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# From Agri-Waste to Sustainable Use: A Case Study of Straw Management Reform in Northeast China

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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 $CO_2$ and $PM_{2.5}$ emissions from the agricultural sector. Since 2013, China has reformed its agri-waste governance to promote sustainable use of straws. However, few studies have analyzed the structural change and field operation of its agri-waste policies, and limited evidence has been drawn on the effectiveness of these policies. The objective of our article is to investigate the reform of China's straw governance and examine the effectiveness of such reform with a specific focus on farmers in the Northeast China. We used both qualitative and quantitative approaches to investigate how China's straw governance reform was designed and implemented, and how effectiveness of such reforms in addressing the field straw-burning issue in Northeast China. Field observation shows that the reforms were designed and implemented with two hybrid policy instruments: (a) 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) a market-based instruments (MBIs) that provide subsidies to the industries and cooperatives for sustainable straw use. The empirical results show that reform significantly decreased farmers' straw burning behavior and increased their straw field returning and straw bailing for power generation.

## 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. 2021, 2022). Maximizing the use of agricultural waste can enhance food security, mitigate environmental degradation, and boost economic benefits (Sharma et al. 2019; Muscolo et al. 2021). 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 (Theesfeld and Jelinek 2017; Bhattacharyya et al. 2020; Lin and Begho 2022). For example, both China and India are the world's largest producers of straw, yet more than 20% of these straws were burned in open air (Jain, Bhatia, and Pathak 2014; Fang, Wu, and Xie 2019). This open-air straw burning (OSB) not only neglects the potential benefits of straw reutilization but also contributes a substantial share of air pollution and carbon emissions (He, Liu, and Zhou 2020; Guo 2021; Lai et al. 2022).

Several developing countries, including China, introduced national regulations on controlling OSB (Theesfeld and

Jelinek 2017; Bhuvaneshwari, Hettiarachchi, and Meegoda 2019; Huang et al. 2021). 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; 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 reported OSB regulations implementation 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 (Wang, Wang, and Yin 2021; Cao and Ma 2023). 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 (Wang, Tang, and Wang 2017; Fang, Shi, and Xie 2022).

To enhance the OSB regulations, the Chinese government has reformed its straw management governance since 2013. At the central government, the National Development and Reform Commission reformed its governance strategies from simply prohibiting OSB to the combination of stricter OSB prohibition and sustainable straw reutilization, including straw field returning to improve soil organic matters, straw processing to animal feed, and other applications, such as power generation (National Development and Reform Commission (NDRC) 2013).[2] This policy reform initiated a series of reforms in the local governments. First, different from the previous OSB policy, the reform was mainly by introducing the satellite-enhanced OSB monitoring system (Wang, Wang, and Yin 2021). Second, in many regions, local governments have introduced straw-returning subsidies to encourage farmers to adopt different straw-returning technologies (Wang et al. 2022). A few studies examined the effectiveness of such reform in controlling OSB. However, existing empirical studies were mainly concentrated on investigating the effectiveness of a single policy measure, while neglecting the synergies among different policy instruments. For instance, Sun, Ge, and Zhou (2019) found that farmers in villages with stricter OSB regulations engaged in lower OSB behavior, whereas He, Liu, and Zhou (2020) argued that the significant decrease in farmers' OSB behaviors could be due to introduced subsidies.

Moreover, almost no studies have analyzed the associated costs and benefits of such reform in straw management. In fact, in practice, a policy reform often consists of multiple measures that can be introduced simultaneously, and these measures often interact with each other. The reform in Heilongjiang province in 2018 is a representative case of such complexity. As China's largest grain-producing province, Heilongjiang accounted for 11.3% of the nation's total grain output in 2022. However, widespread OSB resulting from grain production has emerged as a major agri-environmental concern. Satellite data showed that in 2016, OSB incidents in Heilongjiang comprised 60%–70% of China's total OSB (The Paper News 2016).[3] To curb OSB, the national government implemented the straw management reform in Northeast China in 2017 (Minstry of Agriculture and Rural Affairs [MARA] 2017).[4] 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 for the stricter satellite-enhanced monitoring system, Heilongjiang province made an investment of an additional 4.3 billion yuan (0.6 billion dollars) in promoting straw-utilization subsidies (Heilongjiang Daily [HD] 2019).[5]

Taking advantage of the well-timed panel data that we collected in Heilongjiang, we have two objectives to achieve in this study. First, we want to conduct a detailed documentation of the reform of straw governance in Heilongjiang province and a comprehensive cost–benefit analysis of the proposed policy measures. Second, we are motivated to examine the effectiveness of such hybrid policy measures and their synergies 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 utilize the analytical frameworks developed by Lemos et al. (2006) to conduct a qualitative review of all collected policy documents to identify the stakeholders and the policy instruments. We then used the methods from Xing et al. (2022) and Cheng et al. (2022) to calculate emissions of greenhouse gas (GHG) and particulate matter 2.5 ($PM_{2.5}$) 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 $PM_{2.5}$ reduction. To achieve the second objective, we show both macro- and micro-level descriptive statistics before and after the reform, then we use the 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 analysis. Specifically, we used the fixed-effect logit model, which was developed by Pforr (2014).

