Transition to sustainable management or revert to traditional approaches? The impact of punishment and machine availability on farmers' straw burning

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Abstract:

The core principle of China's straw-burning policy revolves around the approach of "combining blocking and dredging." This principle entails two main strategies: imposing stricter punishment for straw burning (blocking) and increasing the availability of machinery for sustainable management (dredging). However, the impact of these measures on the transition pathways for farmers' straw disposal approaches remains unclear. This paper utilizes a two-wave household survey conducted in Heilongjiang and employs a multinomial logit model to examine the effects of punishment and machinery availability on farmers' straw disposal practices. Our findings indicated that while punishment for straw burning effectively reduced its occurrence, they primarily pushed farmers back to traditional disposal methods, such as manual collection, with few impacts on promoting sustainable practices like straw returning and baling. Additionally, these impacts were most pronounced among medium-sized farmers (5-20 ha), with limited impacts observed among small-scale (0-5 ha) and large-scale farmers (>20 ha). In contrast, the availability of straw-utilization machinery mainly encouraged the shift from burning to sustainable management and was effective across nearly all farm sizes. Our findings highlight the importance of supportive policies in guiding farmers toward sustainable agricultural waste management instead of relying on mandatory measures, particularly for small-scale and large-scale farmers.

Keywords: Straw burning, Punishment, Machine availability, Sustainable management, Northeast China

1. Introduction

The circular economy, based on reducing, reusing, and recycling, addresses issues from the linear production model and aims to minimize resource input and waste generation, fostering environmental quality, economic prosperity, and social equity (Kirchherr and Piscicelli 2019, Kirchherr *et al.* 2017). Waste management is one of the most important stages of the life cycle of agricultural production within the circular economy, given the large waste volume generated by agriculture and its high reuse potential both on farms and in other sectors (Kapoor *et al.* 2020, Velasco-Muñoz *et al.* 2022, Velasco-Muñoz *et al.* 2021). Maximizing the use of agricultural waste benefits improving food security, mitigating environmental degradation, and boosting economic benefits (Muscolo *et al.* 2021, Sharma *et al.* 2019). However, agricultural waste has not been effectively utilized globally. A major concern is the widespread waste of crop residues—straws—that could have been utilized as soil manure, animal feed, and industrial materials (Qiu *et al.* 2014). Instead, these crops are often burned in the open air by farmers in many developing countries (Bhattacharyya *et al.* 2020, Lin and Begho 2022, Theesfeld and Jelinek 2017). For example, China and India are the world's top producers of straw, yet more than 20% of this straw is burned (Fang *et al.* 2019, Jain *et al.* 2014). This straw burning not only reduces the reuse potential of straw but also constitutes a significant source of air pollution, posing substantial threats to public health (Guo 2021, He *et al.* 2020, Lai *et al.* 2022).

To tackle the problem of straw burning, the central government in China has advocated for a basic principle of policy measures, known as the "combination of blocking and dredging," since 2013 (National Development and Reform Commission (NDRC) 2013). On the one hand, the central government mandated that provincial authorities implement stringent regulations to restrict farmers' straw-burning activities (blocking). On the other hand, provincial governments were tasked with enhancing financial support to develop infrastructure for straw utilization, thereby facilitating sustainable straw management by farmers (dredging). Based on these principles, the provincial government designed the policy measures. For blocking, many provinces have implemented stringent monitoring systems to enhance the enforcement of related punishments. These punishment measures involve imposing timely monitoring, fines, and, in some cases, administrative detention on farmers (Wang *et al.* 2021a). For dredging, substantial investments in straw-utilization subsidies have been introduced by various provinces to enhance farmers' machine availability for sustainable straw management (Wang *et al.* 2022).

Previous studies have explored the impact of policy measures based on these principles on straw burning. Hou *et al.* (2019) and Sun *et al.* (2019) both conducted household surveys in 2013, but their findings differ significantly. Hou *et al.* (2019) , who surveyed households in Northeast China, discovered that while straw-burning punishment had a limited effect on farmers' straw-burning activities, the machinery availability was influential. In contrast, Sun *et al.* (2019) , who surveyed households in Jiangsu, found that straw-burning punishments were effective in controlling straw burning, whereas subsidies for sustainable straw management had little impact. In addition to these household-level analyses, Nian (2023) and Cao and Ma (2023) conducted macro-level analyses using satellite-based data on straw-burning hotspots. Their findings were consistent, revealing the limited impacts of the punishment and the significant impact of biomass power plants in controlling straw burning.

While previous analyses have improved our understanding of the impacts of policies aimed at reducing straw burning, they have not further explored how these policies affect farmers' decisions regarding the management of unburned straw. Filling this knowledge gap is crucial for assessing whether the policies are achieving their intended outcomes. There are two primary alternative pathways for disposing of unburned straw. The first is reverting to traditional practices, where straw is manually collected and used as household fuel. The second is sustainable management using machinery, which includes techniques such as returning straw to the field or baling it. The "blocking and dredging" policy principle is designed to encourage the latter pathway, promoting more sustainable and less labor-intensive methods over traditional, manual approaches. Therefore, empirically identifying how unburned straw is managed provides a deeper understanding of whether the actual effects of the policy measures deviate from their intended targets. This analysis will also help determine which policy measures are more effective in achieving the desired outcomes.

To address this knowledge gap, we conducted a household survey in Heilongjiang to empirically analyze how punishment and machinery availability influence the transition pathways of farmers' straw disposal approaches. Heilongjiang is the well-suited region for this analysis, as its government implemented a straw-burning control (SBC) project in 2018, which included both increased punishment for straw burning and enhanced availability of machinery for sustainable straw management. Located in Northeast China, Heilongjiang is the country's leading grain-producing province. This high level of grain production has resulted in significant straw disposal challenges, with a notably high incidence of straw burning. In 2017, Heilongjiang accounted for 28.2% of the total number of open straw-burning incidents in China (Wang *et al.* 2022). To address this issue, Heilongjiang launched a straw-burning SBC project in 2018, establishing a stringent straw-burning monitoring system, and made significant investments in straw-utilization machinery and other infrastructure to support the transition from burning to sustainable straw management.

The household survey comprised two waves. The first wave, conducted in 2018 before the implementation of the SBC project, gathered data on farmers' straw disposal practices during the burning season from Autumn 2017 to Spring 2018. This survey included 1,305 observations from 15 counties in Heilongjiang. The second wave, carried out in 2019 after the project's implementation, collected data on straw disposal during the burning season from Autumn 2018 to Spring 2019, resulting in a total of 811 observations. Additionally, we utilized a multinomial logit model to analyze the transition pathways for farmers' straw disposal approaches, including shifts from straw burning to manual collection, from straw burning to sustainable management, and from manual collection to sustainable management.

In the remainder of the study, we first provide contextual information, including an overview of straw-utilization approaches and the policy background. We then describe the data and method. Moreover, we presented empirical results. Finally, the study concludes with a discussion of our findings.

