From agri-waste to sustainable use:
A case study of straw management reform in Northeast China

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Details about the data, methods, and framework are presented in Supplementary Information (SI).

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Abstract:

Sustainable agri-waste utilization is a crucial stage in transforming agricultural production into low-carbon. Straws, as the primary agricultural waste, are not effectively reused by farmers in developing countries. Burning straws can be widely observed and it is one of the main sources of CO2 emission from the agricultural sector. Since 2013, China has reformed its agri-waste governance to promote sustainable use of straw. However, few studies have analyzed the structure and operation of its agri-waste policy in the field, and limited evidence has been drawn on the effectiveness of these policies. The objective of this study is to investigate the reform of China's straw governance in China, and examine the effectiveness of such reform. We employed a combination of quantitative and qualitative approaches to investigate to what extent and how the reforms addressed the straw-burning issues. We found that the reform significantly decreased farmers' straw burning behavior and increased rural farmers' straw returning and straw bailing for power generation. Such transformation in straw management was attributed to hybrid policy instruments: (a) command-and-control (C&C) measures that used satellite-based straw-burning data to evaluate the straw-burning monitoring performance of local governments and village committees, and (b) market-based instruments (MBIs) that provide subsidies to the industries and cooperatives for sustainable straw use.

Keywords: Hybrid Policy Instruments; Command-and-Control; Market-Based Instrument; Agricultural Waste; Sustainable Straw Management

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1. Introduction

Sustainable agri-waste management is one of the most important components of the circular economy (Kapoor et al., 2020; Velasco-Muñoz et al., 2022; Velasco-Muñoz et al., 2021). Maximizing the use of agricultural waste can enhance food security, mitigate environmental degradation, and boost 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.[1] In many developing countries these crop residues are often burned in the open air by farmers (Bhattacharyya et al., 2020; Lin and Begho, 2022; Theesfeld and Jelinek, 2017). For example, both China and India are the world's largest producers of straw, yet more than 20% of these straws were burned in an open air (Fang et al., 2019; Jain et al., 2014). This open-air straw burning (OSB) not only neglects the potential benefits of straws reutilization, but also contributes a substantial share of air pollution and carbon emissions (Guo, 2021; He et al., 2020; Lai et al., 2022).

Several developing countries, including China, introduced national regulations on controlling OSB (Bhuvaneshwari et al., 2019; Huang et al., 2021; Theesfeld and Jelinek, 2017). However, the effectiveness of these regulations is rather unclear. In China, statistics from the satellite monitoring shows a substantial surge in OSB incidents between 2000 and 2014 (Yin et al., 2021). Several descriptive studies indicate that China's early regulations have limited effect in reducing OSB (Cao and Ma, 2023;

1 There are multiple approaches to reuse the crop straws sustainably. Details on sustainable straw use are shown in Appendix Figure S3.

Nian, 2023). For instance, the study by Hou et al. (2019), who collected household data from 2003 to 2013 in Northeast China, found that the regulations had limited effects on decreasing farmers' OSB activities, although the proportion of villages officially implemented OSB regulations increased from 21.5% in 2008 to 53.7% in 2013. The failure of early OSB regulation was mainly due to two factors. First, there was no timely monitoring of OSB. A significant information asymmetry between regulators and local farmers paralyzed the implementation of the regulation (Cao and Ma, 2023; Wang et al., 2021). Second, farmers have no alternative approaches to reuse the excessive straw due to limited access to straw-utilization infrastructures, which often demands a substantial public investment (Fang et al., 2022; Wang et al., 2017).

To enhance the OSB regulations, the Chinese government has reformed its straw management governance since 2013. Specifically, at the central government, the National Development and Reform Commission [NDRC] reformed its governance strategies from simple prohibiting OSB to the combination of stricter OSB prohibition and sustainable straw reutilization, including straw returning to improve soil organic matters, straw processing to animal feed, and other applications, such as power generation (NDRC, 2013). This policy reform has initiated a series of reforms in the local governments. First, different from the previous OSB policy, the reform of OSB reform was mainly by introducing the satellite-enhanced OSB monitoring system (Wang et al., 2021). Second, in many regions, local government have introduced straw-returning subsidies to encourage farmers to adopt different straw-returning technologies (Wang et al., 2022a). A few early studies examined the effectiveness of reform in controlling OSB. For example, Sun et al. (2019) found that farmers in villages with stricter OSB regulations engaged in lower OSB behavior; While He et al. (2020) shows that subsidies might led to a significant decrease in farmers' OSB behaviors.

However, few studies have analyzed the associated costs and benefits of such reform in straw management. In fact, existing empirical studies were mainly concentrated on investigating the effectiveness of a single policy measure, while neglecting the synergies among different policy instruments. In practice, a policy reform consists of multiple measures which can be introduced simultaneously, and these measures often interact with each other. To curb OSB, the national government implemented the straw management reform in Northeast China in 2017 (Minstry of Agriculture and Rural Affairs (MARA), 2017).[2] The reform mandated an increase in the proportion of straw utilization in Northeast China from 66.6% to 80% by 2020, prompting Heilongjiang to introduce its own straw management reform in 2018 in response. Except the stricter satellite-enhanced monitoring system, Heilongjiang province made an investment of additional 4.3 billion yuan (0.6 billion USD) in promoting straw-utilization subsidies (Heilongjiang Daily (HD), 2019). The reform in Heilongjiang province was a typical case, which enables us to examine the potential interactive effect of different regulatory measures on farmers' straw management behavior.[3]

Taking advantage of the panel data we had collected in Heilongjiang province, therefore, we have two objectives to achieve in this study. First, we want to conduct a detailed documentation of the reform of straw management in Heilongjiang province and a comprehensive cost-benefit analysis of the proposed policy measures. Second, we are motivated to examine the effectiveness of the different policy measures and their

2 The policy was specifically targeting on provinces in the northeast China, including Heilongjiang, Jilin, Liaoning provinces and the east part of Inner Mongolia.
3 Heilongjiang province is one of China's major grain production province, its total grain production has reached 77.6 million tons in 2022, constituting 11.3% of China's total output. Widespread OSB has become its major agri-environmental concern. According to satellite-based data, the incidents of OSB in Heilongjiang comprised 60-70% of China's total OSB in 2016 (The Paper News, 2016).

synergies within the reform on local farmers' OSB and straw returning practices. We combined both qualitative and quantitative approaches to provide empirical evidence. Specifically, to achieve the first objective, we first utilize the analytical frameworks developed by Lemos et al. (2006) to conduct the qualitative review of all collected policy documents to identify the stakeholders and the policy instruments. We then employed the methods from Xing et al. (2022) and Cheng et al. (2022) to calculate emissions of greenhouse gas (GHG) and particulate matter 2.5 (PM2.5) using OSB rates obtained from household surveys. Furthermore, we estimated the social benefits of the OSB reform, specifically focusing on avoiding welfare loss from the reduction in GHG emissions and PM2.5 reduction. To achieve the second objective, we first provide some macro- and micro-level descriptive statistics before and after the introduction of straw management reform, then we use the collected county level data in Heilongjiang for both satellite-based OSB spots in 2016-2019 and two-wave repeated farm surveys during 2018 and 2019 to conduct the empirical regression analysis. Specifically, we used the fixed-effect logit model, which was developed by Pforr (2014).

