due to improved air quality, both of which go beyond the scope of our paper.

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## Declaration of interest

None.

## Appendix A

**Table A1**
Descriptive statistics of the key variables.

| | Obs. | Mean | Std. dev. | Min | Max |
|---|---|---|---|---|---|
| Percentage of open field burning | 761 | 23.3 | 38.8 | 0 | 100 |
| Percentage of domestic fuel | 761 | 57.3 | 43.7 | 0 | 100 |
| Percentage of residue retention | 761 | 7.7 | 24.7 | 0 | 100 |
| Percentage of other uses | 761 | 19.4 | 35.4 | 0 | 100 |
| Mandatory regulation on burning crop residue at village level (yes = 1; no = 0) | 761 | 0.39 | 0.49 | 0 | 1 |
| Availability of residue choppers at village level (yes = 1; no = 0) | 761 | 0.05 | 0.22 | 0 | 1 |
| Demonstration projects of conservation practices at village level (yes = 1; no = 0) | 761 | 0.04 | 0.20 | 0 | 1 |
| Family members with off-farm jobs (yes = 1; no = 0) | 761 | 0.38 | 0.49 | 0 | 1 |
| Farm size (ha) | 761 | 3.8 | 5.4 | 0.15 | 106.7 |
| Wealth level (thousand RMB) | 761 | 106.9 | 94.8 | 0 | 800 |

**Table A2**
Correlations of policy instruments with lagged crop residue use.

| | Mandatory regulation | Availability of residue choppers | Demonstration of conservation projects |
|---|---|---|---|
| Open field burning in previous period | 0.0005 | −0.0016 | 0.0041 |
| | (0.0015) | (0.0015) | (0.0037) |
| Burnt as domestic fuel in previous period | 0.0019 | 0.0014 | 0.0032 |
| | (0.0017) | (0.0011) | (0.0029) |
| Residue retention in previous period | −0.0010 | −0.0014 | 0.0038 |
| | (0.0015) | (0.0012) | (0.0038) |
| Constant | 0.2721* | −0.0141 | −0.2641 |
| | (0.1408) | (0.0657) | (0.2787) |
| Observations | 491 | 491 | 491 |
| $R^2$ | 0.899 | 0.750 | 0.848 |

This table shows the effects of crop residue use in previous periods on the adoption of policies in the following periods.
Dependent variable = percentage of respective residue management method (0–100).
We conducted the DID analysis to examine the impacts of these policies one at a time.
Standard errors, shown in parentheses, are clustered within households.
* $p < 0.1$.

**Table A3**
Robustness checks: year fixed effects.

| | (1) | (2) | (3) |
|---|---|---|---|
| | Open field burning | Domestic fuel | Residue retention |
| Mandatory regulation on burning crop residue at village level (yes = 1; no = 0) | 2.136 | −7.783* | 4.705 |
| | (3.294) | (4.464) | (3.270) |
| Availability of residue choppers at village level (yes = 1; no = 0) | −7.766* | −14.745* | 21.333** |
| | (4.164) | (8.846) | (9.739) |
| Demonstration project of conservation practices at village level (yes = 1; no = 0) | −6.313 | 3.688 | 7.052 |
| | (7.092) | (6.457) | (4.639) |
| Family members with off-farm jobs (yes = 1; no = 0) | 0.166 | 0.789 | −0.053 |
| | (2.683) | (3.952) | (4.090) |
| Farm size (ha) | 0.119 | −0.078 | −0.045 |
| | (0.106) | (0.092) | (0.029) |
| Wealth level (thousand RMB) | 0.166 | 0.789 | −0.053 |
| | (2.683) | (3.952) | (4.090) |
| Constant | 9.890 | 73.774*** | 5.641 |
| | (13.345) | (11.476) | (3.788) |

(continued on next page)

**Table A3** (*continued*)

| | (1) | (2) | (3) |
|---|---|---|---|
| | Open field burning | Domestic fuel | Residue retention |
| Observations | 761 | 761 | 761 |
| $R^2$ | 0.900 | 0.888 | 0.690 |
| Number of households | 270 | 270 | 270 |

This table shows the effects of various policy instruments on uses of crop residue and the results are obtained by estimating Eq. (1) and including year fixed effects.
Dependent variable = percentage of respective residue management method (0-100).
Standard errors, shown in parentheses, are clustered within households.
*** p < 0.01.
** p < 0.05.
* p < 0.1.