2. Straw-utilization approach and policy background

2.1 Alternative pathways for straw burning

To avoid straw burning, farmers have two pathways for straw disposal (Figure 1). One pathway is manual collection, a traditional approach where farmers use sickles to cut the straw at its base, collect it by hand, and then transport it to their homes for use as household energy and animal feed. Due to its labor-intensive nature, this method has become less popular in recent times. Another pathway involves mechanized sustainable management, which includes two approaches. The first is straw returning, which involves leaving the residual straw in the field using techniques such as straw covering, deep plowing, or shredding. This practice aims to minimize disruption to the next planting cycle while enhancing soil organic matter and carbon sequestration (Bu *et al.* 2020, Jin *et al.* 2020, Lu *et al.* 2009, Wang *et al.* 2021b), reduce chemical fertilizer use (Hu *et al.* 2020, Yin *et al.* 2018), and increase crop yields (Huang *et al.* 2021, Wang *et al.* 2018). The second mechanized approach is straw baling, which involves using a baler to package residual straw into bales. These bales can then be transported, stored, and reused by households (household energy and animal feed) and straw-utilization industries (power generation and organic fertilizer). Thus, straw baling facilitates further utilization at the household and industrial scales (Qiu *et al.* 2014).

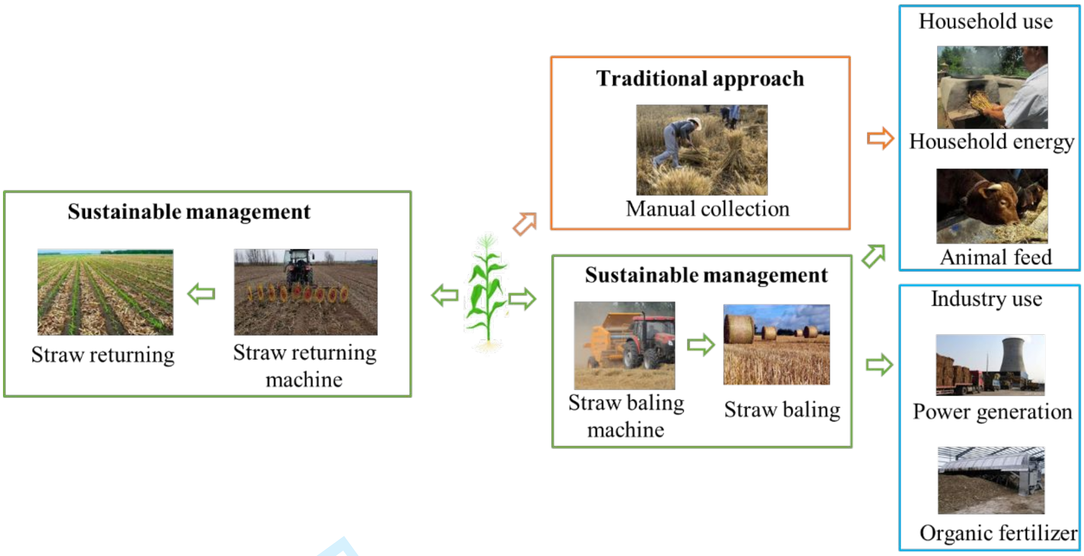


Figure 1 Alternative pathways for straw burning

Note: The orange color represents the traditional approach, such as manual collection. The green color represents sustainable management, including straw returning and baling. The blue color represents households (household energy and animal feed) and straw-utilization industries (power generation and organic fertilizer) utilization of collected straw. The pattern of straw sustainable management is summarized by the authors.

2.2 Policy background of straw-burning control (SBC) project in Heilongjiang

In 2017, the national government implemented a specialized policy for straw burning in Northeast China in 2017 (Minstry of Agriculture and Rural Affairs (MARA) 2017). This plan mandated an increase in the proportion of straw sustainable management in Northeast China from 66.6% to 80% by 2020. In response, the Heilongjiang government implemented the SBC project in 2018, which incorporated the principles of blocking and dredging.

(1) Blocking: establishing a straw-burning monitoring system

To implement effective straw-burning supervision, the SBC project adopted a strict top-down accountability monitoring system known as the "Grid Management System (GMS)" (Heilongjiang People Government (HPG) 2018). This system geographically divided the whole area into four-level grids, ranging from prefecture-level, county-level, township-level, to village-level. Each grid established a straw-burning management committee. The committee members were heads of departments, including agriculture, police, and environment, while the committee leaders were the chief executives in the locality, such as county heads. Each level committee's performance is evaluated using clear and measurable indicators. Specifically, the number of straw-burning spots in the grid detected by the remote sensing satellite served as the assessment and inspection standard for the committee's performance. When the number of straw-burning spots surpassed the designated standard, members of the management committee, particularly those in key leadership roles, faced administrative punishments. These punishments encompassed criticism, mandatory public apologies, and adverse effects on their promotion evaluations.

(2) Dredging: investment in straw-utilization facilities

Although top-down command and supervision can block farmers' straw burning, they cannot address the farmers' dilemma in straw utilization. To address the farmers' dilemma in straw utilization, Heilongjiang provided straw-utilization subsidies to attract the participation of the private sector, investing 4.3 billion CNY (0.6 billion dollars) in total for straw sustainable management (Heilongjiang Daily (HD) 2019).

The subsidy was a systematic subsidy scheme rather than a single subsidy item. Specifically, these subsidized schemes consisted of two parts. The first part was to motivate farmers to adopt straw returning. The provincial government provided 600 CNY/ha (84 USD/ton) subsidies for straw return. Meanwhile, the provincial government subsidized over one-third of the investment in straw-returning machines. The second aspect focused on establishing a straw-recycling chain to stimulate demand for straw across various industries. The initial step in building this chain involved subsidizing investments in using straw for electricity generation. The provincial government set a target to stimulate the establishment of 1,282 fuel stations by 2020, where straw would be converted into raw materials for biomass power plants. Investments in constructing these stations were eligible for subsidies ranging from 30% to 70%. Additionally, enterprises utilizing straw as industrial materials could receive a subsidy of 100 CNY/ton (14 USD/ton). Finally, the provincial government subsidized straw-baling machines by at least 30%, facilitating the collection of straw at the farm level.

3. Data and Method

3.1 Data

To sample the households, we utilized a stratified random sampling approach, initially selecting household farms in 2018 and tracing these samples in 2019. In 2018, we chose 15 counties, ensuring coverage of all temperature zones in Heilongjiang (Figure 2). Within each selected county, we randomly selected three townships and, within each township, three villages. From each village, we randomly selected ten farmers based on the household registration list. In 2019, we revisited the same 15 counties but randomly traced two out of the three townships per county. The selection methods for villages and farmers remained consistent with those used in 2018. When traced farmers were unavailable on the survey day, we used random numbers to select replacement farmers. Additionally, due to summer floods, some villages were excluded from the survey as initially planned. Overall, we surveyed a total of 2,116 observations, comprising 1,311 observations in 2018 and 811 observations in 2019. Our sample included 475 traced farmers, resulting in a total of 950 observations.