In short, the results from our study show that, first, the cost-benefit analysis indicates the straw management reform in Heilongjiang province has generated benefits amounting to 6.4 billion yuan (0.9 billion USD), substantially offsetting the public investment of 4.3 billion yuan (0.6 billion USD) in straw-utilization subsidies. This result aligns with Bhattacharyya et al. (2021), who found that decreasing OSB in India can prevent economic and environmental losses amounting to 757 yuan/ha/year (106 dollars/ha/year). Second, our findings challenge previous studies, such as those by Wang et al. (2021) and Sun et al. (2019), that attributed the decrease of OSB in China to strict monitoring exclusively. We show that the reform in Heilongjiang integrates both stricter monitoring measures with subsidies for straw utilization. Moreover, the reduction in straw burning attributed to the reform was primarily driven by the latter measure. Third, the policy interventions did not target farmers exclusively. Instead, the reform engaged a range of stakeholders, ranging from local governments, farmer communities to the straw utilization market actors to motivate actions that create a supportive environment for sustainable straw use by farmers.

2. **Research Design**

2.1 Quantitative data collection

We collected both macro- and micro-level data to analyze the changes in farmers' OSB behavior before and after the reform. At macro levels, we collected satellite-based OSB spots in Heilongjiang from 2015 to 2019. The data for satellite-based OSB numbers is from NASA's website. We used MOD production from TERRA (MOD14A2), which monitors OSB in the daytime (around 10:30 and 13:30 local time). We collect OSB data for four months per year. [4] Given that the grain production cycle in Northeast China typically spans from May to mid-October, OSB for land preparation occurs either around October to November (after harvest) or around next year, March to April (before seeding). These four months constitute one OSB season. We count the daily per county spatially distributed OSB data to sum the actual number of OSB spots per county over a month.

At the micro-level data, we conducted a two waves rural household survey in Heilongjiang in July 2018 (before the reform of straw management) and July 2019 (after the reform). We inquired about farmers' straw utilization practices. Regarding the sampling method, we employed a stratified random sampling approach to select

4 The OSB was mainly observed during March, April these two before farmers sowing the seeds, or around October and November after the autumn harvest.

household farms for the 2018 survey and then traced these selected samples in the 2019 survey (Figure 1). This combination of random sampling and tracing ensures that our survey data accurately reflects the changes in the overall straw-utilization situation in Heilongjiang before (autumn 2017-spring 2018) and after the reform (autumn 2018-spring 2019). Detailed information on the sampling method and statistical characteristics are shown in Supplementary Information (SI).

After obtaining the overall OSB rates in Heilongjiang from our survey data, we processed to calculate the GHG and $PM_{2.5}$ emissions resulting from OSB using the method and emission factors developed by Xing et al. (2022). The calculation involved two steps. First, we quantified the amount of straw burned in Heilongjiang as follows:

$$B_n = D_n \times G_n \times C_n \times H_n \tag{1}$$

where n indicates the crop types (soybean, maize, rice). D_n represents the amount of grain of crop n, collected from the National Bureau of Statistics of China (Table S2). G_n and C_n donate straw-grain and collection ratios of crop n, respectively (Table S3; Xing et al. (2022)). H_n indicates the average OSB rate among farmers, calculated from our two-wave household survey.

Subsequently, we calculated the emissions of GHG and $PM_{2.5}$ from OSB based on the following equation (2):

$$E_i = \sum_n B_n \times R_i \tag{2}$$

where i denotes the emission types (GHG and $PM_{2.5}$). R_i indicates the emission factors of emission i, which are shown in Table S5.

After the calculation of emissions of GHG and $PM_{2.5}$, we further conducted a cost-benefit analysis to assess the social benefits of the reform. The reform's costs, detailed in the following sections, amount to 4.3 billion yuan (0.6 billion dollars) in straw-utilization subsidies. Regarding the benefits of the reform, Cheng et al. (2022)

suggested that the social benefits of environmental policies stem from the reduction in welfare losses due to decreased pollution emissions. Thus, we quantified the reform's benefits as the avoided welfare losses due to GHG and $PM_{2.5}$. We used the following equation (3) to calculate the social benefits:

$$S = \sum_i \Delta E_i \times P_i \tag{3}$$

where ΔE_i denotes the decreased pollution emissions due to reform. which were the difference in emissions of GHG and $PM_{2.5}$ before and after the reform using Equation 2. P_i indicates the price of emissions per unit. The price of GHG is sourced from Cheng et al. (2022), around 40 dollars per CO_2 ton (285 yuan/ton). The price of $PM_{2.5}$ is derived from Cheng et al. (2020) at 0.84 billion yuan/ug.m^3.

[Insert Figure 1 around here]

2.2 Qualitative data collection and analytical framework

To examine how the straw management reform developed policy instruments to address farmer's OSB behavior, our analysis involved a meticulous review and analysis of policy documents related to the reform. This reform encompasses three pivotal documents issued by the Heilongjiang provincial government in September 2018.

(1) "*Harbin Prefecture, Suihua Prefecture, Zhaozhou County, and Zhaoyuan County Three-Year Action Plan for Straw Comprehensive Utilization*," which systematically outlined the reform of policy strategies for prohibiting OSB from 2018 to 2020.[5]

(2) "*Interim Regulations on Rewards and Penalties for the Work of Banning Open-air Straw Burning*," which elucidated the mechanism for penalties and rewards governing the efforts of local governments in implementing the strategies outlined in the first document.

(3) "*Notice on Implementation Opinions of Heilongjiang Province Corn Straw Subsidy for Deep Loosing and Burying and Returning to Field Operations*," which outlined the objects and procedures for receiving subsidies mentioned in

5 The strategies comprise two main components: strategies tailored for key areas (Harbin, Suihua, Zhaozhou County, and Zhaoyuan County) and strategies designed for other prefectures.

the first document.

