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The pathway of sustainable straw management in China

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La voie de la gestion durable de la paille en Chine

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Abstract

Straw has dual characters: waste and resource. After crop harvest season, enormous straw is generated in China. With the improvement in farmers' living, household use of straw is decreasing. On the contrary, the crop yield and straw are increasing simultaneously, which brings about a surplus of straw. Farmers have to choose either full straw return or straw burning in farmland. Considering the negative effects of full straw return, straw burning in the farmland is the cheapest and most convenient way to get rid of it. With the raising awareness of environmental protection, straw burning is strictly controlled by Chinese government. In addition, straw comprehensive utilization has been implemented, which can be helpful for consuming the straw resource, thereby reducing straw burning voluntarily.

However, it has four problematic issues with current practices of straw utilization, which hinder the transition from conventional straw management to sustainable straw management. Namely, diseconomy of straw disposal by dominant smallholder farmers; the uncertainty of optimal straw return scheme; the unreliability of straw feedstock supply chain modelling and lacking sustainable safeguard mechanism. Thus, the research objectives of the thesis are to provide countermeasures for addressing these issues.

To begin with, straw is created and generated on farmland after crop has been harvested, therefore how to consume it on farmland is the first step. Straw burning is prohibited, and then straw return is indispensable. So, this thesis first explores the optimal scheme of straw return, to maximize the benefit (crop yield increase) and determine the amount of straw return. Concerning the huge regional and crop-type differences, China's corn belt (Northeast China) is chosen as a study area for exploring optimal scheme of straw return.

And then, in comparison with straw burning in farmland, adopting straw return practice requires extra costs. Eco-compensation with monetary incentive can stimulate farmers to choose to straw return practice voluntarily. Then this thesis explores the mechanism and reasons that farmers should be compensated for agronomic, environmental and ecological aspects, and policy suggestions for innovative incentives are given.

Furthermore, apart from a certain amount of straw resource that can be returned to farmland as organic fertilizer, the remaining straw resource (leftover) can be recycled for other purposes. For straw recycling, straw must be removed from farmland to the gate of utilization terminal. Therefore, straw feedstock supply chain is indispensable. Before the real and practical arrangement of straw feedstock supply chain, modelling is a useful method for providing important assistance. Then, this thesis fills the knowledge gap in establishing a straw feedstock supply model that could satisfy the specific conditions in China and ensures a stable and reliable straw supply with optimal arrangements and minimum costs.

Besides, how to make sure that this system can be operated smoothly and sustainably requires sustainable safeguard mechanism. The system of sustainable straw management is complicated, with the stakeholders of farmers, brokers, producers, consumers as well as the government. How to balance their interests and make benefits need tactical mechanism design. Therefore, this thesis will give policy suggestions on sustainable safeguard mechanisms to make sure that sustainable straw management can run on a long-time basis.

Moreover, the potential abatement of carbon emission with sustainable straw management has been assessed. Taking corn straw in Northeast China as a case study, the potential abatement of carbon emission is estimated to be 222.3 million tons of CO_2 eq. annually. In addition, the potential solutions for practicing innovative incentives, and the extension of StrawFeed model with techno-economic models with agricultural production management have been clarified and discussed.

Finally, this thesis concludes that sustainable straw management is an important measure for straw valorisation and sustainable agriculture in China. This work supports that sustainable straw management in China can achieve multiple UN Sustainable Development Goals simultaneously, and the experience and lessons learned from China can also enlighten other developing countries faced with similar challenges.

Keywords: straw, straw return, straw burning, bioenergy, straw feedstock supply chain, innovative incentive, subsidy, carbon trading

Résumé

La paille a une double caractéristique : elle est à la fois un déchet et une ressource. Après la saison des récoltes, une quantité énorme de paille est produite en Chine. Avec l'amélioration des conditions de vie des agriculteurs, l'utilisation de la paille par les particuliers diminue. En parallèle, le rendement des cultures et le volume de pailles augmentent simultanément, ce qui entraîne un surplus de paille. Les agriculteurs doivent choisir entre le retour complet de la paille et le brûlage de celle-ci sur les terres agricoles. Compte tenu des effets négatifs du retour complet de la paille, le brûlage de la paille sur les terres agricoles est le moyen le plus économique et le plus pratique de s'en débarrasser. Avec la sensibilisation croissante à la protection de l'environnement, le brûlage de la paille est strictement contrôlé par le gouvernement chinois. En outre, l'utilisation globale de la paille a été mise en œuvre, ce qui peut être utile pour consommer la paille comme une ressource, réduisant ainsi le brûlage volontaire de la paille.

Cependant, les pratiques actuelles d'utilisation de la paille posent quatre problèmes, qui entravent la transition de la gestion conventionnelle de la paille vers une gestion durable. Il s'agit de la « déséconomie » de l'élimination de la paille par les petits exploitants agricoles dominants, de l'incertitude du schéma optimal de retour de la paille, du manque de fiabilité de la modélisation de la chaîne d'approvisionnement en paille, et de l'absence de mécanisme de sauvegarde durable. Ainsi, les objectifs de recherche de cette thèse sont de fournir des contre-mesures pour résoudre ces problèmes.

Pour commencer, la paille est créée et générée sur les terres agricoles après la récolte des cultures, donc la façon de la consommer directement sur les terres agricoles est la première étape. Le brûlage de la paille étant interdit, le retour de la paille est indispensable. Ainsi, cette thèse explore d'abord le schéma optimal de retour de la paille, afin de maximiser le bénéfice (augmentation du rendement des cultures) et de déterminer le montant du retour de la paille. Compte tenu des différences considérables entre les régions et les types de cultures, la ceinture de maïs de la Chine (Nord-Est de la Chine) est choisie comme zone d'étude pour explorer le schéma optimal de retour de la paille.

Par rapport au brûlage de la paille sur les terres agricoles, l'adoption de la pratique de la récupération de la paille entraîne des coûts supplémentaires. L'éco-compensation avec incitation monétaire peut stimuler les agriculteurs à choisir volontairement la pratique du retour de la paille. Ensuite, cette thèse explore le mécanisme et les raisons pour lesquelles les agriculteurs devraient être compensés pour les aspects agronomiques, environnementaux et écologiques, et des suggestions politiques pour des incitations innovantes sont données.

En outre, à part une certaine quantité de paille qui peut être retournée aux terres agricoles comme engrais organique, le reste de la paille peut être recyclé à d'autres fins. Pour être recyclée, la paille doit être enlevée des terres agricoles jusqu'à la porte du terminal d'utilisation. La chaîne d'approvisionnement en paille est donc indispensable. Avant l'arrangement réel et pratique de la chaîne d'approvisionnement en matières premières de la paille, la modélisation est une méthode utile pour fournir une assistance importante. Cette thèse comble donc le manque de connaissances dans l'établissement d'un modèle d'approvisionnement en paille qui pourrait satisfaire les conditions spécifiques de la Chine et assurer un approvisionnement en paille stable et fiable avec des arrangements optimaux et des coûts minimaux.

En outre, la façon de s'assurer que ce système peut être exploité sans heurts et de manière durable nécessite un mécanisme de sauvegarde durable. Le système de gestion durable de la paille est complexe, avec les parties prenantes que sont les agriculteurs, les courtiers, les producteurs, les consommateurs ainsi que le gouvernement. La manière d'équilibrer leurs intérêts, et de faire des bénéfices, nécessite la conception d'un mécanisme tactique. Par conséquent, cette thèse donnera des suggestions politiques sur les mécanismes de sauvegarde durable pour s'assurer que la gestion durable de la paille peut fonctionner sur une base à long terme.

En outre, la réduction potentielle des émissions de carbone grâce à la gestion durable de la paille a été évaluée. En prenant la paille de maïs dans le Nord-Est de la Chine comme cas d’étude, la réduction potentielle des émissions de carbone est estimée à 222,3 millions de tonnes d'équivalent CO_2 par an. En outre, les solutions potentielles pour mettre en pratique des incitations innovantes, et l'extension du modèle StrawFeed avec des modèles techno-économiques avec la gestion de la production agricole ont été clarifiées et discutées.

Enfin, cette thèse conclut que la gestion durable de la paille est une mesure importante pour la valorisation de la paille et l'agriculture durable en Chine. Ce travail soutient que la gestion durable de la paille en Chine peut atteindre simultanément plusieurs objectifs de développement durable de l'ONU, et l'expérience et les leçons tirées de la Chine peuvent également éclairer d'autres pays en développement confrontés à des défis similaires.

Mots-clés : paille, retour de la paille, brûlage de la paille, bioénergie, chaîne d'approvisionnement en matières premières de la paille, incitation innovante, subvention, échange de carbone.

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List of abbreviations

NEC: Northeast China
ES: Effect size
LSD: Least significant difference
SD: Standard deviation
MC: Monte Carlo
NF: Nitrogen fertilizer
AS: Amount of straw
SOM: Soil organic matter
TN: Total nitrogen
LN: Liaoning province
JL: Jilin Province
HLJ: Heilongjiang province
IM: Inner Mongolia
SDG: Sustainable development goal
WTA: Willingness to accept
CVM: contingent value method
UAV: Unmanned aerial vehicle
WTP: Willingness to pay
GHG: Greenhouse gas
BCP: Bioenergy conversion plant
MILP: Mixed integer linear programming
SR: Straw return
SF: Straw feed
SE: Straw-based bioenergy
SM: Straw utilization mitigation
SB: Straw burning in the field
FM: Final straw utilization mitigation
CNY: Chinese Yuan (currency in China)
APIs: Application Programming Interfaces

Chapter 1

General context and problematic issues

Adapt from:

Wang, S., Yin, C., Li, F., Richel, A., 2023. Innovative incentives can sustainably enhance the achievement of straw burning control in China. Sci. Total Environ. 857, 159498.

With the growing population globally, agriculture is also expanding simultaneously. After crop has been harvested, enormous straw is generated. If straw cannot be disposed of properly, farmers would like to take the decision of straw burning in the field ("straw burning" for short, or called "straw open burning"). Such phenomenon can be widely observed in developing countries, such as China, India, Thailand, Vietnam and so on, which are also the major agricultural countries with intensive populations. With the raising awareness of environmental protection, straw burning ban has been implemented to control straw burning phenomenon in China. Although it has achieved a remarkable performance by reducing fire spots in farmland, it still cannot be eliminated. Instead of using straw in single way, straw comprehensive utilization can maximize its benefits. Therefore, it is eager to explore a pathway of sustainable straw management in China.

1. The initiative of straw management in China

The history of straw burning can be split into three historical stages: (1) before reform and opening (before 1978); (2) after 1978 to 2008; (3) after 2008. In different historical stages, the motivation and scale of straw burning are distinct remarkably.

1.1 Stage 1: Scarcity of straw for farmers

In the past (before 1978), straw burning is rare in China, because straw is a valuable resource for farmers (Xinhua Net, 2015). Due to the shortage of production and living materials (fertilizer, forage and fuel), straw has multiple functions of feeding animals, organic fertilizer, or even biomass fuel for cooking and heating. Therefore, farmers would like to spend time and effort collecting and carrying straw feedstock from farmland to their houses, and pile it up for storage.

1.2 Stage 2: The raising of straw burning

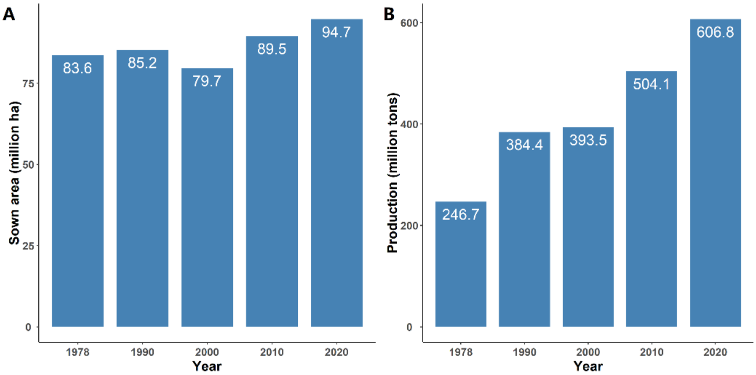


Figure 1-1: The sown area (A) and production (B) of staple food (rice, wheat and corn) in China. Data are from NBS (2021).

Since 1978, China has made major reform in agriculture, and adopted Household Responsibility System (Gibson, 2019; Sun and Chen, 2017; Xie and Jiang, 2016). This system has remarkably positive effects on agricultural growth and crop yield increase (Gibson, 2019; Liu et al., 2016a; Sun and Chen, 2020; Zheng et al., 2020) where it motivates farmers' enthusiasm for agricultural production. The statistical data from NBS (2021) reveal that the sown area of staple food (rice, wheat, corn) is increasing steadily from 83.6 million ha in 1978 to 94.7 million ha in 2020 (**Figure 1-1 A**). On the contrary, the production of staple food is raising dramatically from 246.7 million to 606.8 million tons in 2020 (**Figure 1-B**). Along with the increase in food production, the quantity of straw resource is increasing simultaneously. Based on the straw-grain ratio from Bi et al. (2009), it can be estimated that the quantity of straw in 2020 is 2.6 times greater than that in 1978. Such increment puts burden on efficient straw disposal.

On the other hand, the conventional use of straw resource in rural China is also decreasing. In the past, straw is an important biomass feedstock for rural energy consumption. Farmers burn straw directly for cooking and heating. With the development of rural China, the infrastructure has been improved gradually, and most Chinese families have become more prevalent with electricity (Zou and Luo, 2019). Farmers' income is also increasing significantly, and high-income rural family is more affordable for choosing various energy commodities like coal or LGP (Han et al., 2018b; Wang et al., 2017). In addition, to facilitate access to renewable energy, the subsidy is given by the government in rural areas (Sun et al., 2014). The substantial energy transition in rural China is underway from simply conventional biomass energy (using straw and firewood directly) to modern energy commodities (Qiu et al., 2018). Therefore, the straw used for energy consumption in rural China (both absolute and relative quantity) is declining significantly (Han and Wu, 2018; Niu et al., 2019; Wu et al., 2019; Zhang et al., 2009).

Besides, using straw for feeding livestock is less than before (Figure 1-2). In the past, livestock production is mainly by the rural family on a scattered small scale in China. Farmers collected and delivered straw feedstock from farmland and feed the livestock directly. With the rising demand for meat, egg and milk, smallholder family production is gradually replaced by specialization of livestock production, and it results in the decoupling of crop and livestock production systems (Ma et al., 2022; Zhang et al., 2019a; Zhou et al., 2020). Straw feed is substituted by forage and grain (Jin et al., 2021b). A long-term rural family survey across China indicates that the proportion of rural families still remaining in both crop and livestock production systems has rapidly decreased from 71% in 1986 to merely 12% in 2017 (Jin et al., 2021b).

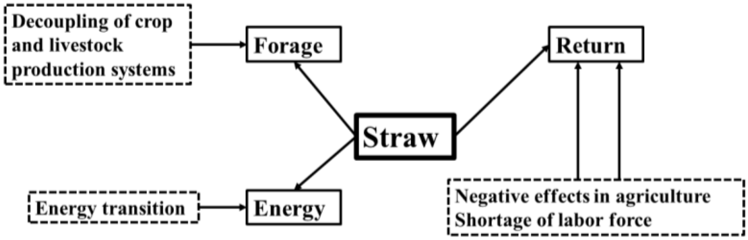


Figure 1-2: The challenges of straw utilization by ordinary rural families.

In addition, straw return is also facing strong challenges for several reasons. To begin with, although straw could be regarded as organic fertilizer and straw return could increase soil organic matter (Berhane et al., 2020; Goswami et al., 2020; Li et al., 2018b), and enrich soil nutrients (Goswami et al., 2020; Liu et al., 2014; Yadav et al., 2019; Wang et al., 2022a), it could not be consumed or decomposed by the farmland in due course of time (Kuang et al., 2014; Li et al., 2018a), especially during cold and dry winter in the north China areas (high latitude zones). The unfavourable hydrothermal conditions make straw uneasy for decomposing and biodegradation, which would impede root penetration (Jin et al., 2020; Li et al., 2018a). The crop yield cannot be promoted, and even worse faces yield loss. On the contrary, the leftover straw burning: straw ash, can be regarded as a valuable organic fertilizer that can improve soil nutrient as well as promote crop's phosphorus uptake (Schiemenz and Lobermann, 2010). Secondly, some farmers believed that straw return could exacerbate crop pest infestation, weed and disease (Aguiar et al., 2021; Ren et al., 2019). So, the fire from straw burning has the function of soil sterilization (Bockus et al., 1979; Kadam et al., 2000; Yang et al., 2020a). Finally, no matter for straw is returned to farmland as organic fertilizer or straw is removed from farmland for other purposes (bioenergy, feeding etc.), they require extra inputs more labour force and machine use, (Yang et al., 2020b; Comino et al., 2020), which are uneconomical for dominant ordinary farmers (smallholder farmers). Another major cause of straw burning is the shortage of labour force in China. Rural-urban migration brings about the young and energetic population outflow in rural areas (Zhong et al., 2013), whereas straw utilization and management is a labour-intensive activity. The remaining elder people, children as well as women have difficulty with straw management properly. Besides, straw removal and recycling demand coordination with other entities (power plants, animal farms), but farmers usually do not tolerate any disturbance in ordinary cropping and harvesting operations, and they have not been economically stimulated to alter their agronomic practices to cooperate with straw collection (Lu et al., 2020, 2021), and in order to convince farmers to adopt management strategy of straw comprehensive utilization voluntarily, the more monetary subsidy should be granted (Comino et al., 2020; Huang et al., 2019; Yang et al., 2020b). Therefore, straw burning is widely applied by farmers (Guan et al., 2017; Qin and Xie, 2011) because it is the cheapest and most convenient way to dispose of straw (Hong et al., 2016; Jiang et al., 2021; Kaur, 2020; Roder et al., 2020), and farmers have their own experiences to be confident in this behaviour.

1.3 Stage 3: The implementation of straw burning ban policy and comprehensive utilization scheme

With the raising awareness of environmental protection from the whole society and the expansion of urban boundary, the hazards of straw burning are gradually recognized, mainly from health, visibility and fire.

(1) Air pollutants and health issues

To begin with, the smoke from straw could threaten human health, harmful air pollutants are emitted from straw burning, including particulate matter (PM), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOC), polycyclic aromatic hydrocarbons (PAHs) (Chen et al., 2018; Jiang et al., 2021; Lai et al., 2009). Specifically, PM from straw burning damages health by impairing the function of the lung (Seglah et al., 2020; Saggu et al., 2018), and raises the illness of bronchial asthma (Lai et al., 2009; Jacobs et al., 1997; Torigoe et al., 2000). In China, the annual $PM_{2.5}$ emissions from straw burning can represent 7.8% of overall anthropogenic emissions (Zhang et al., 2016). PAHs from straw burning are potential carcinogens (Ding et al., 2008; Jenkins et al., 1992; Lai et al., 2009; Omar et al., 2002; Yu et al., 2008), and result in lung cancer (Batra, 2017). Singh (2018) summarized the illness of cough, pulmonary symptoms, irritation and dryness of the eyes that could be attributed to smoke during straw burning season. The empirical evidence from He et al. (2020) illustrated that a strong relationship with the increase in cardiorespiratory disease in China, induced mortality significantly. The smoke-related illness would end up raising the medical cost and putting a heavy burden on the rural family (Seglah et al., 2020).

(2) Smog & driving and airline safety

Secondly, the smog and haze from straw burning could severely reduce and impair the visibility of car drivers and pilots (Bhattacharyy et al., 2020; Chen et al., 2018; Li et al., 2019a; Wang et al., 2015b), and thereby the highways have to be shut down and airports have to be closed (Jiang et al., 2021; Zhang et al., 2017). These accidents bring serious risks to traffic safety and cause losses to the national economy (Jiang et al., 2021; Lai et al., 2009; Yang et al., 2020a).

(3) Fire risk & human life and property safety

Thirdly, fire from straw burning is usually out of control, where it could spread to ambient areas and threaten the safety of human life and property (Giannoccaro et al., 2017; Palmieri et al., 2017; Zhang et al., 2017). It is reported that farmers are suffering from the wounds from conflagration, such as body burns, serious foot injury as well as high body temperature (Seglah et al., 2020).

Therefore, straw burning is a common challenge that has negative environmental impacts globally. In order to control straw burning behaviour, many countries have proposed and implemented policies and regulations. In the U.S., since 1999 the USDA issued Agricultural Burning Policy, which is used to guide straw burning management (USDA, 2006). After that, Smoke Management Program is promulgated and straw burning pollution should be controlled, in accordance with the supervision from USEPA (National Wildfire Coordinating Group, 2001). The U.K. formulated restrictions and rules for guiding farmers about straw burning management (Department for Environment, Food & Rural Affairs, 2021). Besides, The EU members (e.g., Germany) also have similar policies and experience on straw burning control (Nikola Nikolov, 2011).

In China, by taking the opportunity to hold the 2008 Olympic Games in Beijing, Chinese government paid high attention to air pollution control (Qin et al., 2019), and issued policies on straw burning ban (Ministry of Environmental Protection, 2008) as well as accelerating straw comprehensive utilization (The State Council, 2008). Strict measurements have been implemented to eradicate straw burning behaviour and preserve high air quality. On the other hand, there is a new development in agricultural production. The dominant smallholder farmers can be split into parallel smallholder farmers as well as large-scale farmers in agricultural system. The endowments between smallholder farmers and large-scale farmers are distinct, and thus their behaviour of adopting sustainable straw management as well as burning straw in the farmland is also different. In fact, straw burning ban and encouragement of large-scale farming are two effective measures for addressing straw burning behaviour in China, and they have achieved significant performances. According to the spatio-temporal assessment of straw burning fire spots in farmland of China (Zhang et al., 2019d), the overall number of fire spots has been declining from 7765 in 2014 to 2811 in 2018 (**Figure 1-3A**), which reflects a favourable trend of straw burning control. However, for major food production regions, straw burning behaviour is still resistant. For example, Northeast China (including Jilin, Liaoning and Heilongjiang Provinces) represented over 56% of overall fire spots in China (**Figure 1-3B**). In order to explain such a phenomenon, the divergence of farmers' endowments and their impact on straw management capacity are fully explored in the following section.

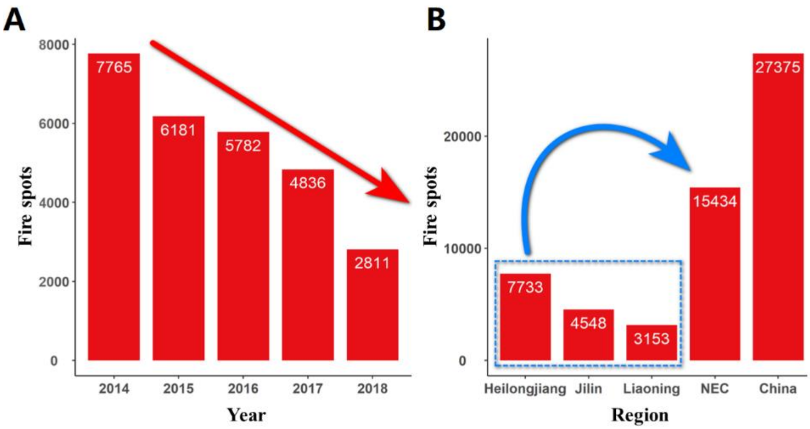


Figure 1-3: The overall straw burning fire spots in farmland of China from 2014 to 2018 (A), and the fire spots distribution in region (B). The source of data is from Zhang et al. (2019d).

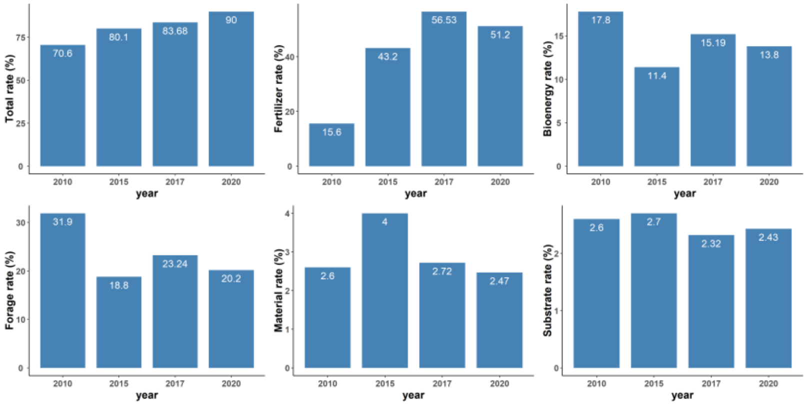


Figure 1-4: The dynamic changes of straw comprehensive rate in China. The data are from NDRC (2011), NDRC (2016), People's Daily (2018) and Huaan Securities (2021) respectively.

In addition, the dynamic changes in straw utilization rate also reveal that, the implementation of straw utilization scheme can be helpful for straw burning control, because it turns agricultural waste into a valuable resource for sustainable development. As illustrated in **Figure 1-4**, the total straw utilization rate is increasing steadily from 70.6% in 2010 to 90.1% in 2020, and the previous straw burning practice has been gradually replaced by straw utilization, and the straw burning rate has decreased from 29.4% in 2010 to 9.9% in 2020. Interestingly, straw-to-forage rate has decreased significantly, whereas straw-to-fertilizer rate has raised dramatically between 2010 and 2015. That is because of the declining household small-scale animal production and specialization of modern animal farms in China. Using straw for feeding animals has the problems of seasonal supply of straw feedstock and low nutrition. Hence, from the perspective of economics and stability, large-scale animal farms are keener on using feed. Unlike other utilization modes that cannot be utilized in the farmland, and require straw removal from farmland into other destinations, using straw as fertilizer means returning straw feedstock into farmland as organic fertilizer directly. Hence, it is adopted by more and more farmers.

2. The major straw utilization modes in China

In order to promote the effectiveness and efficiency of straw comprehensive utilization in China, straw comprehensive scheme has been proposed. In China, straw has mainly five utilization modes: fertilizer (straw return), forage (feed for animal breeding), biofuel (bioenergy), substrate as well as material (paper production etc.).

2.1 Straw return

Straw return as organic fertilizer is an important agronomic practice. Straw could be regarded as organic fertilizer and straw return could increase soil organic matter (Goswami et al., 2020; Wang et al., 2021b; Li et al., 2018b; Berhane et al., 2020), and enrich soil nutrients (Goswami et al., 2020; Yadav et al., 2019; Lehtinen et al., 2015; Liu et al., 2014). Therefore, straw return is also an important management tool for improving crop yield (Chen et al., 2017) as well as reducing chemical fertilizer application (Song et al., 2018).

2.2 Bioenergy

Because of fast economic growth and promoted living standards, the demand and supply of energy is an important concern that has great attention. According to China Statistical Yearbook (2021), China’s energy yield is increasing dramatically, from 1.39 billion tons of standard coal in 2000 to 4.08 billion tons of standard coal in 2020. Similarly, China’s energy consumption is also raising remarkably, from 1.47 billion tons of standard coal in 2000 to 4.98 million tons of standard coal in 2020 (**Figure 1-**

5). The comparison between energy yield and consumption in China demonstrates that energy consumption always exceeds the energy yield in China. In other words, there is a huge gap between yield and consumption, and China needs to import a large number of energy products to satisfy its demand. Energy is a crucial fuel and booster for industry and the economy, and the unbalanced energy structure could threaten the sustainability and reliability of China's economic development. Therefore, energy security is an important national development goal and Chinese authorities put high attention to it.

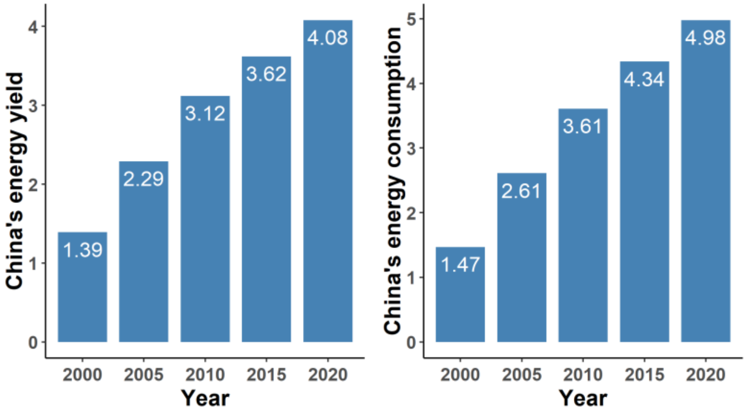


Figure 1-5: China's energy yield (left) and energy consumption (right) between 2000 and 2020. The data are from NBSC (2021).