The outcome variable in this study is farmers' straw disposal decisions. To quantify this, rural farmers were asked: "What is the primary method you use to dispose of straw for each plot?" The response options were: 1) straw burning, 2) straw returning, 3) straw baling, and 4) manual collection of straw. We then combined straw returning and straw baling into a category labeled "sustainable management." Consequently, farmers' straw disposal decisions are classified into three categories: 1) straw burning, 2) manual collection, and 3) sustainable management.

The key independent variables include two main factors: the intensity of straw-burning punishment and the availability of machinery for straw management. First, the intensity of straw-burning punishment is assessed through farmers' perceptions. We measured this variable (referred to as 'punishment') using two questions. During the surveys, farmers were asked: "Would you incur punishment if you burned straw? (0=no; 1=yes)." If the response was 'yes,' we followed up with: "Do you think the punishment for burning straw is severe?" The responses were rated on a Likert scale from 1 to 3 (1=light; 2=neutral; 3=heavy). The punishment variable thus ranges from zero to four (0: no punishment; 1: light; 2: neutral; 3: heavy). Second, we assessed farmers' perceptions of the availability of machinery for straw management (referred to as ‘machine availability’). Farmers were asked: “Can you find facilities for straw returning in your local area?” and “Can you find facilities for straw baling in your local area?” Responses were scored as 0 (no) or 1 (yes). These responses were then combined into a single index with three levels: 0 (no machines), 1 (one of the two machines available), and 2 (both machines available). Other control variables are shown in Table 1.

Table 1. Statistical description

	All sample					Traced sample				
	Observation	Mean	Std. Dev.	Min	Max	Observation	Mean	Std. Dev.	Min	Max
Straw disposal	2,116	2.019	0.858	1	3	950	2.046	0.828	0	1
Punishment	2,115	1.326	1.187	0	3	950	1.332	1.196	0	3
Machine availability	2,100	0.802	0.802	0	2	947	0.850	0.803	0	2
Household variables										
Village committees, 1=yes	2,116	0.158	0.365	0	1	950	0.176	0.381	0	1
Age, year	2,115	50.310	9.501	23	85	949	50.779	9.325	23	85
Education, year	2,064	7.869	2.778	0	15	934	7.839	2.832	0	15
Farm variables										
Farm size, ha	2,107	13.585	37.656	0	667	948	13.429	35.272	0.1	667
Plot number	2,081	7.282	9.115	0	230	937	7.265	6.976	1	60
Maize, 1=yes	2,107	0.397	0.489	0	1	949	0.421	0.494	0	1
Soybean, 1=yes	2,107	0.421	0.494	0	1	949	0.437	0.496	0	1
Wheat, 1=yes	2,107	0.182	0.386	0	1	949	0.141	0.348	0	1

Note: We chose 15 counties in Heilongjiang for our study. The dataset comprises 2,116 valid observations, distributed as 1,305 observations in 2018 and 811 observations in 2019. Additionally, among the traced households, the dataset has 475 households, resulting in a total of 950 observations.

3.2 Method

We employed the multinomial logit (ML) model to estimate the impacts of punishment and machine availability on farmers' straw disposal. The ML model is suitable for analyzing cases where the dependent variable is discrete and categorical rather than continuous. In this context, although the dependent variable is recorded as "0, 1, 2..." these numbers merely represent different categories and do not imply ordinal or numerical relationships among the levels. Thus, the ML model allows us to examine farmers' transitions between various straw disposal methods and provides a detailed understanding of how punishment and machine availability affect these transitions.

(1) Basic setting

For each farmer i, the choice of straw disposal is represented by j= 1, 2, 3, corresponding to straw burning, manual collection, and sustainable management, respectively. y_{ij}^{*} denote as the latent propensity for farms i to choose straw disposal j. With this notation, I assume the following relation between the propensities, y_{ij}^{*}, and independent variables, the vector $\mathbf{x}_i$:

$$y_{ij}^{*} = \mathbf{x}_i \boldsymbol{\beta}_j + \varepsilon_{ij} \quad (1)$$

In this equation, $\boldsymbol{\beta}_j$ is the coefficient vector, which must be estimated. The error term, ε_{ij}, is independent and identically distributed across all outcomes j. I assume farmer i will choose the maximum y_{ij}^{*} among three options. Thus, the link to the chosen outcome is defined by

$$\Pr\,(y_i = j|\beta, \mathbf{x}_i) = \Pr\,(\max y_{ik}^{*} = y_{ij}^{*}|\beta, \mathbf{x}_i) \quad (2)$$

With these assumptions, I can derive the probabilities of each outcome. To guarantee identifiability, straw burning is set as the base outcome (j = 1). Based on this setting, for each farm i, the probability of each outcome is as follows:

$$\Pr\left(y_i = j \,\middle|\, \beta, \mathbf{x}_i\right) = \begin{cases} \frac{\exp\,(\mathbf{x}_i\,\boldsymbol{\beta}_3)}{1+\sum_{k\neq1}\exp\,(\mathbf{x}_i\,\boldsymbol{\beta}_k)} & j=3 \\ \frac{\exp\,(\mathbf{x}_i\,\boldsymbol{\beta}_2)}{1+\sum_{k\neq1}\exp\,(\mathbf{x}_i\,\boldsymbol{\beta}_k)} & j=2 \\ \frac{1}{1+\sum_{k\neq1}\exp\,(\mathbf{x}_i\,\boldsymbol{\beta}_k)} & j=1 \end{cases} \quad (3)$$

Hence, compared to the base outcome, the log odds of the other two straw disposal methods can be written by:

$$\ln\left(\frac{\Pr\left(y_i=j \,|\, \beta, \mathbf{x}_i\right)}{\Pr\left(y_i=1 \,|\, \beta, \mathbf{x}_i\right)}\right) = \begin{cases} \mathbf{x}_i\,\boldsymbol{\beta}_3 + \varepsilon_{3i} & j=3 \\ \mathbf{x}_i\,\boldsymbol{\beta}_2 + \varepsilon_{2i} & j=2 \end{cases} \quad (4)$$

In this equation, I am particularly interested in $\boldsymbol{\beta_2}$ and $\boldsymbol{\beta_3}$ a, which represents the impact of the independent variables on the transition from straw burning to manual collection (j = 2) and sustainable management (j = 3), respectively.

(2) The marginal effect estimation

After estimating the coefficient vector, $\boldsymbol{\beta_2}$ and $\boldsymbol{\beta_3}$, the ML is allowed to calculate the marginal effects of independent variables. The marginal effects represent the probability of each outcome $\Pr\left(y_i = j \,\middle|\, \beta,\mathbf{x}_i\right)$ for a one-unit change in the independent variable $\mathbf{x}$. The marginal effect estimation includes two steps. The first step is to calculate predicted probabilities for each outcome j using the following equation:

$$\widehat{\Pr(y_i = j|\hat{\beta},\mathbf{x}_i)} = \begin{cases} \frac{\exp\,(\mathbf{x}_i\,\widehat{\boldsymbol{\beta}}_3)}{1+\sum_{k\neq1}\exp\,(\mathbf{x}\,\widehat{\boldsymbol{\beta}}_k)} & j=3 \\ \frac{\exp\,(\mathbf{x}_i\,\widehat{\boldsymbol{\beta}}_2)}{1+\sum_{k\neq1}\exp\,(\mathbf{x}_i\,\widehat{\boldsymbol{\beta}}_k)} & j=2 \\ \frac{1}{1+\sum_{k\neq1}\exp\,(\mathbf{x}_i\,\widehat{\boldsymbol{\beta}}_k)} & j=1 \end{cases} \quad (5)$$

In this equation, $\Pr(y_i = j)$ represents the predicted probability that farmer i chooses straw disposal method j. The vector $\widehat{\boldsymbol{\beta}}_k$ are the estimated coefficients using equation 3.