We adopted the analytical framework developed by Lemos et al. (2006) to review all the documents and identify the governance structures underlying the policy documents. The governance structure is a crucial concept for deconstructing and analyzing policy designs when studying policy strategies for environmental and other related issues. The concept of governance structure can be dissected into two components: first, “structure” refers to a set of reward or penalty rules (institution) coordinating stakeholder actions (North, 2012). Second, “governance” refers to the aim of coordinating these actions and shaping stakeholders’ collective actions in addressing specific social issues (Kooiman, 1993). Therefore, the governance structure is problem-solving oriented. It can be interpreted as a set of rules designed by the local government or related entities, such as enterprises, to coordinate stakeholders to collectively address specific problem (Vatn, 2015, 2018). Based on this definition, the central question of governance structure is that for specific social issues, which stakeholders should be organized, and what rules should be designed to motivate their actions effectively?

Regarding the stakeholders to be organized, Lemos et al. (2006) framework proposes three key stakeholders to achieve effective environmental governance: the state, market, and community (presented in Figure 2). Each social arena offers unique capacities: the state’s authority to act across jurisdictions, the market’s ability to leverage economic incentives, and communities’ capacity to mobilize local knowledge and solidarity. Lemos et al. (2006) argued effective environmental governance requires hybrid forms of collaboration across the dividing lines represented by markets, states, and communities. This collaborative approach seeks to mitigate the weaknesses of individual stakeholders while leveraging their respective strengths. For instance, involving market stakeholders in environmental collaborations typically targets the inefficiencies of state intervention by introducing competitive pressures in the delivery of environmental services. Similarly, integrating community and local perspectives into environmental governance is valued for providing context-specific insights that can help address complex environmental issues and ensure a fairer distribution of benefits from environmental assets. The endorsement from the state can help address legitimacy concerns often associated with market-oriented approaches. Furthermore, state stakeholders facilitate the coordination of fragmented efforts among decentralized communities and market participants, lending coherence and authority to collective actions aimed at environmental stewardship.

Regarding the rules to be designed, we expanded Lemos et al. (2006) framework by incorporating policy instruments designed to motivate stakeholders to act in alignment with policy targets (as shown in Figure 2). In (agri-)environmental governance, policy instruments can be categorized into two types. First, the command-and-control (C&C) measures, which refers to a mandatory administrative directive issued by governments, such as orders, bans, and quotas, that require stakeholders to either undertake or refrain from specific actions. Second, the market-based instruments (MBI), which involves positive or negative economic incentives provided by governments, such as subsidies and taxes, to encourage stakeholders to adopt or refrain from particular behaviors (Blackman et al., 2018; Tang et al., 2020; Xepapadeas, 2011). Williamson (1999) argues that MBI can better motivate stakeholders' capacity to address complex issues due to the incentives they provide. In contrast, C&C can better ensure that stakeholders adhere to policy planning through extensive administrative control. Given the limitations of these two instruments, a hybrid form combining these policy tools may better serve environmental governance by meeting the complex and planned requirements necessary to motivate various stakeholder actions.

To illustrate the structure and the operation of the OSB reform, we adopted and modified the analytical framework developed by Lemos et al. (2006), as shown in Figure 2. We applied such analytical framework to identify the governance structure underlying the three aforementioned policy documents. Specifically, we solicited all relevant documents according to the following steps: (1) identifying the stakeholders mentioned in the documents; (2) categorizing the identified stakeholders into the state, market, and community; and (3) identifying the policy instruments within the documents that either incentivize or penalize stakeholders.

[Insert Figure 2 around here]

3. Result

3.1 Cost and benefits of the straw management reform

<u>(a) Changes in farmers' OSB behavior</u>

The reform led to a significant decrease in farmers' OSB incidents captured by satellite data (as shown in Figure 3). Specifically, during the period spanning Autumn 2015 to Spring 2018 (Figure 3a–c), counties with monthly OSB spot counts exceeding ten, indicated by varying shades of red, predominantly covered extensive areas of Heilongjiang. This trend persisted despite a minor decline prior to the implementation of the reform (Figure 3c). In contrast, post-implementation, only a few counties exhibited OSB spot counts surpassing ten, primarily concentrated in the northwestern region of Heilongjiang (Figure 3d).

[Insert Figure 3 around here]

<u>(b) Shift in farmers' strategies regarding straw disposal</u>

We further used the household data to show the evolving strategies among farmers regarding straw disposal. As shown in Figure 4, farmers' strategies regarding straw disposal moved away from burning straws towards more sustainable utilization (return and bale) after the reform. This transition appears consistent across all farm sizes. Specifically, prior to implementation, OSB 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 hectares (Figure 4a). In contrast, following implementation, only 17% of farmers relied on OSB as their primary method of straw disposal. Notably, unburned straw no longer followed the traditional method of manual collection but instead shifted towards new and sustainable practices, including straw returning and baling (Figure 4b). 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%.

[Insert Figure 4 around here]

<u>(c) Emissions and cost-benefit analysis</u>

After identifying the OSB rates shown in Figure 4, we calculated the emissions of GHG and $PM_{2.5}$ and conducted a cost-benefit analysis, as illustrated in Figure 5. The total emissions from OSB decreased by 3.7 Mt CO_2-eq and 0.4 Mt $PM_{2.5}$-eq (Figure 5a and b) following the reform implementation. Specifically, prior to the reform, the total emissions of GHG and $PM_{2.5}$ from OSB were 6.0 Mt CO_2-eq and 0.6 Mt $PM_{2.5}$-eq. After the reform, these two numbers decreased to 2.3 Mt CO_2-eq and 0.2 Mt $PM_{2.5}$-eq. Maize, in particular, contributed the most to these reductions due to its significantly higher straw production compared to other crops, accounting for 61.2% of the GHG decrease and 62.2% of the $PM_{2.5}$ decrease. More detailed results are presented in Table S4. In terms of cost-benefit analysis, the benefits of the reform substantially exceed its costs (Figure 5c). Specifically, the reform prevented a welfare loss of 6.4 billion yuan (0.9 billion dollars), with $PM_{2.5}$ reductions contributing the most significant share, amounting to over 5.3 billion yuan (0.7 billion dollars). Compared to the 4.3 billion yuan in straw-utilization subsidies, detailed in the following section, the reform generated a 2.1-billion-yuan economic surplus. As a result, the benefits from the reform significantly outweighed its costs, indicating its positive social benefits.

[Insert Figure 5 around here]

3.2 The governance structure of the reform

We visualized the governance structure of the reform using the analytical framework to elucidate the driving forces behind the reductions in farmers' OSB practices (as shown in Figure 6). The governance structure of the reform exhibits three characteristics. First, stakeholders from multiple distinct but related sectors engaged in the reform, including representatives from the state, market, and community sectors. Second, the policy instruments integrating stakeholders' interests operate as a hybrid form, incorporating both C&C and MBI. Third, the community, comprising village communities and cooperatives, acts as the intermediary connections of farmers with both the state and the market.