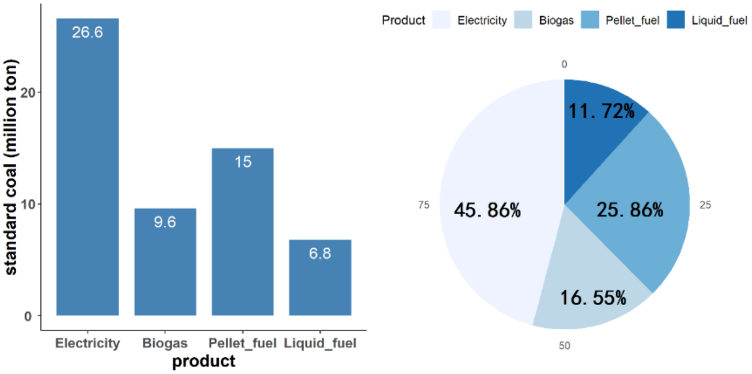


Figure 1-6: The plan for China's bioenergy development in 2020. The left is the bioenergy products (unit: standard coal) and the right is the proportion. The data are from the "13th Five-Year-Plan of Biomass Energy Development" (National Energy Administration, 2016)

According to the "13th Five-Year-Plan of Biomass Energy Development" (National Energy Administration, 2016), in 2020, China is expected to produce 15 billion kWh of bio-electricity, 8 billion metrics of biogas, 30 million tons of pellet fuel, and 6 million ton of biofuel, and these bioenergy products can substitute a large number of conventional fossil fuels, which are equivalent to 26.6, 9.6, 15 and 6.8 million tons standard coal respectively (See **Figure 1-6**). Among these bioenergy products, power generation is the dominant mode, which could represent 45.86% of overall bioenergy production (based on standard coal equivalence). In addition, bioenergy projects are continuously increasing. Especially, straw-use bioenergy is now facing a great development opportunity, because it could be regarded as a carbon-neutral energy source. The amount of greenhouse gas released during the straw utilization process is almost equivalent to carbon capture through photosynthesis while crop growing. Therefore, straw would play an important role in the transition to renewable and clean energy and in achieving carbon neutrality in China by 2060.

In front of energy scarcity as well as global warming mitigation, turning the surplus of straw into fortune can be very attractive. By considering the chemical and physical properties (Niu et al., 2016), plenty of research has been carried out to assess the potential of a suitable amount of straw for bioenergy proposes from either international or regional scope. Based on the average global straw production between 1997 and 2001, Kim and Dale (2004) assessed that the global potential of bioethanol production from straw was 442 GL yearly, which could substitute 353 GL of petrol (was equal to 32% global petrol consumption). By calculating Net Primary Productivity between 2000 and 2014, Tum et al. (2016) inferred that global straw bioenergy potential was 35.9 EJ. yearly. Bentsen et al. (2014) conducted a nationwide analysis of straw production (averages over 2006-2008), and estimation revealed that theoretical energy potential was 65 EJ. yearly, which could account for 15% of the world's primary energy consumption. On the national scale, Jiang et al. (2012) estimated that straw could provide 7.4 EJ. bioenergy yearly, representing 8.27% of the total energy consumption of China in 2009. Li et al. (2012) estimated that China's straw could generate 1.75 × 105 GWh of electric power and 43 million tons of bioethanol in 2008. Qiu et al. (2014) calculated that the amount of straw for bioenergy business was 73.5-120.5 million tons of standard coal equivalent, which accounted for 2.5-3.8 of China's total energy consumption in 2012. Muth et al. (2013) predicted that by 2030, over 207 million tons of straw would be used for bioenergy, and such resources could produce 68 billion liters of biofuels in the USA. The evaluation showed that straw resource had the potential of generating 16.25 GW of power in India between 2008 and 2009.

2.3 Forage

China become the second-largest economy in the world. Accompanying the promotion of economic growth, the people's demand for meat and milk is also raising simultaneously. According to the statistics from FAOSTAT (2022), global and China's meat (Beef and Buffalo meat) yields are both increasing, from 59 million tons in 2000 to 72 million tons in 2020, and 5 million tons in 2000 to 7 million tons respectively. Similarly, global and China's milk yields are both increasing, from 580 million tons in 2000 to 72 million tons in 2020, and from 5 million tons in 2000 to 7 million tons respectively. In order to support the booming development of the breeding industry, a stable and reliable forage supply is of utmost crucial. For feeding cattle and cows, the most widely used feed is alfalfa and oat grass. To satisfy the huge demand for forage in China, the local production is not enough and China needs to import a large amount of alfalfa and oat grass from other countries. According to the statistics from China's customs (China Forage Industry, 2021), China imported 136 million tons of alfalfa, and the U.S. is the dominant exporter with 1.18 million tons of alfalfa (accounting for 87% of the overall import amount). Besides, the rest of the major exporters are Spain, South Africa, Sudan and Canada and so on, with 100.8, 31.3, 15.5, 10.9 thousand tons of alfalfa respectively. In addition, oat grass is also an important feed and China relies on import heavily. The import of oat grass in China is entirely from Australia, which was 334.7 thousand tons of oat grass in 2020. In order to alleviate the reliance on importing feed and securing national food production, using localized feed is attractive. Therefore, straw-to-feed project is a practical and plausible solution.

Apart from a direct straw return to farmland, straw-to-feed utilization is the simplest and cheapest mode (Cheng et al., 2020). Currently, there are two major methods for straw-to-feed utilization: direct crushing or fermentation process (Cheng et al., 2020). The straw can be either crushed directly and then mixed with other conventional forage, or fermented with refining treatment and then mixed with other conventional forage. From the perspective of straw nutrients, the experimental evidence indicates that straw (corn straw) can substitute a portion of alfalfa in the diet without scarifying the production of milk from dairy cows (Zhang et al., 2021; Li et al., 2020) as well as meat from bull (Rahman et al., 2019). In addition, milk from the cows fed with corn and wheat straw had lower saturated fatty acids and higher unsaturated fatty acids than commercial milk with conventional forage (Li et al., 2021) In other words, the quality of milk produced by straw feed is healthier than milk from commercial milk companies with conventional forage. From the perspective of environmental performance, straw feed is relatively cleaner than conventional feed, because it has the environmental benefits of substitution effect of crop production as well as close transportation distance (Hong et al., 2016; Wang et al., 2019). Hence, concerning these benefits, straw feed is widely used globally, such as in Ethiopia, Tanzania Mexico and so on.

Because of the drawbacks of straw-to-feed utilization, it is still at a low level for large-scale animal farms to adopt. It lacks a national supportive policy for straw-to-feed utilization. From the perspective of provincial level, Jilin province (located in Northeast China) has a supportive policy (Jilin government, 2021). But its emphasis has been paid on subsidizing animal breeding and manure management, whereas for straw-to-feed utilization only credit-guaranteed loan has been given for straw feed processing. According to the assessment from Huang et al. (2021), replacing commercial feed with straw feed have positive environmental impacts on milk production system, by reducing global warming potential, acidification potential, eutrophication potential, non-renewable energy use, water use and land use. Therefore, referring to straw return and straw-based bioenergy utilization, straw-to-feed utilization should also pay high attention, and specialized subsidy and supportive policies should be designed and implemented in the future.

2.4 Material

In people’s daily life, paper is indispensable. It can be used for not only writing and commutation, but also for packaging or sanitary purposes. For paper production, wood is an important feedstock. However, with the raising concerns of environmental and ecological protection, the preservation of forests become more and more important. According to the statistics from FAOSTAT (2022), the global forest area remains stable for a long-time period, from 4158 million ha in 2000 to 4059 million ha in 2020. In China, with the help of the programs of returning land from farming to forestry as well as afforestation, the forest area in China is increasing steadily, from 177 million ha in 2000 to 220 million ha in 2020. Adversely, compared with the proportion of forest area, China is the major paper manufacturing country in the world. In 2000, China produced 8 million tons of paper, which represented about 8.08% of global paper production. But in 2020, China produced 25 million tons of paper, which could be represented 28.4% of global paper production. Facing the strong challenges and pressure of ecological conservation as well as environmental protection, it is eager for finding alternative feedstock for securing the material supply in paper production. Therefore, the straw-to-paper project is a practical and plausible solution.

Plenty of studies have been carried out for assessing the environmental performance of straw-based paper production (Singh and Arya, 2021; Ma et al., 2019; Man et al., 2020; Sun et al., 2018). Although straw-based pulp has greater environmental impacts than wood-based pulp (Sun et al., 2018), especially due to higher energy and chemical requirements, the greenhouse gas emissions in the life cycle under straw-based paper production can be significantly reduced, when carbon sink at the planting stage is concerned (Man et al., 2020). Hence, straw-based paper production can make contributions to not only feedstock scarcity but also environmental protection.

2.5 Substrate

Straw can be used as substrate for cultivation, such as mushroom (Dorr et al., 2021; Sánchez, 2010) and vegetable production (Farag et al., 2016). Mushroom is an important food that has great nutrients and is beneficial for human health (Gummert et al., 2020; Cuesta and Castro-Ríos, 2017; Feeney et al., 2014). According to the statistics from FAOSTAT (2022), the global and China's mushroom yields are both raising dramatically, from 9 and 7 million tons in 2000 to 43 and 40 million tons in 2020 respectively. China is the world's largest mushroom-production country, which represents over 93% of overall global mushroom production. Straw is an important substrate in mushroom cultivation. Therefore, for farmers in developing countries mushroom cultivation from straw is an important way for increasing income (Nguyen-Van-Hung et al., 2019; Gummert et al., 2020; ImtiaJ. and Rahman, 2008; Shakil et al., 2014; Zhang et al., 2014).

3. The key problematic issues on current practices of straw utilization

3.1 Diseconomy of straw disposal by dominant smallholder farmers

However, for major food production regions, straw burning behaviour is still resistant. For example, Northeast China (including Jilin, Liaoning and Heilongjiang Provinces) represented over 56% of overall fire spots in China. In order to explain such phenomenon, the divergence of farmers' endowments and their impact on straw management capacity are fully explored in the following section.

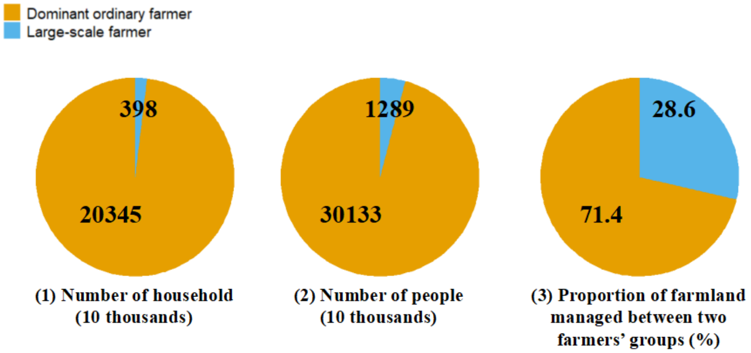


Figure 1-7: The comparison of household, people, and farmland area between dominant ordinary farmers and large-scale farmers in 2016. The data are from the official website of National Bureau of Statistics of China (NBS, 2017a, b; NBS, 2019)

In order to handle the economics of very small size under Household Responsibility System (Shao et al., 2007) as well as farmland abandonment caused by non-agricultural employment of rural labour (Xie and Jiang, 2016), farmland transfer and concentration are encouraged by Chinese authority to improve technical efficiency in agricultural production. During this process, large-scale farmers emerge in China. Although large-scale farmers are very small groups in the number of people and household, it represents over 28% of total farmland in China (See **Figure 1-7**). Large-scale farmers are the new agricultural business entities in various forms, including family farms, stock-holding co-operatives, agricultural companies etc. (Cheng et al., 2021; Lu et al., 2018; Zhao et al., 2017a). Their endowments are remarkably different from dominant ordinary farmers (which are summarized and shown in **Table 1-1**). These differences bring about the divergence in straw disposal capacity, and it results in a significant distinction in decision-making for straw burning.

Table 1-1: The comparison of farmers' endowments between dominant ordinary farmers and large-scale farmers

Characteristic	Dominant ordinary farmers	Large-scale farmers
Farmland size	small	large
Farmland distribution	fragmentation	concentration
Capital input	low	high
Recognition of environment	low	high

Deterrent of punishment	low	high
Straw disposal capacity	weak	efficient
Risk of straw burning	high	low

(1) Farmland size

Literally, the most obvious difference between dominant ordinary farmers and large-scale farmers (new agricultural business entities) is in farmland size. In China, farmland size per rural household is around 0.52 ha on average (Song and Jiang, 2015; Zheng et al., 2018). According to a field survey by Ye and Zhu (2018) from nine major food production provinces in China, farmland size of new agricultural business entities is over 80 times greater than dominant ordinary farmers. In Xingyan city, one of the major crop production areas (granary) in China, large-scale farmers occupy more than 54% of farmland. In response to the injunction of straw burning from Chinese authority, conservation tillage (e.g., straw mulching) is encouraged to avoid soil erosion and preserve soil fertility. In order to overcome the negative effects and shortcomings of straw return, the use of machine is indispensable. During straw return process, specialized straw return machine should be utilized (Zhang et al., 2019b; Wang et al., 2021b, c) to crush the straw and break the stubble (Jia et al., 2010). Furthermore, agronomic management practice has to change to follow the conservation tillage, particularly in the seedling stage. In order to break through the thick mulched straw, seedling and laminating machine could be helpful for seedling and root germination (Liu et al., 2021a; Wang et al., 2006; Zhang et al., 2014). However, even incorporating government subsidy, the gain from crop yield increase could not compensate for the cost of mechanized straw return (Wang et al., 2021b), and farmers are reluctant to adopt this conservation practice. A similar occasion can be observed in India, where some local dominant ordinary farmers cannot pay for the service of using the so-called ‘Happy seeder’ when straw is returned (Kaur 2020). Compared to dominant ordinary farmers, large-scale farmers have scale advantages (Cheng et al., 2021) in terms of procuring agricultural machine or affording agricultural machinery service at preferential price.

(2) Farmland distribution

Under Household Responsibility System, farmland allocation not only considered demographic characteristics (e.g., the number of family members in rural households), but also took soil fertility and location into account (Chen and Brown, 2001; Shao et al., 2007). The soil could be either fertile or barren, and advantageous positions (such as close to river/dam, plain) usually have higher crop yield. However, the quantity of good farmland is limited within a village. In order to achieve egalitarian principles, farmland has to be allocated equally, on the basis of size, soil fertility as well as location (Chen and Brown, 2001), and this further results in fragmentation (Liu et al., 2016a; Prosterman et al., 1996; Zheng et al., 2020). Farmers have to spend massive time travelling between fragmented parcels (Chen and Brown, 2001). In contrast, large-scale farmers circulate and transfer contiguous farmland, and the number of parcels usually merges into one. Apart from the same reason for mechanized straw return in farmland size, concentrated and contiguous farmland could attract straw recycling companies (straw-based power plants, animal farms) to collect and remove straw feedstock. At present, the mainstream of straw feedstock supply chain is in full mechanization (Sun et al., 2017; Wang et al., 2022b). Transportation activity is one of the major bottlenecks in straw feedstock supply chain, so concentrated and contiguous farmland could reduce transportation cost by shortening transportation distance, thereby the ultimate straw feedstock supply cost could be saved a lot (Wang et al., 2021a). Straw recycling companies usually prefer to settle long-term supply contract with large-scale farmers to ensure sustainable and stable straw feedstock supply, instead of negotiating with myriads of dominant ordinary farmers with low provision capacity.

(3) Capital input

The financing capacity and income of large-scale farmers are usually better than dominant ordinary farmers (Ye and Zhu, 2018). Correspondingly, they could invest more capital in agricultural production to maximize profit. In order to cope with high cost of mechanized straw return when they do not have sufficient capacity to dispose of straw properly, they are even willing to pay for the service of straw removal (Zuo et al., 2020). On the other hand, instead of cropping in a conventional way with low price, some large-scale farmers are usually keen on cropping high value-added agricultural products (Lu et al., 2018), and organic agriculture is one of the representative modes of better selling price (price premiums) (Panneerselvam et al., 2011; Qiao et al., 2015; Shreck et al., 2006). In organic agriculture, straw becomes precise organic fertilizer rather than agricultural waste (Zhang et al., 2021a; Mendoza, 2004). Large-scale farmers could earn more money to compensate for the yield gap in organic agriculture, and straw could be fully utilized. On the contrary, cost, procedure as well as criteria of organic farming certification (e.g., inspection from third-party certification entity, ban of using synthetic fertilizers and pesticides) (Karalliyadda and Kazunari, 2020; Manhoudt et al., 2002) are unfavourable for dominant ordinary farmers. Moreover, supporting large-scale farmers has become the national agricultural development strategy in China (Ministry of Agriculture, 2014), and they could apply for special funding and allowance from agricultural bureau (Ministry of Agriculture and Rural Affairs, 2020).

(4) Recognition of environment

The personal characteristics between dominant ordinary farmers and large-scale farmers are distinct, and they could further impact the personal recognition of environment. Becoming large-scale farmers demand well-educated farmers with profound management knowledge as well as a high agronomic experience level (Cheng et al., 2021; Zhao et al., 2017a). In other words, the threshold of large-scale farmers is remarkably higher than in conventional cropping works. According to the field survey by Zhao et al. (2017a) and Ye and Zhu (2018), the majority of large-scale farmers has received a high school education, and even some of their own bachelor's degree. On the contrary, most of the dominant ordinary farmers only receive primary or middle school education. Similarly, the age of the member of large-scale farmers is significantly younger than dominant ordinary farmers (Xu et al., 2020; Ye and Zhu, 2018; Zhao et al., 2017a). Because of better performance in crop yield increase, large-scale farmers have more opportunities in participating in agricultural training (Xu et al., 2020). Education, age as well as training may exert a subtle influence on large-scale farmers and they usually realize the importance and urgency of environmental protection, especially the raising topics and concerns of global warming, climate change, etc.

(5) Deterrent of punishment

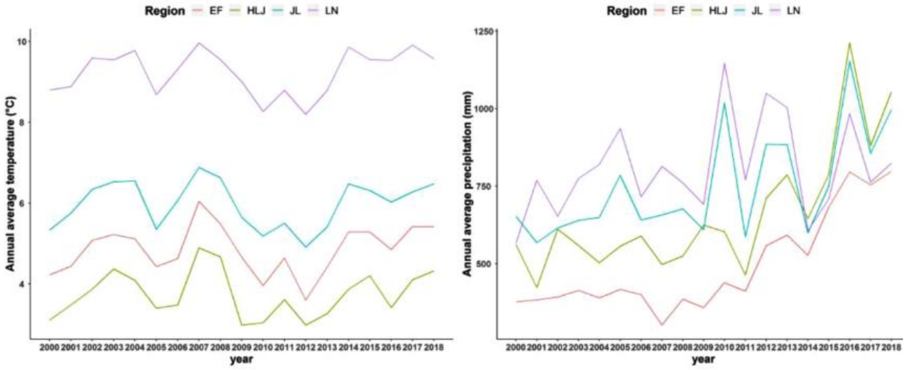
Although strict and compulsory regulations on banning straw burning have been implemented (Raza et al., 2019), the perception of deterrent received by some dominant ordinary farmers and large-scale farmers is different. Because of the massive monetary investment, in front of the strict and compulsory regulation, the large-scale farmers usually become compliant to maintain good relationship and cooperation with local governments, to secure and protect their stable business operation. On the contrary, some dominant ordinary farmers do not be afraid of punishment and penalty. Because of the poor conditions of endowments, some dominant ordinary farmers believe that they have no alternative but to burn the straw, and they also insist that they have the right to do so (pollution right) (He et al., 2020). They follow the experience that their ancestor had done for over thousand years. In addition, some dominant ordinary farmers with very poor family conditions are not afraid of punishment like forfeit. An extreme example happened in Gongzhuling city, a major corn production region (located in the golden corn belt) in China. 15 farmers were chosen for administrative detention instead of forfeit, because they are more worried about economic loss than short-period detention (Fang et al., 2020). In order to mitigate the contradiction and construct a harmonious society, these dominant ordinary farmers are usually received verbal warnings (Hou et al., 2019), and the punishment towards them are weak (Sun et al., 2019).

It should be noticed that the divergency of farmers' endowments is not only the unique phenomenon in China, but also can be observed in developing countries in the world, which is called "smallholder farmers trapped in a vicious cycle" (Meemken and Bellemare, 2020). The low capacity of farming may cause low yield and insufficient profits for adopting eco-environmentally management. Without the invention outside the smallholder farming system, it is hard for them to break the vicious cycle and remain in long-term poverty in many rural areas (Barrett, 2008).

3.2 The uncertainty of optimal straw return scheme

Major food production areas are facing degradation of farmland production (Wen and Liang, 2001; Wang et al., 2009b), and straw return could play an important role in preserving soil fertility. Relevant studies indicated straw resource is organic fertilizer and straw return could be beneficial for crop yield. These effects have been evaluated globally (Chen et al., 2018; Luo et al., 2018; Lu, 2020) or at national level (Huang et al., 2013; Han et al., 2018; Wang et al., 2015; Waqas et al., 2020). Taking corn straw return in NEC (Northeast China, the famous corn belt in the world) as example, corn production circumstance in NEC is different from other areas in China or other countries, and pertinent evaluation lacks thorough research. Local experiments showed that performance of corn yield increase ranged between nearly -30% (Lu et al., 2014b) and over 50% (Lou et al., 2011). It is unconvinced to use the result from a specific experiment, or borrow the result from other areas. So, effect of corn straw return on corn yield should be explored in accordance with unique circumstance in NEC. Moreover, amount of corn straw return also should be considered. NEC is located at relatively high latitudes (from about 39 to 53 N), in the same latitude zone as the UK, France, Germany, Belgium and so on. Climate conditions play important roles in straw decomposition (Wang et al., 2012; Bradford et al., 2016), higher temperature (Wang et al., 2012; Tian et al., 2019) and precipitation (Torres et al., 2015; Cao et al., 2019) could promote straw decomposition rate.

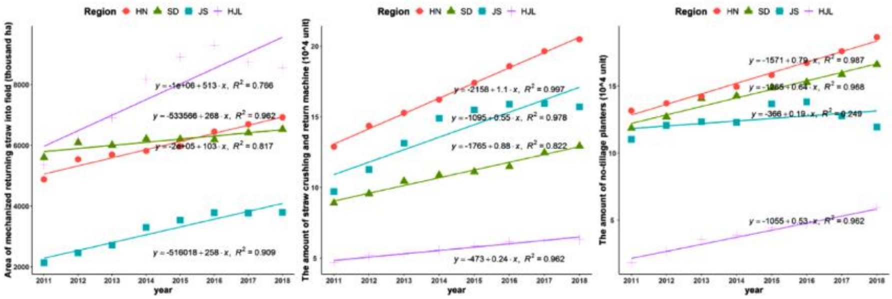
According to the Global Surface Summary of the Day (GSOD) between 2000 and 2018, thermal condition in Liaoning province was better than the other three regions, and the annual average temperature in NEC remains stable for a long period (**Figure 1-8** a). And annual average precipitation in NEC increased dramatically (**Figure 1-8** b), which is favorable to corn straw return. Additionally, unlike crop rotation arrangements (mostly corn-soybean or corn-wheat patterns) in U.S. corn belt (Sahajpal et al., 2014), where crops like soybean with lesser straw produced could alleviate the farmland from discomposing pressure, common practice in NEC is continuous corn cropping (Dou et al., 2018; Zhang et al., 2018a). Continuous and excessive amounts of corn straw return will hinder crop planting. Apparently, corn straw return scheme needs to be optimized.



(a) (b)

Figure 1-8: Weather conditions in Northeast China. (a) Annual average temperature (◦C), (b) annual average precipitation (mm) between 2000 and 2018 in NEC. Data are from GSOD (NOAA, 2020). The abbreviations of EF, HLJ, JL, and LN represent East fourth in Inner Mongolia, Heilongjiang, Jilin and Liaoning respectively.

Furthermore, although corn straw return could increase corn yield, some unfavorable factors hinder farmers' adoption of NEC. To begin with, the shortage of agricultural machines is a problem. Compared with other major crop production regions (Henan, Shandong and Jiangsu provinces) in China, NEC (Data of East fourth in Inner Mongolia are unavailable here) has the largest areas of mechanized returning straw into field, and its increasing tendency is the strongest (**Figure 1-8** a). On the contrary, NEC has remarkably lower holding amount in straw crushing and return machines and no-tillage planters, and its increasing tendency is also lower than in other areas (except Jiangsu, **Figure 1-8** b,c). In addition, due to high cost of straw return, majority of farmers are reluctant to adopt it. A typical mode of corn straw return with agricultural machine in NEC showed that cost could reach to 1350 CNY/ha. Apart from cost, policy support, farmers' perception and education level have significantly influenced farmers' willingness to adopt conservation practice and straw return in NEC (Lv et al., 2013; Yin et al., 2016; Wei, 2016; Zhang et al., 2017a).



(a) (b) (c)

Figure 1-9: The comparison of mechanized straw returning area, straw crushing and return machine and no-tillage planters in China. (a) Area of mechanized returning straw into field (thousand ha), (b) amount of straw crushing and return machine (10^4 unit), and (c) number of no-tillage planters (10^4 unit) between 2011 and 2018. Data are from China Agricultural Machinery Industry Yearbook 2012-2019 (CAAMM, 2012-2019). The abbreviations of HN, SD, JS, and HLJ. represent Henan, Shandong, Jiangsu and NEC (East fourth of Inner Mongolia are unavailable in here) respectively.

Corn straw return is not widely accepted by farmers, and previous survey conducted by Lv et al. (2013) showed that proportion of farmers' actual behaviour of corn straw return in NEC was 11.2% in 2011. However, local government has proposed a magnificent scheme of straw comprehensive utilization. Heilongjiang province has promulgated that, in 2019, 80% of straw should be disposed of properly and 55% should be returned to fields (GOHG, 2019). Jilin province has declared that, by 2021, 79% of straw should be disposed of properly and 37% should be returned to fields (PRDJG, 2019). Thus, popularizing corn straw return would be a challenge.

3.3 The unreliability of straw feedstock supply chain modelling

The operation cost of straw-based industry is usually higher than their conventional alternative, and straw feedstock supply chain is one of the major causes. For example, the cost of straw-based bioenergy products is relatively higher than conventional fossil fuels. In China's power generation industry, straw-based power plants are found to have weak economic sustainability (Zhang et al., 2013; Wang et al., 2020), and they cannot compete with coal-fired power plants. For bioethanol production with higher requirement of technology (e.g., hydrolysis and fermentation), the production cost of bioethanol is too high (Talebnia et al., 2010), and unless with intervention from government (such as policy support in form of tax exemptions, subsidy), the price of straw-based bioethanol cannot compete with petrol (Littlewood et al., 2013). In regard to this, some studies attributed the weak competitiveness of straw-based bioenergy products to feedstock supply chain (Zhang et al., 2013; Wang et al., 2020). Straw feedstock cost accounts for between 40%-70% of total bioenergy production cost (Xu et al., 2020; Tan et al., 2014; Song et al., 2017; Cao et al., 2012; Chen et al., 2006; Ishii et al., 2016; Rentizelas et al., 2009a), depending on scale or energy type.

While many obstacles exist to the establishment and operation of straw-based industry, general worries influence their production, including the high physical volume of straw, costs inherent in collecting and packing straw from farmland, and expenses in shipping straw to producers. Straw feedstock has the features of strong seasonal availability (Lovrak et al., 2020; Bhutto et al., 2017; Vera et al., 2015) and spatially sparse distribution (Sharifzadeh et al., 2015; Natarajan et al., 2016), the cost estimation of its supply is entirely different with conventional fossil fuel supply. This bottleneck hinders the substitution of fossil fuel with straw-based bioenergy in energy-intensive industries and delays the target of achieving carbon neutrality in China. Conch Cement, the second-largest cement manufacturer in the world, tries to substitute coal with straw feedstock in cement production. A demonstration project in Anhui province is designed to consume 300 thousand tons of straw feedstock annually, in return to save 20% of coal consumption (Zhang and Zhang, 2021). However, in reality, the cost of straw feedstock supply is far beyond expectation, and actual substitution rate only increased by 10%.