Briefly, the results show that the cost–benefit analysis indicates the straw management reform in Heilongjiang province has generated benefits amounting to 6.4 billion yuan (0.9 billion dollars), substantially offsetting the public investment of 4.3 billion yuan (0.6 billion dollars) 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 107 dollars/ha/year. Moreover, our findings challenge previous studies that attributed the decrease of OSB in China to strict monitoring exclusively (Wang, Wang, and Yin 2021; Sun, Ge, and Zhou 2019). We show that the reform in Heilongjiang integrates both stricter monitoring measures with subsidies for straw utilization. The reduction in straw burning attributed to the reform was primarily driven by the latter measure. In addition, the policy interventions did not target farmers exclusively. Instead, the reform engaged a range of stakeholders, ranging from local governments, and farmer communities to the straw utilization market actors to motivate actions that create a supportive environment for sustainable straw use by farmers.

Our study contributes to the existing literature in the following aspects. First, by integrating both qualitative and quantitative analyses, we provide comprehensive documentation and clarification of the design and impacts of China's straw governance

reforms. Our approach contrasts with previous studies that focused on a single dimension, allowing for a more holistic examination of the OSB policy. Second, unlike prior research, which has largely emphasized the policy's effectiveness, our study includes a cost–benefit analysis, offering valuable insights into the efficiency and economic feasibility of such reforms. This adds a practical dimension to policy evaluation, which was often overlooked in environmental-related studies. Finally, the combination of satellite data and household survey data addresses the inherent limitations of each approach. The micro-level household data, which is susceptible to its potential self-reporting bias, could be further validated through comparison with satellite data, whereas the satellite data, which might lack detailed behavioral information, can be further enhanced by the household surveys. This triangulated approach strengthens the quality of our empirical analysis.

## 2 | Research Design

### 2.1 | Quantitative Data Collection and Cost–Benefit Analysis

#### 2.1.1 | (a) Data Collection

We collected both macro- and micro-level data to analyze the changes in farmers' OSB behavior before and after the reform. At the macro-level, we collected satellite-based OSB spots in Heilongjiang from 2015 to 2019. The data for satellite-based OSB numbers are from NASA's website. We used MOD production from TERRA (MOD14A2), which monitors OSB during the daytime (~10:30 and 13:30 local time). We collect OSB data for four months per year.[6] 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 March to April of the following year (before seeding). These four months (both before seeding and after harvest) 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 two waves of rural households' surveys in Heilongjiang in July 2018 (before the reform of straw management) and July 2019 (after the reform), respectively. In 2018, 15 counties were selected, covering all temperature zones in Heilongjiang (Figure 1). We randomly chose three townships in every selected county and three villages per township. In terms of the farmer selection, we randomly selected ten households per village. In 2019, we traced 15 counties and randomly traced two out of three townships.[7] The selection methods of villages and farmers were the same as in 2018. Following the exclusion of invalid data, our dataset comprises 2116 observations, of which 1305 observations from the 2018 survey and 811 observations from the 2019 survey. Among the traced households, we have 475 households surveyed both in 2018 and 2019, resulting in a total of 950 observations. Further details on the statistical characteristics of both the entire sample and the traced sample are found in Table S1 in Supplimentary Information (SI). The combination of random sampling and tracing ensures that our survey data accurately