[Insert Figure 6 around here]

<u>(a) C&C: monitoring through an accountable monitoring system</u>

To implement effective OSB supervision, the reform adopted a strict top-down accountability monitoring system known as the "Chief Responsibility System (CRS)" to enforce the OSB regulation (Figure S6). 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 an OSB 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 OSB 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 OSB 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. Functionally, the provincial government, at the top of the CRS, not only held the mandate to devise the frameworks of incentives and penalties for subordinate government levels but also evaluated their performance. Positioned at a crucial juncture within the CRS, county-level governments were tasked with executing OSB regulations. They bore the responsibility of devising practical strategies to curb OSB, taking into account real-world limitations.

(b) MBI: increase straw-utilization facilities through a subsidy scheme

Although top-down command and supervision can block farmers' OSB, they cannot address the farmers' dilemma in straw utilization. To address the farmers' dilemma in straw utilization, Heilongjiang provided subsidies to attract the participation of the private sector, investing 4.3 billion yuan (0.6 billion dollars) in total for straw utilization (Heilongjiang Daily (HD), 2019). The subsidy was a systematic subsidy scheme rather than a single subsidy item (Figure S7). Specifically, these subsidized schemes consisted of two parts. The first part was to motivate farmers to adopt straw returning. The provincial government provided 600 yuan/ha (84 dollars/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, the government encouraged feed enterprises to expand their breeding scale and upgrade feed technologies to incorporate straw. Furthermore, enterprises utilizing straw as industrial materials could receive a subsidy of 100 yuan/ton (14 dollars/ton). Finally, the provincial government subsidized straw-baling machines by at least 30%, facilitating the collection of straw at the farm level.

(c) Community: where state and market cooperate

Village committees and cooperatives within the farmers' community were designated as the endpoint of the reform, serving as direct links to farmers. Specifically, village committees were tasked with directly monitoring farmers' activities in OSB through physical patrols. As the final level of CRS was established at the village level (Figure S6), the performance of village committees in monitoring was also assessed based on the number of OSB spots detected by satellites. If two spots were detected in a village in a single day, the village committee would face penalties. Moreover, CRS emphasized that the county government should allocate subsidies to support the work of village committees, rewarding their efforts in physical patrols. As for cooperatives, their responsibility was to offer straw-returning and straw-baling machinery services (see Figure S8). The subsidy for straw-returning was directly disbursed to the cooperatives. The subsidy process entailed cooperatives marketing their straw-returning services to farmers and then applying for subsidies according to the service areas covered. Subsequently, the local government assessed the quality of the cooperatives' services and allocated subsidies based on this evaluation. Throughout this process, the village committee was tasked with assisting farmers in negotiating service prices and drafting service contracts with the cooperatives. Furthermore, cooperatives also functioned as brokers in the straw market, providing baling services for farmers and selling the straw to biomass power plants. These baling services were subsidized by the local government in accordance with practical needs.

3.3 The comparison of C&C and MBIs

As discussed above, the straw management reform in Heilongjiang province is a hybrid policy instruments that includes both C&C and MBIs. Both instruments aim to enhance the institutional environment for farmers. For instance, policy instruments in C&C were measured by farmers' perceptions of the intensity of penalties for OSB. It was rated on a scale from 0 to 3, in which 0 indicates perceived no penalties, while 3 indicates a rather heavy penalty. Policy instruments in MBIs were assessed by farmers' perceptions of machinery availability for straw utilization. It was also rated from 0 to 3. We found that farmers have experienced greater improvements in access to straw-utilization machinery following the reform compared to changes in penalties for OSB (as shown in Figure 7). Specifically, farmers' perceptions of penalties increased by approximately one-third, while perceptions of machinery availability nearly doubled relative to the pre-reform. These results suggest that subsidies to straw-utilization machinery (defined as MBIs) have a larger influence on farmers' institutional environment than C&C instruments.

[Insert Figure 7 around here]

Empirically, we compared the effectiveness of these institutional changes (penalty and machine availability) in decreasing OSB. We used the fixed-effect logit model developed by Pforr (2014). The dependent variable of the logit model indicates whether farmers' primary method of straw disposal is OSB, while the key independent variables are farmers' perceptions of penalties and machine availability. We detail the model specification of the logit model in SI and present the results in Figure 8. The color scheme represents the coefficients of the independent variables, indicating their impacts on farmers' engagement in OSB. Notably, the coefficients of levels 1-3 represent the difference in impact on controlling OSB compared to the impact of level 0 (i.e., no penalty or machine availability). Columns (1) and (2) show the estimated results using the whole sample, whereas columns (3) and (4) show the estimated results using the traced sample.

As shown in Figure 8, penalty and machine availability both serve as drivers preventing farmers from OSB; however, machine availability demonstrates a more pronounced impact on controlling OSB. This finding is evident by the coefficients of *penalty* and *machine availability* variables in columns (1) and (3). As shown in column (1), the coefficients of *penalty* and *machine availability* are both negative and significant at a 1% level, while the value of the *penalty*'s coefficient is much smaller than that of *machine availability*'s coefficient. When using the traced sample in column (3) to estimate the logit model, the results remain consistent. Another notable finding from Figure 8 is that the impact of the penalty and machine availability increases as their levels rise. This trend is evident by the coefficients of *penalty* and *machine availability* variables in columns (2) and (4). As depicted in columns (2) and (4), the coefficients of *penalty* and *machine availability* inflate as their levels increase.

Combining the findings from Figures 7 and 8, we observed that MBI has had a greater impact on improving the institutional environment (Figure 7), particularly in terms of machinery availability, compared to the intensity of penalties shaped by C&C. Additionally, this improvement in the environment has demonstrated a more significant influence on controlling OSB (Figure 8). Therefore, we argue that the reduction in OSB shown in Figure 4 is primarily attributable to MBI rather than C&C.

4. Conclusion and Discussion

Summarizing the qualitative and quantitative investigations, we found that the straw management reform in Heilongjiang province significantly decreased farmers' OSB behavior. Specifically, first, our quantitative result indicated that the benefits from the reform significantly outweighed its associated costs, indicating significant positive social benefits (as presented in Figures 4 and 5). Although the reform invested over 4.3 billion yuan (0.6 billion dollars) in straw-utilization subsidies, these subsidies decreased farmers' OSB behavior from 47% to 17% and cut GHG by 3.7 Mt and $PM_{2.5}$ emissions by 0.4 Mt. Bhattacharyya et al. (2021) also reported similar results, finding that decreasing OSB in India can prevent economic and environmental losses amounting to 757 yuan/ha/year (106 dollars/ha/year). These findings underscore the social value of policy intervention in straw and other waste management.