Besides, one of the major obstacles to hindering the application of previous modelling in biomass feedstock supply is the transparency of simulation process. For some feedstock supply articles (Cao et al., 2016; Panichelli and Gnansounou, 2008), the components in the supply chain did not elaborate, and the selection of key parameters is not reported. The technical and mathematical details are seldom disclosed, and their applicability is somewhat restricted due to the lack of reproducibility. It is hard to reproduce or reuse the simulations from some existing studies. Therefore, transparency is then beneficial for inspection of cost estimations, and the experience and lessons learned from other related studies could be helpful to check the completeness and consistency of the supply chain. For example, for mechanical collection, loading baled straw feedstock is indispensable before transportation, where it is neglected in some studies, and it could be suspicious that the carelessness may result in cost underestimation.

3.4 Lacking sustainable safeguard mechanism

The intangible institutional arrangement is also indispensable in straw comprehensive utilization. Five major stakeholders, namely, farmers, brokers, producers, consumers, and the government, involve in straw comprehensive utilization. Their works and benefit demands are entirely different and sometimes contradicted. Generally speaking, farmers, brokers, producers and consumers have the up-down steam relationship and interactions (**Figure 1-10**). Usually, their relationships are pair-wise, which means that each stakeholder will interact with their up-stream or down-stream partner (Farmers-to-Brokers, Brokers-to-Producers, Producers-to-Consumers relationships). Hence, it requires an independent as well as impartial entity that coordinates such complicated relationships, and government can play such a role. Besides, as for the holder of public finance and social resource, the stakeholders are also eager for lobbying government for favorable policy. The specific works and benefit demand of these stakeholders are elaborated as follows:

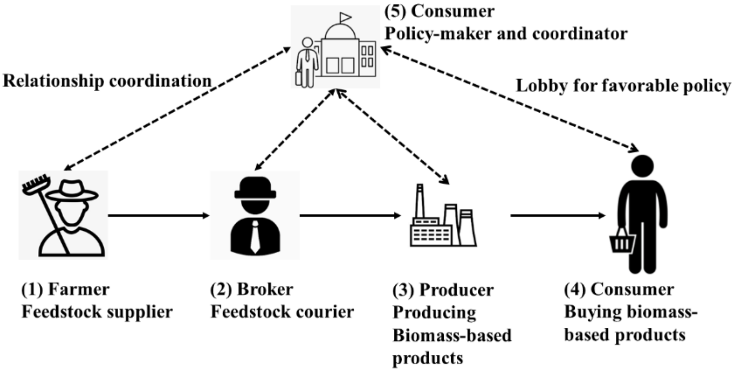


Figure 1-10: The relationship and interaction among the major entity in straw comprehensive utilization, including farmers, brokers, producers, consumers as well as the government.

(1) Farmers

Farmers are feedstock suppliers in straw comprehensive utilization. From the perspective of farmland scale and distance, farmers have distinct perceptions towards straw feedstock selling behaviours, and thus the selling prices of straw also fluctuate. In accordance with the degree of straw demand for farmers, there are three scenarios in straw price: ① farmers sell the straw feedstock based on its original value; ② farmers own excessive amount of straw feedstock; ③ farmers are in a Monopoly position in front of straw users.

For some farmers, they are more capable of disposing of straw resources in an ecofriendly manner. Hence, they could decide the straw price at a relatively reasonable price, from either the substitution effect of straw return or the competition effect of using straw for feed or household energy consumption. But on the contrary, for some straw disposal seriously exploits their precious labor resources, especially during intense harvesting season (Wu, 2001; Xu and Yan, 2016; Feng, 2014; Huang, 2012). Long-term and excessive straw return would bring negative impacts on crop production. It would increase crop disease prevalence, pest infestation and weed germination (Aguiar et al., 2021; Ren et al., 2019). Farmers have to raise expenditures for more pesticides and labor. In addition, low temperature makes straw uneasy for decomposing and biodegradation (Li et al., 2018; Kuang et al., 2014), which would impede root penetration (Li et al., 2018) in cold regions. Multi-year consecutive straw returning may decrease crop yield (Kadam et al., 2000). The field survey from Huang et al. (2019) showed that some farmers doubt that straw incorporation would increase crop yield, and another field survey from Yang et al. (2020) showed that full straw incorporation is not welcomed by farmers. These unfavourable factors frustrate farmers' enthusiasm for straw utilization by themselves. In this circumstance, some farmers have a strong enthusiasm to dispose of the straw in the most convenient way. In the areas with abundant straw production and lack of efficient disposal ways (e.g., cold and dry weather would decrease straw decomposition rate and thus is unfavourable for straw incorporation as organic fertilizer), farmers are even willing to pay for cleaning the farmland with straw removal, especially under the strict ban of straw burning in the farmland. In such situations, the price of straw feedstock is negative (See **Figure 1-11**, scenario②).

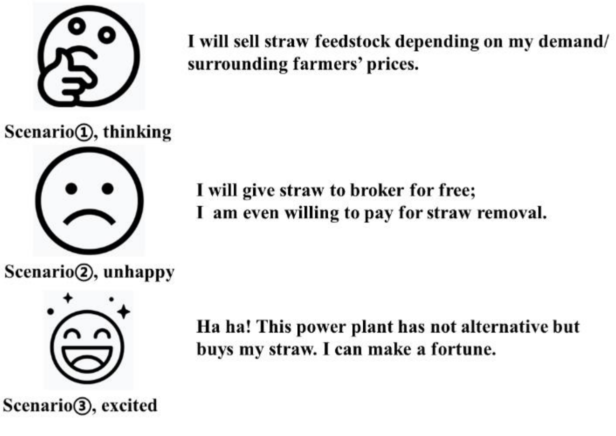


Figure 1-11: The illustration of famers' attitudes towards selling straw in different scenarios. ① famers sell the straw feedstock based on its original value; ② farmers own an excessive amount of straw feedstock; ③ farmers are in a Monopoly position in front of straw users (producers).

For large-scale producers with strong demand for straw feedstock (straw-based power plant, e.g.), farmers may sell the straw at a high price (See **Figure 1-11**, scenario③). Before the construction of straw utilization project, the negotiation between farmers and producers is easy and straightforward because producers are helping farmers to utilize the by-product in agricultural production. However, after the straw utilization project has been built, the feedstock supply is entirely relied on local farmers. With the transportation distance increasing, the supply cost of straw feedstock is raising simultaneously. It will be uneconomical to transport straw feedstock in remote areas. Farmers have time and patience to negotiate with broker by raising straw price because selling price is the sideline business. On the contrary, counting on the huge investment in straw-based biomass production, the idle operation and shortage of straw feedstock supply could bring about heavy economic loss. Farmers may have risked blackmail with egregious prices by taking the advantage of local monopoly position. To sum up, farmers have a flexible position in selling straw, and it is difficult to balance the conflict and secure the interest of brokers and producers. In addition, farmers are usually the vulnerable group (low income & low education), so they have strong interest appeal to government for preferential policy. Hence, how to deal with the subtle relationship between farmers, brokers, and producers requires sustainable safeguard mechanism.

(2) Brokers

In most cases, producers do not face farmers directly, and it usually requires an intermediary (bridge) between producers and farmers. In developing countries, farmland is in small pieces owned by millions of household farmers (Cao et al., 2016; Sun et al, 2017). Data from FAOSTAT (2022) illustrate that, in 2017, arable land per farmer (rural population) in China, India and Thailand was 0.20, 0.18 and 0.48 ha respectively, whereas, in Australia, Belgium and USA 8.92, 3.59 and 2.71 ha respectively. With the increase of mechanization in developing countries, some researchers assumed that farmer-owned tractors could be used in straw feedstock transportation (Sun et al., 2017; Fang et al., 2014; Huo et al., 2016). But the disagreement was proposed by other studies (Rentizelas et al., 2009; Rentizelas et al., 2009b). To begin with, farmers are busy harvesting or planting for next-season crops, and both agricultural machines and labour are intensive (Rentizelas et al., 2009b). Because of the relatively low economic simulation of selling straw, farmers would not endure any inconvenience or impediment with harvesting (Kadam et al., 2000). Emissions from tractors are significantly greater than from trucks in transportation (Lijewski et al., 2013), and the low carry capacity of tractors increases the idle transportation frequencies (Wang et al., 2017). Wang et al. (2015) investigated that the maximum distance farmers could tolerate by themselves was 5 km. Such distance cannot satisfy the needs of large-scale bioenergy projects. There is a dilemma that the time of straw feedstock collection and transportation are short, and to keep the straw feedstock of good quality. Therefore, the “bridge” between farmers and producers, brokers, are emerged.

Producers outsource the work of straw collection and transportation works, and purchases straw feedstock from brokers directly (Liu et al., 2015; Zhao and Li, 2016; Tan et al., 2017, Zhang, et al, 2013; Wang et al., 2020). Brokers are farmers who have a commercial mind and good communication capacity (Wang et al., 2016). They have a good personal relationship with local farmers, and they can collect and transport the straw feedstock from farmers more easily. For producers, they can spread the risk of straw feedstock supply (the costs of vehicle procurement and driver recruitment are huge, Ravula et al., 2008), and concentrate their attention on straw-based biomass production. In addition, instead of negotiating with myriads of farmers for straw feedstock supply (Zhang et al., 2009), producers can propose the procurement requirement with brokers to control the quality of straw feedstock. For example, to require moisture of straw does not exceed a specific standard (17%, e.g.). Good incorporation with brokers can make sure that straw supply could be sustainable, thereby influencing the successful operation of straw-based biomass utilization projects.

(3) Producers

Producers are the core of straw comprehensive utilization. Without the participation of producers, the whole scheme of straw comprehensive utilization cannot work. Farmers would have to either burn the straw in the farmland or return the straw into the farmland involuntarily. The job of brokers would be disappeared and consumers do not have any other option for consumption. The appearance of producers increases the new alternative and new possibility in straw comprehensive utilization. As for an interest group, they want to minimize the cost of straw feedstock supply (dealing with farmers and brokers) as well as in production process and maximize the profit in selling products (dealing with consumers). The development of straw-based biomass industry in China is still in the early stage, and producers have strong interest appeal in preferential policy from the government.

(4) Consumers

Thanks to the development straw-based biomass industry, consumers have more options and alternatives for consumption. For example, the rancher can choose to purchase straw-based forage to feed the animal that substitutes the conventional forage in a scientific way. Instead of consuming conventional fossil fuel, consumers can choose to use clean and renewable energy such as bio-electricity, straw-based bioethanol or straw pellet fuel, which can substitute coal or gasoline remarkably. With the intervention of straw-based biomass products by competition with existing products, consumers can take advantage of two aspects: economy and environment. From the perspective of the economy, consumers make decision depending on the fluctuating price. Consumers are more willing to purchase cheaper products. From the perspective of environment, with the raising awareness of global warming and environmental protection, some consumers are willing to purchase renewable and cleaner products, even though they are much more expensive than conventional products. Hence, consumers have an interest in demand from producers that the cheaper is the better, and on the other hand, consumers also have strong interest appeal in preferential policy from government that supports them to satisfy their needs for fulfilling social responsibility (see **Figure 1-12**).

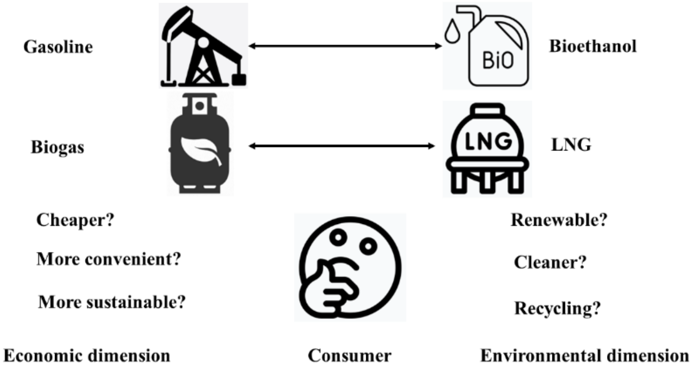


Figure 1-12: The graphical illustration of consumers' decision-making is influenced by economic and environmental dimensions.

(5) The government

The government takes the position of promoter in straw comprehensive utilization. To begin with, it designs and promulgates the scheme of straw comprehensive utilization from both national and regional levels. And then, the government becomes the coordinator that mediates and dissolves the conflict between farmers and brokers as well as brokers to producers. In addition, the government takes responsibility of allocate public expenditure fairly and scientifically. Farmers, brokers, producers and consumers all have strong interest appeals in preferential policy from the government. It is necessary to determine the priority and the scale of supporting policy and subsidy, that make the straw comprehensive utilization scheme can operate smoothly and successfully. Then, the sustainable safeguard mechanism is necessary and the government can achieve top-level design.

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Chapter 2

Research objectives and thesis outline

1. Research objectives

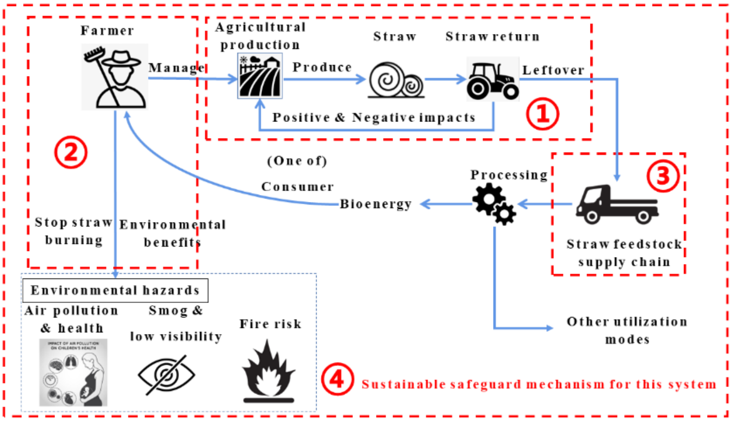

Figure 2-1: Schematic diagram for elaborating the system of sustainable straw management.

In order to better explain research objectives of this thesis, a schematic diagram for elaborating the system of sustainable straw management has been drawn (**Figure 2-1**). Based on the aforementioned discussion of the initiative as well as problematic issues of straw management, the objectives of this thesis can be split into four directions:

1.1 Optimal scheme of straw return

First and foremost, straw return is the first instinct for farmers who want to adopt sustainable straw management, because straw is produced in the farmland, and farmers are the main body executing this practice. Farmers also can be beneficial from optimal scheme of straw return with crop yield increase. Concerning the huge regional and crop-type differences, China's corn belt (Northeast China, NEC) is chosen as a study area for exploring optimal scheme of straw return.

This thesis is trying to appeal to the problems of uncertainty of straw return scheme and provide policy suggestions to motivate farmers to adopt corn straw return in NEC. Although corn straw return seems to be simple, such a method could make the most advantage of corn yield increase in NEC, if implemented scientifically. Excessive straw return would not only be harmful to crop yield, but also brings heavy metals hazard (Yang et al., 2020) for food safety. A comprehensive and quantitative understanding of corn straw return effect may contribute to closing yield gaps between attainable and actual crop yields, and to guiding agricultural practices better. There has been plenty of meta-analysis for corn straw return on corn yield (Rusinamhodzi et al., 2011; Marcillo et al., 2017; Schmidt et al., 2018; Zheng et al., 2019; Zhang et al., 2019), biased selection of coefficients may cause wrong regional evaluation, and furthermore mislead decision-making. Thus, reducing the bias (similar climate conditions and quality of labor and machine) of data should be considered.

1.2 Innovative incentives for farmers

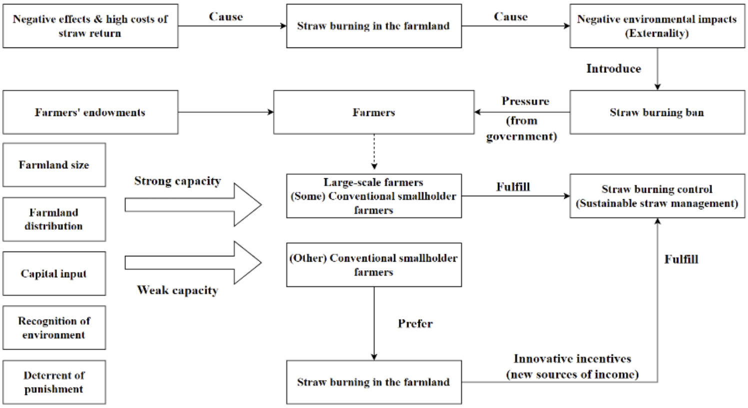

Figure 2-2: The effect mechanism of farmers' endowments on straw behaviour and their impact on the implementation of straw burning ban.

Secondly, due to the divergence of farmers' endowments, straw burning ban faces dilemmas and obstacles in some rural areas (the effect mechanism of farmers' endowments on straw behaviour and their impact on the implementation of straw burning ban is illustrated in **Figure 2-2**), and how to solve this problem ultimately requires "carrots and sticks" tactic, which means that straw burning ban should be strictly implemented on one hand, and monetary motivation should be also provided for farmers on the other hand. From the perspective of government, subsidy is a direct policy measurement that can motivate farmers. However, it still has some limitations (**which are fully discussed in this thesis**), including the potential financial burden as well as the threshold for farmers' participation, which hinder its performance on farmers' motivation. Therefore, instead of increasing the burden on finance, **this thesis purposes innovative incentives for new income source for compensation**.

1.3 Straw feedstock supply chain modelling

Thirdly, in order to achieve the objective of reducing cost, model is a critical approach in strengthening understanding that leads to promoted straw supply chain efficiency. Gosens (2015) established a comprehensive database with information on 236 biomass power plants in China, and most of the projects did not report the supply cost of straw feedstock. These results are the uncertainty of cost estimation, which brings financial risk into operation. Zahraee et al. (2020) emphasized that the expensive cost of feedstock and the unreliable supply chain are the major obstacles to bioenergy development. Straw feedstock could be utilized in various forms, and economic and life cycle assessment for renewable resource has become an active and energetic domain of research in recent years. Hence, reliability and cost competitiveness of straw-based production would rely significantly on straw feedstock collection and provision, simultaneously reducing the supply cost would be critical. However, how straw feedstock is supplied or delivered to bioenergy conversion plants (BCP) are full of knowledge blank and uncertain. Until now, either from academia or industry, providing the relative accurate cost estimation of straw feedstock for bioenergy is lacking. To solve the realistic challenge in straw feedstock supply chain faced by China, and undertake the global responsibility of mitigating global warming by achieving carbon neutrality in time, **this thesis fills the knowledge gap in establishing a straw feedstock supply model that could satisfy the specific conditions in China and ensures a stable and reliable straw supply with optimal arrangements and minimum costs.**

1.4 The construction of sustainable safeguard mechanism

Last but not least, concerning the complicated relationship in the system of sustainable straw management, how to coordinate the interest of each stakeholder (farmers, brokers, producers, consumers, and the government) are crucial. Sometimes, one stakeholder has strong motivation for seizing higher profits by impairing the others, whereas it may bring about a short-time interest but damage the sustainability of the whole system. In other words, if one of the stakeholders is withdrawn from the system, the whole system may collapse and everyone may become the loser. **Therefore, this thesis is trying to construct a sustainable safeguard mechanism that makes sure that sustainable straw management can run on a long-time basis.**

2. The state-of-the-art of this thesis

There must be something new that should be drawn to attention in this thesis, which can be summarizes as follows:

2.1 Integration of meta-analysis and system dynamics with Monte Carlo (MC) simulation

This thesis integrates meta-analysis and system dynamics with Monte Carlo (MC) simulation, makeing results more applicable for regional evaluation in NEC. Research diagram of this section is shown in **Figure 2-3**. To begin with, this thesis examines effects of corn straw return on corn yield in NEC on the basis of the results of published literature. Apart from corn straw return, unbalanced inputs of nitrogen fertilizer (NF) and the amount of corn straw return (AS) could make results incomparable. In consequence, this thesis introduces n-fold cross-validation (Hallmark et al., 2007; Fensterseifer et al., 2017; Singh et al., 2017) to recognize and remove the outlier until the gap is no longer statistically significant, thus eliminating distinction. Based on adjusted effect size (ES), an inventory of corn yield from corn straw return is compiled, and entropy method is used to get the final effect for regional evaluation. To reflect cost and benefit of corn straw return clearly, a system dynamics analysis with MC simulation is introduced to analyse earn and loss from corn straw return by farmers. Furthermore, this thesis contrives an extreme scenario by assuming that corn price would rise, fuel price would slump, and testes how corn straw return would interact. Finally, this thesis gives a cogent answer to reflect realistic conditions in NEC, and provides a valuable reference for decision-making on corn production in NEC and China's food security.

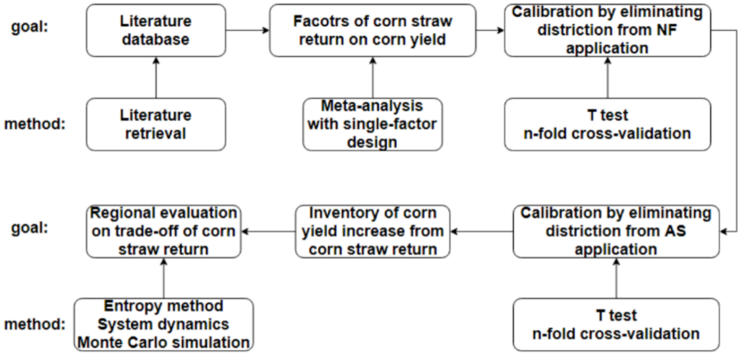

Figure 2-3: The methodological framework of optimal scheme of corn straw return in Northeast China.

2.2 StrawFeed model: An open-source & GIS-enabled linear programming model

Nowadays, most simulations rely on computer programming, which could increase efficiency significantly. However, studies rarely report specific computer software used for programming, let alone provide the original codes for reproducibility. This would be harmful to reusing the simulations for a specific application and hinder further improvement and optimization. Also, Latterini et al. (2020) argued that compared to relying on costly commercial software, using open-source software could be more user-friendly. It could achieve personal extension, such as adding harvesting operation analysis in feedstock supply chain. Thus, using open-source software, such as R language, is becoming an increasingly preferred choice. According to the definition from Open-Source Initiative, open-source software allows the user freedom to run, review, alter, enhance and modify the code for any purpose (Engard, 2010; Open Source Initiative, 2020). Such advantages would be particularly beneficial for simulation and modelling. Open source could provide users with step-by-step guidance on how to calculate each number, and make the results more plausible and comparable. The users could learn directly from the public source codes, and even make modifications to satisfy their personalized needs. Compiling the codes for simulation of straw feedstock supply with open-source software could make the analysis both transparent and highly reliable in the long run basis, and the transparent methodologies for bioenergy planning would be more possible to output the correct solutions (Zubaryeva et al., 2012).

Therefore, this thesis proposes an open-source & GIS-enabled linear programming model called StrawFeed for the simulation and optimization of various straw feedstock supply activities. For better interpretation performance, this thesis chooses to use the open-source programming language R to compile the codes for model manipulation, which could help serve in different application situations in bioenergy production in China. The model is applied to a case analysis of corn straw supply for power generation in Nongan county, Jilin province, China.

2.3 Unique circumstance and experience of straw management in China

As for the current review, Lohan et al., (2018) reviewed the rice straw burning issues in north-west states of India, and Porichha et al., (2021) the straw management practices in India, by comparing straw burning with straw-based bioenergy utilization. Zhao et al., (2017b) explored straw burning and regional hazards in China, from the perspective of temporal/spatial patterns as well as chemical composition. Singh et al., (2021) reviewed the global rice straw burning practices, and discussed the various alternatives with a contribution to environmental and climate changes. Bhattacharyya et al., (2021) reviewed the economic and environmental benefits of straw burning ban in India. Although considerable articles and reviews on straw burning and straw management have been conducted, there is still a lack of comprehensive and systematic review of exploring the status, obstacles, implications, and motivation of straw burning behaviour as well as the dilemma of straw burning control, especially revealing the unique circumstance and experience in China. straw burning control is not only an environmental issue but also a multidisciplinary topic with knowledge from agriculture, (agricultural) economics and (environmental) management.

3. Thesis outline

The chapters of this thesis follow the objectives mentioned above and are presented in seven chapters. The research framework of this thesis is shown in **Figure 2-4**. **The first chapter** concerns the general context of the thesis research and the problematic issues, followed by the **second chapter**, which explains the objectives, thesis outline, as well as the state-of-the-art of this thesis. **Chapter three** is an integrated regional evaluation with meta-analysis and system dynamics on effect of corn straw return on corn production in Northeast China, which provides an inventory of corn straw return on corn yield in NEC, and discusses the difference between ordinary and extreme scenarios on corn straw return practice. **Chapter four** discusses the limitations of subsidy policy and proposes the ideas of innovative incentives of transferred payment from other stakeholders as well as carbon trading, which can be regarded as alternative solutions for farmers who are willing to adopt sustainable straw management in the future. **Chapter five** presents the construction of straw feedstock supply chain model (StrawFeed model), which can be helpful for simulating the operation of straw feedstock supply in China. **Chapter six** is devoted to elaborating on the sustainable safeguard mechanism from the perspective of reliable straw feedstock supply chain, by investigating the challenges and opportunities with scenario analysis. **Chapter seven** presents a general discussion for each chapter evaluating how these solutions can make contribution to achieving sustainable straw management. In addition, **chapter seven** also draws the major conclusion that should be taken into consideration, and provide policy implication for future study.

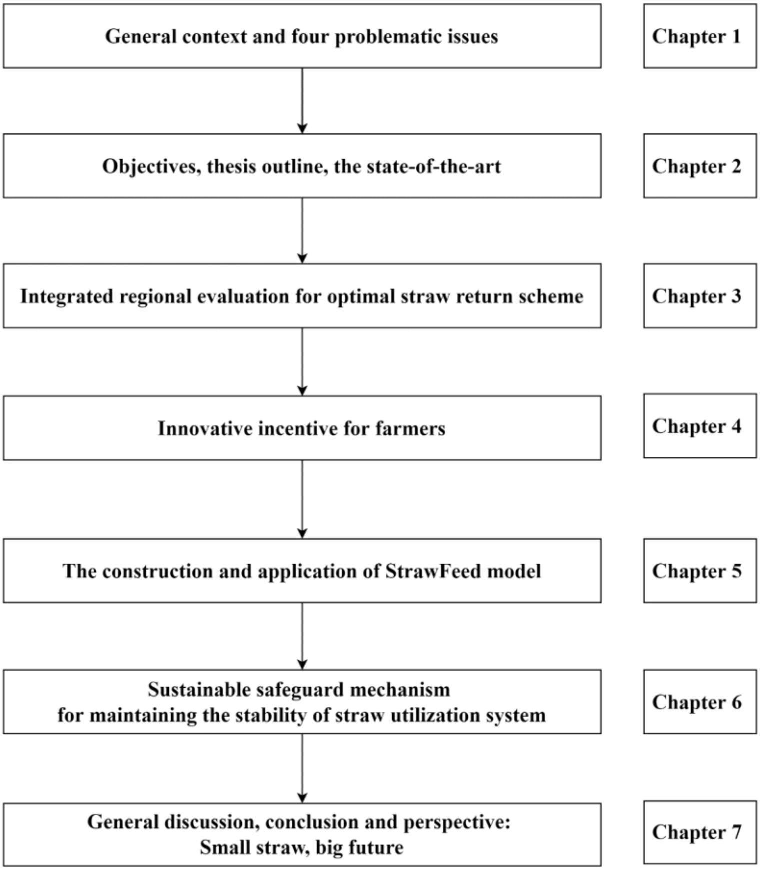

Figure 2-4: The research framework of this thesis.

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Chapter 3

Optimal scheme of corn straw return in Northeast China

Adapt from:

Wang, S., Huang, X., Zhang, Y., Yin, C., Richel, A., 2021. The effect of corn straw return on corn production in Northeast China: An integrated regional evaluation with meta-analysis and system dynamics. Resour. Conserv. Recy. 167, 105402.