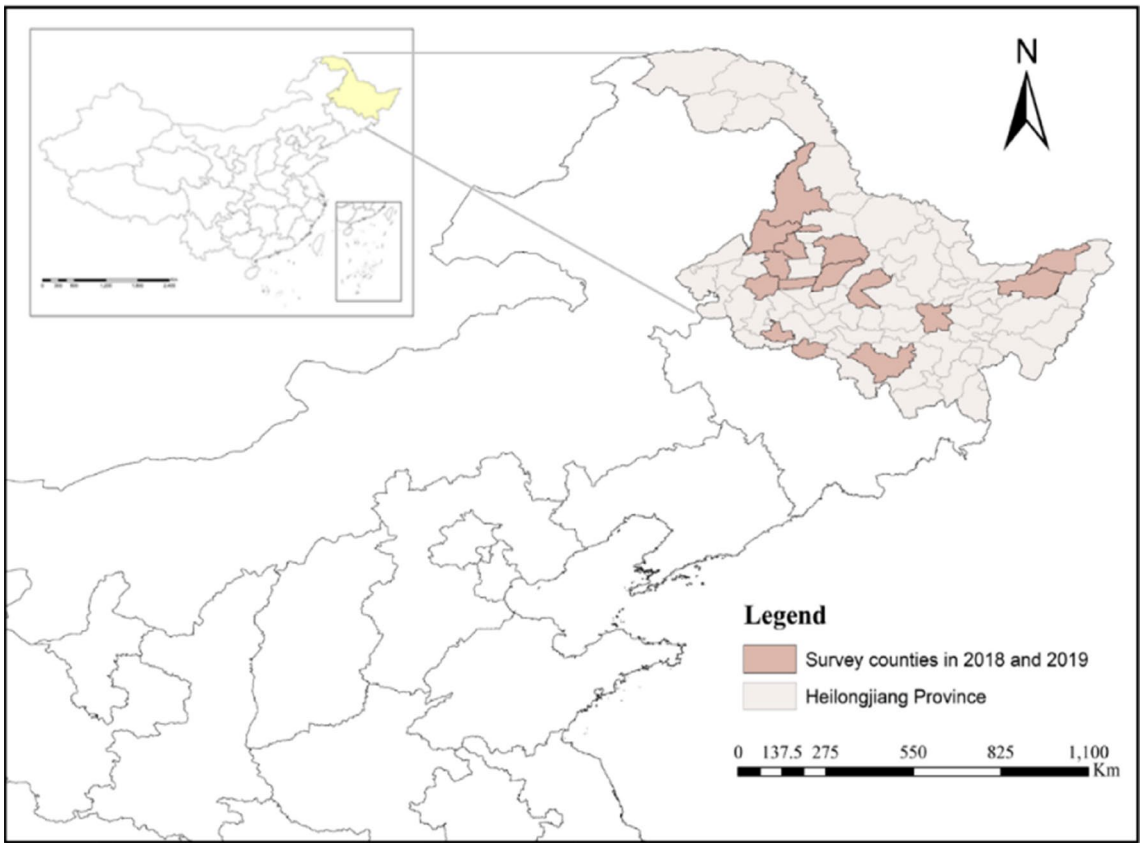


**FIGURE 1** | Sampled counties in Heilongjiang province in 2018 and 2019.

reflects the changes in the overall straw-utilization situation in Heilongjiang before (autumn 2017–spring 2018) and after the straw governance reform (autumn 2018–spring 2019).

The farmer survey was administrated with three blocks of information. First, we quantified rural farmers' OSB practices using a targeted question in both survey rounds: What is the primary method you use to dispose of straw for each plot? (1 = OSB; 2 = straw returning; 3 = straw baling; 4 = manual collection). Second, we included two intermediate variables to evaluate farmers' perceptions regarding penalties (C&C measure) and machinery availability for straw returning and baling (MBI measure). Specifically, we ask How do you feel about the penalties if you burn the straws? Farmers' perception of penalties ("Penalty") was categorized into four levels: (0 = no, 1 = light, 2 = neutral, 3 = strong). Their perception of machinery availability was measured by asking How do you feel about the machinery (including both for straw-returning and for straw bailing) availability to deal with excessive straws? Their responses were categorized into three levels: (0 = no access to machinery; 1 = access to one machine; 2 = access to both machines; 3 = access to both machines with sufficient supply). Lastly, we collected data on various farmer characteristics, such as family size, household head's age, farm size, crop types, and other additional factors (see Table S1 in SI).

#### 2.1.2 | (b) Cost–Benefit Analysis

To conduct the cost–benefit analysis, we first identify the associated costs of the reformed policies. In this study, we focused straightforwardly on its direct financial public investments. For example, Baade and Matheson (2016) conducted a cost–benefit analysis of the Olympics, using investments in sports and general infrastructure reported by the International Olympic Committee to assess host costs. Similarly, for the straw governance reform in Heilongjiang, the provincial government reported an investment of 4.3 billion CNY (0.6 billion USD) in straw-utilization subsidies to support straw utilization during the project's first OSB season from Autumn 2018 to Spring 2019 (Heilongjiang Daily [HD] 2019). Therefore, we use the 4.3 billion CNY (0.6 billion USD) investment as the cost for the initial year of the reform.

On the benefits side, Cheng et al. (2022) suggested that the benefits of environmental policies stem from the reduction in welfare losses due to decreased pollution emissions. Adopting this perspective, the benefits of the reform were primarily measured by the reduction in welfare losses resulting from decreased pollution. In terms of type of pollution emissions, Xing et al. (2022) calculated the pollution emissions from OSB with a focus on GHG and $PM_{2.5}$. In our study, we adopt the same strategy with the focus on the reductions in GHG and $PM_{2.5}$ emissions. The calculation of the reform's benefits involves three steps.

First, we quantified the amount of straw burned in Heilongjiang as follows:

$$B_n = D_n \times G_n \times C_n \times H_n \quad (1)$$

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 in SI). $G_n$ and $C_n$ donate straw-grain and collection ratios of crop $n$ (Table S3 in SI; Xing et al. 2022). $H_n$ indicates the average OSB rate for crop $n$, a critical parameter in Equation (1). This value is derived from the farmer survey question, What is the primary method you use to dispose of straw for each plot? (1 = OSB; 2 = straw returning; 3 = straw baling; 4 = manual collection). After collecting the responses, we calculated the average OSB rate among the surveyed farmers for each specific crop. Given the nature of our random sampling, this figure can be highly representative of the overall OSB rate for crop $n$ in the region of Heilongjiang.

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

$$E_i = \sum_n B_n \times R_i \quad (2)$$

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 in SI. Once we have a clear calculation of emissions of GHG and $PM_{2.5}$, we used the following equation to calculate the benefit of the reform:

$$S = \sum_i \Delta E_i \times P_i \quad (3)$$

where $\Delta E_i$ 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 $m^3$. Details concerning the calculation are presented in Table S6 in SI.