Second, our qualitative analysis showed that the reform employs both C&C and MBIs to address the challenges of OSB, and the synergies among different measures are obvious. Specifically, a satellite-enhanced monitoring system (as a C&C measure) mitigates the information asymmetry between higher and lower levels of government by establishing clear performance indicators, while the over 4.3-billion-yuan public investment in straw-utilization subsidies (as a MBI measure) were allocated to the straw industry and cooperatives has significantly incubated the straw-utilization market, and provided more alternative approaches for farmers to transit into a sustainable straw management.

Third, we found that stakeholders involved in the reform extend beyond a single government sector, encompassing the straw-utilization market and the farmers' community (as shown in Figure 6). The government acts as the initiator and promoter of the reform, while the straw-utilization market is responsible for building the strawcycling chain, and farmers' community, including village committees and cooperatives, serves as intermediaries, connecting farmers with the government and the market. This echoes findings by previous studies on muti-stakeholder collaboration in environmental governance (Abas and Wee, 2014; Bodin, 2017; Innes and Booher, 2003; Perdana et al., 2023), which highlights the extensive collaboration between public and private sectors. Our research builds on these studies and further underscores the intermediary role of farmer communities in linking the public and private sectors.

In developing countries, where farmers are numerous and widely dispersed (Hazell et al., 2010; Poulton et al., 2010), bridging the last-mile gap between farmers, the market, and the government is a common challenge (Minten et al., 2013; Wang et al., 2022b). Our study shows that the participation of rural communities in agri-environmental governance is essential, and it can be achieved by leveraging the existing social networks and local knowledge among farmers with low transaction costs. Moreover, our study indicates that to promote a sustainable agri-environmental governance, policymakers need more hybrid policy instruments, which consist of both C&C and MBIs measures to motivate different stakeholders to collaboratively create a supportive environment for farmers. Achieving a sustainable straw utilization will not only benefit rural China but also many other developing countries facing similar challenges about agricultural waste.

Figures

Figure 1. Sampled counties in Heilongjiang province in 2018 and 2019

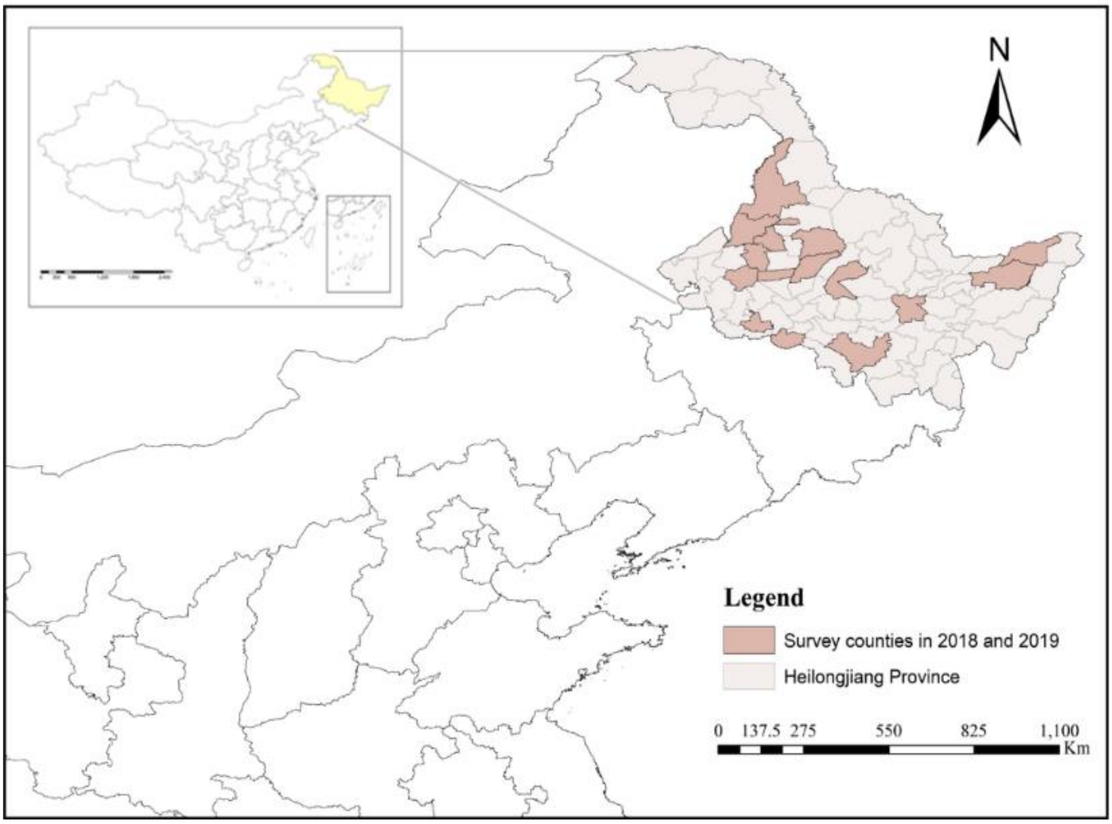
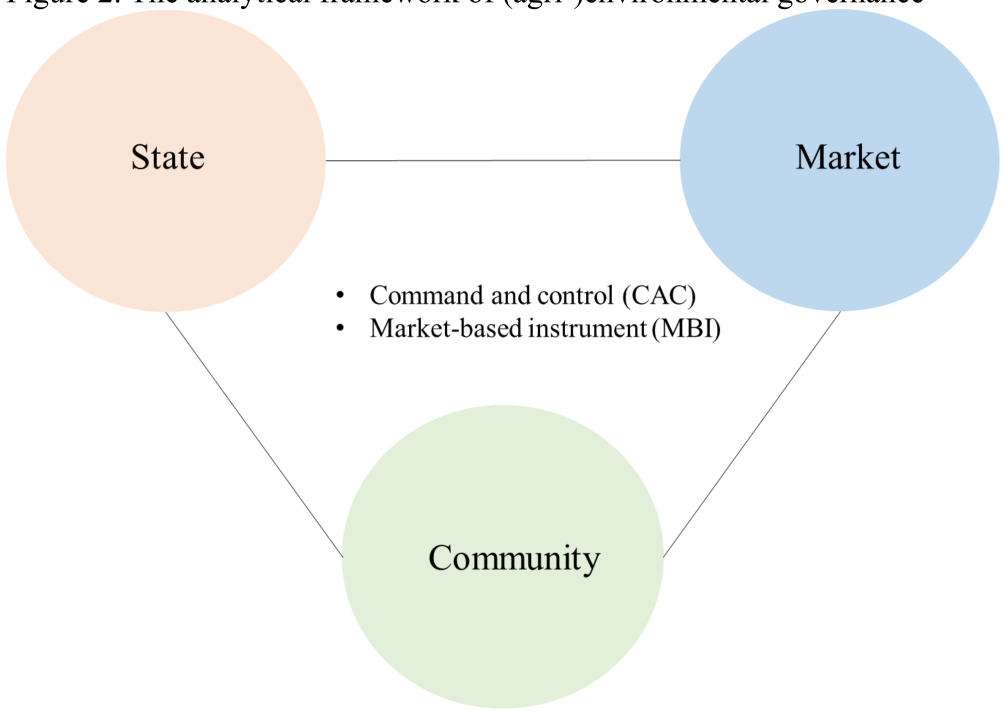
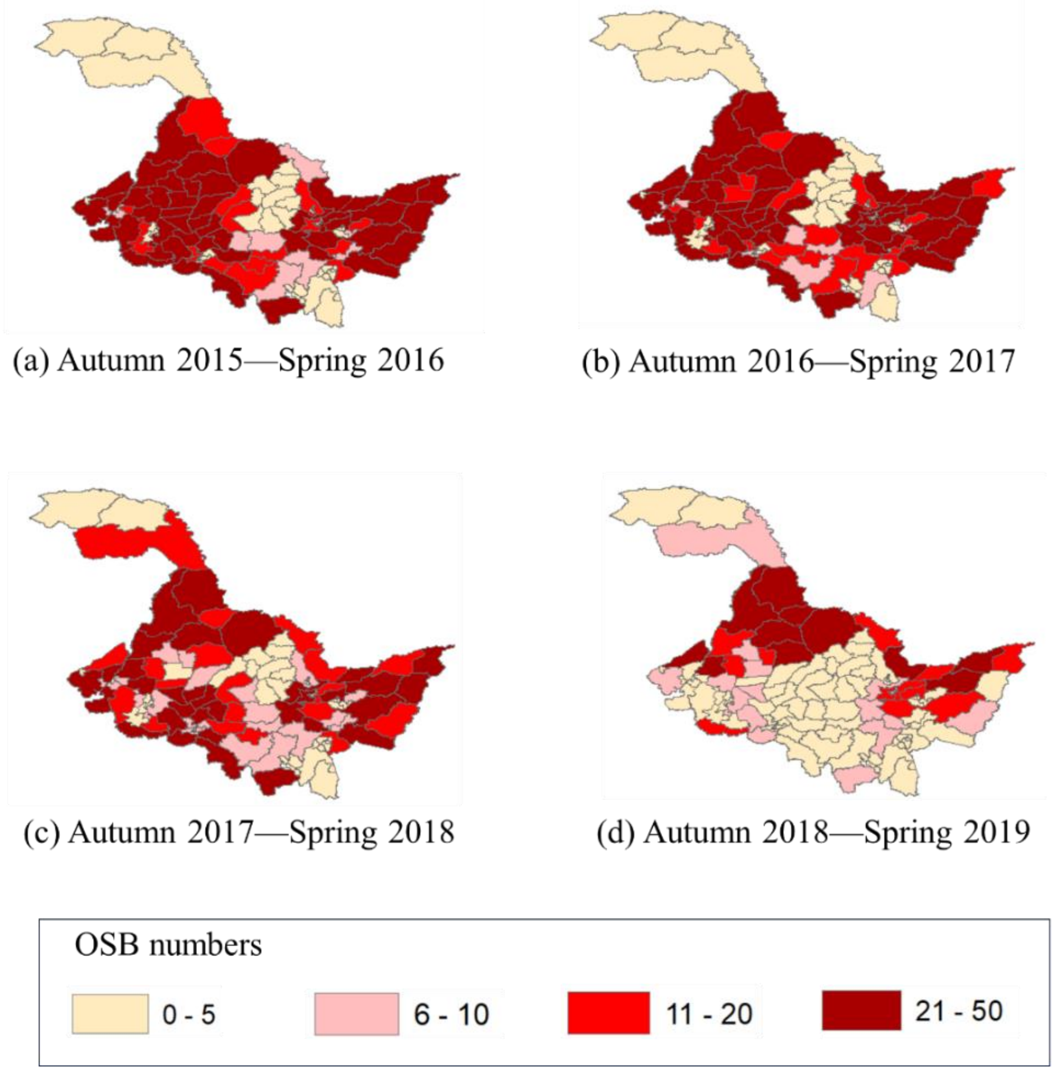