**Table A4**
Robustness checks: one policy at a time.

| | Open field burning | | | Domestic fuel | | | Residue retention | | |
|---|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| Mandatory regulation on burning crop residue at village level (yes = 1; no = 0) | 2.267 | | | −6.399 | | | 5.065 | | |
| | (3.587) | | | (4.572) | | | (3.133) | | |
| Availability of residue chopper at village level (yes = 1; no = 0) | | −8.542* | | | −14.922* | | | 21.169** | |
| | | (4.618) | | | (7.826) | | | (8.239) | |
| Demonstration project of conservation practices at village level (yes = 1; no = 0) | | | −6.342 | | | −3.256 | | | 12.906** |
| | | | (7.308) | | | (7.031) | | | (5.155) |
| Family members with off-farm jobs (yes = 1; no = 0) | 0.314 | 0.378 | 0.473 | 1.741 | 1.827 | 1.804 | −0.540 | −0.673 | −0.841 |
| | (2.535) | (2.532) | (2.531) | (3.696) | (3.705) | (3.730) | (3.742) | (3.704) | (3.711) |
| Farm size (ha) | −0.599* | −0.617* | −0.604* | 0.047 | 0.051 | 0.070 | 0.554*** | 0.563*** | 0.532** |
| | (0.341) | (0.336) | (0.343) | (0.217) | (0.211) | (0.210) | (0.200) | (0.205) | (0.219) |
| Wealth level (thousand RMB) | 0.110 | 0.112 | 0.110 | −0.083 | −0.086 | −0.088 | −0.033 | −0.032 | −0.027 |
| | (0.102) | (0.105) | (0.105) | (0.107) | (0.114) | (0.114) | (0.037) | (0.033) | (0.037) |
| Constant | 10.719 | 11.234 | 11.650 | 72.885*** | 71.011*** | 71.338*** | 4.589 | 5.603 | 5.176 |
| | (12.159) | (11.869) | (11.926) | (12.466) | (12.833) | (12.905) | (4.559) | (3.967) | (4.510) |
| Observations | 761 | 761 | 761 | 761 | 761 | 761 | 761 | 761 | 761 |
| $R^2$ | 0.901 | 0.902 | 0.901 | 0.892 | 0.894 | 0.892 | 0.719 | 0.732 | 0.721 |

This table shows the effects of various policy instruments on uses of crop residue and the results are obtained by estimating Eq. (1) and including province × year fixed effects.
Dependent variable = percentage of respective residue management method (0–100).
Standard errors, shown in parentheses, are clustered within households.
*** p < 0.01.
** p < 0.05.
* p < 0.1.

**Table A5**
The differences in key socio-economic variables between the control and treatment groups in 2003.

| | Mandatory regulation | | | Availability of residue choppers | | | Demonstration of conservation projects | | |
|---|---|---|---|---|---|---|---|---|---|
| | Control group | Treatment group | Diff. | Control group | Treatment group | Diff. | Control group | Treatment group | Diff. |
| Number of family members | 4.07 | 4.24 | −0.17 | 4.13 | 3.89 | 0.25 | 4.09 | 4.32 | −0.23 |
| Age of the household head | 40.53 | 40.23 | 0.30 | 39.89 | 44.15 | −4.26** | 40.00 | 44.53 | −4.53* |
| Education of the household head | 7.67 | 7.86 | −0.19 | 7.77 | 7.31 | 0.47 | 7.71 | 7.90 | −0.19 |
| Gender of the household head (1 = male; 0 = female) | 0.98 | 1.00 | −0.02 | 0.98 | 1.00 | −0.02 | 0.98 | 1.00 | −0.02 |
| Percentage of off-farm labors | 8.20 | 6.62 | 1.58 | 7.54 | 6.80 | 0.75 | 7.58 | 6.14 | 1.44 |
| Wealth level (thousand RMB) | 125.41 | 111.20 | 14.21 | 120.17 | 98.46 | 21.71 | 115.31 | 147.53 | −32.22 |
| Farm size (ha) | 3.02 | 2.87 | 0.16 | 2.78 | 2.27 | 0.51 | 2.71 | 2.91 | −0.21 |
| Income from off-farm jobs (thousand RMB) | 2363.02 | 2840.54 | −477.52 | 2695.47 | 1373.08 | 1322.40 | 2607.05 | 1923.68 | 683.37 |
| Observations | 116 | 74 | | 207 | 35 | | 223 | 19 | |

** p < 0.05.
* p < 0.1.

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