### 2.2 | Qualitative Data Collection and Analytical Framework

#### 2.2.1 | Qualitative Data Collection

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

1. Harbin Prefecture, Suihua Prefecture, Zhaozhou County, and Zhaoyuan County Three-Year Action Plan for Straw Comprehensive Utilization.[8] It systematically outlined the reform of policy strategies for prohibiting OSB from 2018 to 2020. The strategies comprise two main components: strategies tailored for key areas (Harbin, Suihua, Zhaozhou County, and Zhaoyuan County) and strategies designed for other prefectures.

2. Interim Regulations on Rewards and Penalties for the Work of Banning Open-air Straw Burning.[9] It 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.[10] It outlined the objects and procedures for receiving subsidies mentioned in the first document.

### 2.2.2 | Analytical Framework

After we collected related government documents, we adopted the analytical framework developed by Lemos et al. (2006) to review all these 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 primary components: first, the "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). The governance structure is designed with a clear problem-solving orientation. It can be interpreted as a set of rules designed by the local government or related entities, such as cooperatives and/or 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 contacted and 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 (different administrative levels of government), the market (primarily machinery markets), and the 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 that effective environmental governance requires hybrid forms of collaboration across the dividing lines represented by different actors. 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, the state facilitates the coordination of fragmented efforts among decentralized communities and market participants, lending coherence and authority to collective actions aimed at environmental stewardship.

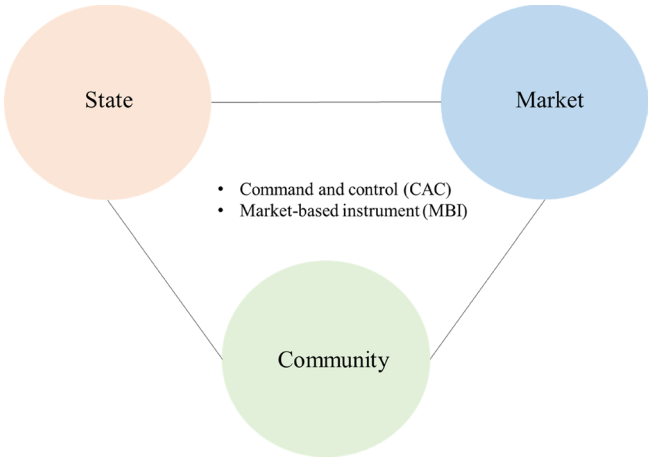


**FIGURE 2** | The analytical framework of (agri-) environmental governance. The analytical framework was developed by Lemos et al. (2006) to reflect the potential interplay among the state (government or related public sector), the market (the private sectors), and the community (the rural village, the collectives).

Regarding the rules (specific instruments or measures) 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 refer 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 involve positive or negative economic incentives provided by governments, such as subsidies and taxes, to encourage stakeholders to adopt or refrain from particular behaviors (Xepapadeas 2011; Blackman et al. 2018; Tang et al. 2020). 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 operation of the OSB reform, we adopted and modified this analytical framework. We 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, the market, and the community; and (3) identifying the policy instruments within the documents that either incentivize or penalize stakeholders.

## 2.3 | Hypothesis on This Study

Based on the modified analytical framework, the power distribution and the limitation of each actor, we propose the following hypothesis:

**Hypothesis 1.** Hypothesis on farmer's behavioral change on OSB: *The reform in Heilongjiang can significantly reduce OSB rates among farmers, as measured by satellite data and household survey responses.*

**Hypothesis 2.** Hypothesis on cost–benefit balance: *The environmental benefits of reduced GHG and $PM_{2.5}$ emissions from the reform outweigh the initial costs of straw-utilization subsidies invested by the Heilongjiang government.*

**Hypothesis 3.** Hypothesis on hybrid governance structure: *The reform utilized a hybrid governance structure, integrating C&C and MBI approaches, to encourage the participation of the state, the market agents, and the community stakeholders in OSB governance.*

**Hypothesis 4.** Hypothesis on perception and compliance: *Farmers' perceptions of penalties for OSB (C&C) and the machine for alternative straw utilization (MBI) positively influenced their decision to adopt alternative straw disposal practices, reducing OSB prevalence.*

# 3 | Result

## 3.1 | Costs and Benefits of the Straw Governance Reform

### 3.1.1 | Changes in Farmers' OSB Behavior

The descriptive statistics from the satellite data show that the reform led to a significant decrease in farmers' OSB incidents (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).[11]

### 3.1.2 | Shift in Farmers' Strategies Regarding Straw Disposal

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 (burn) toward more sustainable