Figure 2. The analytical framework of (agri-)environmental governance



Note: The analytical framework was developed by Lemos et al. (2006) to reflect the potential interplay among the state (government or related public sector), the market (the private sectors), and the community (the rural village, the collectives).

Figure 3. Spatial and temporal changes in OSB spots in Heilongjiang



(a) Autumn 2015—Spring 2016

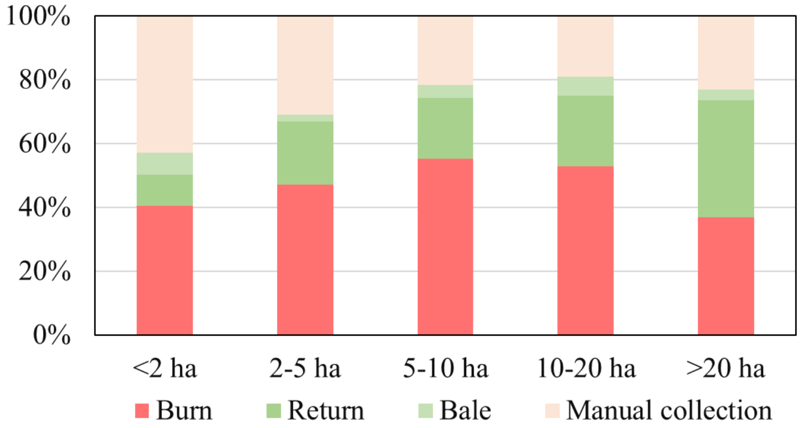
(b) Autumn 2016—Spring 2017

(c) Autumn 2017—Spring 2018

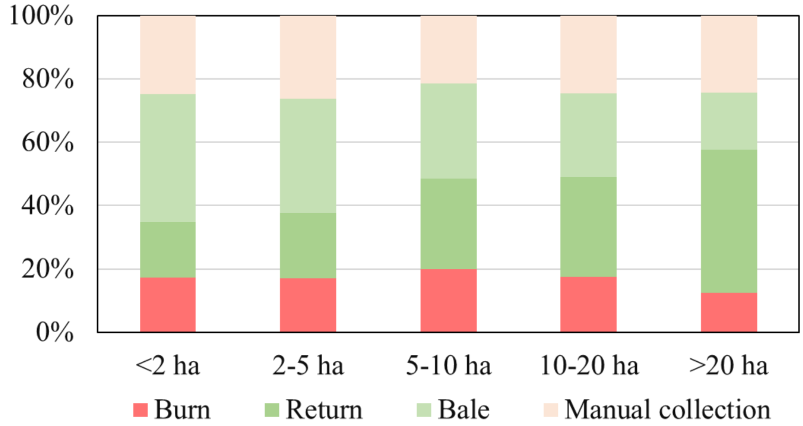
(d) Autumn 2018—Spring 2019

Note: (a) Data is sourced from NASA's website. (b) The red depth indicates the monthly average of open-air straw-burning (OSB) spots within the county. (c) Figure 3a-c reports the OSB spots before the implementation of open-air straw-burning management (OSBM), while Figure 3d reports the OSB spots after the reform.