It is uneasy to explore the performance of straw return utilization in China because of the differences in geography and straw type. Therefore, China's corn belt (Northeast China) is chosen as a study area for exploring optimal scheme of straw return.

1. Introduction

Annual world corn (Zea mays L.) production is about 1148 million tons for 2018 (FAOSTAT, 2020). Asian farmers contributed to 32% of world's total with three countries being dominant, i.e., China, Indonesia and India, producing 27% of total corn (FAOSTAT, 2020). China has a great demand for corn consumption, not only as food, but also as the major forage for breeding industry. The U.S. is a typical example of agricultural production environment in the world because of large-scale family farms and high coverage of modern technology. Corn production "Corn Belt" in U.S. is concentrated in the Midwest (Green et al., 2018). China has a similar corn production area that cast off the characteristics of traditional small-scale agricultural production, which is praised as the "Corn Belt" in China (Lu et al., 2014a): Northeast China (NEC), including Liaoning, Jilin, Heilongjiang provinces and the east part of Inner Mongolia (Chifeng, Tongliao, Hulunbuir and Hinggan). According to the statistics (NBSC, 2012-2019; BSC 2012-2019; BST 2012-2019; BSHu 2012-2019; BSHi 2012-2019), NEC is made up of around 38% of China's total corn sowing area and 41% of total corn production (**Figure 3-1**). Also, the corn production per capita is around 0.8 ton (**Figure 3-2**), which is nearly 5-times greater than China's average level. So, it is the corn granary that is for food security support in China with high corn commodity rate (over 80%, Li and Sun 2016; Kong, 2020). After harvesting, NEC has enormous corn straw, which is gradually becoming the problem that hinders corn production. Therefore, the aim of this thesis is trying to provide an optimal corn straw return scheme by integrating meta-analysis and system dynamics.

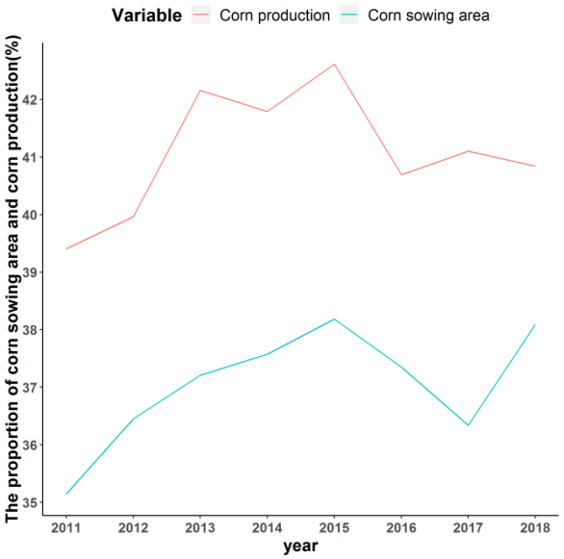

Figure 3-1: The NEC's proportion of corn sowing area and corn production in China (data are excluded from Hong Kong, Macau and Taiwan regions). The sources of data are from NBSC (2012-2019), BSC (2012-2019), BST (2012-2019), BSHu (2012-2019), and BSHi (2012-2019).

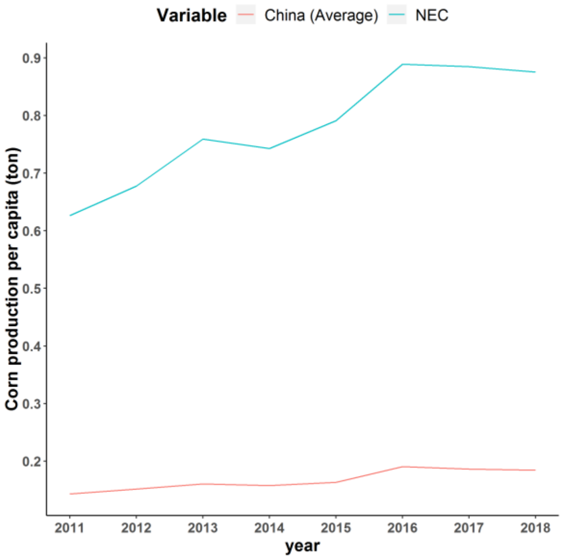

Figure 3-2: The comparison of corn production per capita (ton) between the average level of China (data are excluded from Hong Kong, Macau and Taiwan

regions) and Northeast China. The sources of data are from NBSC (2012-2019), BSC (2012-2019), BST (2012-2019), BSHu (2012-2019), and BSHi (2012-2019).

2. Materials and methods

2.1. Data search and collection

Relevant literature on corn straw return on corn yield is searched by using the online databases of the Chinese Academy of Agricultural Sciences (http://www.isiknowledge.com/ and http://www.cnki.net/) and Google Scholar (http://scholar.google.com/) between 2000 and 2019. The search objects are "straw", "crop residue", and "crop residual". Diverse expressions of straw return are "incorporation", "manure", "application", "mulch", "management", and "addition". Publications in both Chinese and English are included, and the process of literature search is conducted following PRISMA statement (Liberati et al., 2009; Moher et al., 2009) to identify studies. To be considered, the publications have to fit the following criteria: Current agricultural production in China uses NF and avoided exaggerating the effect of straw return, the studies have to be conducted in the farmland (excluded in laboratory); Treatment and control are straw return and straw removal respectively; Input of NF should be equivalent in control and treatment; The locations of the experiment are provided inside the boundary of NEC; Other treatments (straw return with use of plastic mulching etc.) are excluded. Data of soil organic matter (SOM), total nitrogen (TN), and pH are chosen from soil surface (0-20 cm depth). Mean, SD (Standard Deviation), and the number of replicates of treatments is directly acquired from publications, and data from figures could be extracted by using WebPlot Digitizer software (www.automeris.io/WebPlotDigitizer/).

However, plenty of publications provided the results of the least significant difference (LSD) instead of the precise SD. So, SD of these articles could be inferred from p value (Higgins and Green, 2011). Literature that did not report either SE, SD or LSD would be excluded. In total, 216 observations are obtained from 63 published articles, and the database of corn straw return in NEC (**Figure 3-3**) is built. Observations with missing values in SOM, TN and pH are omitted during the individual sub-group analysis. It is assumed that the unreported modes of tillage are using the popular tillage (plowing tillage) in NEC (Tian et al., 2019), and unreported applications of NF and AS return are imputed with the median instead. According to the classification standard of soil nutrient indicators in China (CNSSO, 1992; Huang et al., 2015; MLR, 2016), the soil nutrients are partitioned into two groups with threshold values of 20 g/kg for SOM, 1.0 g/kg for TN. As for the threshold of pH, according to common practices in meta-analysis (Linquist et al., 2013; Valkama et al., 2013; Huang et al., 2018) and Soil Quality Information Sheet from (USDA Natural

Resources Conservation Service, 1998), pH below 6.6 or over 7.3 could be classified as acidity or alkalinity in the soil, whereas pH between 6.6 and 7.3 is neutral. In addition, to consider the number of observations of soil pH in literature and area distribution of dryland soil conditions from Soil Type Database of China (Shi and Song, 2016), soil pH around 6.6 could make good balance between acidic, neutral and alkaline soil in NEC. Therefore, threshold value of 6.6 for pH is determined.

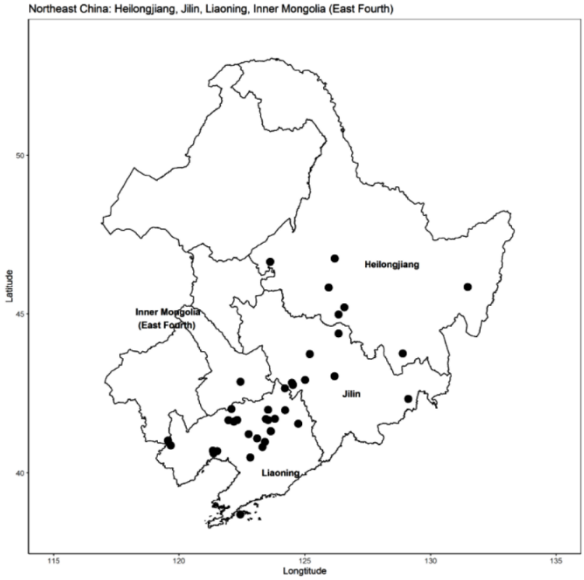

Figure 3-3: The geographical distribution of sites of field experiments across NEC included in the meta-analysis.

2.2. Method of meta-analysis

Meta-analysis is a formal quantitative statistical method to summarize results from independent experimental studies (Curtis and Wang 1998; Yu et al., 2018). This thesis used effect size (ES) to quantify the effect of straw return on corn yield:

$$ES = \frac{X_e}{X_c} \qquad (1)$$

where X_e is mean of treatment group and X_c is mean of control group. In meta-analysis, each treatment is compared to its corresponding control treatment. To express treatments effect on a common scale, natural logarithm of the response ratio is used (Curtis and Wang 1998; Yu et al., 2018):

$$\ln ES = \ln\left(\frac{\overline{X_e}}{\overline{X_c}}\right) = \ln \overline{X_e} - \ln \overline{X_c} \qquad (2)$$

The variance (V) of is:

$$V(\ln ES) = \frac{(S_e)^2}{n(\overline{X_e})^2} + \frac{(S_c)^2}{n(\overline{X_c})^2} \qquad (3)$$

where Se and Sc are the corresponding SD, and n is the number of replicates. The weighted average of logarithmic response ratios is calculated for all independent studies:

$$\ln\left(\overline{ES}\right) = \frac{\sum_{i=1}^{m} w_i \ln ES_i}{\sum_{i=1}^{m} w_i} \qquad (4)$$

where w_i is weight for study i, calculates as inverse of the sample variance ($w_i = 1/v_i$). Thus, studies with large variances among replicates had smaller weights. $\ln ES_i$ is logarithmic response ratio for study i, m is the number of studies, and $\ln \overline{ES}_i$ is mean ES.

For better visualization and interpretation, ES could be converted into percentage by this equation (Liu et al., 2014; Curtis and Wang 1998; Morgan et al., 2003; Wittig et al., 2007):

$$(e^{\ln ES} - 1) \times 100\% \qquad (5)$$

Due to the variations in soil conditions and mode of tillage, there would be sampling errors between estimates (Hedges et al., 1999; Yu et al., 2020). Therefore, random-effect model (Hedges et al., 1999) is used for meta-analysis and observation is the random factor (Cumpston et al, 2019; Liang et al., 2020), assumed that each individual included in the meta-analysis to be a random sample (Harris et al., 2015). Also, heterogeneities among subgroups are conducted with Cochran's Q test (Viechtbauer, 2010). Soil conditions and mode of tillage are used as moderators in an attempt to explain the heterogeneity. All statistical analyses and calculations in meta-analysis are performed in R software and "metafor" package (Viechtbauer, 2010). If the values of the 95% confidence interval for ES of a category do not overlap with zero, effects studied are considered statistically significant; otherwise, effects are not significant.

2.3. System dynamics with MC simulation

Corn straw return is not merely an agronomic practice, and its performance on corn production is also a comprehensive issue, which includes a series of factors like raising expense on labor force usage, fluctuating fuel prices from agricultural machine usage, and changing food price from tense relations between food supply and demand, etc. System dynamics is a modelling approach used to construct simulation models of social systems, and these computerized models could then support policy analysis and decision-making (Duggan, 2016). With the use of mathematical equations, interactions between different factors could be explored.

System dynamics models have been widely used in agricultural production. Suryani et al. (2019) developed system dynamics model to improve corn productivity in Indonesia. They incorporated elements like soil fertility, planting patterns, corn quality, irrigation, technology, climate, disease and pest attacks in corn production processes. Marin-González et al. (2018) established a biophysical and socio-economic model of the smallholder agricultural systems based on the system dynamics to evaluate smallholder endowments on corn-bean intercropping in highland areas of Central America. Hashemi et al. (2019) built system dynamics model to analyze the cropping patterns in the Qazvin plain, Iran. They also concluded that wheat is a heavily water-consuming crop and the removal of planning wheat would be beneficial for groundwater preservation and farmers' revenue. Walters et al. (2016) studied crops and livestock production systems in the U.S. using system dynamics model including driving indicators like social quality, economics, environmental quality and technology. Vaghefi et al. (2016) investigated how extreme climate changes (drought and flooding) influence Malaysia's rice industry using system dynamics model with economic and policy adjustments.

Although previous studies made substantial progress in simulating cropping with driven factors at the regional level, few studies consider crop residue management specifically. Nevertheless, Rusinamhodzi et al. (2016) did study corn straw management in southern Africa with system dynamics model, but interactions between corn price and cost are not acknowledged. Besides, the causal loop for some variables is too trivial that it would be either time-consuming or obscure research emphasis with system uncertainty or inexplicable and unforeseeable results. Corn demand and supply market is complicated, and incorporates activities and relationships that are not thoroughly clear. Many simplifications and approximations are essential and imperative to reduce system dynamics' complexity. Therefore, in order to avoid infinite interactions, only corn price, corn production cost, straw return with agricultural machine cost, and government subsidy are taken into consideration. In this study, the overall cost of straw return with agricultural machine could be partitioned into two components, fuel consumption and other costs (Sopegno et al., 2016). Other costs incorporate ownership cost of agricultural machine (depreciation) and cost of labor force mainly. Although the use of agricultural machine alleviates the labor intensity, labor recruitment for driving agricultural machine is indispensable. The price of labor recruitment for corn production is increasing dramatically in NEC (**Figure 3-4**), and drivers always require high pay than ordinary agricultural works. Based on the field survey and Cui et al. (2011) and Du et al. (2012), it could be assumed that the weights of fuel consumption and other costs are equivalent.

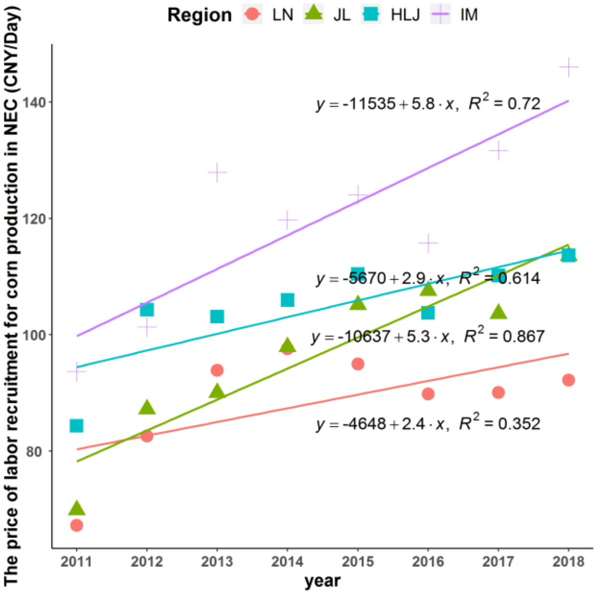

Figure 3-4: The price of labor force recruitment for corn production in NEC (CNY/Day). The abbreviations of LN, JL, HLJ. and IM are Liaoning, Jilin, Heilongjiang and Inner Mongolia respectively. Data are from (PDNDRC, 2012-2019).

Because latent variables like food embargo are hard to be measured directly, so such uncertainty is quantified by Monte Carlo (MC) simulation (Fan et al., 2016). The figure of corn yield without corn straw return is the annual corn yield in NEC. Value of the parameters for the hypothetical ordinary scenario is inferred from current statistics, and the hypothetical extreme scenario is inferred from prospective reports for future movement. Tendency for corn price increase is assumed the situation that food shortage crisis may appear, and tendency for fuel price decrease is assumed the declined demand for fuel and fuel supply competition. The distributions of value for MC simulation follow a triangular distribution, according to Trivedi et al. (2015). Input values are shown in **Table 3-1** and **Table 3-2**, and 10000-times iteration is implemented.

Table 3-1: The fixed values of system dynamics with MC simulation.

Parameter	Value	Unit	Source
Sown area of corn production in NEC (2018)	16047300	ha	NBSC (2019); BSC (2019); BST (2019); BSHu (2019); BSHi (2019)
Annual corn yield in NEC (2018)	6546	kg/ha	NBSC (2019); BSC (2019); BST (2019); BSHu (2019); BSHi (2019)
ES of optimal amount of corn straw return on corn yield	5.83%	-	This research
Fuel consumption of the usage of agricultural machine for corn straw return	112.5	Liter	Field survey and Zhang (2017); Wang et al. (2019a); Wang (2019); Zheng and Chi (2012)
Subsidy for corn straw return	600	CNY/ha	PGOH (2018); DOAJ. (2018); DOFIM (2018)
Straw-grain raito	1.83	-	MOA (2019)
Available coefficient for straw collection	0.85	-	MOA (2019)

Table 3-2: Variables of system dynamics with MC simulation

Parameter	Unit	Ordinary	Extreme	Source
Corn price	CNY/kg	[1.3,1.5,2]	[1.5,2.5,3]	PDNDRC (2012-2019)
Corn production cost	CNY/ha	[9500,9651,9800]	[9600,9800,9900]	PDNDRC (2012-2019)
Fuel price	CNY/Liter	[5.5,6,6.5]	[3,4,5.25]	Cngold (2020)
Other expenses during corn straw return	CNY/ha	[650,675,720]	[680,720,750]	Field survey and Zhang (2017); Wang et al. (2019a); Wang (2019); Zheng and Chi (2012)

Note: Ordinary and extreme scenarios are followed triangular distribution with nominal range [Low, Mode, High].

In general, market is still the fundamental way for adjusting supply and demand of food production, and that is why profitability is the primary thinking for farmers, who could be mobilized and motivated to adopt straw return voluntarily. The purpose of using system dynamics in this study is trying to explore whether corn straw return is profitable or not. Because of the absence of the proportion and amount of the corn straw return to field in NEC, scenarios of whether corn straw return situations influence corn yield are contrived, and hypothetical trade-off for corn production industry and farmers is estimated via cost opportunity approach (Goldsmith et al., 2015; Bartoli et al., 2016; Ssegane et al., 2016).

3. Results

3.1. Meta-analysis in single-factor design

Results from meta-analysis (**Figure 3-5**) revealed that, ES of soil nutrients and pH are not overlapped with zero. Also, ES of soil nutrients is greater at low level than that at high level. ES of soil with alkaline and neutral soil is greater than with acidic soil. Plowing tillage could achieve better yield increase than rotary tillage and no-tillage, whereas the use of no-tillage is statistically insignificant on corn yield increase.

3.2. ES calibration by eliminating impact from mode of tillage, NF application and AS return

ES are distinct between each subgroup, but these distinctions may be exacerbated by diverse applications of NF and AS return, and different usage of tillage mode. According to the results from single-factor analysis, when only considering corn yield increase performance, plowing tillage should be chosen. To begin with, the observations are preserved with plowing tillage. And then, this thesis tested whether the amount of NF and AS applications are different in different subgroups. The results of T-test within each subgroup in soil conditions revealed that, statistical unbalance could be observed. With the help of n-fold cross-validation method, the distinction could be removed, and the results of ES are still robust (**Figure 3-6**).

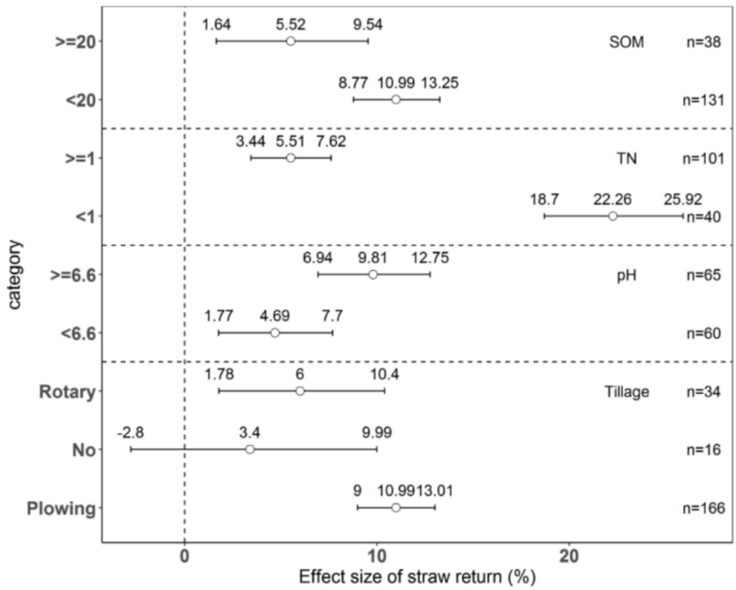

Figure 3-5: Effect size of corn yield calculated using meta-analysis on straw return. Note: Circle symbol represents the mean; the horizontal axis of circle represents the 95% confident interval.

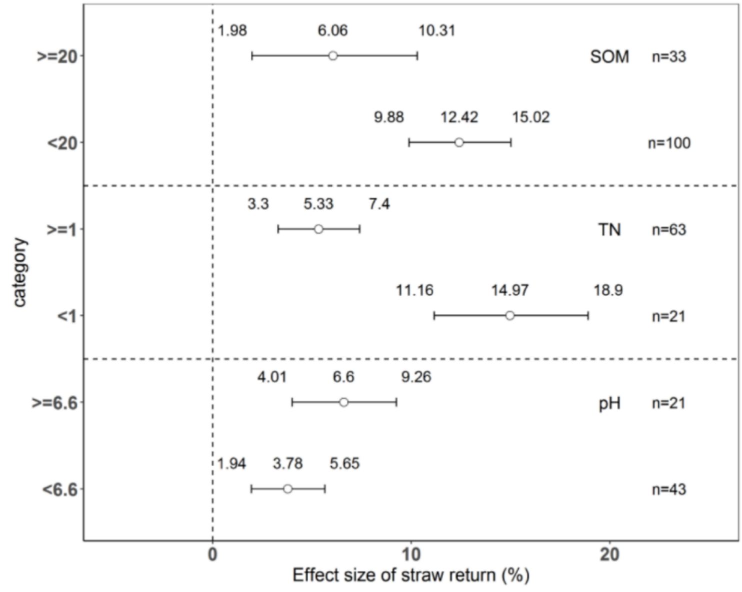

Figure 3-6: Effect size of corn yield on straw return after calibration with mode of

tillage, NF application and AS return.

3.3 Inventory of optimal corn straw return on corn yield in NEC

According to the results, an inventory of corn yield from corn straw return in NEC is compiled (**Table 3-3**). ES of soil conditions indicators are reported one by one, so this thesis introduced entropy method (Zou et al., 2006; Zhang et al., 2014, 2018b) to grasp the weights of each indicator and synthesize it into a comprehensive index to reflect ES. Entropy weights of three soil condition indicators are 0.13 (SOM), 0.10 (TN) and 0.77 (pH) respectively. To assess the performance of corn straw return on corn production in NEC, this thesis used realistic data on dryland soil conditions (Shi and Song, 2016). According to inventory and entropy weights of indicators, optimal scheme of corn straw return is, 48% (7500 kg/ha) of straw accompanied by 209 kg/ha NF, which could bring a 5.83% corn yield increase (around 6.1 million tons of corn) annually. The application of corn straw return could be regarded as an effective measurement to promote corn production in NEC, thereby making contribution to achieving UN sustainable development goal (SDG) 2: “Zero Hunger” (United Nations, 2015). In China, annual consumption of grain per capita was 127.9 kg in 2018 (NBSC, 2019). So, it could be estimated that, with the implementation of optimal corn straw return scheme, raising corn supply could serve about 48.1 million people’s grain consumption. Apart from staple food demand, according to feed-conversion ratio of the pig (3.28; Losinger, 1998), these corns had potential for transforming into 1.87 million tons of pork (without concerning corn-to-feed ratio).

Table 3-3: An inventory of corn yield from corn straw return in NEC.

Category	Threshold	NF	AS	ES mean
SOM>=	20	227	8294	6.06
SOM<	20	216	9027	12.42
TN>=	1	206	7087	5.33
TN<	1	205	6631	14.97
pH>=	6.6	212	7572	6.6
pH<	6.6	202	7092	3.78

Note: The units for SOM and TN are g/kg, and the units for NF and AS are kg/ha.

3.4. Regional evaluation of trade-off of corn straw return

The results of system dynamics with MC simulation indicated that, in the ordinary scenario (**Figure 3-7**), it is uneconomic to adopt corn straw return by farmers voluntarily. Relatively low prices of corn lead to benefit of corn yield increases merely compensating around 90% of monetary expense of fuel consumption in agricultural machine used for corn straw return, not to mention other expense during corn straw return. Granted that the local government provided 600 CNY/ha subsidy for encouraging corn straw return, overall estimation showed that farmers would have deficit under ordinary corn price, cost and policy.

The results in the extreme scenario are quite the reverse (**Figure 3-8**). Due to the increased uncertainty of global food production and the foreseeable food short supply caused by the uncertain factors (for example, "Black Swan" incident: COVID-19), the predictably raising corn price would be favourable for farmers to earn more profit in corn production. Consumers would afford cost of food procurement, but farmers could reduce cost of straw return, especially it is fuel-consuming. The simulation results revealed that, the profit from corn straw return outperformed its costs. Moreover, considering the government subsidy, the extra profit could encourage farmers to be more willing to produce more food and adopt corn straw return with greater enthusiasm.

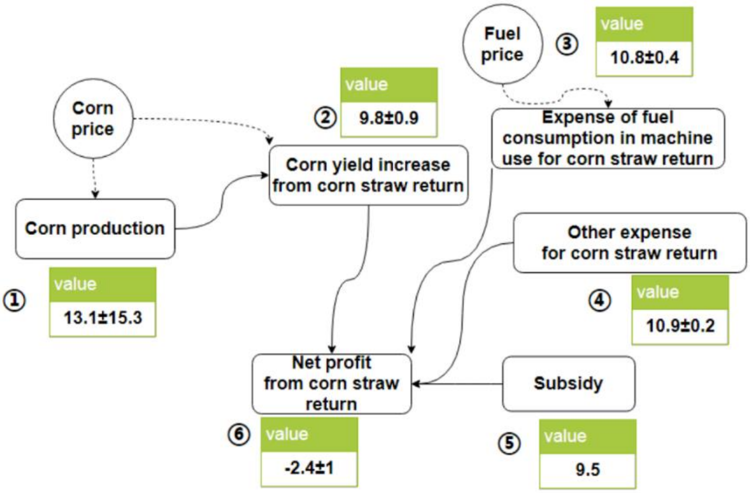

Figure 3-7: Diagram of system dynamics under the ordinary scenario (unit: Billion CNY).

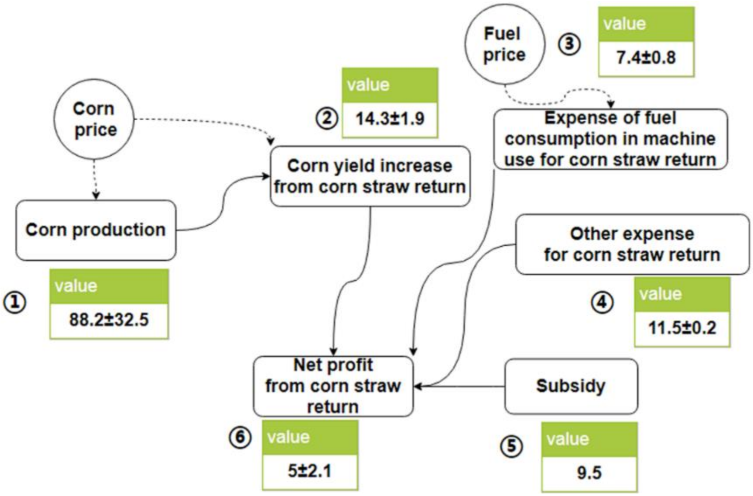

Figure 3-8: Diagram of system dynamics under the extreme scenario (unit: Billion CNY).