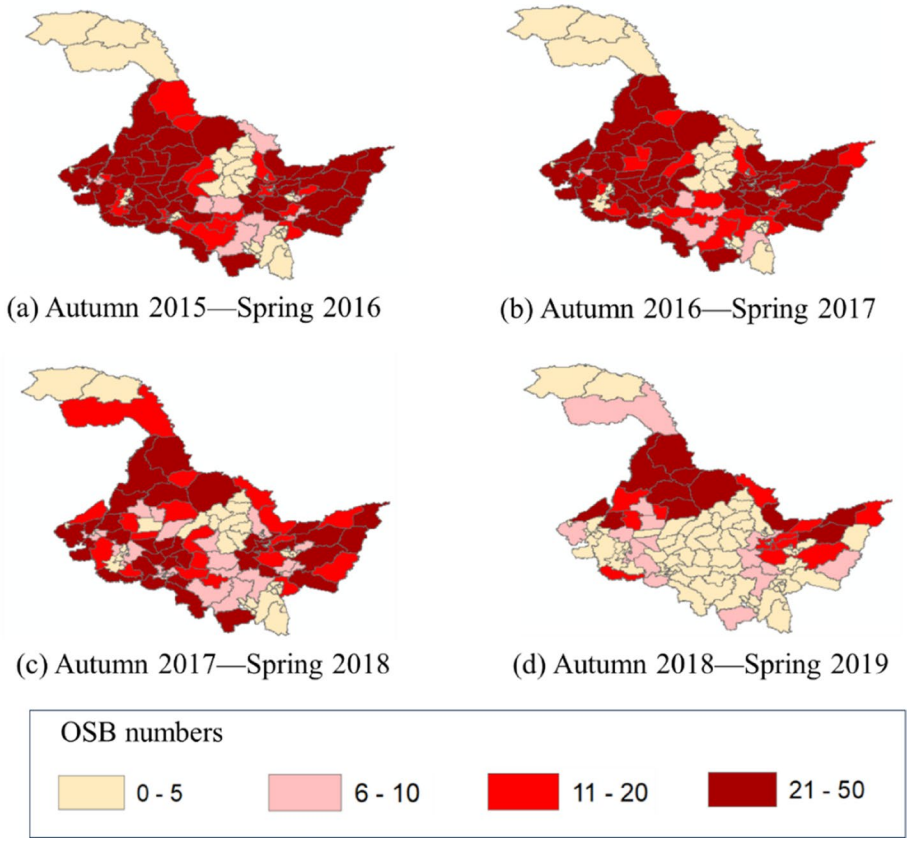


**FIGURE 3** | Spatial and temporal changes in OSB spots in Heilongjiang. (1) Data is sourced from NASA's website. (2) The red depth indicates the monthly average of open-air straw-burning (OSB) spots within the county. (3) Figure a–c reports the OSB spots before the implementation of open-air straw-burning management (OSBM), while Figure (d) reports the OSB spots after the reform.

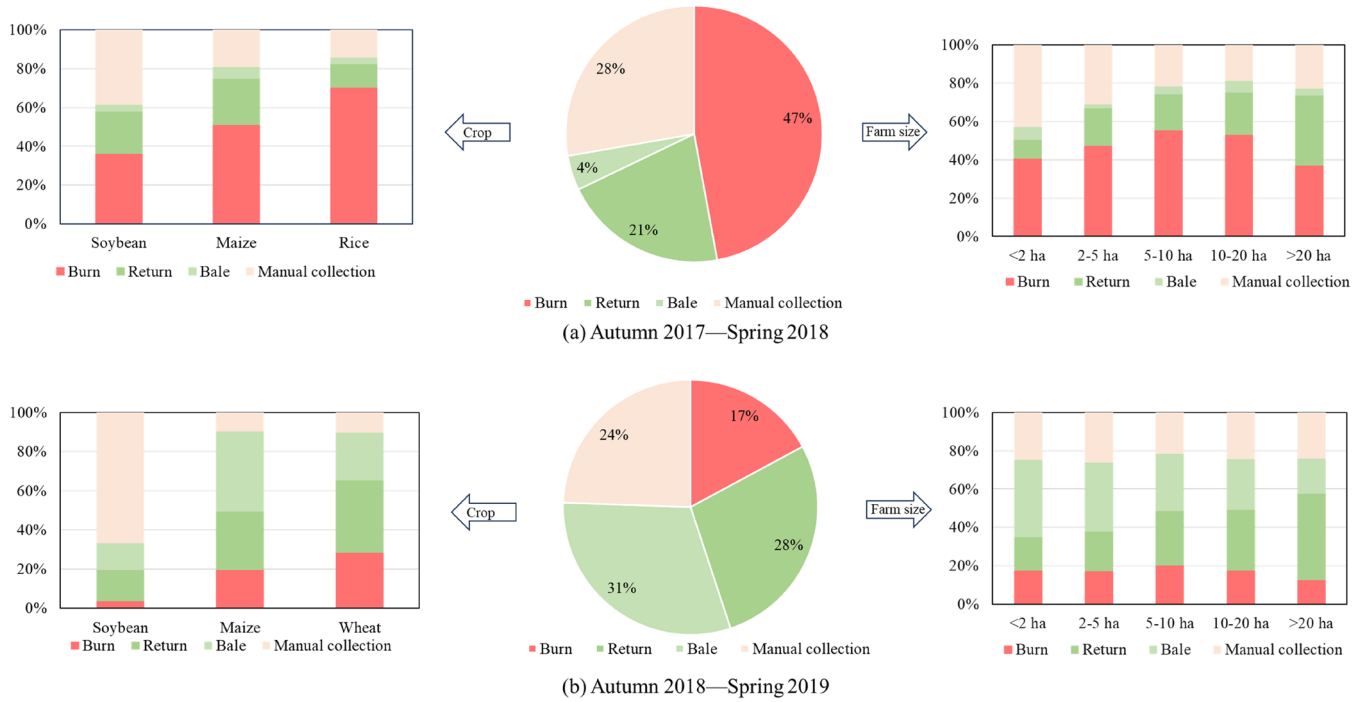


**FIGURE 4** | Temporal changes in farmers' strategies regarding straw disposal. (1) Data is sourced from the pooled dataset from two waves of household surveys. (2) Farmers' strategies regarding straw disposal are measured by the question, What is your main approach to disposing of straws? (3) Figure (a) reports the farmers' straw disposal methods before the implementation of open-air straw-burning management (OSBM), while (b) reports these methods after the project.