The second step is to calculate the individual marginal effects using the predicted probabilities. For variables of interest, such as punishment or machine availability, the marginal effects of the independent variable m on straw disposal method j are given by:

$$\frac{\partial \Pr\,(y_i=j|\hat{\beta},\mathbf{x}_i)}{\partial \mathbf{x}_{im}} = \Pr(\widehat{y_i = j\,|\hat{\beta},\mathbf{x}_i})(\widehat{\beta_{jm}} - \sum_k \Pr(\widehat{y_i = k|\hat{\beta},\mathbf{x}_i})\widehat{\beta_{km}}) \tag{6}$$

After calculating the marginal effects for each farmer using Equation 6, the average marginal effects (LME) across all observations are:

$$LME_{jm} = \frac{1}{N}\sum_{i=1}^{N} \frac{\partial Pr\,(y_i=j|\hat{\beta},\boldsymbol{x}_i)}{\partial \boldsymbol{x}_{im}} \tag{7}$$

The LME is the focus of our analysis and represents the average impact of a one-unit change in the independent variables on the likelihood of farmers choosing option *j*.

4. Result

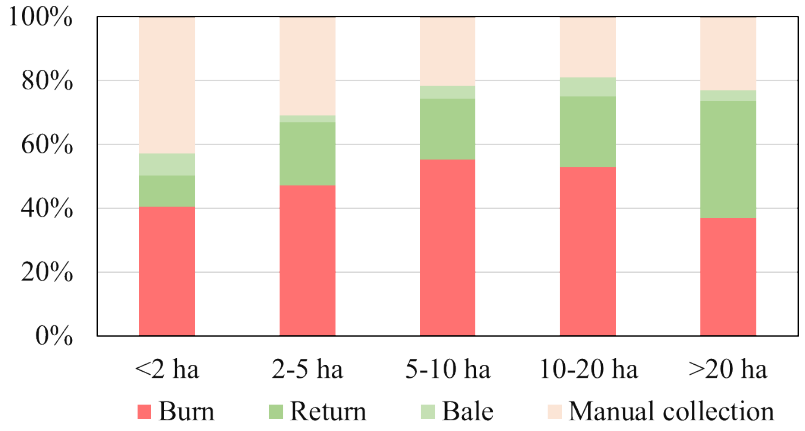
4.1 Descriptive analysis

Before empirically estimating the impacts of punishment and machine availability on farmers' straw disposal approaches, we first described their temporal changes before and after the implementation of the SBC project to provide an intuitive understanding of their relationship.

Figure 2 reports the temporal changes in farmers' straw disposal approaches before (Figure 2a) and after (Figure 2b) the implementation of the SBC project. The figure indicated a notable shift from straw burning to more sustainable management methods following the project's implementation. This transition appeared consistent across all farm sizes. Specifically, prior to implementation, straw burning served as the primary disposal method for over 47% of farmers. Remarkably, this number rose to nearly 60% among farmers with land holdings between 5-10 ha (Figure 2a). In contrast, following implementation, only 17% of farmers relied on straw burning as their primary method of straw disposal. Notably, unburned straw no longer followed the traditional approach of manual collection but instead shifted towards new and sustainable management, including straw returning and baling (Figure 2b). Prior to implementation, farmers employing these two sustainable methods comprised less than 20% of the total, but post-implementation, this figure increased to about 60%.

Regarding the independent variables, both key policy measures—punishment and machine availability—significantly improved following the implementation of the SBC project. As shown in Figure 3, all farm groups experienced significant increases in both punishment and machine availability. Notably, farmers with more than 5 ha of land perceived a greater increase in the supply of straw-returning facilities compared to those with less land. These changes in punishment and machine availability indicated that the reforms implemented by the SBC project have effectively translated macro-level policies into tangible environmental changes that farmers can perceive. Importantly, the policy interventions in Heilongjiang were inclusive, ensuring that smallholders were not neglected.

Panel A: Autumn 2017–Spring 2018



Panel B: Autumn 2018–Spring 2019

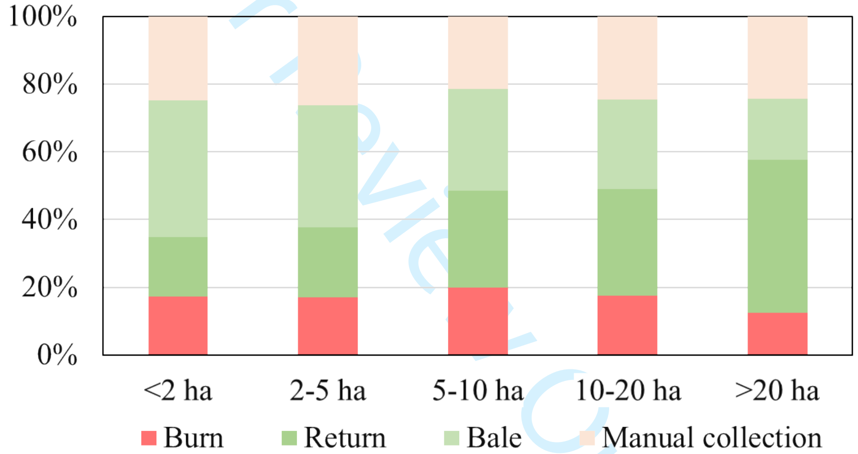
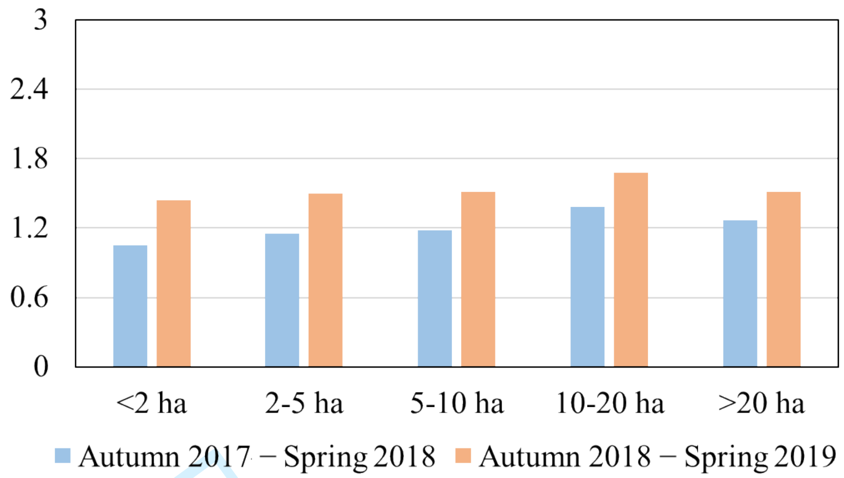


Figure 2. Temporal changes in farmers' straw disposal approaches

Note: (a) Data is sourced from the pooled dataset from two waves of household surveys. (b) Autumn 2017–2018 marks the straw-burning season prior to the implementation of the straw-burning control (SBC) project, while Autumn 2018–2019 represents the season following its implementation.