4. Discussion

4.1 Poorer soil nutrients should be put into a higher priority in corn straw return

Because of high-intensity agricultural production and excessive use of chemical fertilizer (Li et al., 2018a), soil fertility is facing a declining tendency globally (Tan et al., 2005; Lal, 2009). The area of field with poor soil fertility is rising, which will exacerbate crop yield decrease and food shortage (Tan et al., 2005; Lal, 2009). Therefore, straw return is an important amendment for not only improving soil fertility but also increasing crop yield. This thesis tried to find out the distinction between ES on relatively low and high soil fertility, and results from meta-analysis confirmed the tendency observed by other researchers that straw return could achieve greater crop yield when in low soil fertility. In other words, the marginal utility of straw return is diminishing under richer soil fertility, and these results are robust after eliminating the influence of NF application and AS return. A meta-analysis conducted by Zhu et al. (2017) showed that straw return has a negative effect under initial high content of SOM, and a positive effect under initial moderate level on crop yield. Similar results could be found in Chen et al. (2018), the initial TN content lower than 1 g/kg had the highest ES of crop yield increase with organic amendments, and with the increase of initial TN, ES is decreasing dramatically (approaching to 0 when TN is greater than 2 g/kg). A negative correlation also existed between initial content of SOM and ES of crop yield (Chen et al., 2018; Oldfield et al., 2019).

With the improvement of initial soil nutrients, the contribution rate of straw return to yield decreased gradually (Zhu et al., 2017; Zhang et al., 2016). Therefore, to achieve the maximum corn yield increase, soil with lower nutrients should be put into a higher priority in corn straw return in NEC.

4.2 Alkaline soil should be put into a higher priority in corn straw return

The results from the meta-analysis showed that alkaline and neutral soil had better corn yield than acidic soil. Plenty of meta-analysis research (Linquist et al., 2013; Valkama et al., 2013; Huang et al., 2015, 2018) showed a similar tendency that with a decrease in soil pH, crop yield is also dwindling. This finding is consistent with the acidic soil will cause an increase in the divalent cation concentration (decline in microbial activity) and poor nutrient availability (deterioration of soil health), which would lead to a decrease in corn yield (Walter et al., 2000; Zeng et al., 2014). On the other hand, experiment evidence indicated that corn straw return would cause soil acidity (Zhao et al., 2011; Zheng et al., 2014; Wang et al., 2018; Lu et al., 2019). So, corn straw could be regarded as an important soil pH amendment to balance out alkaline soil into neutralization. A concreted example could be put forward in Songnen Plain (located in the central part of NEC), which occupied 9% of saline-alkali land in China (Wang et al., 2009a). Corn straw return could promote the change of soil pH and raise corn yield significantly in saline-alkali land (HAAS, 2016). Therefore, to increase corn yield, alkaline soil should be put into a higher priority in corn straw return in NEC.

4.3 Optimal corn straw return scheme is recommended and part of straw could be removed from field for bioenergy

The optimal amount of corn straw return is 48% (7500 kg/ha) of the total corn straw resource after harvesting. The allied conclusion from Liu et al. (2019) disagreed with current excessive straw return practice (nearly 98% of straw was returned in their study area), and they recommended that 60% was the perfect percentage of straw return. Also, a field experiment conducted by Jiang and Yu (2019) estimated the increased magnitudes of corn yield with corn straw return in NEC were 12.8% on 8000 kg/ha amendment, and slightly greater than on 4000 kg/ha amendment (11%). The results of this thesis suggested that, the optimal scheme of corn straw return is a sustainable agricultural practice. On one hand, full corn straw return exceeds the field carrying capacity, which will impede root penetration (Li et al., 2018b). So, the optimal AS return could reduce such negative effects as much as possible. On the other hand, if straw return is regarded as the only solution for straw utilization, it would be harmful to the development of biomass industry in NEC, and as a by-product, corn straw could be regarded as important raw material for biomass industry. Although the costs of straw collection, transportation and storage are high and use of straw resource is uneconomical at present, further optimization for straw delivery will be helpful to reduce the cost and ultimately, the use of straw is maybe cheaper than the use of coal in the future (Cao et al., 2016). NEC has tremendous energy requirements and great potential for using corn straw. First, due to the high latitude location and Siberian anticyclone, NEC has a large demand for winter heating energy (Xinhua Net, 2019). Except for conventional energy (natural gas or coal), superfluous corn straw resource could serve for household warming with stove burning (Zhao et al., 2015). Also, Zhang and Ma (2015) assessed five types of straw-reuse technologies with emergy analysis and concluded that straw-briquetting and straw-biogas production are the most beneficial technologies in NEC. Second, corn straw could be used for bioenergy. Li et al. (2012) analyzed that direct combustion power generation and bioethanol are suitable for industrial usage in NEC. Li et al. (2013) used a case study on straw power-generating projects in NEC, and found out that straw cogeneration had a high energy utilization rate and brought more economic benefits. Therefore, the rational organization and planning of optimal corn straw utilization would be beneficial for both corn production and the development of bioenergy industry in NEC.

4.4 The dynamic changes in ordinary and extreme scenarios

Although the scale of agricultural production in NEC is significantly larger than other regions, most farmers earn little profit from crop production, being too feeble to manage the byproduct: the straw from cropping. This situation requires extra expense but has even less profit. The results from system dynamics supported the opinion that current mechanism is unsustainable because farmers have not been economically motivated to adopt corn straw return in NEC, even the optimal straw return scheme with the greatest yield promotion is employed. Local government has high pressure on monitoring farmers do not burn straw in open field. Heilongjiang province declared that straw open burning had exceeded coal firing become the primary source of air pollutants in spring of 2020 (Digital Paper, 2020). In Heilongjiang province between the year 2019-2020, over 50 public officials were held accountable for dereliction of their duty to stop straw open burning, and the police detained the suspected farmers who burned straw without permission, and local authority had been deducted nearly

20 million CNY from the budget as punishment (China News, 2020). In other words, the contribution made by straw return is underestimated, and the subsidy is insufficient. Apart from raising crop yield, straw return could bring various environmental benefits (Hong et al., 2016; Palmieri et al., 2017; Yin et al., 2018), such as improving soil nutrients (Zhao et al., 2014; Cui et al., 2017), SOM (Cao et al., 2003; Lu et al., 2010), and reducing damage from straw opening burning (Sun et al., 2016; Wang et al., 2019b). However, farmers only receive a small part of these benefits, and the burden of straw return cost is mainly undertaken by farmers at present stage (Huang et al., 2019). Therefore, findings in this thesis supported that externality of straw return should be compensated by more and more monetary subsidy. Based on system dynamics results, it could be calculated backward that adding at least 150 CNY/ha to present subsidy standard just makes farmers offset the loss from corn straw return, economically. Unlike other crop yield increase methods (high-efficient fertilization or germplasm improvement etc.), as for the part of large-scale industrial agriculture (Johansson et al., 2013), corn straw return with agricultural machine usage is largely dependent upon fossil fuels. Plowing tillage could make the soil fully mix with corn straw, and it accompanies by intensive consumption of fuel. It is worth mentioning that fuel price decrease has a double effect on agricultural production: on one hand, it decreases the direct expense of agricultural machine; while on the other hand, it decreases the price of related agricultural materials, such as chemical fertilizer, pesticides, and plastic mulch and etc. So, results from system dynamics supported that, farmers who adopted corn straw return could receive a special bonus from fuel price plunge. Including the government subsidy, corn straw return could be profitable, and net profit would reach 312 CNY/ha approximately. In the ideal state, the interests of farmers and government should be balanced. If the measurement extension is entirely relied on subsidy, government would suffer a potential financial burden. The findings from the extreme scenario implied that, a dynamic subsidy mechanism could be further developed in the future. When the changes in price are beneficial for reducing the cost of corn straw return, the government could properly reduce the subsidy standard, where it still could keep farmers’ strong enthusiasm for corn straw return.

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Chapter 4

Innovative incentives for farmers to adopt sustainable straw management

Adapt from:

Wang, S., Yin, C., Li, F., Richel, A., 2023. Innovative incentives can sustainably enhance the achievement of straw burning control in China. Sci. Total Environ. 857, 159498.

According to the above discussion in Chapter 3, optimal straw return scheme could be favorable for crop production, but the deficit is the major bottleneck for farmers to adopt sustainable straw management. The other unfavorable conditions, such as raising pest, weed and diseases, or shortage of labor force and agricultural machines, can be solved by providing sufficient expenditure. Concerning the weak capacity and diseconomy of straw disposal for major smallholder farmers, sufficient monetary incentive is indispensable. However, there are some limitations of subsidy policy. Therefore, instead of increasing the burden on finance, it is eager to explore innovative incentives from a new source of income.

1. The limitations of subsidy in straw burning ban

1.1 The role of subsidy for straw return

Straw return practice has the features of low profitability as well as externality. If it is entirely decided and determined by market (supply-demand comparison and cost-benefit analysis), it could result in market failure. Specifically, although straw return could increase crop yield to some extent, it cannot cover the cost (use of machine, labour input, etc.) of straw return (Wang et al., 2021b; Yang et al., 2020b). As for homo economicus, farmers usually choose to do not return straw to farmland. On the other hand, the atmospheric pollutants from straw burning can not only impact local farmers, but they also can spread and influence the people who lived in adjacent areas or urban residents (He et al., 2020). Besides, straw return has the functions of protecting and enhancing soil biodiversity (Gu et al., 2017; Li et al., 2019b; Peng et al., 2016) as well as raising soil carbon (Liu et al., 2006, 2018b; Wang et al., 2019b). These functions have contributed to ecosystem, but farmers cannot be beneficial from straw return instantly and directly. Hence, government can play a crucial role in resource allocation, and public transfer payment: subsidy (from taxpayer to participated farmers), is supposed to cope with these issues.

1.2 The current status of straw return subsidy in China

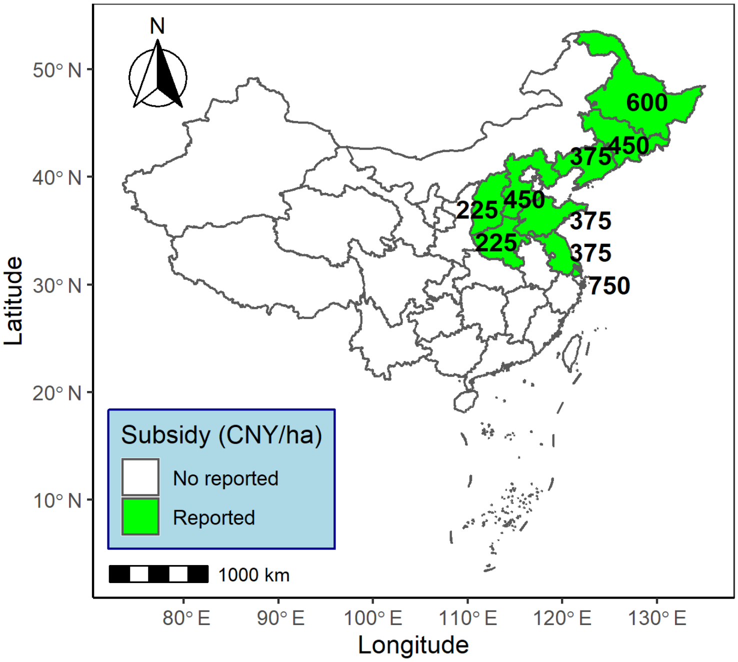


Figure 4-1: The geographical distribution of straw return subsidy in China.

At present, the implementation of straw return subsidy is in the preliminary stage in China, and it has been found in several provinces (see **Figure 4-1**), where it lacks a nationwide policy. The source of subsidy is from central government as well as provincial governments (CACE, 2020; Liu, 2020), but it adopts the pilot project subsidy dominantly. For example, Jilin, Liaoning, and Hebei provinces specifically emphasized the pilot areas of subsidy. In Jilin province, it will create demonstration zone, with an area of 50-200 ha in each county (JLDARA, 2019). In Liaoning province, the requirement is clearer: 333 thousand ha area of farmland in 11 pilot counties (LNDARA, 2022). In Hebei province, it has 172 counties, but only 15 counties have been chosen as pilot counties (HBDARA. 2018). Also, the subsidy level has a strong spatial difference. On average, the subsidy level is around 420 CNY/ha. The subsidy levels in Shanghai and Heilongjiang are the highest (750 and 600 CNY/ha respectively), wherein Shannxi and Henan are the lowest (225 CNY/ha). However, the cost and benefit of straw return can vary by area due to differences in many factors, such as climate and geographical conditions, machine used, method of tillage, soil quality, and even crop price. There is no universal standard of straw return cost, and farmers' perception of straw return always has a strong influence on decision-making. Farmers' willingness to accept (WTA) is usually surveyed by contingent value method (CVM) with questionnaire.

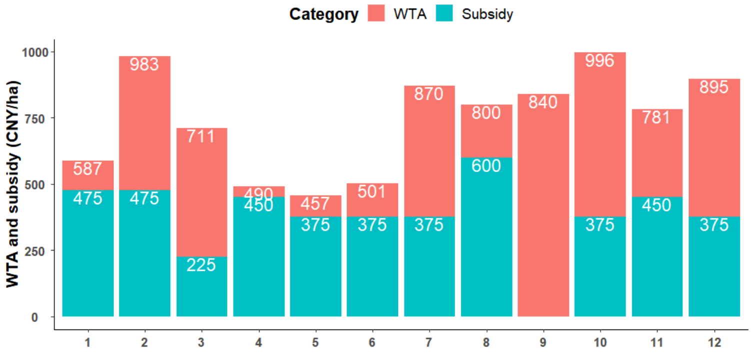


Figure 4-2: Farmers' willingness to accept (WTA) for straw return and the corresponding straw return subsidy in surveyed provinces (CNY/ha). The numbers in horizontal coordinate are the identifier of citation: [1,2] are from Zuo and Huang (2020), [3] is from Yang et al. (2020b), [4-6] are from Huang et al. (2019), [7] is from Yu and Su (2019), [8] is from Li (2018), [9,10] are from Xu et al. (2018), [11,12] are from Yin et al. (2016).

Figure 4-2 illustrates farmers' WTA towards straw return, and the corresponding straw return subsidy in surveyed provinces. The comparison indicates that there is a huge gap between the subsidy provided and farmers' WTA and cannot effectively mobilize and motivate farmers to adopt straw return practice voluntarily. Huang et al. (2019) believed that, inadequate straw return subsidy could hinder the sustainability of straw burning ban as well as straw return policy. Therefore, some researchers (Huang et al., 2019; Han et al., 2018a; Chen et al., 2019) gave policy suggestions that subsidy level should be further increased, thus straw return policy in China should be more dependent on monetary incentive rather than command-and-control regulation. However, the subsidy policy driven by government has two shortcomings: (1) financial burden; and (2) execution effectiveness, which are addressed in the following subsections.

1.3 The potential financial burden from subsidy policy

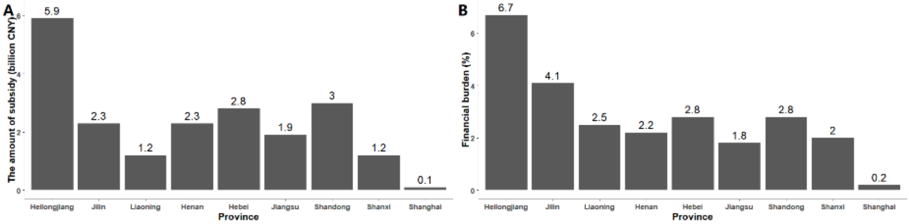


Figure 4-3: The potential estimation of total amount of subsidy (billion CNY) for straw return (A) and its financial burden (B).

The current achievement of straw burning control is based on the administrative measures of straw burning ban as well as the existing subsidy policy in pilot areas. It also explains why straw burning behaviour cannot be eliminated eventually, that is because some farmers are not the beneficiary of subsidy policy. Assuming that subsidy can become full coverage of whole area, it could bring about potential burden on public finance. Based on the subsidy level and sown area, the amount of subsidy needed for straw return and its percentage of financial expenditure for agriculture, forestry and water conservation (In China, these three sectors have belonged to the same item, which is estimated together in government's public expenditure) are estimated respectively (See **Figure 4-3A**). The results illustrate that, apart from Shanghai, the subsidy of straw return is ranged between 1.2 (Liaoning and Shanxi) and 5.9 (Heilongjiang) billion CNY per year, and accounted for between 1.8 % (Jiangsu) and 6.7 % (Heilongjiang) of financial expenditure for agricultural, forestry and water conservation (See **Figure 4-3B**). In China, there are various items of agricultural subsidy that support stable and sustainable operation in agricultural production, thereby ensuring national food security as well as raising farmers' income. In general, the agricultural subsidy is served for: fine seed procurement, grain price safeguard, farm-machinery procurement, ecological compensation (cover crop, straw return, fallow etc.), high-standard farmland construction and so on (Zhang et al., 2021b). For example, eco-compensation is proposed to encourage the planting of green manure by farmers (Li et al., 2020; Li et al., 2021a; Li et al., 2022a). Therefore, it is obvious that, straw return is only one of the items in agricultural subsidy, but it carries a potential financial burden on government's expenditure, especially is unfavourable for major food production areas (Heilongjiang, Jilin, Liaoning, Shandong, etc.) in China. As for subsidy policy, it plays a role in redistribution of social wealth (Azzimonti et al., 2008; Austen-Smith, 2003). If the implementation of straw return practice entirely relies on government's financial expenditure, it may bring about expenditure competition that, other items are influenced by insufficient monetary support and the resource allocation is imperfect.

1.4 The execution performance of subsidy

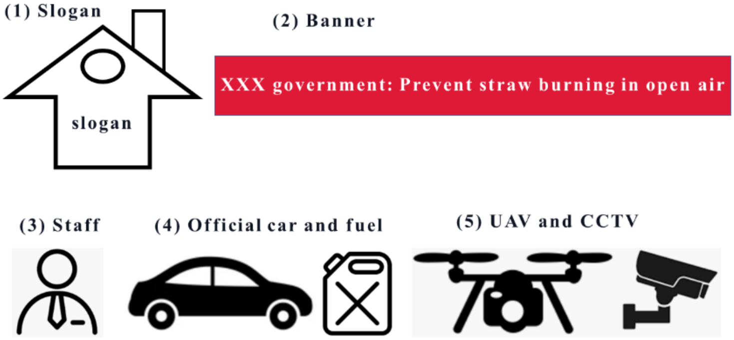


Figure 4-4: The graphical illustration of administrative cost of straw burning ban.

Another challenge in policy of straw return subsidy is the execution performance. In other words, how much subsidies are conveyed to farmers' pocket (claimed by farmers themselves)? According to the results from field surveys (Lu et al., 2022; Zou and Zhou, 2019), a significant share of farmers claims that they do not receive the subsidy. Apart from discussing the malfeasance of officials, the operational cost of command-and-control regulation, as well as quality assessment of straw return practices, impair the execution performance of straw return subsidy. To implement the strict and severe straw burning ban, the inputs of labour force and money are both necessary (See **Figure 4-4**). Specifically, the deployment of local officials who patrol around farmland regularly, and official cars are usually used. Although the use of official cars and fuel cost are free for administrative mission, it will add an extra burden on local finance, particularly for major food production regions with vast sown areas. Besides, straw burning ban is a social campaign in rural areas, and the propaganda is also crucial for raising farmers' awareness of primary-level governance in China. Banner (Ao et al., 2022; Li et al., 2021b) and slogan (Shi et al., 2021a; Zhang and Pan, 2022) on the wall are both popular measurements for rural propaganda. The carder of village will print banner and pose it in the public zone of village, and draw the slogan on the wall. However, the expenditure of banner and slogan on the wall should be taken into account in the campaign for straw burning ban. Finally, with the improvement of new technology, unmanned aerial vehicle (UAV) (Guimarães et al., 2020; Liu et al., 2021c; Yu et al., 2017) and closed-circuit television (CCTV) (Chantara et al., 2012; Fujitani et al., 2020; Lu et al., 2020) are widely used. During straw burning period (before seeding or after harvesting), local officials will use UAV to hover over farmland to grasp the latest movement of straw burning ban, and for the high-risk area that has had many fire accidents previously, the CCTV is installed and monitored by local officials. It is inevitable that these measurements are costly and carry extra financial burden on local finance, so in some regions, straw return subsidy is detained by local officials to compensate for the cost of straw burning ban.

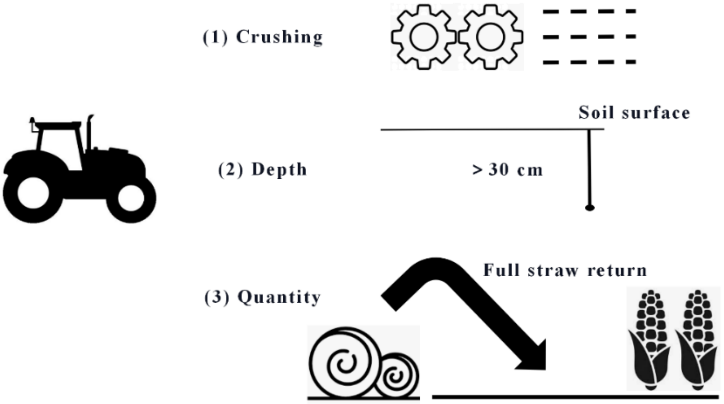


Figure 4-5: The graphical illustration of quality standard of straw return.

On the other hand, the initiative of straw return subsidy is to make sure that straw resource can properly be disposed of by farmers. So, for farmers who want to receive such subsidy, the quality of their straw return practices should be assessed in advance. If straw return practices are performed in low quality or do not fetch the standard, local officials have reason to refuse their application for subsidy. Based on the policy documents of straw return subsidy, the quality standard of straw return can be summarized as three major issues: crushing, depth and quantity (visualized in **Figure 4-5**). To begin with, instead of returning whole straw into farmland, it is suggested to crush the straw into small pieces and make it easier for decomposition. Hence, it will bring about the costs of fuel consumption as well as machine repair. Secondly, for some provinces, they require that deep-plowing tillage is suggested, and the depth should exceed 30 cm. With the increase in depth, the power of tractors for tillage and the costs are rising simultaneously. Finally, if a farmer wants to apply for straw return subsidy, full straw return is required, and the leftover will be checked by officials. A concrete example can be given in Jilin province with detailed working instruction (JLDARA, 2019). The mechanized straw return is mainly executed by new agricultural business entities (large-scale farmers). The farmland should be concentrated together, and the minimal scale should be larger than 2 ha. Moreover, it also has other requirements of depth, quantity of straw as well as agricultural machines. Therefore, pilot policy strategy usually prefers large-scale farmers, and the threshold of application is too high that excludes the smallholder farmers for subsidy acquisition.

2. The innovative incentives of new income source for compensation

2.1 Transferred payment from stakeholders

The aforementioned subsections discuss the experiences and lessons of policy of straw return subsidy in China. For further innovative incentives proposed, it is suggested that, instead of increasing the burden on finance, transferred payment from other stakeholders and carbon trading are more efficient measurements. Clean air is a typical example of a public good, because it has the features of ex-excludability and non-rivalry (Finus et al., 2020). However, because of the externality of straw burning behaviour, the marginal private costs are not identical to the marginal social costs (Sexton and Repetto, 1982). Due to the tragedy of the commons (Ohler and Billger, 2014), farmers will lack the motivation of controlling straw burning or adopting straw return because the costs are paid by a specific group (farmers) but the social benefits of clean air accrue to everyone. However, with the increasing air pollution in environment, clean air is gradually becoming a scarce resource. Hence, people with additional healthy demand are willing to pay for troublemakers in return for mitigating air pollutant emissions or adopting pollutant absorption measurements. In order to elicit the perception of willingness to pay for clean air from stakeholders directly, CVM is a practical and widely-used method. The interviewer will first design questionnaire and investigate the payment level of respondents. A systematic review is conducted by finding all relevant articles about WTP for clean air. Publications selected for this systematic review are found by retrieving scientific databases including, Web of Sciences, Google Scholar as well as CNKI. Combing keywords such as “pay” and “air”, a total of 79 articles have been found eventually. 40 out of these articles reported the respondents’ direct WTP for clean air, while some other articles used proxy variables, such as home prices or scanner data on air purifier sales, to measure the WTP indirectly. The 40 CVM articles with accessible information about the WTP for clean air are summarized in Table **4-1**, including geographical position (country/region), the number of respondents (sample size) the concrete form of WTP. It can be found that, although the WTP can vary due to differences in many factors such as location, income, technology, and perception, it has a huge invisible market and cash flow that some peoples in the society have strong willingness and wealth to pay for clean air. Particularly, for the family that has members with respiratory disease, elderly as well as young people, the payment level can be higher.

Table 4-1: The summary of willingness to pay (WTP) for clean air

Article	Country/Region	WTP
Ain et al. (2021)	Pakistan	73% of respondents do not have willing to pay; 20% of respondents pay up to 5% of their monthly income; 7% of respondents pay up to 10% of their monthly income
Sanchez-García et al. (2021)	Spain	three bid prices: 15 EUR, 30 EUR or 45 EUR.
Wang et al. (2015a)	China	472 CNY per household per year
Akhtar et al. (2017)	Pakistan	10 USD per capita per month
Alberini and Krupni (2000)	Taiwan, China	1.6 to 2.3 times to cost-of-illness
He and Zhang (2021)	China	876 CNY per capita per season
Yao et al. (2019)	China	WTP for improving a lightly polluted, moderately polluted, heavily polluted, or severely polluted day to a clean air day is 8, 9, 13, and 24 CNY per year, respectively
Wang et al. (2019a)	China	22% of respondents are unwilling to pay; 20% and 24% of respondents are willing to pay less than 2 CNY per day and 2-5 CNY per day; 17% and 8% of respondents are willing to pay 5-10 CNY per day and 10-20 CNY per day; Less than 5% respondents are willing to pay 20-50 CNY per day and more than 50 CNY per day
Liu et al. (2016b)	China	55% of respondents are unwilling to pay; 45% of respondents are willing to pay.
Pu et al. (2019)	China	275 CNY per capita per year
Filippini and Martinez-Curz (2016)	Mexico	262 USD per capita per year
Ligus (2018)	Poland	21 PLN per capita per month
Zhang et al. (2020a)	China	869 CNY per capita per year
Guo et al. (2020)	China	65 CNY per capita per year
Chu et al. (2017)	China	27% of respondents are unwilling to pay; 73% of respondents are willing to pay

Yan et al. (2007)	China	100 CNY per capita per year
Sun et al. (2016)	China	1590 CNY per capita per year
Tantiwat et al. (2021)	Thailand	2275 BAHT per capita per year
Shannon et al. (2019)	India	1.3 USD per household per month
Yang et al. (2018)	China	77 CNY per capita per year
Francisco (2015)	Philippines	4 to 6 USD per household per month
Freeman et al. (2019)	China	a median household would pay 22 USD for a one-unit decline in annual average PM2.5 concentration
Liu et al. (2018a)	China	53% of respondents are willing to pay
Carlsson and Stenman (2000)	Sweden	2000 SEK per capita per year
Wang and Mullahy (2006)	China	286000 CNY per capita for saving a statistical life
Vlachokostas et al. (2011)	Greece	Value of a Life Year is approximately 41 000 EUR
Kim et al. (2018)	South Korea	0.025 USD per kWh of electricity use
Istamto et al. (2014)	United Kingdom, Finland, Germany, the Netherlands and Spain	127 EUR per capita per year
Bazrbachi et al. (2017)	Malaysia	1.6 USD per trip
Huang et al. (2017)	China	5.2 million CNY per capita for saving a statistical life
Xue (2019)	China	level of willingness is 2.8 (1 to 5, very unwilling to very willing)
Shi (2019)	China	1173 CNY per capita per year
Deng and Xing (2018)	China	136 CNY per capita per year
Wang et al.	China	32 CNY per capita per month

(2018)		
Mu and Fan (2014)	China	yes/no question.
He and Huang (2014)	China	353 CNY per capita to reduce a pollution day
Xian and Hu (2013)	China	419 CNY per household per year
Zhou et al. (2010)	China	82 CNY per capita per month
Wang et al. (2008)	China	600 CNY per household per year
Cai and Zheng (2007)	China	652 CNY per household per year

However, most of the research did not disclose what background information is given to respondents. The source of air pollutants is also very crucial, because the respondent has preference or priority on how money is used for pollution control. For example, Tantiwat et al. (2021) believed that transportation sector is the major cause of air pollution. Filippini and Martinez-Cruz (2016) described the concrete strategy of air quality promotion to respondents: the improvement of exhaust systems of factory and vehicle as well as substitution of fossil fuel with clean energy. Among these studies, Akhtar et al. (2017), Wang et al. (2019a) and Yang et al. (2018) have attributed that straw burning is one of the major sources of air pollution. Particularly, Yang et al. (2018) contrived the protocol to explain the hazards of straw burning to respondents. The results of survey indicated that, in Henan province, China, 62% respondents are willing to pay for corn straw burning ban, and average WTP reached 76.72 CNY per capita per year. It can be further analysed that, if the WTP can be carried out genuinely in Henan province, it can provide 3.41-3.9 billion CNY economic incentive to compensate for the loss of corn farmers from straw burning ban.