Figure 4. Temporal changes in farmers' strategies regarding straw disposal



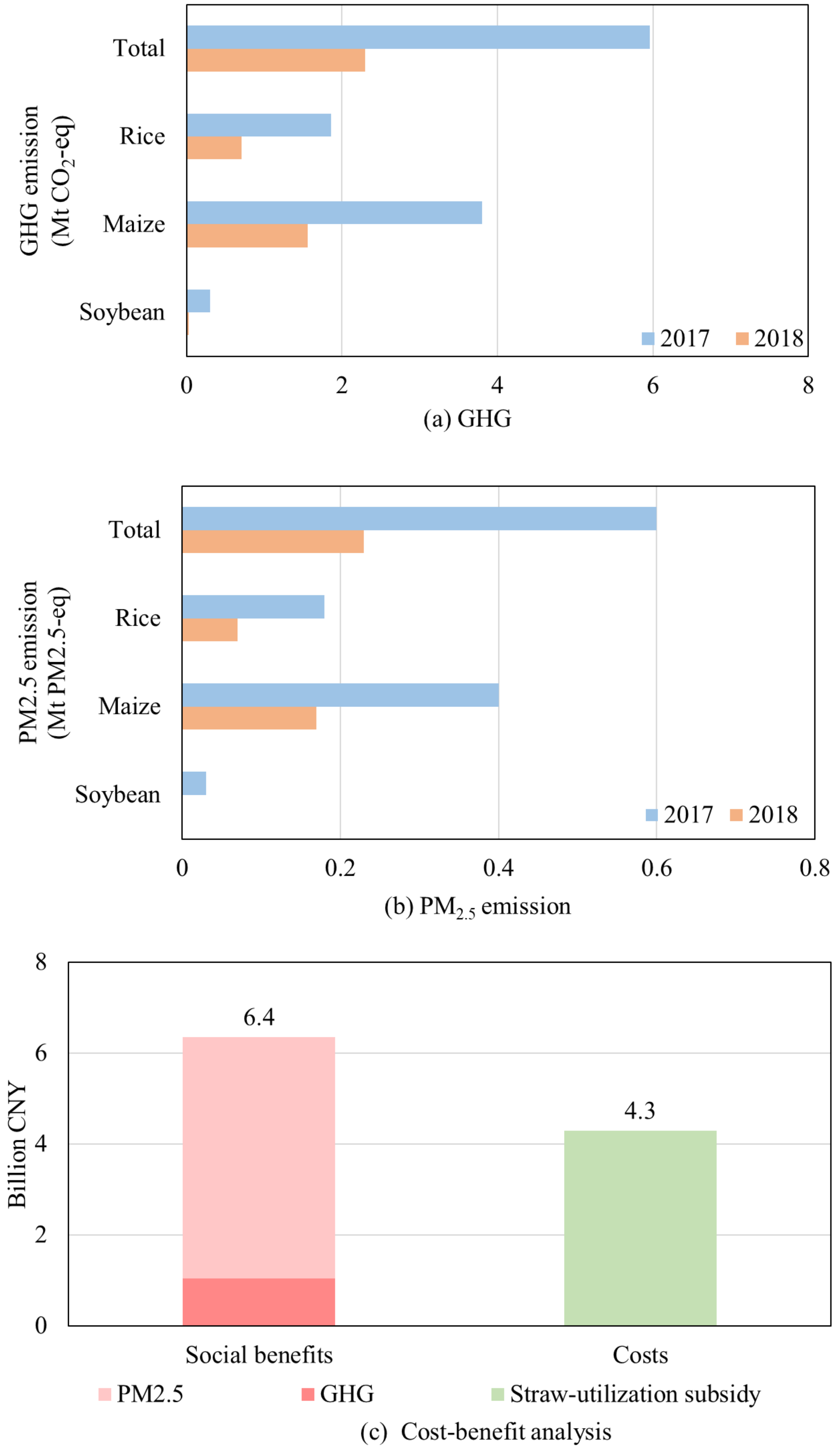
(a) Autumn 2017—Spring 2018



(b) Autumn 2018—Spring 2019

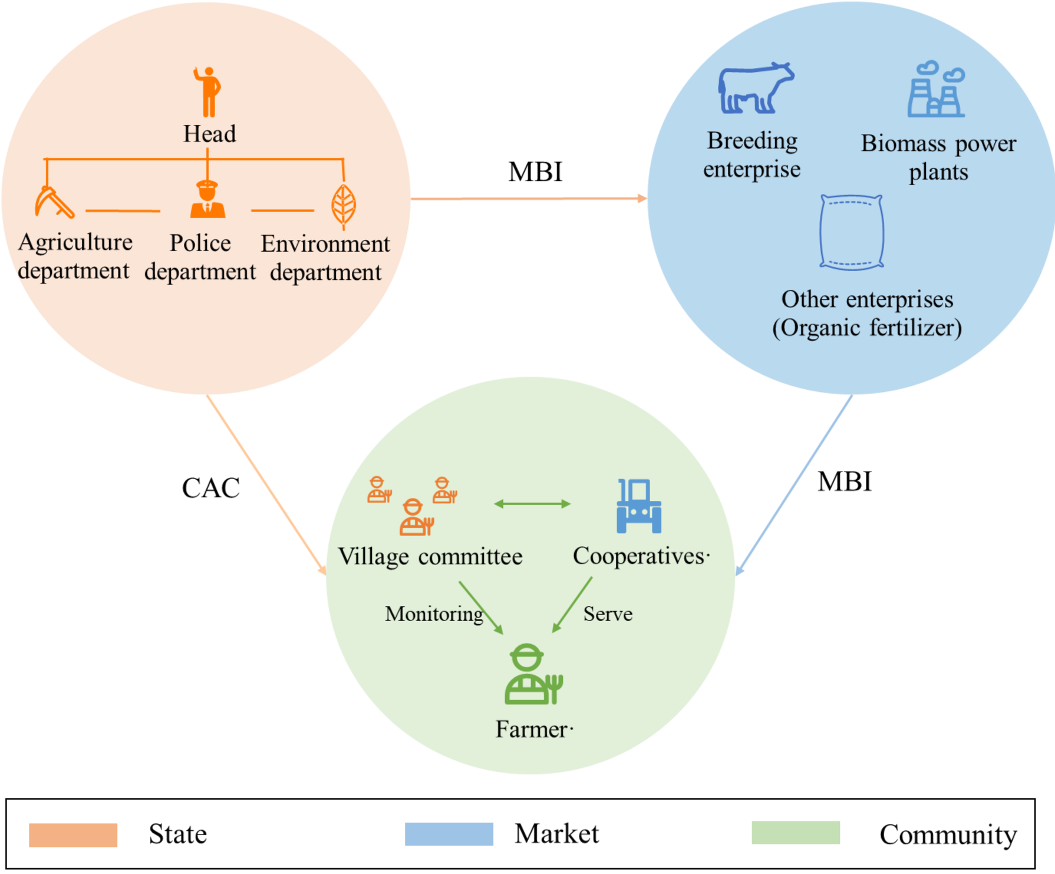
Note: (a) Data is sourced from the pooled dataset from two waves of household surveys.
(b) Farmers' strategies regarding straw disposal are measured by the question, 'What is your main approach to disposing of straws?'.
(c) Figure 4a reports the farmers' straw disposal methods before the implementation of open-air straw-burning management (OSBM), while Figure 4b reports these methods after the reform.
(d) Observations within farm-size groups are illustrated in Figure S4.
(e) The robustness check using a traced sample is presented in Figure S5.