Panel A: Punishment



Panel B: Machine availability

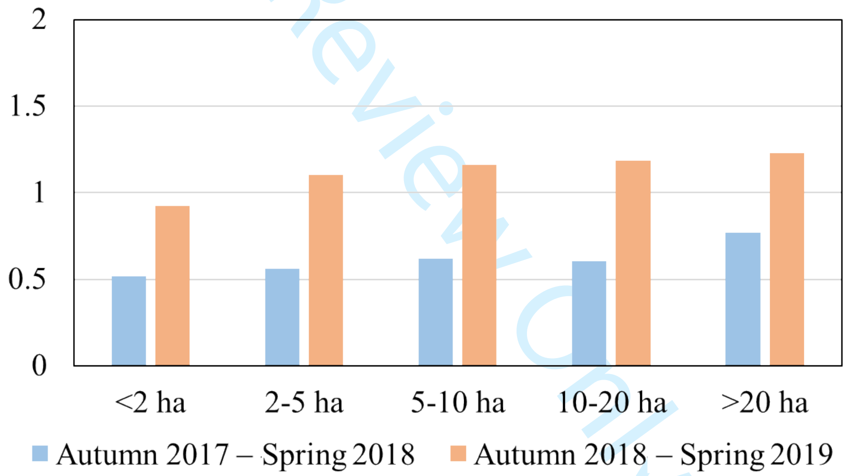


Figure 3. Temporal changes in punishment and machine availability

Note: (a) Data is sourced from the pooled dataset from two waves of household surveys. (b) Autumn 2017–2018 marks the straw-burning season prior to the implementation of the straw-burning control (SBC) project, while Autumn 2018–2019 represents the season following its implementation.

4.2 The impact of punishment and machine availability on farmers' straw disposal

We used equation (4) to estimate the impact of punishment and machine availability on farmers' straw disposal. Table 2 reports the baseline regression results. The outcome variable in column (1) is the logarithm of the ratio of manual collection to straw burning. The coefficients of the independent variables in column (1) indicate their impacts on the shift from straw burning to manual collection. Similarly, the outcome variables in columns (2) and (3) are the logarithm of the ratio of sustainable management (straw returning and baling) to straw burning and the logarithm of the ratio of sustainable management to manual collection. The coefficients in these columns reflect the impact of these transitions. The standard errors are clustered at the village level.

As shown in Table 2, the punishment facilitated the transition from straw burning to both manual collection and sustainable management, with a more pronounced effect on the former. The coefficients of the punishment variable in columns (1) and (2) are significantly positive. This implied that farmers with straw-burning punishment were more likely to adopt manual collection and sustainable management (straw returning and baling) instead of burning compared to those not subject to punishment. Additionally, the coefficient of the punishment in column (1) is higher than in column (2), and its significance is at the 1% level, compared to the 5% level in column (2). This indicated that the punishment had a stronger impact on the shift to manual collection than on sustainable management. In contrast, the coefficient of the punishment variable in column (3) is not significant, suggesting that the punishment did not influence the transition from manual collection to sustainable management. This lack of impact may be because the punishment targets straw burning specifically and does not apply to manual collection practices, leaving those who use manual collection unaffected by local enforcement efforts.

Regarding the impact of machine availability, it facilitated the transition from straw burning to sustainable management, as well as the shift from manual collection to sustainable management. The coefficients for the machine availability variable are significantly positive in columns (2) and (3). This indicated that farmers with access to machinery were more likely to adopt sustainable management rather than continuing with burning or manual collection compared to those without such machinery. In contrast, the coefficient of the machine availability variable in column (1) is not significant, indicating that the machine availability did not influence the transition from straw burning to manual collection. This result was consistent with the expectation that straw-management machines were not designed for manual collection purposes.

Regarding the control variables, Table 2 reveals some interesting findings. First, farmers with larger-scale farmland were less likely to choose manual collection, as indicated by the significantly negative coefficients for farm size in column (1) and positive coefficients in column (3). This may be due to the fact that manual collection is highly labor-intensive for large-scale farms, making it less feasible for them. Consequently, these farmers are more inclined to burn straw when they have limited access to straw-management machines. Second, farmers who serve on village committees were also less likely to choose manual collection, as indicated by the significantly negative coefficients for village committees in column (1) and positive coefficients in column (3). This finding may be because village cadres are both the “referees” and the “players” in straw-burning monitoring. As noted in the policy background, village committees are responsible for overseeing straw burning by farmers. However, because village cadres are also involved in agricultural production themselves, their straw-burning activities receive insufficient oversight at the village level. As a result, they have greater autonomy in selecting their preferred straw disposal approach and are able to avoid the labor-intensive process of manual collection.

Table 2 Estimated impacts of punishment and machine availability on farmers' straw disposal

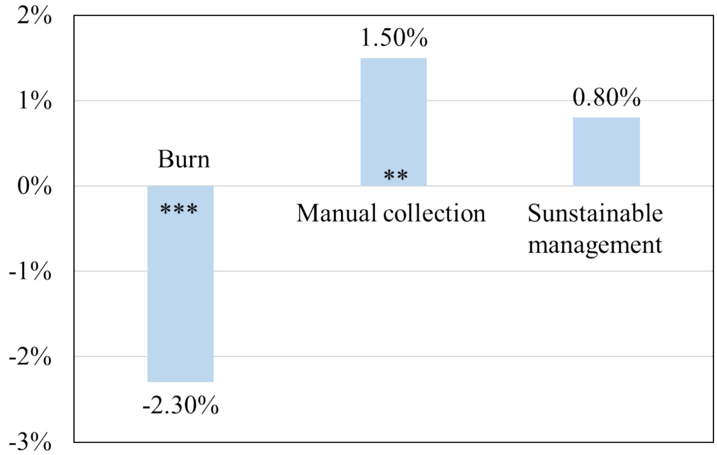
	(1) Manual collection/ Burn	(2) Sustainable management/ Burn	(3) Sustainable management/ Manual collection
Punishment	0.21***	0.15**	-0.06
	(0.08)	(0.07)	(0.07)
Machine availability	0.09	0.73***	0.64***
	(0.12)	(0.12)	(0.11)
Farm variables			
Farm size, ha	-0.51***	-0.05	0.46***
	(0.11)	(0.11)	(0.11)
Plot number	0.01	-0.01	-0.02***
	(0.01)	(0.01)	(0.01)
Soybean, 1=yes	-0.89***	0.78***	1.67***
	(0.27)	(0.26)	(0.24)
Wheat, 1=yes	-1.62***	-0.60*	1.02**
	(0.39)	(0.32)	(0.44)
Household variables			
Village committee, 1=yes	-0.74***	0.06	0.80***
	(0.26)	(0.25)	(0.29)
Age, year	0.01	-0.01	-0.02
	(0.01)	(0.01)	(0.01)
Education, year	0.04	0.03	-0.01
	(0.03)	(0.03)	(0.04)
Year fixed effect	Control	Control	Control
Village fixed effect	Control	Control	Control
Observations	2009	2009	2009
R^2	0.40	0.40	0.40

Note: (a) The data is sourced from a two-wave survey. (b) Standard errors are clustered at the village level. (c) The outcome variable is presented in logarithmic form. (d) *, **, *** indicate statistically significant at the 10%, 5%, and 1% levels, respectively.