Although it has differences in every sample of investigation, it could be useful for exploring the general trend of willingness to pay for air pollution management, after sorting and summarizing the impact factors (which are shown in **Table 4-2** and **Table 4-3**). The results demonstrate that, high-income-group people have a higher willingness and stronger capacity for supporting more money for air pollution control. Besides, the governing factors of working environment (indoor/outdoor working types), expenditure of respiratory diseases, and people suffering from respiratory diseases can have strong influence on willingness to pay, thereby promoting the establishment and operation of transferred payment mechanism by rising needs. At regional level, areas with high air pollution as well as urban areas also have strong demand for paying for clean air, and therefore the construction of transferred payment mechanism can be regarded as an important measure for air pollution control.

In addition, tourism is also an important stakeholder in straw burning ban. Some scenery is usually located in remote area and is close to village and farmland. Air quality is a crucial factor that affects the decision-making of tourists (Ao et al., 2020). The poisonous air pollutants generated from straw burning could reduce the willingness and enthusiasm of tourists. In order to mitigate the exposure risk to air pollutants, they may choose to alter the schedule or change tourist destinations. Such a problem is not only haunted China, but also appeared in developing counties with profound tourist resource (e.g., India, Thailand). Janta et al. (2020), Punsompong and Chantara (2018) raised that haze pollution from straw burning has brought about high economic damage to Thailand's tourism. Specifically, Pani et al. (2018) emphasized that straw burning has caused fewer tourists or shorter visiting days to visit national parks and wilderness areas in Thailand. Another case appears in India. The Taj Mahal is the largest tourist attraction in India, but it is buried in smog during straw burning season (India Travel Staff, 2016). Worse still, the burning trash can lead to discolouration on the TaJ. Mahal, which may cause irreversible damage to both the building itself and local tourism (Armistead, 2016). Hence, in view of the potential economic loss from straw burning, tourism has the motivation and willingness to pay for straw burning ban as well as air quality promotion.

Table 4-2: The result summary of studies of willingness to pay for clean air.

Ref.	Significance	Insignificance
Ain et al. (2021)	Income, ERD, Location.	Education, AQP.
Akhtar et al. (2017)	Suffering, Income.	Gender, Age, Education, Marriage, Fsize.
He and Zhang (2021)	Pollution, Age, Marriage, Gender. Education, Income, WE, Suffering.	Location
Wang et al. (2019a)	WE, AQP, Age, Income.	-
Pu et al. (2019)	AQP, Age, Marriage, WE, Income.	-
Filippini and Martinez-Cruz (2016)	AQP, Suffering, Fsize, Age, Income.	Gender.
Guo et al. (2020)	Age, Gender, Income, Education, Pollution.	-
Chu et al. (2017)	Age, Education.	Gender, AQP.
Yan et al. (2007)	Age, Education, Income, ERD.	Gender, Fsize, AQP, Suffering, Location.
Sun et al. (2016)	Income, WE, AQP, ERD.	Gender.
Tantiwat et al. (2021)	Income, Location, WE.	Age, Marriage, Education, Suffering, AQP.
Yang et al. (2018)	ERD, AQP, Suffering, Education, WE, Income, Fsize.	Age, Gender.
Francisco (2015)	Income, Education.	-
Liu et al. (2018a)	Education, Income.	Gender, Age, Suffering.
Wang and Mullahy (2006)	Age, Marriage, Fsize, Income, ERD	Gender, Education, Suffering, Location, AQP.
Vlachokostas et al. (2011)	Income, Suffering.	Age, Gender, Education, AQP.
Kim et al. (2018)	Fsize, Age, Education, Income	-
Bazrbachi et al. (2017)	Gender, Suffering, Income	Education.
Xue (2019)	Pollution, Education, Income	Gender, Age, Marriage.
Shi (2019)	Gender, Age, Income, Location, AQP	Education, Pollution.
Wang et al. (2018)	Age, Education, Income, Suffering, WE	Gender, AQP.
Mu and Fan (2014)	Age, WE, AQP, Pollution	Gender, Location, Income, Education.
He and Huang (2014)	Income, Pollution, AQP, Gender, Location	-
Wang et al. (2008)	Education, Income, Suffering	Gender, Age, Fsize, AQP, Pollution.

Note: Factors in abbreviation are: Air quality perception (AQP), Expenditure on respiratory diseases (ERD), Fsize (Family size), Working environment (WE), Suffering from disease (Suffering), Pollution (Air pollution). Working environment means the indoor/outdoor working types. It should be noticed that the factors are selected with the criteria of common and universal use.

Table 4-3: The summary of the proportion of significant factors in the selected studies.

Factor	Total	Significance	Proportion
WE	8	8	100
ERD	5	5	100
Income	23	22	95.65
Pollution	8	6	75
Suffering	12	8	66.67
Age	19	12	63.16
Education	19	11	57.89
Fsize	7	4	57.14
AQP	16	8	50
Location	8	4	50
Marriage	6	3	50
Gender	18	5	27.78

Note: ‘Total’ is the appearance of factor in the selected studies, and ‘Significance’ is the appearance of factors in the selected studies that are statistically significant.

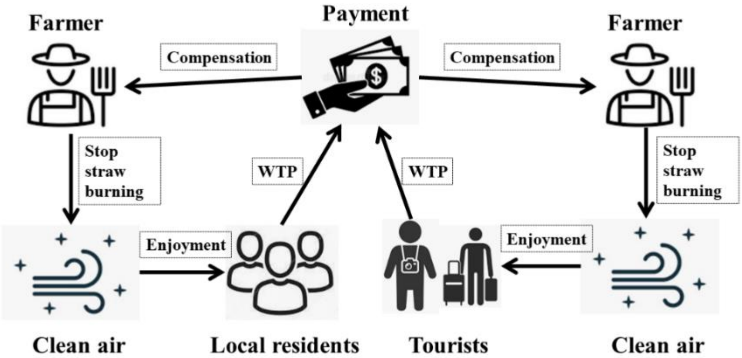


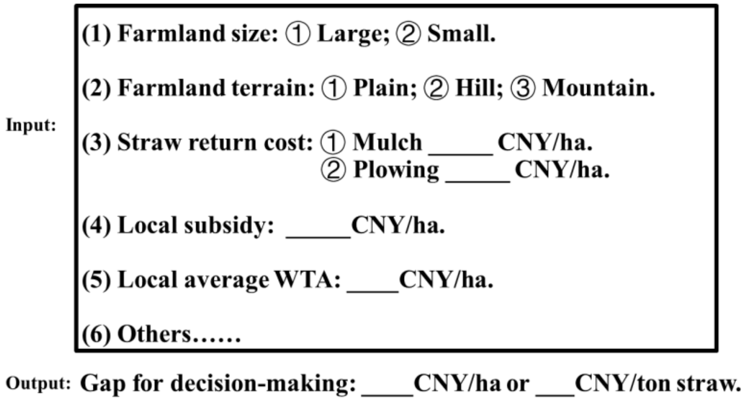
Figure 4-5: The visualization of transferred payment mechanism

On the other hand, farmers who live around have stronger motivation to participate in straw burning ban voluntarily, because they can be beneficial from booming development of local tourism (Huang et al., 2021). Some of the family members are tourist practitioners, and farmers can earn extra revenue from processing and selling tourist souvenir (Sun, 2011). Therefore, if the transferred payment mechanism can be set up (visualized in **Figure 4-5**), it can achieve better performance in straw burning ban as well as reach a win-win solution.

2.2 Carbon trading

Carbon trading is another source of increasing farmers' income from straw burning ban. Since Kyoto Protocol was adopted in 1997, agricultural sector has been regarded as an important source of GHG mitigation, and straw burning (field burning of agricultural residues) is one of the crucial components for abatement. China has developed its own domestic carbon markets, and specifically, seven sub-national carbon markets are in operation (Ren and Lo, 2017). By adopting DID model, Qi et al. (2021) found out that Chinese carbon trading can reduce carbon emission significantly. However, Chinese carbon markets are concentrated on energy-intensive sectors, such as power generation, irons & steel, petrochemical, cement industries and so on (Liu and Jin, 2020), and agricultural items are not incorporated at the present stage (Jin et al., 2021a). Only in Hubei, pilot carbon market, 1.07 million tons carbon credit has been trading with revenue of 16 million CNY for farmers, in the name of poverty alleviation (Jin et al., 2021a). In agricultural sector, the studies on carbon market and trading mainly involve forest management (Blanc et al., 2019; Rooney and Paul, 2017; Paul et al., 2013; Zhou and Gao, 2016), sequestration of soil organic carbon (Yadav et al., 2009; Badgery et al., 2021), peatland rewetting (Günther et al., 2018), nitrogen fertilizer application (Niles et al., 2019), whereas the study for straw comprehensive utilization from perspective of agriculture is rare. Straw can be regarded as biomass feedstock for bioenergy production (Wang et al., 2022c, d), and for clean and renewable energy, straw-based bioenergy has better environmental performance than fossil fuel, thereby the carbon credits from substitution can be traded in carbon market (Ahmadi et al., 2020).

Straw burning injects GHG and aerosols into the atmosphere which could have a negative impact on global warming as well as climate change (Zhou et al., 2017). Carbon market should not only achieve the objective of GHG mitigation, but also provide extra benefits for increasing farmers' income (Lee et al., 2016), which is usually a vulnerable and disadvantaged group in society. The common practice for estimating the GHG emissions of straw burning is by multiplying straw resource data and emission factors (Fu et al., 2021). Emission factors of straw burning can be obtained and collected from previous studies (Shi et al., 2021b), and they are summarized in Table 3. It shows that the significant variety in emission factors of CO_2, and the values of CH_4 remain stable. It is one of the major causes of estimation uncertainty (Wu et al., 2018; Yang and Zhao, 2019; Zhang et al., 2019c). On the other hand, straw return is an important carbon sink method under the background of carbon neutrality. Although it could bring about the increment of GHG emission from soil respiration (Li et al., 2022b) and fuel consumption of machine use, it can be offset by sequestrating carbon in soil. Huo et al. (2022) further estimated that the emission factor of mechanized straw return ranges between -118.6 g CO_2 eq/kg straw in plowing tillage and -136.1 g CO_2 eq/kg straw in no-tillage. Therefore, straw return can be regarded as the substitution of straw burning and also earn extra credit from GHG mitigation. When the carbon sequestration in soil and other types of crops (e.g., potato, peanut, cotton) is also concerned, the potential of GHG mitigation could be larger. The impact mechanism of carbon trading is to encourage farmers to adopt straw sustainable management and fill the cost gap by trading substituted straw burning emissions from carbon market. With sufficient subsidy, farmers can be mobilized and motivated to adopt sustainable straw management practice, thereby reducing straw burning behaviour voluntarily. According to the above-mentioned discussion, farmers' endowments as well as the cost of straw return are the governing factors that influence farmers' decision-making. Hence, in carbon trading mechanism, the information should be reported as inputs, and thus the value of carbon credit for each straw management can be estimated case by case (the graphical illustration is shown in **Figure 4-6**).



Input:

(1) Farmland size: ① Large; ② Small.

(2) Farmland terrain: ① Plain; ② Hill; ③ Mountain.

(3) Straw return cost: ① Mulch _____ CNY/ha.
② Plowing _____ CNY/ha.

(4) Local subsidy: _____CNY/ha.

(5) Local average WTA: ____CNY/ha.

(6) Others……

Output: Gap for decision-making: ____CNY/ha or ___CNY/ton straw.

Figure 4-6: The graphical illustration of input-output design of price determination for straw burning in carbon trading.

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Chapter 5

The construction and application of straw feedstock supply model (StrawFeed model)

Adapt from:

Wang, S., Huang, X., Yin, C., Richel, A., 2021. A critical review on the key issues and optimization of agricultural residue transportation. Biomass Bioenerg. 146, 105979.

Wang, S., Yin, C., Jiao, J., Yang, X., Shi, B., Richel, A., 2022. StrawFeed model: An integrated model of straw feedstock supply chain for bioenergy in China. Resour. Conserv. Recy. 185, 106439.

1. Literature review and motivations

The interest in the research and application of straw feedstock supply increased in the mid-1990s with a focus on corn straw in the US and Europe. These and other similar studies compared a series of various circumstances based on available data to decide the optimal solutions and recognize weaknesses. Now, China, India and other developing countries have become the primary research contributors to straw feedstock supply chain (Wang et al., 2021a). An integrated review of Calvert (2011) concluded that inadequate baseline information (e.g., the spatial-temporal distribution of biomass feedstock) prevented the relevant stakeholders (government responsible for promulgating sector-incentive policy; private investors engaged in bioenergy production) to make correct and responsible decisions. So, the integrated model is contrived that relevant stakeholders could be used to evaluate the sustainability performance of straw feedstock supply chain.

The costs for straw-based bioenergy production could be divided into three components (Mol, 1997): feedstock procurement cost, supply cost for collection and transportation, as well as the cost of establishing and operating the bioenergy conversion plant. Each component has its unique feature. As for straw-based biomass feedstock, procurement is negotiating with farmers to obtain their permission for collecting straw resources. The emissions in different conversation technologies are distinct significantly (Biomass Energy Resource Center, 2009; BASIS, 2015; Niu et al., 2016). The greenhouse gas emissions in biogas-to-electricity are remarkably higher than straw-burning power generation (Said et al., 2020; Wang and Wang, 2020). On the contrary, liquid biogas used for substituting LGP could achieve greater potential greenhouse gas emissions reduction than straw-burning power plants (Soam et al., 2017). So, the separation and determination of system boundary in production, especially in feedstock supply and energy conversion and management stages, could be extremely useful to explain and clarify the uncertainty.

There are two major types of system boundary: cradle-to-gate and cradle-to-grave (Garcia and Freire, 2014; Proietti et al., 2013; Qin et al., 2016). **Table 5-1** sorted out and summarized the representative studies of straw feedstock supply chain, they are selected based on the previous reference database (Wang et al., 2021a) and reported the monetary costs in detail. The cost components are classified according to the description and authors' judgment. It could be observed that the cost components incorporated in every supply chain are distinct significantly, and the clarification and determination of system boundary are necessary and crucial, which could result in misleading decision-making.

Table 5-1: Cost components comparison with other articles in the straw feedstock supply chain.

Article	Pur	Rak	Bal	Loa	Tra	Unl	Sto	Pre	Con	TP	PD	Country
Xu and Chen (2020)	√		√	√	√	√	√			√		China
Tan et al. (2014)	√		√	√	√	√	√			√		China
Sun et al. (2017)	√		√	√	√	√	√					China
Song et al. (2017)	√			√	√		√	√	√		√	China
Xing et al. (2008)	√		√	√	√	√	√					China
Yu et al. (2013)			√	√	√	√	√					China
Fang et al. (2014)			√	√	√	√	√					China
Huo et al. (2016)	√		√	√	√	√	√					China
Cao and Shen (2012)	√			√	√	√		√				China
Yu and Fan (2009)	√		√	√	√	√						China
Ma et al. (2015)	√		√		√				√			China
Chen et al. (2006)	√			√	√							China
Liu et al. (2019)	√		√		√							China
Zhang et al. (2009)	√		√	√	√		√			√		China
Wang et al. (2017)	√		√	√	√	√	√					China
Chen et al. (2012)	√		√		√		√					China
Delivand et al. (2011)	√		√	√	√	√	√					Thailand
Ishii et al. (2016)			√	√	√	√	√		√	√	√	Japan
Allen et al. (1998)			√	√	√	√	√	√				UK
Rentizelas et al. (2009a)	√			√	√	√	√	√	√		√	Greece
Hess et al. (2007)			√	√	√	√	√	√				US
Sokhansanj et al. (2006)			√	√	√	√	√	√				US

Rentizelas et al. (2009b)	√		√	√	√	√	√	√				Greece
Kadam et al. (2000)		√	√	√	√		√					US
Suh et al. (2011)				√	√	√						US
Wang et al. (2020)	√		√		√		√		√			China
Chiu et al. (2016)		√	√		√							China
Roy et al. (2012a)			√		√			√	√			Japan
StrawFeed		√	√	√	√							China

Notes: The abbreviation of column names are: Pro (Procurement), Rak (Raking), Bal (Baling), Loa (Loading), Tra (Transportation), Unl (Unloading), Sto (Storage), Pre (Pretreatment), Con (Conversion), TP (Target profit), PD (Product distribution)

(1) Procurement cost

Procurement cost is a popular cost component in straw feedstock supply chain (18 pieces of article, 62% of overall representative studies), and the procurement prices are diverse significantly, but the estimations are unified: the quantity of straw feedstock required to multiply by the procurement price. Procurement cost of straw feedstock is determined by the opportunity cost of alternative uses of straw, which are circumscribed by various situations and prices are changed dynamically.

In the areas with abundant straw production and lack of efficient disposal way (e.g., cold and dry weathers would decrease straw decomposition rate and thus is unfavourable for straw incorporation as organic fertilizer), farmers are even willing to pay for cleaning the farmland with straw removal, especially under the strict ban of straw burning in the farmland. In such situations, the price of straw feedstock is negative (BCPs could earn extra revenue from straw feedstock collection from farmers, Junginger et al. (2001)). Since it depends too much on the outcome of negotiations with local farmers, in IBSAL model (Integrated Biomass Supply Analysis and Logistics model developed by Oak Ridge National Laboratory), the procurement cost of biomass feedstock is excluded (Sokhansanj et al., 2006; Kumar and Sokhansanj, 2007) borrowed the parameter of procurement from other literature, and added it to overall supply cost additionally. So, it could be estimated independently, and could not be optimized through straw feedstock supply chain.

Figure 5-1: Example of a typical hayrake used in Jilin province (Photograph taken by the author of thesis)

(2) Raking

It is astonishing that, except for (Kadam et al., 2000; Chiu et al., 2016) and StrawFeed model, raking activity is ignored in most of the studies (3 pieces, 10%). The application of mechanical harvesting with combine harvesters could reduce the labor force requirement and alleviate farmers' burden in crop production, and become popular in both developed and developing countries. But it results in the straw spread out in the farmland (Nguyen et al., 2016). Raking with hay rake could gather and concentrate the straw together, which could speed up the working efficiency for baling, and preserve the quality and structure of the baled straw. Hay rakes are widely used in China (See also **Figure 5-1**) and the US. Although the cost of raking only accounted for a small proportion of overall straw feedstock supply cost, it is necessary to point out this omission in terms of the completeness of the straw feedstock supply chain and to enlighten the future estimation with caution.

(3) Baling

Now, baling is the common practice in straw feedstock supply chain (24 pieces, 83%), and this is largely due to mechanical collection, which is gradually substituting manual collection by farmers directly. In comparison with loose straw, baled straw is more compressed, which is beneficial for transporting with lesser volume, and more easily managed in warehousing. The mechanical operation could reduce labor force requirement dramatically (Nguyen et al., 2016), and the working efficiency in mechanical collection is significantly better than manual collection, thereby the unit cost could also be lower (Sun et al., 2017). The mechanization also raises the entry threshold in straw feedstock supply chain. Local farmers cannot afford the investment cost of baling, which promotes the level of specialization. BCP could also reduce transaction costs by negotiating with massive farmers.

(4) Transportation

Transportation is an indispensable activity in every supply chain (100%). So, how to reduce the cost and improve the working efficiency in transportation activity attracts the most interest. Ko et al. (2018) and Wang et al. (2021a) both reviewed the current literature on transportation activity in biomass feedstock supply chain and provided the constructed suggestion on how to promote the reliability and sustainability of transportation activity.

(5) Storage

Whether to incorporate storage activity (20 pieces, 69%) is decided by the acquisition modes selected by BCP. There are two common straw feedstock acquisition modes in China: self-acquisition mode and broker acquisition mode (Wen and Zhang, 2015). For self-acquisition mode, the responsibility of straw feedstock provision should be fully undertaken by BCP, and they require to establish and operate supply chain. They have to purchase straw feedstock from local farmers directly and accomplish the activities independently. By adopting this mode, all cost components in the supply of straw feedstock should be included in cost accounting. In broker acquisition mode, BCP outsources the straw feedstock supply work to brokers. Brokers are local farmers who have a commercial mind and good communication capacity. They believe that providing service between farmers and BCP could earn more money than agricultural production. They have a good personal relationship with local farmers, and could more easily collect straw feedstock from farmers (Wang et al., 2021a). BCP does not involve intermediate activities, and they wait and receive straw feedstock at plants. Under such circumstances, brokers would not undertake the work for storage, because the system boundary for them is “cradle-to-gate”: their work would be terminated when their feedstock provided is weighted and passes the quality inspection. The cost component of storage would be excluded from straw feedstock supply in broker acquisition mode. Storage cost could be calculated by the quantity of straw feedstock required (Sun et al., 2017), or it could be further simplified by a fixed cost for calculation. Kadam et al. (2000) assumed that the storage cost is 4.5 USD for every ton of rice straw in California, US.

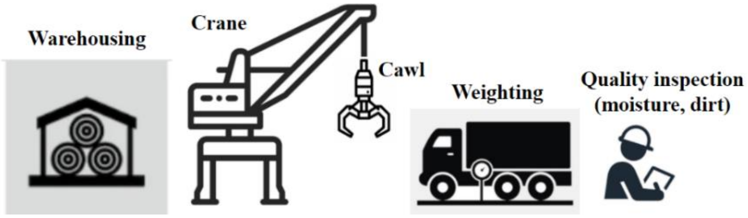

Figure 5-2: Graphical illustration of unloading and delivery-to-warehouse activities by large-scale BCP

(6) Loading & unloading

Similar to storage activity, BCP is responsible for unloading activity (18 pieces, 62%) in broker acquisition. After straw feedstock is transported to the plants, it would be unloaded and managed with cranes and stacked into the warehouse in order (See also **Figure 5-2**). For the small-scale BCP with crane equipment, the cost of unloading activity is much cheaper. Loading feedstock in the field should be conducted simultaneously due to the limited time period, whereas the transportation fleet arriving at BCP should queue up for unloading, and proper amount of unloading machines (forklifts or loaders) could satisfy the need. Hence, some researchers treated the cost of unloading activity is identical to loading activity (23 pieces, 79%), which may result in the overestimation. Alternatively, Kadam et al. (2000) neglected the cost estimation in unloading activity, and they believed that straw feedstock could be "dumped" from the trucks.

(7) Bioconversion and product distribution

Some studies indicated that the straw feedstock supply chain is the subordinate link of straw-based bioenergy production system, and the costs in production stage, include pretreatment (drying, grinding, cooling etc.) and bioconversion (briquetting for pellet fuel or power generation for electricity) are estimated. However, (Song et al., 2017; Ishii et al., 2016; Rentizelas et al., 2009a) further expanded the system boundary on product distribution (selling) stage. Song et al. (2017) and Ishii et al. (2016) estimated the costs of delivering pellet fuels (from corn and rice straw) to consumers respectively. Rentizelas et al. (2009a) calculated the costs of electricity transmission and distribution networks. Hence, the inconsistency of system boundaries would have a remarkable influence on the outcome, and the comparison between different studies should have careful consideration (Soimakallio et al., 2011).

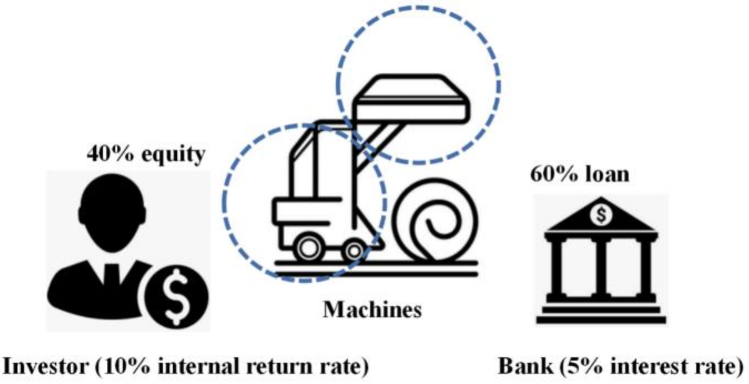

Figure 5-3: The graphical illustration of capital investment adopted from Lin et al. (2013).

(8) Target profit

Target profit is a novel argument in straw feedstock supply chain (4 pieces, 14%). In most cases, the investment does not consider the rate of return on capital. In fact, if the straw feedstock chain is regarded as an independent commercial operation, the investors also claim the profit (interest) from the investment, apart from investment recovery. Taking a concrete example, Lin et al. (2013) contrived a hypothetical scenario in which bioenergy investors held 40% equity, and the remaining 60% of the overall capital investment comes from business lending (e.g., bank load or enterprise bond). Furthermore, occupancy expenses for these two different sources are distinct: the internal return rate from bioenergy investors is 10%, but the interest rate from load is 5% (See also **Figure 5-3**). The occupancy costs for investment should be considered because the capital is not given gratis, and the target profit could be estimated independently. However, it is improper to treat it as a cost component. The critical issue to ensure the sustainable operation of the straw feedstock supply chain is how to allocate the target profit among the stakeholders (farmers, brokers, investors).

(9) The system boundary in StrawFeed model

The full production chain of bioenergy production is complicated, and thus many simplifications, as well as approximation and system boundary settlement, are necessary to reduce model complexity (Nilsson, 1999). This thesis concentrated on the supply activity (cradle-to-gate), because cradle-to-gate boundary is a more realistic option, and gate-to-grave data is often not readily available. As in China, straw feedstock supply is the bottleneck that restricts the development of straw-based bioenergy production, and broker acquisition mode is gradually becoming the mainstream that substitutes self-acquisition mode. The simulated results from StrawFeed model could serve for analyzing interaction of stakeholders among farmers, brokers, and BCP with the cost components of procurement price and target profit. StrawFeed model also fills the knowledge gap of the absence of a sustainable and reliable straw feedstock supply model that could incorporate economic, environmental and social dimensions.

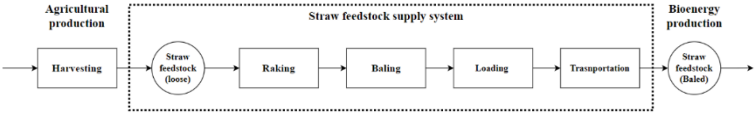

Figure 5-4. The components and technical details in straw feedstock supply model (StrawFeed)

Figure 5-4 shows the overall scope and the important components of the StrawFeed model, where the ellipse represents the materials, the circle represents middle-term and finished products, and the rectangle represents activities. The model focuses on feedstock collection and provision activities. Straw feedstock supply could be classified into the following different tasks: (1) Raking. After harvesting, straw is scattered in the field, and it is hard to collect. Using hayrake could gather scattered straw together. (2) Baling. The low-density straw feedstock could be compressed into bale (hay) by balers. (3) Transportation. Road travelling is carried out using a set of trucks. (4) Loading. Loading straw feedstock to trucks by forklift. In the past, straw feedstock is collected by local farmers artificially. A detailed description of StrawFeed model would be declared in the following sections.