utilization (return and bale) following the implementation of the OSBM project. This transition appears consistent across all farm sizes.[12] 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 and 10 ha (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 using these two sustainable methods comprised about 25% of the total (Figure 4a), but post-implementation, this figure increased to about 60% (Figure 4b). To verify this trend, we conducted a robustness check using the traced sample in Figure S5 in SI, which confirmed a similar pattern.

For crops such as maize and rice, farmers predominantly adopted two sustainable methods for straw disposal following the implementation of the OSBM project (Figure 4b). Notably, 71% of maize farmers utilized these methods as their primary disposal approach. In contrast, although soybean farmers also reduced the rate of OBS from 36% to 3%, they primarily collected straw by hand and used it as household energy. Prior to the OSBM project, OSB was most prevalent among rice farmers, with 70% using it as their primary method of straw disposal (Figure 4a). After the project's implementation, only 28% of rice farmers continued to use OSB as their main method (Figure 4b). Although this percentage remains higher compared to maize and soybean farmers, it represents a significant improvement from previous levels.

### 3.1.3 | Emissions and Cost–Benefit Analysis

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,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 SI. 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.

## 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.

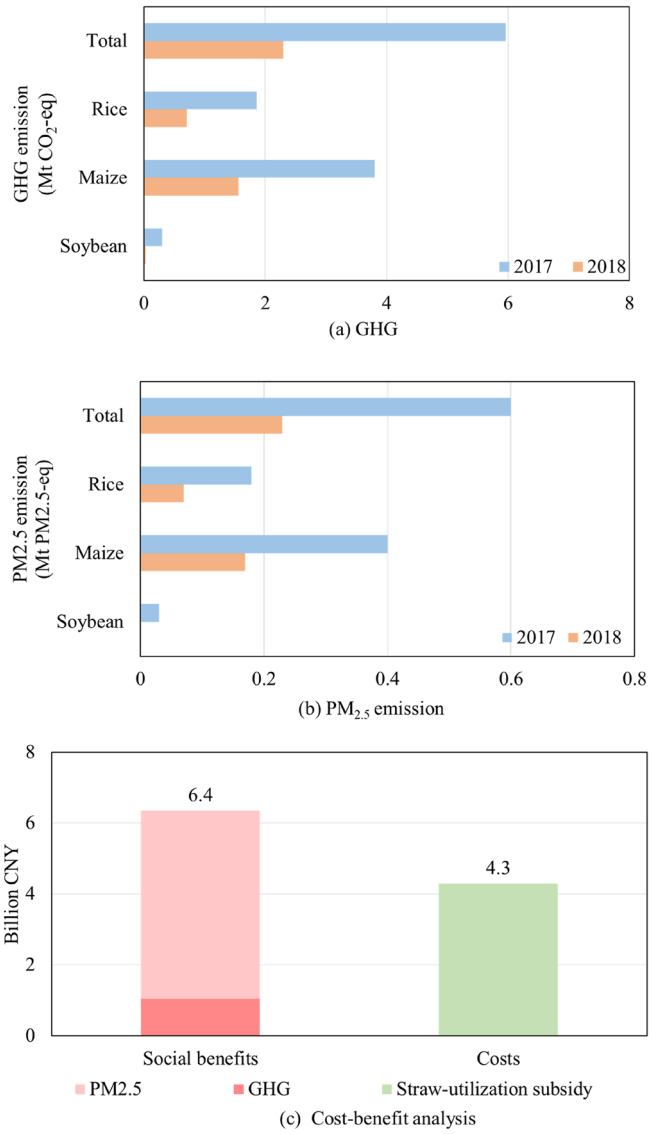


**FIGURE 5** | The associated cost–benefit analysis of the straw management reform. (1) GHG: greenhouse gas; $PM_{2.5}$: Particulate matter 2.5 (2) The years 2017 and 2018 correspond to the open-air straw-burning (OSB) seasons before (Autumn 2017–Spring 2018) and after (Autumn 2018–Spring 2019) the open-air straw-burning management (OSBM) reform, respectively. (3) More details are shown in Tables S4–S6.

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.

#### 3.2.1 | C&C: Monitoring Through an Accountable Monitoring System

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 in SI). 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.

#### 3.2.2 | 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 in SI). 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/ha) 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 1282 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.