Figure 5. The associated cost-benefit analysis of the straw management reform



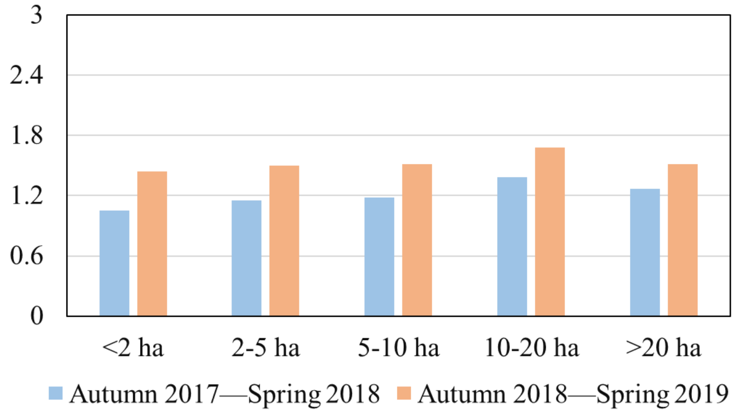
Note: (a) GHG: greenhouse gas; $PM_{2.5}$: Particulate matter 2.5 (b) The years 2017 and 2018 correspond to the open-air straw-burning (OSB) seasons before (Autumn 2017-Spring 2018) and after (Autumn 2018-Spring 2019) the open-air straw-burning (OSBM) reform, respectively. (c) More details are shown in Tables S4 and S6.

Figure 6. The governance structure of the straw management reform

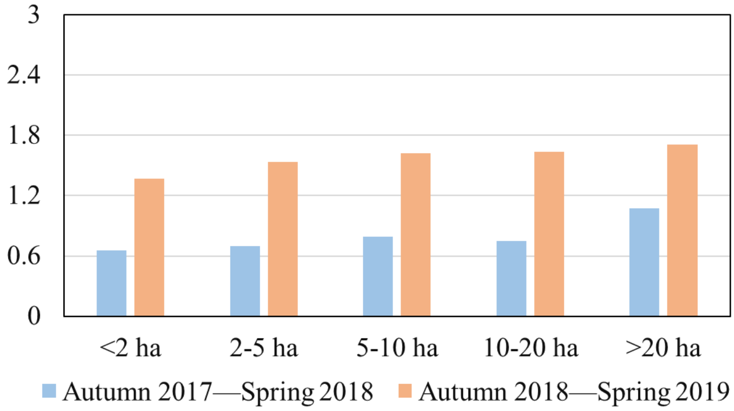


Note: (a) This governance structure was developed by the authors based on the analytical framework in Figure 2. (b) CAC: command-and-control, MBI: market-based instrument. (c) OSBM: open-air straw-burning management.

Figure 7. Temporal changes in the institutional environment



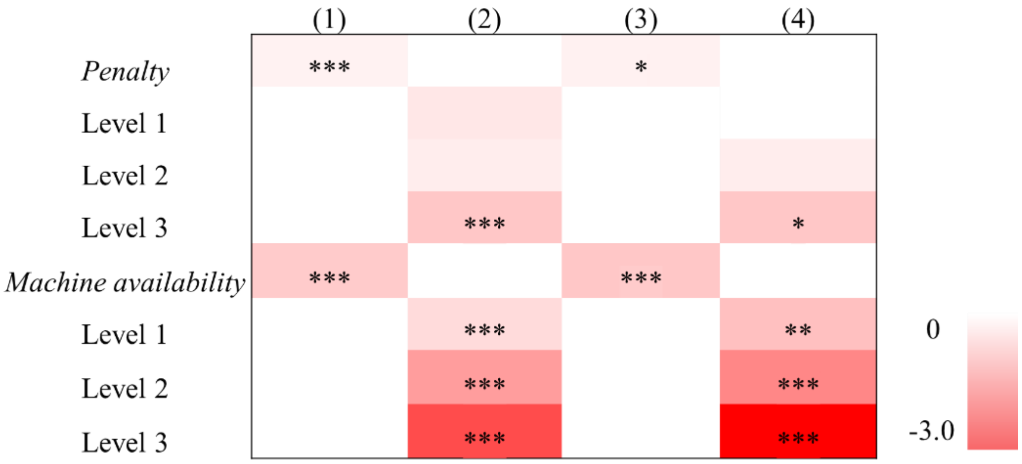
(a) Penalty perception index



(b) Machine availability perception index

Note: (a) Data is sourced from the pooled dataset from two waves of household surveys.

Figure 8. Effect of institutional environmental on farmers' engagement in OSB



Note: (a) Columns (1) and (2) display the estimated results using the entire sample, whereas columns (3) and (4) show the estimated results using the traced sample. (b) The dependent variable is whether farmers' primary method of straw disposal is OSB. (c) The control variables and specific coefficients of variables are shown in Table S7. (d) The color scheme represents the coefficients of the independent variables, indicating their impact on farmers' engagement in OSB. (d) Standard errors are clustered at the village level. (e) *, **, *** indicate statistically significant at the 10%, 5%, and 1% levels, respectively.

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