2. The inputs in StrawFeed model

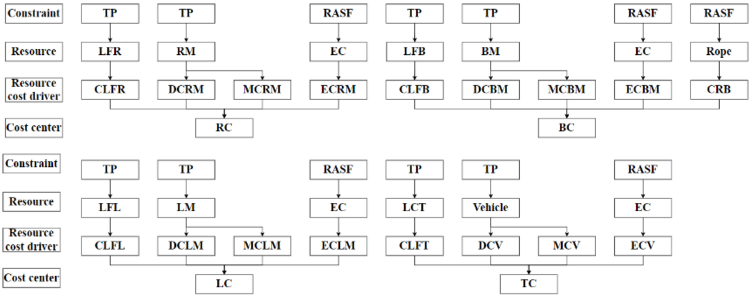

Figure 5-5. The components and description of StrawFeed model are based on an activity-based costing methodology. The abbreviations are listed as follows: (1) Constraint. TP: Time period; RASF: Required amount of straw feedstock. (2) Resource: LFR: Labor force recruitment for raking; RM: Raking machine; EC: Energy consumption; LFB: Labor force recruitment for baling; BM: Baling machine; LFL: Labor force recruitment for loading; LM: Loading machine; LFT: Labor force recruitment for transportation. (3) Resource cost driver: CLFR: Cost of labor force recruitment for raking; DCRM: Depreciation cost for raking machine; MCRM: Miscellaneous cost for raking machine; ECRM: Energy consumption for raking machine; CLFB: Cost of labor force recruitment for baling; DCBM: Depreciation cost for baling machine; MCBM: Miscellaneous cost for baling machine; ECRM: Energy consumption for loading machine; CRB: Cost of rope for baling; CLFL: Cost of labor force recruitment for loading DCLM: Depreciation cost for loading machine; MCLM: Miscellaneous cost for loading machine ECLM: Energy consumption for loading machine; CLFT: Cost of labor force recruitment for transportation; DCV: Depreciation cost for vehicle; MCV: Miscellaneous cost for vehicle; ECTM: Energy consumption for transportation vehicle. (4) Cost center: RC: Raking cost; BC: Baling cost; LC: Loading cost; TC: Transportation cost; SC:

Supply cost.

In order to clarify the StrawFeed model more clearly, an accounting methodology, activity-based costing, is introduced to promote the accuracy of straw feedstock supply cost information. The activity-based costing methodology has been adopted by energy industries (Oh and Hildreth, 2013; Korpunen and Raiko, 2014; Kaiser, 2019; Tinoco et al., 2021). The whole straw feedstock supply process could be modularized, and the description of this methodology application is shown below in **Figure 5-5**. The activity-based costing methodology is particularly useful in scenario analysis, which provides a clear logic chain for how to change the specific parameter that would impact the eventual supply cost.

2.1. Raking and baling

StrawFeed model could simulate collection activities of raking and baling for each farmland. The selection of the necessary machines could be optimized by StrawFeed model, and the collection working efficiency is restricted by the capacity of the chosen machine. Straw feedstock collection is first by raking, and the raked straw could be baled and directly sent to BCP. The selection of a suitable machine is a crucial decision for straw feedstock supply because of the availability of a series of current and innovative technologies. The collection cost comprises the amortized capital cost representing the procurement of hayrakes, balers, and tractors (power source for dragging hayrakes and balers), as well as the operating cost including drivers, energy consumption, maintenance, insurance and repairs. The energy consumption is determined by the required amount of straw feedstock which is known as a-priori and the energy consumption rate. The calculation procedures for the unit cost of straw feedstock in collection activity are shown in supplementary.

2.2. Transportation

Transportation tasks include in-field transportation such as roadside of baled straw feedstock as well as long-distance transportation between farmland and BCP. Due to the soggy and muddy conditions of farmland, in-field transportation cannot be overlooked. Unlike the previous assumptions or applications that either dragging baled straw feedstock to the roadside and loading it with forklifts (it also requires ground-harden surface), or using shovel loader but with lower working efficiency, StrawFeed model adopts an off-road (rough-terrain) forklifts that could overcome the difficulty in in-field transportation and load simultaneously. It is not only popular in China, but it is also exported to other countries. For long-distance transportation, StrawFeed model mainly considers road transportation using trucks, but it could also incorporate river, sea or railway transportation if appropriate. This could enable StrawFeed model to determine the optimal logistic arrangements as well as optimize the vehicle selections and combinations. Transportation working efficiency is circumscribed by the carrying capacity of vehicles. The transportation and loading costs comprise the amortized capital cost representing the procurement of vehicles and off-road forklifts, and the operating cost includes drivers, energy consumption (diesel), maintenance, insurance and repairs. The energy consumption for transportation depends on the distance between different destinations, as well as the energy consumption rate of the vehicles.

The length of idle time also impacts the straw feedstock supply cost. Different from the collection activity of scattered operation in farmland, the transportation activity involves delivering and concentrating straw feedstock in one centralized BCP. Therefore, when a large number of transport vehicles is required or local transportation infrastructure is insufficient, it may cause traffic congestion and postpone delivery efficiency. In addition, if the straw feedstock handling activity (unloading, moisture testing, weighting) associated with the transportation is operating simultaneously, it would also prolong the truck idle time and thereby increase the supply cost, which should be taken into consideration (Yu et al., 2010). Referring to other literature (Sun et al., 2017), StrawFeed model simplifies the complicated situation of idle situation and assumes that the idle time in transportation activity is 0.5 hour for every round trip. The calculation procedures for the unit cost of straw feedstock in transportation activity are shown in supplementary.

2.3. Spatial distribution of straw feedstock in farmland

The characteristics of the scattered distribution of straw in cropland should be taken into consideration. Nearly all studies applied to case studies of straw supply inside an administrative boundary (Hiloidhari and Baruah, 2011; Jenkins, et al., 2020; Singh, et al., 2011), and a significant share of area (buildings, mountain and water, Jenkins, et al., 2020) cannot be regarded as a straw production area. So, land cover classification is necessary to distinguish the collectable area, and straw should only be allocated to these areas. In other words, the intensity of straw distribution is irregular. However, simple assumptions of straw distribution are made in some of the studies. Singh et al. (2011), Chiu et al. (2016) and Sun et al. (2017) assumed that straw was evenly distributed in the study area. Uniformly spatial distribution of straw may cause underestimation of allocation intensity. For instance, if cropland is concentrated on a specific area and the location of bioenergy factories is close to cropland, uniform distribution will exaggerate transportation distance and distort the cost of transportation.

The use of land cover dataset can significantly promote the accuracy of straw distribution. Nie et al. (2020) assessed the technical potential of bioenergy schemes in China with crop growth models and GIS. Land cover dataset came from Data Center for Resources and Environmental Sciences, the Chinese Academy of Sciences was used to identify the cropland from the field, thereby estimating the intensity of straw resource. To estimate the EU bioenergy potential from straw, European land cover raster data are an important source for building up geographical layers for cropland Monforti et al. (2013, 2015). With the rapid progress and development of remote sensing technology, instead of vague assumption of uniform distribution of straw resource in cropland or downloading the existing land cover data, using high-resolution satellite imagery directly for land use classification can be beneficial for regular monitoring information update. Ahamed et al. (2011) reviewed the most common-use vegetative indices and satellite imagery sensors that can be used for biomass feedstock production system. But the accuracy of land cover classification should also be concerned. Hiloidhari et al. (2017) emphasized that land use classification accuracy should be tested in advance, and the accuracy should exceed 85% is recommended for straw supply planning (Hiloidhari et al., 2017; Foody, 2002). The quality of the satellite image and land cover classification methods may impact classification performance. Ma et al. (2017) reviewed 173 publications that studied land cover classification worldwide with meta-analysis, and they found that overall mean accuracy of only four types (among twelve) of sensors (UAV, SPOT-5, QuickBird, IKO-NOS) can exceed 85%. Also, they (Ma et al., 2017) evaluated the accuracy of different supervised classification methods, and concluded that random forest algorithm is better than support vector machines and other methods. Table 1 summarizes the applications of remote sensing technology in bioenergy planning. These examples provide good references for integrating remote sensing technology with straw supply chain design. With the detailed information on straw distribution, better solutions for determining the locations of facilities with optimization methods, including mixed integer linear programming (An et al., 2011; Chukwuma, 2019), k-means clustering (Mueller et al., 2010; Scaramuzzino, 2019), kernel density method (Hohn et al., 2014), p-median model (Comber et al., 2015), can further promote the estimation accuracy of straw transportation.

Therefore, it is suggested that remote sensing technology could become the submodel embedded in the StrawFeed model. It could provide the geographical coordination of farmland, which could be useful for estimating transportation distance and facility site location optimization in advance.

2.4. The distance estimation

When straw resource is located and allocated geographically, and positions of bioenergy factories are determined, the transportation distance can be calculated with a series of measurements. Different measurements of straw transportation distance may lead to exaggerate or underestimate the cost of transportation severely. If there are no existing or planned facilities, a hypothetical position can be contrived by user-define (Yogendra et al., 2011), or it can be assumed by conventional fuel factories replaced by bioenergy factories (Junginger et al., 2001). With the geographic coordinates of locations, instant thinking of calculating transportation distance uses straight-line distance (Euclidean distance, Jenkins et al., 2020). Singh et al. (2010) used straight-line distance to estimate the transportation cost of delivering straw to power plant in India. Yu et al. (2012) assumed that the delivery route is straight-line without considering potential geographic obstruction. Cao et al. (2016) demonstrated that they calculated straw transportation between villages (the smallest unit of straw resource allocated) and straw transfer stations (warehouses) with straight-line distance. Similarly, Wang et al. (2015) assumed that distance between cropland (paddy field in Jiangsu, China) and transfer stations is a straight line or near a straight line. Huo et al. (2016) also used straight-line distance to estimate maize stover transportation distance. Apparently, many researchers have recognized that straight-line distance seriously underestimates realistic transportation, and an adjustment is introducing tortuosity factor (road-bending factor), which can be regarded as reflecting circuitous and intricate road conditions (Jenkins et al., 2020).

The general rule of the tortuosity factor is in croplands with poorer infrastructure (mostly in developing countries), the value should also be raised (Sultana and Kumar, 2014; Diep et al., 2012). On the contrary, in developed cropping areas with better transportation conditions or flat terrain, the tortuosity factor could be lower (Diep et al., 2012). However, in practice, analysis of traffic infrastructure and road conditions for getting appropriate tortuosity factor is rare. Some researchers used the tortuosity factor proposed by others, but failed to explain its applicability. Based on personal experience, some researchers assumed the tortuosity factor directly without giving reasons. Hence, Sultana and Kumar (2014) built up a systematic framework for estimating tortuosity factor in biomass transportation with GIS, and such methodology would be beneficial for getting a more accurate tortuosity factor based on local conditions. A case study in western Canada showed that the tortuosity factor could vary between 1 and 3.16.

Winding factor is another form of tortuosity factor, but many researchers treated it independently. During straw transportation stage, winding factor has a strong influence on straw transportation. So, winding factor is one of explanations that realistic transportation distance is significantly greater than straight-line distance (Leboreiro and Hilaly, 2011). Bennett and Anex (2009) chose the value of winding factor as 1.2. Instead of designating a specific winding factor, Leboreiro and Hilaly (2011) conducted a sensitivity analysis to evaluate the influence of different values of winding factor on transportation cost of supplying corn stover for ethanol production in the USA. Apart from wind, the National Standard “Fuel consumption for trucks in operation” (Standardization Administration of China, 2009) released by Chinese authority summarized a series of tortuosity factors, which consist of road conditions, temperature, altitudes etc. From the given tortuosity factors, a straight line only exists when driving on a first-class highway; temperature is greater than 5 ◦C but lower or equal to 28 ◦C; and latitude is lower than 500 m. Determination of choosing a specific value of tortuosity factor should be based on local transportation conditions.

Whether using straight-line distance directly or adjustment with tortuosity factor, travelling routes of straw transportation are unknown. Another more popular way is using traffic road networks in straw supply chain. To overlap different types of maps (administrative, straw distribution, road network etc.) into a final map, bioenergy factory locations can be optimized in accordance with the shortest transportation distance (lowest cost-efficient) constraints (Voivontas et al., 2001). Calderon et al. (2017) proposed a complicated framework to evaluate the economics of supplying straw and other biomass for producing synthetic natural gas in the UK. In their study (Calderon et al., 2017), mixed integer linear programming (MILP) model was implemented on UK road network to optimize transportation distance and cost. Similarly, Zimmer et al. (2017) evaluated the delivery cost of straw and other biomass to produce biofuel for transportation sector by implementing MILP model on the Chilean traffic network. Another way to find the shortest transportation is via path-finding. In ArcGIS, follow the instructions of Network Analyst extension can assist the users to model the cost-efficient travelling routes for designing a straw supply chain (Hiloidhari et al., 2017). As for the first published pathfinding algorithm (Dijkstra, 1959; Sidhu, 2020), Dijkstra is popular in computing optimal travelling routes between specified start and goal nodes (cropland and bioenergy factories), thereby optimizing the geographic selection of facility location in the sustainable straw supply chain (Liu et al., 2017; Kuisma et al., 2013; Laasasenaho et al., 2019). In the future, algorithm comparison (Astar, genetic, Floyd, etc., Yan et al., 2020) and algorithm improvement (Guo et al., 2019) can be implemented for further travelling routes and transportation distance optimization.

There is a trend that using emerging electronic navigator applications, which can also help to illuminate and enlighten improvement of straw supply chain. With the development of state-of-the-art navigation applications, using paper maps is decreasing dramatically. The survey for drivers towards the use of navigators in 2019 (IT family, 2019) illustrated that only 4.4% of respondents still insisted on paper maps. Apart from another 9.8% of respondents who were driving without any navigator, the rest of respondents chose at least one type of electronic navigators. A survey of over 500 smartphone owners about their reliability on electronic navigator applications (Panko, 2018) showed that more than 77% of smartphone owners use navigation applications routinely, and Google Maps is the most popular application (more than

67% of respondents). Because the services of Google are unavailable in China, other domestic applications are filling the gap. According to survey data in China (Zhiyan Consultant Company, 2019; Wheeler, 2012), users of smartphone navigator applications were over 0.72 billion people in 2018 (accounted for 51.43% of the total population), and the most popular applications were AMAP (60.1%) and Baidu Maps (58.8%). In academia, a new adjustment in publications is proposed to accommodate electronic navigation applications for straw transportation. Elsevier journals including Bioresource Technology launched with an alternative three-pane article view form, and the middle pane features could be enriched with Google Maps (Wheeler, 2012), to achieve better visualization performance for facility locations and straw transportation routes optimization.

Table 5-2: The degree of using Google Maps and Baidu Maps in straw transportation

Reference	Country	Product	Degree of use
Galanopoulos et al. (2018)	Germany	Bioethanol	*
Aguayo et al. (2017)	USA	Bioethanol	***
Liu et al. (2014)	China	Biofuel	**
Ling et al. (2019)	Malaysia	Electricity	***
Galanopoulos et al. (2020)	Germany	Bioethanol	*
Glithero et al. (2013)	UK	Bioethanol	**
Kingwell and Abadi (2014)	Australia	Electricity	*
Martins et al. (2018)	Brazil	Bioethanol	**
Aviso et al. (2020)	Philippines	Electricity	*
Li et al. (2019)	China	Electricity	*
Thengane et al. (2020)	USA	Electricity	*
Tanzer et al. (2019)	Brazil and Sweden	Marine biofuel	**
Singh et al. (2018)	Ghana	Bioethanol	*
Keeffe et al. (2017)	Germany	Biodiesel	**
Sanchez et al. (2016)	USA	Bioenergy with Carbon Capture and Storage	**
Gutierrez et al. (2019)	Australia	Bioethanol	*
Egieya et al. (2019)	Slovenia	Biogas and electricity	***
Zirngast et al. (2019)	Slovenia	Biogas	***
Tiammee and Likasiri (2020)	Thailand	Fuel briquette	*

Note: The degree of using these applications can be categorized as follows: (1) “*” only report a statement that they used Google Maps or Baidu Maps (without citation); (2) “**” citations are given; (3) “***” visualization of facility locations and transportation routes are provided.

There are plenty of advantages of using these electronic navigator applications in straw supply chain. To begin with, geographical information, such as the newly constructed traffic infrastructure or the availability of specific traffic route, can be updated regularly. Also, the consistency of theoretical and realistic straw transportation route design can be guaranteed. Users can be beneficial from free electronic navigator applications (access through smartphone or computer), instead of owning professional navigator. Therefore, using these electronic navigation applications can promote the precision of estimating straw transportation distance and further optimize straw supply chain. The current implementations of Google Maps and Baidu Maps are summarized (19 pieces of article) and discussed how they are performed in straw supply chain optimization (see **Table 5-2**). The degree of using these applications can be categorized as follows: (1) “*” only report a statement that used Google Maps or Baidu Maps (without citation); (2) “**” citations are given; (3) “***” visualization of facility locations and transportation routes are provided. The result shows that the implementations of these applications are in the early stage, and most of the studies (79%) only treated them as online distance calculators. In fact, more functions in these applications can be remarkably beneficial for optimizing transportation distance, thereby reducing the supply cost of straw for bioenergy utilization. They have functions of not only providing geographically shortest pathway with clear navigation instructions and time reminder, but also providing the cheapest pathway (avoiding the use of expressway) or the most time-saving pathway (longer journey but fewer traffic flow and traffic lights, according to analysis on historical traffic congestion data). These functions can satisfy diverse demands of straw transportation to some extent. Learning difficulty is one of the major obstacles of manipulating these applications, especially for non-professional users. Hence, in order to fill in the gaps, a comprehensive method for manipulating Baidu Maps for distance estimation, travelling route optimization and graphical visualization is proposed, and it is compiled via R software, which could be easy to reproduce the works according to user-defined requirements.

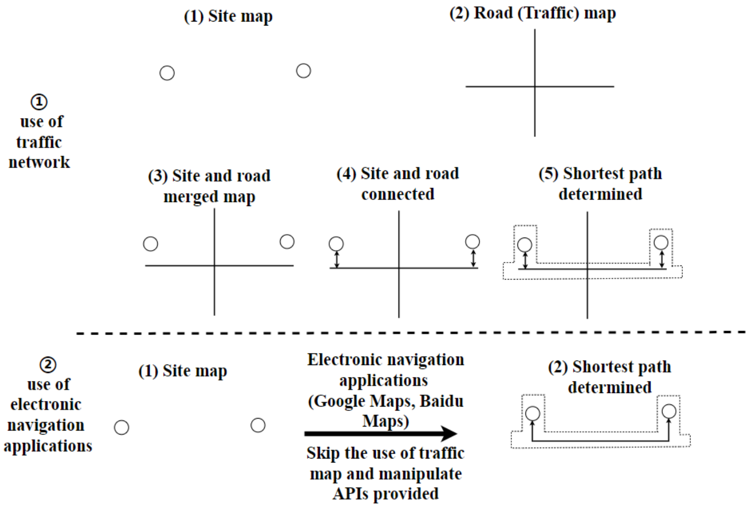

Figure 5-6: A simplified example demonstration to compare the use of traffic network and electronic navigation applications.

The gist of manipulating traffic networks is merged with different map layers. A simplified example demonstration is shown as follows (**Figure 5-6**). To begin with, the site map is given when the locations of starting (farmland) and destination (BCP) are determined. And then, import the traffic network into software and overlay the two maps into one map. Next, by connecting the site locations to their nearest traffic network, a geometric traffic network could be created, and the shortest pathway between farmland and BCP could be decided with various algorithms (Liu et al., 2017; Kuisma et al., 2013; Wang et al., 2021a) at the end. In addition, the timeliness of the traffic network is another concern, especially in the fast-growing developing countries where the traffic infrastructure is promoting rapidly. The obsolete data may affect the performance of transportation distance. Hence, it is recommended to use electronic navigation applications that could solve these drawbacks. When the site locations with geographic coordination are given, the optimal pathway with dynamically updated information could be returned, based on the different constraints (shortest transportation distance with priority of using tollway or longer journey with avoiding tollway, etc.). Now, this computerized operation service is easily manipulated with APIs that are released by these electronic navigation applications. Therefore, instead of rewriting and compiling the new way and codes for optimal pathway selection for straw feedstock transportation, using the services from Google Maps or Baidu Maps could receive better performance in distance estimation.

2.5. Time period of straw feedstock supply

The straw feedstock is only available after crop harvesting. Theoretically, the time period for straw feedstock supply starts from crop harvesting to field preparation for the next-season crop. Time period for single-cropping system is remarkably longer than multiple-cropping system. Also, long-time exposure to straw feedstock would bring dry matter loss, and fungi generated would cause hygiene problems and deteriorate the quality. So, the field is not the proper place for straw feedstock storage, and it should be collected and removed to the centralized and covered storage in bioenergy factory on time. In StrawFeed model, the working efficiency of straw feedstock supply is constrained by available working days (time period), which are determined by the users according to the feedstock requirement.

2.6. Objective function

The StrawFeed model currently uses a cost-based objective function. The objective function is then formulated as the minimization of the total cost for the straw feedstock supply chain which is represented as:

$$\text{Objective} = (\text{Raking\_cost}+\text{Baling\_cost}+\text{Loading\_cost}+\text{Transportation\_cost})/\text{Required\_amount\_of straw\_feedstock}$$

3. Model application: Corn straw supply in Nongan county, Northeast China

3.1. The background information of case study region

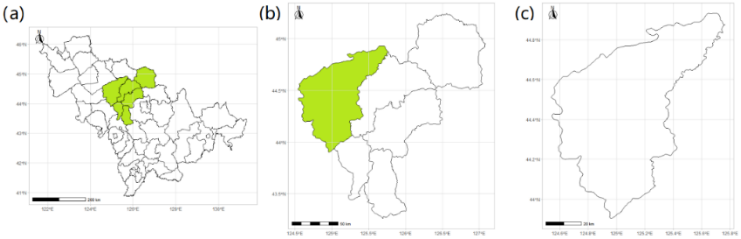

Figure 5-7: The geographical illustration of case study. (a) Jilin province (regions filled with green color is Changchun city); (b) Changchun city (region filled with green color is Nongan county); (c) Nongan county.

StrawFeed model could potentially be used to analyze the provision of any type of straw feedstock in any geographical area subject to the availability of data. This work applied the model to a hypothetical case of corn straw supply in Nongan county, Northeast China (See also **Figure 5-7**). The selection of corn straw is motivated rudimentary by the profound amount of corn straw produced in China but lacked sufficient utilization patterns. Corn could not only satisfy the food demand, but it is also an important raw material for feeding animals and food processing. Domestic corn production is not enough. According to the prediction report, China would import 22 million tons of corn in 2021 (Chinese Agriculture Outlook Committee, 2021). Chinese authority plans to expand the corn sowing area to cope with potential food shortage. It is announced that, Huang-Huai-Hai region (another major corn production region in China) and Northeast China would increase 660 thousand ha of corn land (Ministry of Agricultural and Rural Affairs, 2021).

Moreover, the selection of Northeast China as the geographical area is because it is praised as one of the corn belts in the world, whereas the competing capacity against the Midwest corn belt in the US. In addition, in comparison with other corn cropping areas in China, the farmland resource endowment is much better, with flat terrain and concentrated farmland as well as a relatively low rural population. Therefore, it is suitable for developing family farms with a high mechanization degree of crop production at high corn commodity rates. These advantages are also favourable for the construction and operation of straw feedstock supply chain. In addition, the corn cropping system in Northeast China is one crop per annual, so BCP could have a longer time period for straw feedstock collection and transportation. The county is a crucial administrative unit in China (Long et al., 2021). It undertakes the major task for agricultural production that could provide adequate straw feedstock for large-scale bioenergy production. It has an industrial foundation and demands bioenergy products to some extent. Also, the county has proper administrative power to manage and supervise the operation of BCP, and provide incentives and motivation policy. Therefore, it is no doubt that the potential for straw-based bioenergy development at county level is significant and the demand is urgent.

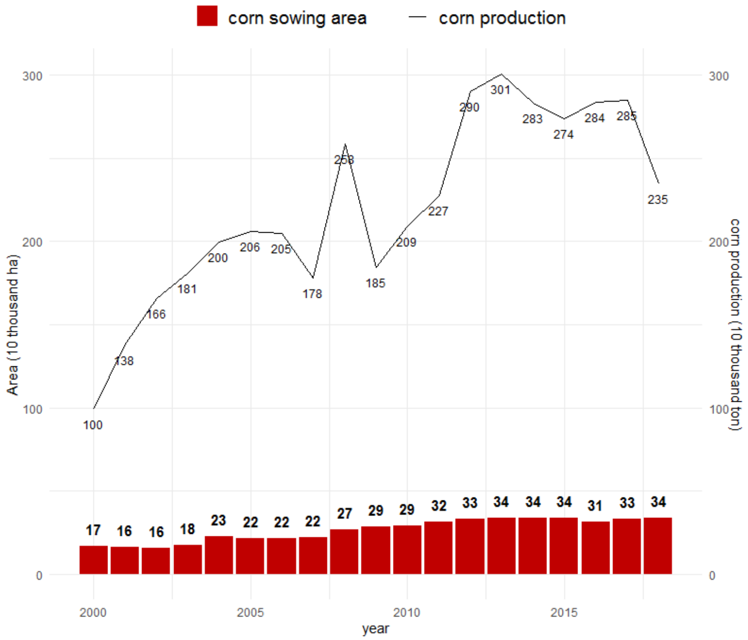

Figure 5-8: The corn sowing area (line) and production (bar) in Nongan County. The statistical data are from Statistic Bureau of Jilin (2019).

On the bioenergy production side, producers prefer to preserve constant and uniform quality of feedstock (Lin et al., 2013). The reason why Nongan county is chosen as the study area is that corn yield in this county is the highest among other counties in Northeast China, with a sown area of 338299 ha and 2349102 tons in 2018 (See also **Figure 5-8**). Also, the annual corn production and sown area in Nongan county have increased steadily since 2000 and remained stable since 2010. So, it is regarded as a major corn production county in Northeast China. Besides the current and short-term leading production of straw feedstock, the long-term assessment for local cropping structure is very important and useful. For instance, cassava stalk is discarded from the consideration for bioenergy production in North Thailand, because of the gradually decreased production over 10 years (Junginger et al., 2001). The historical data of corn production in Nongan county showed a booming trend, so the long-term stable and sustainable straw feedstock provision could be guaranteed. The case study considered a hypothetical BCP at Nongan town Guoyuan village (44°44’685” N, 125°08’03” E) that is central to the straw collection area, and a centralized storage yard is adjacent to BCP. The selected BCP and its storage location have an existing railway and highway infrastructure, which might be a useful selection criterion to enable multi-model straw feedstock transportation in the future. The corn straw distribution is the same as the existing distribution of corn farmland, while the geographical distribution of the corn farmland is determined using the land cover classification criterion proposed by (Tang et al., 2018). Since the corn farmland distribution is located with high-resolution images from remote sensing technology, it did have the geographical coordinate as a parcel. The transportation distance between every corn farmland and BCP is calculated by using Baidu Maps (the major service provider for electronic navigation applications in Mainland China).

The yield of corn in Nongan county was 6.9 tons/ha in 2018. Based on the straw-grain ratio and collectable coefficient (the conversion rate that measures the stubble height to impact the leftover straw), it could be measured that the theoretical maximum amount of corn straw is around 11 tons/ha. The agricultural machine data are taken from the National agricultural machinery testing and appraisal management service information platform (Agricultural machinery experiment and appraisal station, 2021) and Jilin agricultural machinery procurement subsidy information system (Jilin Agricultural Machine Management Bureau, 2021). The data for off-road forklifts are taken from the literature (Wei, 2014). It is assumed that this BCP in Nongan county required 200 thousand tons of corn straw.

The availability of straw feedstock has strong seasonal restrictions. The start day of straw collection cannot exceed the crop harvest day. According to the corn planting season in Northeast China, the harvest time for corn is in late September. The moisture of fresh corn straw after harvesting is high (>30%). So, the common practice is to let the corn straw expose in the farmland and wait for the water evaporation. Therefore, the work schedule of straw collection could be started in October. Straw supply chain is seriously affected by weather conditions (temperature, rainfall etc.). Northeast China is located in the high latitude zone, and the temperature would be extremely low in the winter. Sokhansanj et al. (2006) suggested that, if the temperature is lower than -10 ◦C, that day should be considered as a non-work day for straw collection. Based on local experience, the straw supply work should be completed before snowing (Ning, 2018). So, it would be terminated in early November, and it could be assumed that the time period for straw supply is 40 days. The time period for straw supply can be adjusted in accordance with the local needs or actual requirement from BCP.