We further calculate the marginal effects of punishment and machine availability on the three straw disposal approaches using equation (7). Figure 4 reports the results. Columns (1), (2), and (3) represent the marginal effects of punishment and machine availability on straw burning, manual collection, and sustainable management, respectively.

As illustrated in Figure 4, the punishment significantly reduced straw burning and primarily encouraged farmers to revert to manual collection. The coefficients for the punishment on the burn and manual collection outcome variables are both significant, with values of -0.023 and 0.015, respectively (Panel A). In contrast, the coefficient for the punishment on the sustainable management outcome variable is not significant, with a value of only 0.008 (Panel A). This indicates that a one-unit increase in the punishment decreased the likelihood of straw burning by 2.3%. The reduced likelihood was largely redirected toward a 1.5% increase in the likelihood of manual collection, with a smaller portion contributing to a 0.8% increase in the likelihood of adopting sustainable management. In contrast, machine availability significantly facilitated the transition from both straw burning and manual collection to sustainable management. The coefficients for machine availability in Panel B are all significant at the 1% level, with values of -0.06, -0.04, and 0.10. This indicated that a one-unit increase in machine availability decreased the likelihood of straw burning by 6% and manual collection by 4% while increasing the likelihood of adopting sustainable management by 10%.

Panel A: Punishment



Panel B: Machine availability

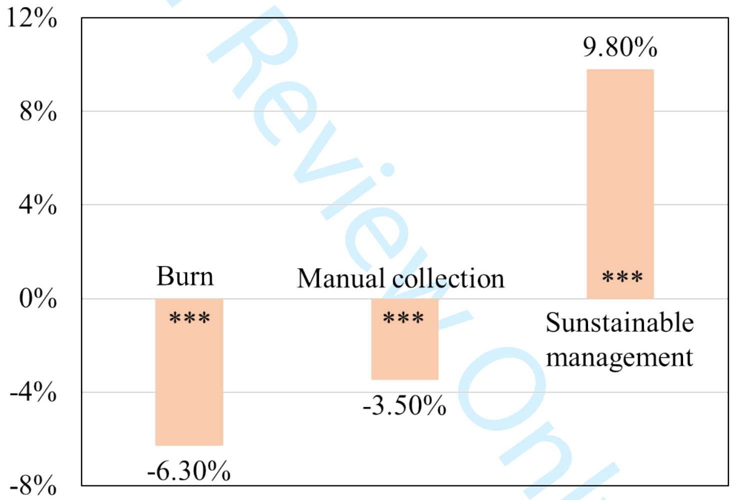


Figure 4 Marginal effects of punishment and machine availability on farmers' straw disposal

Note: (a) The data is sourced from a two-wave survey. (b) Standard errors are clustered at the village level. (e) *, **, *** indicate statistically significant at the 10%, 5%, and 1% levels, respectively.

4.3 Heterogeneity analysis

Since Table 2 reveals that farm size and village committees also influence farmers' straw disposal practices, we further investigated whether the impacts of the punishment and machine availability vary with farm size and village committee involvement.

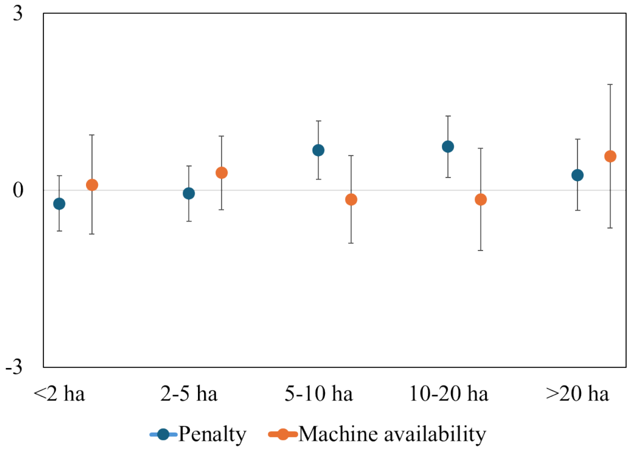
We began by conducting a heterogeneity analysis based on farm size, dividing the dataset into five groups, as illustrated in Figures 2 and 3. Figure 5 presents the results of this analysis, with dots representing the coefficients of independent variables. Blue dots indicate the impact of the punishment variable, while orange dots represent the effect of machine availability. Panels A through C show the dependent variables for transitions from straw burning to manual collection, straw burning to sustainable management, and manual collection to sustainable management, respectively. Confidence intervals are set at the 95% level. If a confidence interval crosses the zero line on the x-axis, it indicates that the corresponding coefficient is not statistically significant at the 5% level. The standard errors are still clustered at the village level.

As shown in Figure 5, the impact of the punishment on the transition from straw burning to manual collection exhibits a "U" shape (Panel A). Specifically, the impact of the punishment on the transition from straw burning to manual was most pronounced among medium-sized farmers (5-20 ha), with significance at the 1% level. In contrast, this impact is not significant for small-scale farmers (0-5 ha) and large-scale farmers (>20 ha), indicating that the punishment did not influence these groups. This may be because small-scale farmers' burning activities are less likely to be detected by monitoring supervisors due to the dispersed nature of their farmland and the smaller scale of their fires. For large-scale farmers, transitioning from straw burning to manual collection is often prohibitively labor-intensive and less feasible.

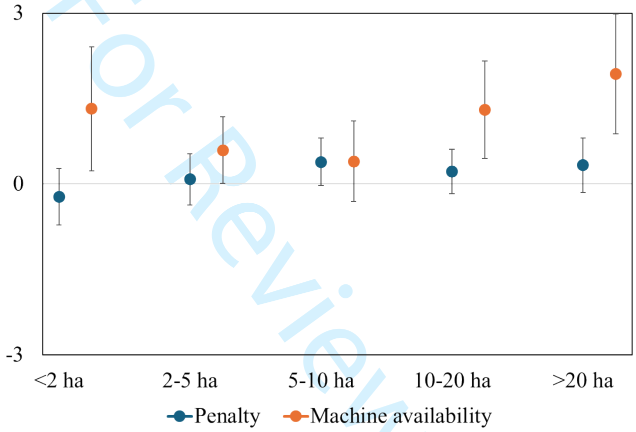
Moreover, the impact of punishment on the transition to sustainable management is limited across all farm sizes (Panel B). The coefficients for the punishment variable are not significant at the 5% level for any farm size. Although the coefficient for farmers with 5–10 ha is significant at the 10% level, it remains insignificant for other groups. Notably, this finding is different from the results reported in column (2) of Table 2, where the coefficient of punishment is significant when estimated using the whole sample. This discrepancy may arise due to several factors. First, the reduced sample size within each subgroup can diminish statistical power, making it harder to detect significant effects compared to the analysis of the entire sample. Second, the heterogeneous impact of punishment across different farm sizes could mean that the overall significance observed in the whole sample is driven by effects in specific subgroups, which are less pronounced or inconsistent when analyzed separately.