#### 3.2.3 | 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

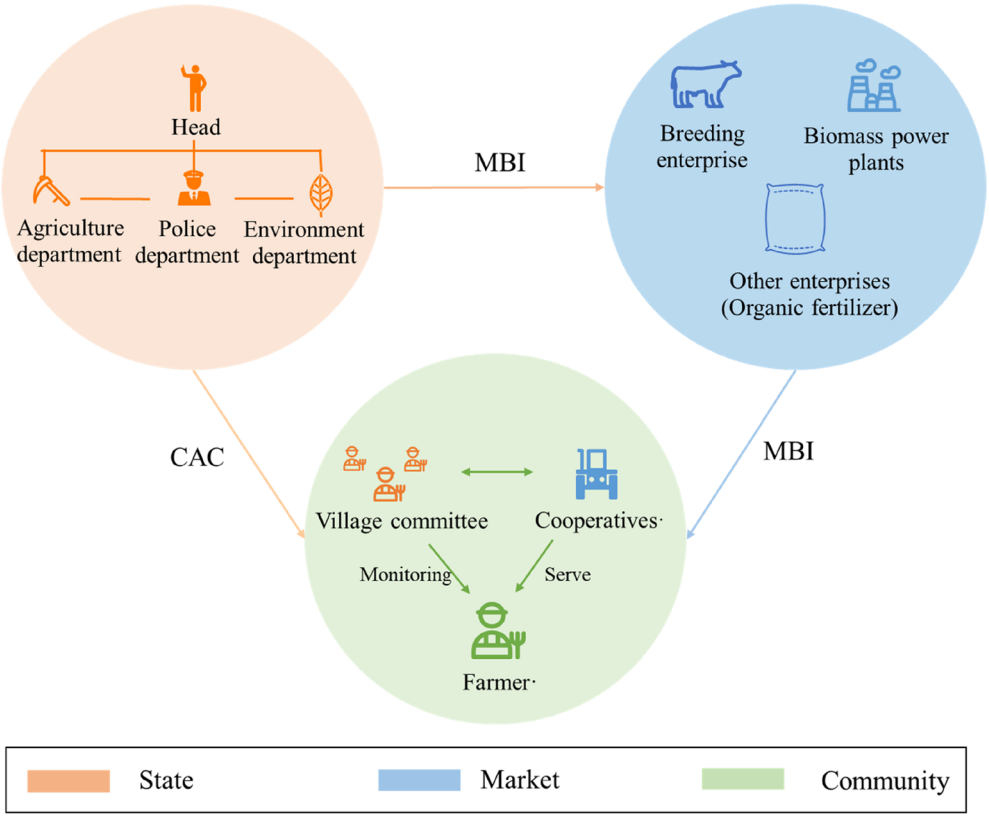


**FIGURE 6** | The governance structure of the straw management reform. (1) This governance structure was developed by the authors based on the analytical framework in Figure 2. (2) CAC: command-and-control, MBI: market-based instrument.

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 in SI), 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 in SI). 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

Based on the abovementioned analysis, the straw management reform in Heilongjiang province represents a hybrid policy instrument 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, whereas 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.

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

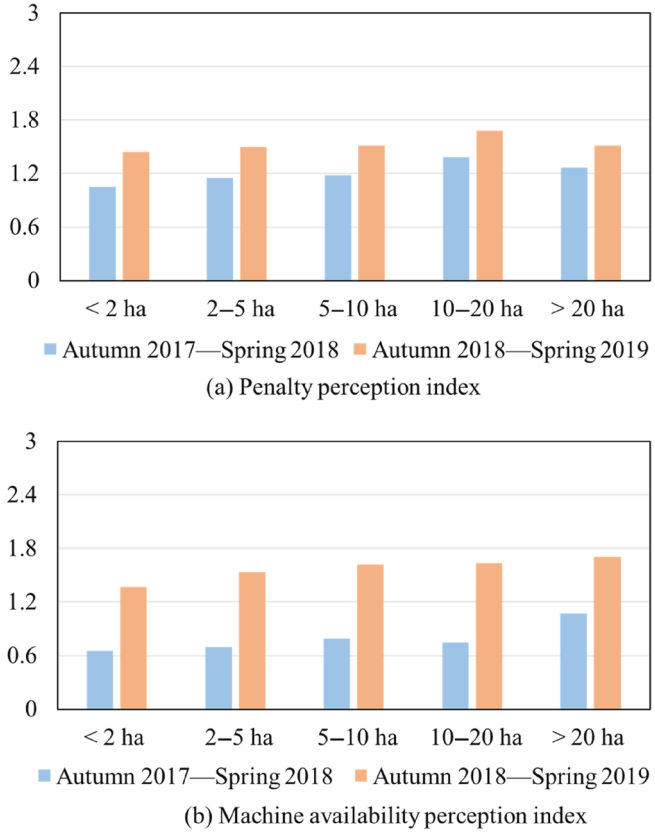


**FIGURE 7** | Temporal changes in the institutional environment. (1) Data is sourced from the pooled dataset from two waves of household surveys.