In contrast to the punishment, the impact of machine availability on the transition from straw burning to sustainable management is significant across nearly all farm sizes and exhibits an inverse “U” shape (Panel B). Notably, this impact is most pronounced among farmers with 0-2 ha and those with over 10 ha, compared to farmers with 2-10 ha. The likely reason for this inverse “U” shape is that farmers of different scales adopt distinct sustainable methods for straw disposal. Specifically, farmers with 0-2 ha primarily utilized collective straw baling in 2018 (Figure 2), organized by the village committee. This method did not require extensive knowledge or skills from the farmers. However, farmers with 2-10 ha need to adopt straw-returning practices, and solely relying on straw-utilization machines is insufficient for them. Therefore, the impact of machine availability is reduced for this group. Conversely, farmers with over 10 ha are typically rural elites with substantial knowledge and skills in adopting straw-returning practices, making machine availability more impactful for them.

Panel A: Manual collection/Burn



Panel B: Sustainable management/Burn



Panel C: Sustainable management/ Manual collection

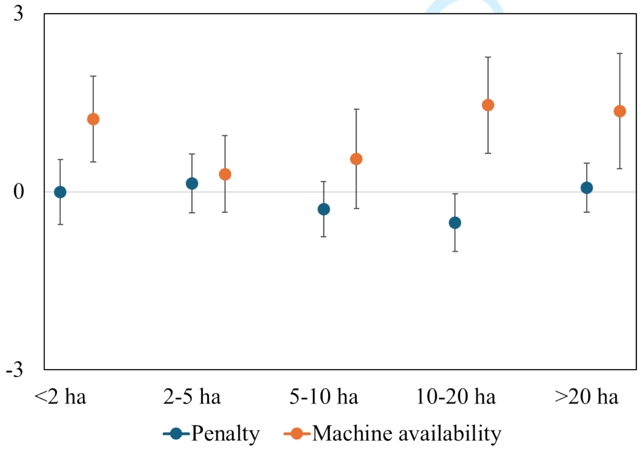
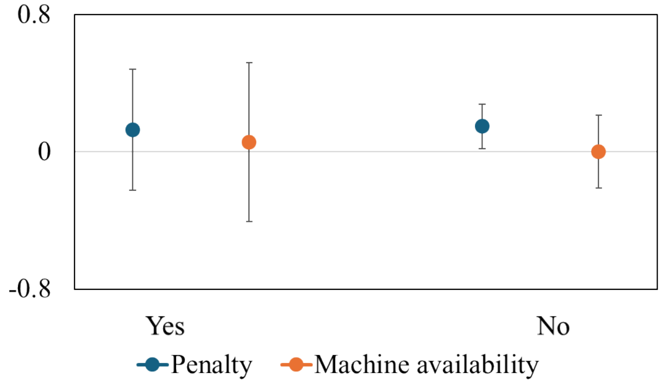


Figure 5 Estimated heterogeneous impacts based on farm size

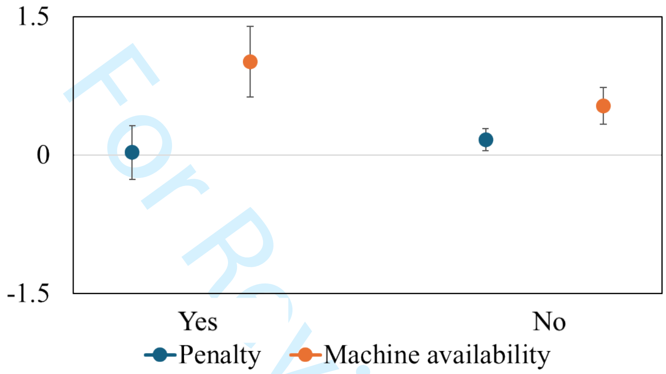
Note: (a) The data is sourced from a two-wave survey. (b) Standard errors are clustered at the village level. (c) The control variables are consistent with those presented in Table 2. (d) The outcome variable is presented in logarithmic form. (e) Confidence intervals are set at the 95% level.

We further conducted a heterogeneity analysis based on the village committee, as shown in Figure 6. The results reveal that farmers serving on village committees are not significantly influenced by punishment in their straw disposal practices. Specifically, the coefficients for punishment are not significant for either the transition from straw burning to manual collection (Panel A) or to sustainable management (Panel B) within this group. In contrast, regular farmers experience a significant impact from punishment at the 5% level, effectively discouraging straw burning. This discrepancy may arise from the village cadres' dual roles as both farmers and straw-burning supervisors, which might reduce their effectiveness in monitoring and enforcing punishment. Regarding machine availability, the impact is more pronounced among farmers who serve on village committees (Panels B and C). The coefficients for machine availability in this group are higher, suggesting that village committee members with access to machines are more likely to transition to sustainable management compared to those without access. This could be because village committee members have priority access to machines, enhancing their ability to adopt sustainable practices.

Panel A: Manual collection/Burn



Panel B: Sustainable management/Burn



Panel C: Sustainable management/ Manual collection

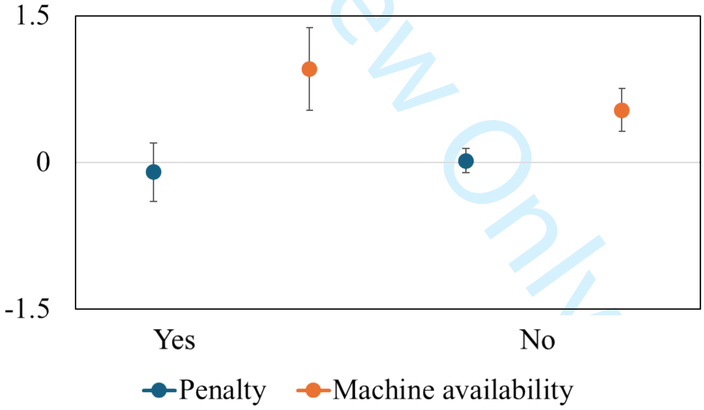


Figure 6 Estimated heterogeneous impacts based on village committee

Note: (a) The data is sourced from a two-wave survey. (b) Standard errors are clustered at the village level. (c) The control variables are consistent with those presented in Table 2. (d) The outcome variable is presented in logarithmic form. (e) Confidence intervals are set at the 95% level.

4.4 Robustness check

Finally, we used the traced sample to conduct a robustness check on our baseline regression results. The advantage of the traced sample is that it allows us to include individual fixed effects instead of village fixed effects, thereby increasing the robustness of our findings. However, the drawback is that it utilizes only half of the observations from the entire dataset, which significantly reduces statistical power. We continued to estimate equations (4) and (7) using the traced sample, with the results presented in Tables 3 and 4. As illustrated in Table 3, the effects of punishment and machine availability on the three transitions remain consistent with those obtained from the full sample. Although the coefficients for the punishment and machine availability variables are larger, their significance persists at the 5% level. Similarly, the marginal effects estimated using the traced sample, as shown in Table 4, align with those derived from the full sample. These findings indicate that the baseline results are robust and consistent when analyzed using the traced sample.

Table 3 Estimated impacts of punishment and machine availability on farmers' straw disposal using traced sample

	Manual collection/ Burn		Sustainable management/ Burn		Sustainable management/ Manual collection	
	(1)	(2)	(3)	(4)	(5)	(6)
Sample size	Full	Traced	Full	Traced	Full	Traced
Punishment	0.21***	0.44**	0.15**	0.42**	-0.06	-0.02
	(0.08)	(0.22)	(0.07)	(0.20)	(0.07)	(0.29)
Machine availability	0.09	0.30	0.73***	2.54***	0.64***	2.24***
	(0.12)	(0.40)	(0.12)	(0.38)	(0.11)	(0.41)
Observation	2009	916	2009	916	2009	916
Farm variables	Control	Control	Control	Control	Control	Control
Household variables	Control	Control	Control	Control	Control	Control
Individual fixed effect	Control	Control	Control	Control	Control	Control

Note: (a) The data is sourced from a two-wave survey. (b) Standard errors are clustered at the village level. (c) To intuitively compare the differences between the full and traced samples, we presented the results from Table 2 again in columns (1), (3), and (5). (c) The farm and household variables are consistent with those presented in Table 2. (d) The outcome variable is presented in logarithmic form. (e) Confidence intervals are set at the 95% level.

Table 4 Marginal effects of punishment and machine availability on farmers' straw disposal using the traced sample

	Burn		Manual collection		Sustainable management	
	(1)	(2)	(3)	(4)	(5)	(6)
Sample size	Full	Trace	Full	Trace	Full	Trace
Punishment	-0.023***	-0.023**	0.015**	0.009	0.008	0.014
	(0.008)	(0.009)	(0.008)	(0.008)	(0.008)	(0.010)
Machine availability	-0.063***	-0.096***	-0.035***	-0.049***	0.098***	0.145***
	(0.014)	(0.015)	(0.010)	(0.014)	-0.013	(0.015)

Note: (a) The data is sourced from a two-wave survey. (b) Standard errors are clustered at the village level. (c) To intuitively compare the differences between the full and traced samples, we presented the results from Figure 4 again in columns (1), (3), and (5). (d) *, **, *** indicate statistically significant at the 10%, 5%, and 1% levels, respectively.

4 Conclusion and discussion

This study analyzed the effects of punishment and machine availability on farmers' straw disposal practices, revealing significant variations based on farm size and village committee involvement. The findings demonstrate that punishment effectively reduced straw burning, especially among medium-sized farms (5-20 ha), with a notable shift toward manual collection. However, the punishment had a limited impact on smallholders and large-scale farmers, likely due to challenges in enforcement and the labor-intensive nature of the manual collection. In contrast, machine availability significantly promoted the adoption of sustainable practices across all farm sizes, with its impact being most pronounced among smallholders and large-scale farmers. Additionally, village committee members were less likely to engage in manual collection, likely due to their dual roles as both regulators and participants in straw burning.

Our findings deepen the understanding of the role of punishment in controlling straw burning, building upon existing research. Hou *et al.* (2019) found that straw-burning punishment had limited effects. In contrast, our research indicates that the punishment can control straw burning, but often lead farmers to revert to traditional methods such as manual collection. This discrepancy may be attributed to differences in the policy context. Although both studies focus on Northeast China, Hou *et al.* (2019) analyzed data from 2013, a period when straw-burning regulations were largely nominal and often overlooked by the government. In contrast, our data, collected in 2018 and 2019, reflects a time when straw burning had become a significant concern for both provincial and central governments in Northeast China. Supporting our interpretation, Sun *et al.* (2019) found that in 2013, punishment significantly reduced straw burning in Jiangsu province, where a stringent straw-burning monitoring system had been implemented, similar to the one established in Heilongjiang by late 2018.

In terms of machine availability, our findings are consistent with those of Hou *et al.* (2019), who noted that machine availability can reduce farmers' engagement in straw burning. Our study extends this understanding by revealing that machine availability not only decreases engagement in straw burning but also supports the transition from both straw burning and manual collection to sustainable management. The above findings are also supported by macro-level analysis conducted by Nian (2023) and Cao and Ma (2023). Their research indicates that biomass power plants, which enhance farmers' access to straw disposal, can reduce straw-burning incidents at the county level.

The findings of this study have significant implications for advancing sustainable agricultural practices and ensuring the long-term sustainability of rural communities. A multifaceted approach that combines regulatory measures with incentives, investments in agricultural technology, and support for local regulatory bodies is essential for achieving these goals (Smith 2019). To address the diverse needs of farmers effectively, policymakers should consider the following strategies:

First, relying solely on punishment may not be sufficient to achieve widespread adoption of sustainable practices, particularly among smallholders and large-scale farmers. To enhance effectiveness, policies should be designed to address the diverse needs and constraints of different farm sizes (Shiferaw *et al.* 2009). This could involve integrating punishment with complementary measures such as incentives, subsidies, and educational initiatives. For instance, offering financial incentives for adopting sustainable practices or providing subsidies for necessary equipment could encourage more widespread adoption (Yang and Zhao 2015). Additionally, targeted educational programs that inform farmers about the benefits and techniques of sustainable practices could foster a more comprehensive approach to sustainability.

Second, the critical role of machine availability highlights the need for ongoing investment in agricultural technology and infrastructure. Improving access to appropriate machinery, especially in areas where smallholders are prevalent, could significantly enhance the adoption of sustainable straw disposal methods. Policymakers should consider implementing measures such as government-subsidized equipment programs, cooperative ownership models, or public-private partnerships to increase access to essential technologies (Whetsell *et al.* 2020). By ensuring that farmers have access to the right tools and equipment, these measures could facilitate a smoother transition to sustainable practices.

Finally, the dual role of village committees as both regulators and participants in straw disposal requires careful consideration. To improve the effectiveness of policy interventions, it is crucial to equip these local bodies with adequate resources and incentives for equitable regulation enforcement. Furthermore, village committees should be encouraged to lead by example, demonstrating best practices in straw disposal and sustainability. By doing so, they can serve as role models within their communities, thereby reinforcing the importance of compliance and sustainable practices.

The primary limitation of our study is its use of a static analysis, which pools data from two periods for evaluation. This approach limits our ability to capture the dynamic nature of farmers' responses to policy changes over time and may overlook gradual behavioral shifts or delayed reactions. As a result, the study offers a constrained view of the long-term effectiveness and sustainability of the policies under examination. Additionally, our focus on a single region, Heilongjiang, limits the generalizability of our findings to other areas with different agricultural contexts and policy environments. Further studies across diverse regions would help to validate and expand upon our results.

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