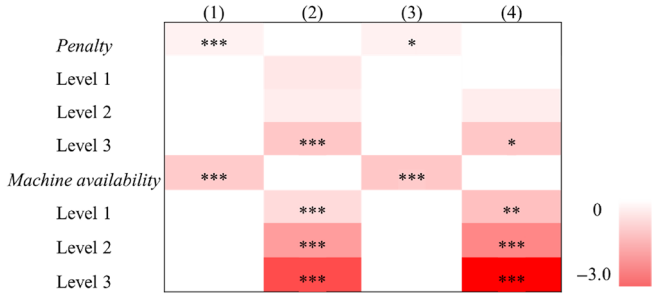


**FIGURE 8** | Effect of institutional environmental on farmers' engagement in OSB. (1) Columns (1) and (2) display the estimated results using the entire sample, whereas columns (3) and (4) show the estimated results using the traced sample. (2) The dependent variable is whether farmers' primary method of straw disposal is OSB. (3) The control variables and specific coefficients of variables are shown in Table S7. (4) The color scheme represents the coefficients of the independent variables, indicating their impact on farmers' engagement in OSB. (5) Standard errors are clustered at the village level. (6) *, **, *** indicate statistically significant at the 10%, 5%, and 1% levels, respectively.

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. More details regarding the estimated coefficients of all variables are provided in Table S7 in SI.

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. 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. Second, our qualitative analysis showed that the reform uses 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 have significantly incubated the straw-utilization market, and provided more alternative approaches for farmers to transit into 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. The government acts as the initiator and promoter of the reform, while the straw-utilization market is responsible for building the straw-cycling chain, and the farmers' community, including village committees and cooperatives, serves as intermediaries, connecting farmers with the government and the market.

The findings of this study underscore key insights for policy implementation. First, the governance structure of the OSB reform in Heilongjiang highlights the active involvement of multiple stakeholders to promote sustainable agri-waste management, including the government, the waste-utilization market, and the farming community. This collaborative, multi-sectoral approach facilitates the development of a waste-cycling supply chain and enhanced communication channels for effective policy implementation (Abas and Wee 2014; Bodin 2017; Perdana et al. 2023). Second, the design of policy instruments of the OSB reform in Heilongjiang highlights the collaborative cooperation of multiple stakeholders requiring the integrated use of C&C and MBI approaches. Given the varying interests and attentions of stakeholders, a diverse set of policy tools creates a tailored policy framework that aligns with stakeholders' specific needs and objectives, guiding collective actions toward a consistent policy target (Howlett 2009; Swanson et al. 2010). Third, the cost–benefit analysis indicates that active agri-waste management efforts are essential, given the significant environmental and social benefits they provide. This finding supports the value of public financial investments for pollution mitigation and the promotion of rural sustainability.

The limitations of our study are as follows: Although our case study on OSB reform in Heilongjiang offers valuable insights for sustainable agricultural waste management, its generalizability may be constrained by cultural contexts and environmental conditions. The unique social and economic dynamics of the region may not accurately reflect those in other areas, and factors such as soil quality and climate variability could affect the effectiveness of straw management practices. Furthermore, the absence of a control group in our policy evaluation may introduce biases due to potential confounders. Future research should incorporate comparative analyses to strengthen the validity of causal claims regarding agricultural waste management policies.

## Author Contributions

**Zhiwei Yu:** conceptualization, methodology, software, writing – original draft preparation, visualization; **Fan Li:** conceptualization, methodology, writing – reviewing and editing; **Wei Si:** supervision, data curation, project administration; **Weifeng Zhang:** supervision.


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## Conflicts of Interest

The authors declare no conflicts of interest.

## Endnotes

[1] There are multiple approaches to reuse the crop straws sustainably. Details on sustainable straw use are shown in Figure S1.

[2] See policy document (in Chinese): https://www.gov.cn/zwgk/2013-05/27/content_2411933.htm.

[3] See news (in Chinese): https://www.thepaper.cn/newsDetail_forward_1571087.

[4] The policy was specifically targeting on provinces in the northeast China, including Heilongjiang, Jilin, Liaoning provinces and the east part of Inner Mongolia. See policy document: http://www.moa.gov.cn/nybgb/2017/dlq/201712/t20171231_6133708.htm.

[5] See news (in Chinese): https://www.gov.cn/xinwen/2019-11/17/content_5452873.htm.

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

[7] The reduction of the tracked number of townships was mainly due to financial limitation. To ensure our follow-up survey were representative (inherit no sample selection bias), we randomly selected two townships out of the three townships we surveyed in 2018.

[8] See policy document (in Chinese): http://epaper.hljnews.cn/hljrb/20180716/367327.html.

[9] See policy document (in Chinese): https://www.waizi.org.cn/policy/48454.html.

[10] See policy document (in Chinese): https://www.nongjitong.com/news/2018/446546.html.

[11] In Figures S2 and S3, we analyzed the effects of the reform on OSB and the development of straw-utilization machines in the second and third years following its reform. The data indicate that the number of OSB spots consistently remained lower than pre-intervention levels, even after multiple post-intervention assessments. Furthermore, there was a significant increase in the number of straw-utilization machines following the policy intervention. These findings suggest that the policy has had a lasting impact on reducing OSB.

[12] We outlined the sample distribution for the farm-size group in Figure S4.

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**Supporting Information**

Additional supporting information can be found online in the Supporting Information section.