Table 5-3: The cost components (CNY/ton) of straw feedstock supply partitioned by activities (raking, baling, loading and transportation) in different scenarios

Activities \ Scenarios	Baseline	Weather	Optimal	Hiring	Subsidy
Raking	1.0	1.1	1.8	0.8	0.9
Baling	84.3	92.9	84.3	66.9	75.7
Loading	14.3	15.4	14.3	12.2	14.3

Transportation	72.5	85.3	162.8	61.6	72.5
Supply Cost	172.0	194.6	263.2	141.5	163.4

Notes: The column "Baseline" represents baseline case, and the columns "Weather", "Optimal", "Hiring", "Subsidy" represent scenario1-4 correspondingly.

3.2. Results and discussion

Based on the statistical data in 2018, the results showed that, 18218 ha of corn farmland is necessary to produce 200 thousand tons of corn straw feedstock annually, which accounted for 5.4% of the total corn sowing area in Nongan county. The feedstock supply costs are 172 CNY/ton (See also **Table 5-3**). Among the costs, baling-relating cost is the most significant cost, accounting for 49% of the total supply cost, followed by transportation (42.1%), loading (8.3%) and raking (0.6%); as for cost category, cost for energy consumption is the highest cost, accounting for 30.8% of the total supply cost, followed by cost of labor force recruitment (25%) and machine depreciation (22.7%). The other cost is the most minor cost category that, only took up 21.5 % of the total supply cost. The results also show that the requirement of the machine is 9 hayrakes, 125 balers, 134 tractors, 53 forklifts and 406 trucks. The overall investment for machine procurement would be reached approximately 90 million CNY. The mean transportation distance is 14.5 km and using Euclidean distance without considering the realistic driving circumstance underestimated the transportation distance (8.2km), so using electronic navigation applications (Baidu Maps, Google Maps, etc.) are the promising ways to promote the accuracy of cost calculation.

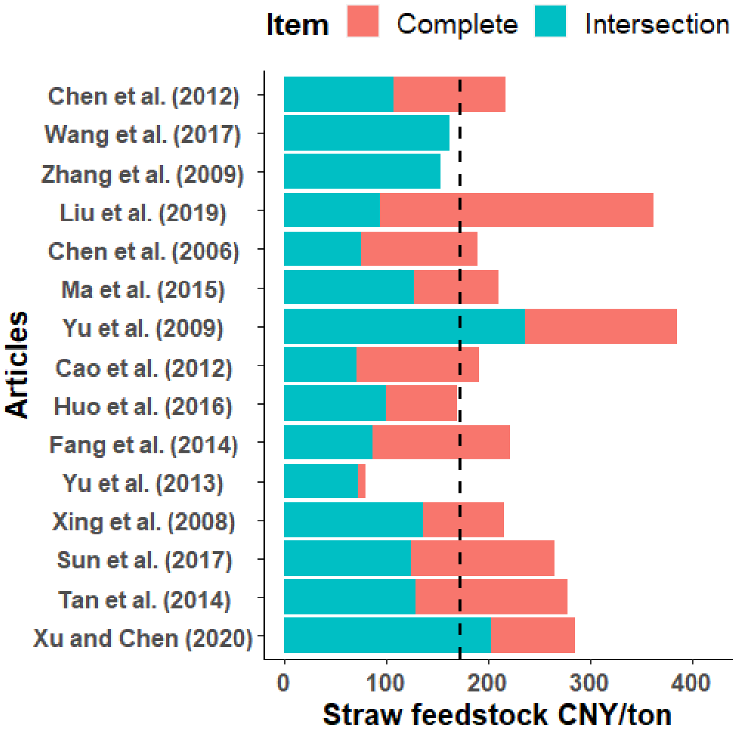

Figure 5-9: The comparison of straw feedstock supply cost in China. The dashed line represents the estimated result from StrawFeed model (172 CNY/ton). The item 'Complete' stands for the overall supply cost contains cost component reported from articles respectively, and 'Intersection' stands for the common cost components between StrawFeed model and cited articles.

Figure 5-9 compared straw feedstock supply cost from StrawFeed model with other similar studies from China. Instead of comparing the full supply chain with different research boundaries, the intersection of similar cost components is also extracted. The results indicated that, considering the geographical and temporal heterogeneity, the cost estimation from StrawFeed model is reasonable, and located in the intermediate position among others. According to interviews with local brokers and BCP in Jilin province by media, the procurement price for straw feedstock by BCP is around 300 CNY/ton. After excluding the cost, the profit from straw feedstock supply chain could reach roughly 128 CNY/ton.

Sensitivity analysis is practical tool to explore the robustness and reliability of StrawFeed model (Saba et al., 2020). It is helpful for identifying and quantifying the impacts and potential risks of business operation (Dimitriou et al., 2018). With respect to fuel price, labor cost, idle time, speed (in transportation) and daily working hour are included in sensitivity analysis. The purpose is to identify the impacts of a ± 25% change in these crucial parameters on overall straw feedstock supply cost. The result is shown in Supplementary Material Table S2. Daily working hour is the greatest contributor to the variance in straw feedstock supply cost. This is because the increase or decrease can directly affect the number of machines used correspondingly. The second-largest contributor is the fuel price. With the promotion of mechanization, the diversity of fuel prices can also bring about the fluctuation of straw feedstock supply cost.

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Chapter 6

Sustainable safeguard mechanism

Adapt from:

Wang, S., Yin, C., Jiao, J., Yang, X., Shi, B., Richel, A., 2022. StrawFeed model: An integrated model of straw feedstock supply chain for bioenergy in China. Resour. Conserv. Recy. 185, 106439.

1. The benefit-sharing mechanism of major stakeholders in straw feedstock supply chain

For the implementer of straw feedstock supply chain, how to allocate this profit reasonably is a critical issue that should balance the interests of all stakeholders among investors, farmers and brokers themselves. This is an attempt by brokers to ensure sustainable and reliable straw feedstock supply in operation (See also **Figure 6-1**).

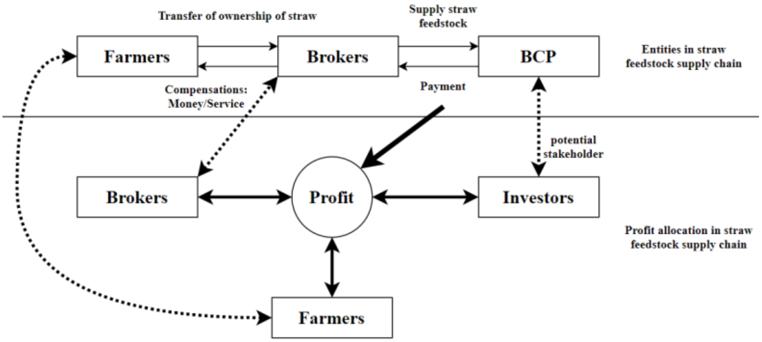

Figure 6-1: The graphical illustration of major entities in straw feedstock supply chain, and the profit allocation among the major entities.

1.1. Brokers to farmers: farmers could earn extra profit from selling straw

Even though farmers are willing to provide the straw feedstock complimentary in the early stage, due to the requirement from agricultural production, they are eager to share the profit with long-term suppliers. Bioenergy production has economies of scale (Visser et al., 2020; Zhao et al., 2020; Aui et al., 2021). In other words, with the increase in production scale, the unit production cost could be cheaper by the relative reduction of unit variable capital investment. In addition, market distortion is induced by taxation preference and allowance policy favouring one single plant over another, expelling small-size BCP by larger ones, thus benefiting from economy of scale. So, bioenergy investor prefers large-scale bioenergy production scheme. For example, the capital investment for a 50MW straw-based power plant in Jilin province could reach 553 million CNY (UNFCCC CDM, 2021a). However, large-scale production has high concerns about the sustainability of feedstock provision. The bargaining power of buyers (BCP) is weaker due to the non-replacement of local suppliers (Zhao et al., 2016), and the feedstock provision entirely relies on local supply. Farmers may have risk to blackmail with egregious prices by taking the advantage of local monopoly position.

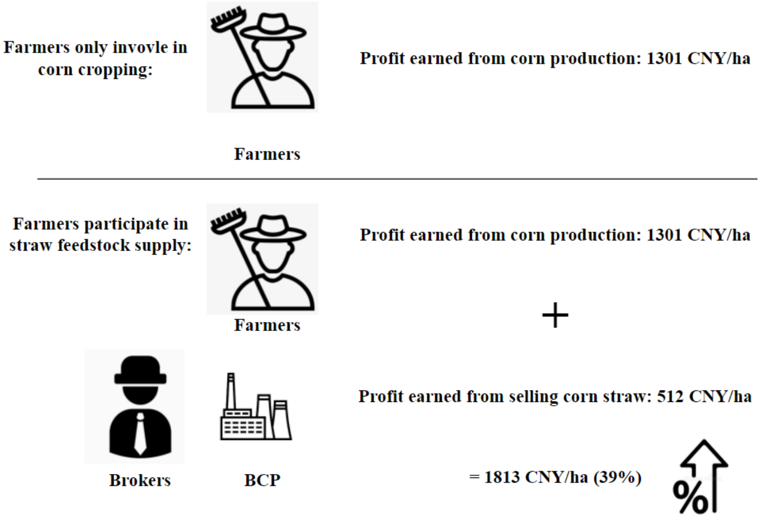

Figure 6-2: The graphical illustration of the benefit of straw feedstock supply chain on farmers in Jilin province.

Under such circumstance, it is necessary to share the benefits with farmers in return for their support. In this respect, straw-to-energy production projects and straw feedstock supply chain should also undertake the social responsibility of employment creation and income increase. During the straw feedstock supply period, there is a demand for recruitment of massive laborers, and it also would not compete with farmers' ordinary agricultural production because it occupies farmers' idle time. The results from StrawFeed model indicated that around 623 skilled farmers could be recruited, and the BCP would spend about 8.6 million CNY on labor recruitment, which accounts for 25% of straw feedstock supply cost. Selling straw feedstock could bring a new source of increasing household income by utilizing crop residues in agricultural production. According to the cost-benefit analysis of corn production in Jilin province, farmers could earn a net profit of 1301 CNY/ha (excluding rent). Assuming that the profit of straw feedstock supply could be partitioned among major entities equally, with the inclusion of selling straw feedstock, farmers could earn an extra profit of 504 CNY/ha (See also **Figure 6-2**), where the income from agricultural production could raise about 39%. Therefore, instead of burning the straw as waste, selling it on the market for bioenergy production is a better solution (Palmieri et al., 2017). Hence, it could be observed that the development of bioenergy production and straw feedstock supply chain could also achieve social benefits.

1.2. Brokers to BCP: BCP could become potential stakeholder to provide monetary support

StrawFeed model also has the function of estimating the capital investment of straw feedstock supply chain. The results indicate that, the capital investment is about 90 million CNY. This figure is 18% of the investment of a typical straw-based power station in Nongan county (UNFCCC CDM, 2021b). Nguyen et al. (2016) proposed a similar estimation that, the investment in rice straw feedstock supply chain in the Mekong River delta of Vietnam represented 10-20% of the total investment in bioenergy production. Considering unfavourable factors in operation, the straw feedstock supply chain is fragile and risky, which makes it challenging to attract investors. The owned capital from brokers cannot satisfy the monetary requirement to some extent. In this case, brokers should have long-term strategic consciousness, and how to benefit BCP from sharing profit. As for consumers of straw feedstock, they also have a strong willingness to secure the sustainability and reliability of straw feedstock supply chain. BCP could become the potential benefactors and investors to provide monetary support, and become one of the major stakeholders in straw feedstock supply chain. If the profit is shared equally among entities, the procurement price from brokers can be reduced by around 14% (257 CNY/ton). With the reasonable profit allocation mechanism, it could be expected that a triple-win solution could be achieved among farmers, brokers and BCP. In addition, apart from straw-based bioenergy utilization, other straw consumers (animal farms, mushroom cultivation farms, paper mills) can also be beneficial from benefit-sharing mechanism.

2. The challenges and opportunities in straw feedstock supply chain in China

Apart from baseline research, scenario analysis is also useful for revealing comprehensive circumstances in straw feedstock supply chain (Palmieri et al., 2016). This manuscript contrives four scenarios that reflect the potential challenges that may impair profitability, and the potential opportunities that could reduce the supply cost, where the policy instruments in China are considered:

2.1. Weather sensitivity

Straw collection and transportation could only be processed after crop harvesting, and as time passed, the quality of straw feedstock in fields would be lost gradually. So, the time for straw feedstock is restricted and urgent. But the weather (e.g., rainfall, snowfall, strong wind etc.) would significantly delay the working efficiency and impair the sustainability of straw feedstock supply chain (Kaylen et al., 2000). Rain and snow would hinder baling and transporting corn straw, thereby reducing the limited working days. Rain has double unfavourable effects on straw supply, which not only influence the working efficiency of the facility, but also results in straw that is too wet to bale. Also, the rain would turn the field become muddy and soggy, thus restricting the tractors' mobility. Under heavy rain, the common-use wheeled tractors may not be functional, and they have to be replaced with crawler tractors, which would impede working efficiency and bring extra cost. Besides, the rainfall would be absorbed by the straw, and it would be uneconomical to transport "water" in the straw. The BCP would reject the procurement of straw with moisture higher than 17%. Although these risks have been acknowledged in the literature, their damage to sustainable supply and supply cost has not been quantified.

There are several studies that assessed the influence of weather on agricultural production. Seldom studies, however, examined the concrete influence of weather change on straw feedstock supply, which is highly related to agricultural production. Nilsson (1999) and Sokhansanj et al. (2006) examined the direct influence of weather on straw feedstock supply, and gave the quantity criteria of relationship between participation/snowfall and affected working day/hour. Mapemba et al. (2008) believed that the conventional supply models did not recognize that feedstock harvest days are restricted by weather, and the ignorance of weather constraints may result in the inexactitude estimation of supply cost. So, it is necessary to incorporate weather variation in straw feedstock supply chain, to give a clear answer for how it would impact the supply cost, thereby influencing the decision-making.

Scenario 1: Identify the impact of weather change delay time period of straw feedstock supply.

2.2. The competition use of straw feedstock

Instead of full straw return or straw burning in the farmland, an optimal scheme of straw utilization is proposed, which is more attractive for farmers. Systematic analysis from Wang et al. (2021b) indicated that straw incorporation could significantly increase crop yield than straw removal from farmland. If the proportion of straw returning is at a reasonable level, straw would be the organic fertilizer, which is beneficial for promoting soil fertility and increasing crop yield.

In straw-based biomass industry, the competed use of straw feedstock is fully aware by many researchers, and feedstock availability should be assessed and discussed beforehand. Soil protection and conservation is the major source for straw utilization, and it is also the most accessible source to be quantified. Because the incorporation of straw as organic fertilizer into soil is an agronomic practice that is comprehensively studied, and such evidence from agricultural experiments provides the guidelines that could assist the quantification of straw feedstock. Borjesson and Gustavsson (1996) believed that in Sweden, only 2 tons per ha of straw feedstock are available for bioenergy production, and the remaining part would be used for animal husbandry sector as well as incorporated into farmland to preserve soil fertility. Kadam et al. (2000) believed that full straw removal would bring soil nutrient depletion, which required additional nutrient amendment to compensate for this loss. Considering that straw mulching on erodible land has the function of preventing soil erosion, Kaylen et al. (2000) gave a conservative assumption that only 10% of crop straw could be utilized for straw-to-ethanol production in Missouri, US. Banowetz et al. (2008) utilized the USDA NRCS soil conditioning Index Worksheet to estimate that the mean proportion of straw incorporation was approximately 4480 kg/ha, and they further calculated that available (cereal) straw feedstock for bioenergy utilization in the Pacific Northwest represented one-third of total straw production. Based on the function of decreasing water loss and soil erosion, Liu and David (2014) estimated demand for soil on corn straw on a national scale. Liska et al. (2014) argued that removal of corn straw for biofuel production might lead to reduced soil organic carbon and increased greenhouse gas emissions in the US corn belt. Menandro et al. (2019) conducted field experiments to investigate (sugarcane) straw removal effect on soil health and ecosystem services in Brazil. The results indicated that full straw removal may cause soil compaction and impair soil biodiversity. So, they suggested that partial straw removal could be a strategic measurement to balance the requirement of soil health protection and straw feedstock sustainable provision. Also, Banowetz et al. (2008) pointed out that the competing use of straw feedstock, for instance, fodder and bedding for dairy production enterprises are preferable.

The benefits of maintaining soil organic carbon stocks and other ecological service functions have been analyzed thoroughly, but few have estimated the economic loss in lesser straw feedstock supply compared with full straw removal, as required by the profit maximization guided to commercial bioenergy enterprises.

Scenario 2: Compare the different straw amounts that are removed from farmland (full/half).

2.3. Cross-regional operation of machine

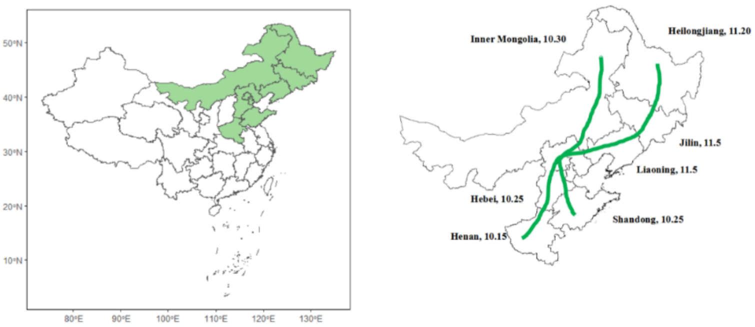

Figure 6-3: The schedule of corn harvesting and mobility of agricultural machines in North China. For (Henan, 10.15), the former is the province's name, and the latter is the expected date of corn harvesting.

Straw supply chain is strongly dependent on agricultural production, so it has seasonal restrictions. China is located in the Northern hemisphere, where crops mature from south to north. After satisfying the local needs of harvesting, idle agricultural machines could be moved to the north. Such movement would cross multiple administrative regions, so it is called cross-regional operation of agricultural machines (Ren et al., 2020; Yang et al., 2013). The movement path of agricultural machines could be estimated based on the harvesting time in different regions (See also **Figure 6-3**). This operation mode could promote utilization rate of agricultural machines, and also improve the spatial spillover of agricultural mechanization (Zhang et al., 2021).

In the past, the poor traffic conditions in rural areas hindered the mobility of agricultural machines. Nowadays, transportation conditions have been promoted, especially in rural areas. Furthermore, the Chinese government has also promulgated an incentive policy for free transportation fee of agricultural machines engaged in cross-regional operation by highway (Zhang et al., 2014, 2017; Ministry of Transport, 2020). Such measures remarkably reduced financial burden of cross-regional operation of agricultural machines.

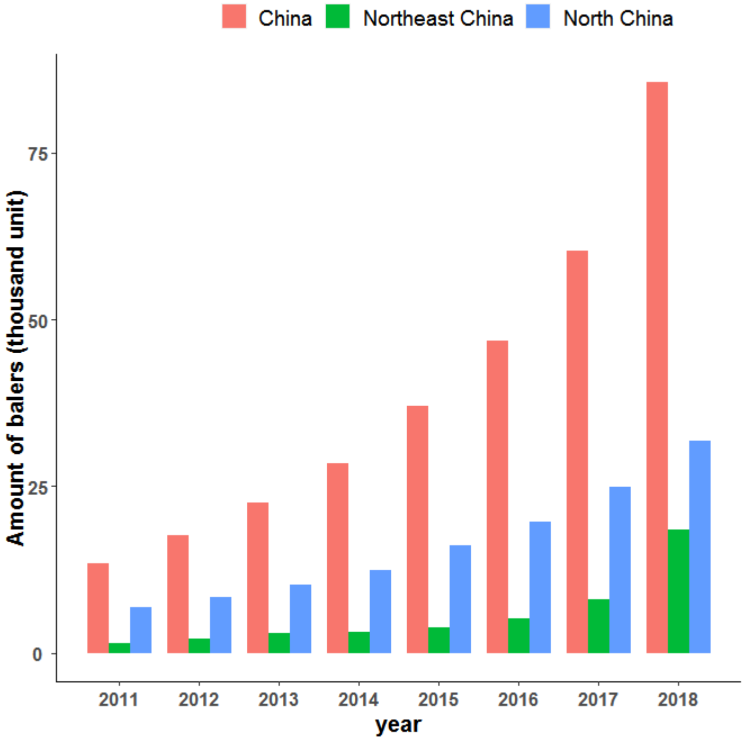

Figure 6-4: The holding number of balers in China, Northeast China (Heilongjiang, Jilin and Liaoning provinces) and North China (Hebei, Shandong, Shanxi, Henan, Inner Mongolia provinces). The statistical data are from CAAMM (2012-2019).

On the other hand, the amount of agricultural machinery is restricted, and the regional deployment is unbalanced. In 2011, there were only 13.5, 1.4 and 6.8 thousand balers in China, Northeast China and North China respectively. With the vigorous development of the manufacturing industry, agricultural machines are no longer in short supply. The number of balers is increasing dramatically in general, but the growth in Northeast China and North China is significantly lower than the national level (See also **Figure 6-4**). So, BCP in Northeast and North China could be beneficial for importing balers from other regions. Such internal mobility of agricultural machinery could alleviate the machine shortage during the harvesting season, and the owner could earn more profit from the machinery rental. In general, previous proposals to supply straw feedstock for bioenergy production have not been economical due to the costs involved in the huge investment for machine procurement. In cases where cross-regional operation is plausible in China, hiring machines may provide an appropriate choice to reduce the supply cost, where the machines could be fully utilized and the idle time could be diminished.

Scenario 3: Assess the impact of hiring machines, where depreciation based on tenancy is analyzed.

2.4. Exclusive machine procurement subsidy for farmers

Because straw comprehensive utilization could be beneficial for reducing straw burning in the farmland, thereby mitigating atmospheric pollution and promoting economic growth, the government is advocating for introducing straw utilization projects. It is reported that, in Jilin province, nearly 100 biomass-based power plants are under construction or in operation (Beijixing, 2019). Also, in order to achieve the goal of clean air, coal is restricted and straw pellet is an important energy source alternative for satisfying the heating demand, especially for the areas experiencing long and cold winter. Straw pellet has great market demand. So, some BCP choose to own the machines to ensure reliability and supply security. On the one hand, they are worried about the competition of intensive demand for rental machines, especially the time period of straw supply is fixed and limited. On the other hand, the dynamic and continuous operation of agricultural machines from cross-regional work would increase the failure rate, thus affecting the straw supply efficiency.

In China, in order to raise the mechanization level and motivate the willingness to use agricultural machines, the government provides subsidies for agricultural machine procurement. In straw supply chain, balers and tractors could be beneficial from government subsidy (Ministry of Agricultural and Rural Affairs, 2019). However, the subsidy is only granted to farmers, and BCP cannot apply (National People's Congress, 2005). Therefore, instead of purchasing hayrakes, balers and tractors directly, the incorporation with brokers could reduce the procurement cost.

Scenario 4: Identify how the pursuit of procurement subsidy for agricultural machine impact feedstock supply cost.

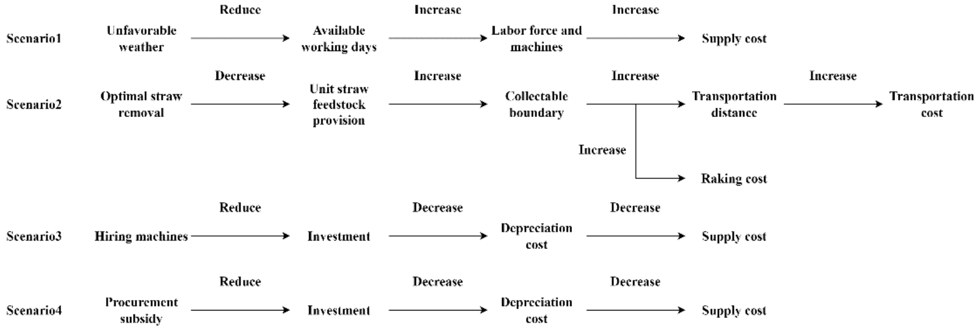

Figure 6-5: The workflow of how parameters changed to influence the supply cost in each scenario.

The pathways of the influence from the change of parameters on final straw feedstock supply cost from these four scenarios are summarized and illustrated in **Figure 6-5**.

3. Risk identification and management of straw feedstock supply chain with scenario analysis

3.1. Weather factors

The results from StrawFeed model showed that, supply cost almost increases by 22.6 CNY per ton when the available working days are reduced by 25% (only 30 working days are available). In other words, reducing the number of supply days by 25% resulted in an increase in the estimated cost of delivering straw feedstock by 13%. This is because in the case of fewer working days, more collection machines and trucks are required to complete the feedstock collection and transportation tasks. Similarly, Mapemba et al. (2008) found that harvest costs almost double when the available harvest days are reduced by 50% in delivering biomass feedstock in Oklahoma, US. Furthermore, extreme weather will bring more devastating repercussions. If the crop production is destroyed by extreme weather, it could lead to a total crop failure and impair the stable straw feedstock supply (“everything goes wrong”, Junginger et al. (2001)). For instance, Northeast China used to experience severe agricultural meteorological disasters, and the area of total crop failure could reach 33% of the crop sowing area (Wang et al., 2021b; He et al., 2019). The work of straw supply may come to a standstill for the absence of straw feedstock. Such a situation should also be incorporated into enterprise risk-based inspection.

Hence, how to manage the risks from weather uncertainty is crucial for the sustainable and stable operation of straw feedstock supply and bioenergy production. The corresponding suggestions are proposed as follows: (1) Weather is an important criterion for BCP site selection. The low rainfall and snow amount in the supply area could increase the likelihood of successfully collecting and transporting straw feedstock from crops. (2) Accurate weather forecasting is indispensable for BCP. Based on the historical and forecasted weather data, BCP should establish a weather-working days coupling evaluation mechanism to appraise the requirements of the machine before executing straw collection works. When the weather could be foreseen to be unfavourable for straw supply, the BCP should arrange the proper number of machines dynamically, and make sure that the demanded amount of straw should be supplied on time.

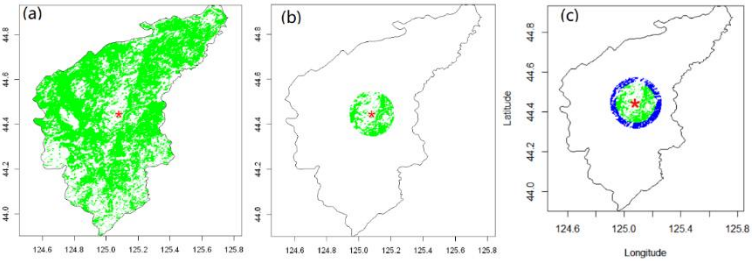

Figure 6-6. The distribution of crop cropping and straw collectable areas in Nongan county. (a) The distribution of corn cropping area in Nongan county; (b) the straw feedstock collectable area for BCP in baseline case; (c) the straw feedstock collectable area for BCP in optimal straw utilization scenarios. The green color in (b) and (c) represents the mean transportation distance is below 14.5 kilometers, and blue color in (c) represents the collectable radius is greater than 14.5 kilometers but lower than 18 kilometers.

3.2. Amount of straw removal

The amount of straw that could be removed from field is significantly lower than full straw removal, and the change of available coefficient (amount of straw removal) that would impact the straw supply cost is largely unknown. The results of StrawFeed model reveal that, decreasing availability coefficient could bring a longer collectable radius and mean transportation distance, and thereby fuel consumption and vehicle requirement would raise simultaneously (See also **Figure 6-6**). The unit cost of straw supply in half amount of straw removal is 53% higher than the baseline scenario (full straw removal). In other words, an optimal scheme of straw comprehensive utilization (the requirement of straw for soil nutrient or competition use) could achieve environmental and ecological benefits for the public and farmers, but it has a risk to damage the profitability of BCP. However, if straw feedstock is entirely removed without returning to farmland, it could cause the depletion of soil nutrients. Straw return to farmland has a great potential to reduce the use of chemical fertilizers (Yin et al., 2018). It is reported that, full corn straw return in Northeast China could counterbalance 38.2% of N, 30.9% of P_2O_5, and all of K_2O in chemical fertilizers (Song et al., 2018). Based on the usage of chemical fertilizer from Ministry of Agriculture (2013) and the cost of chemical fertilizer from National Development and Reform Commission (2021), it could be further estimated that, theoretically farmers should pay a maximum of 1055 CNY per ha for maintaining constant soil fertility, under the circumstance of full straw removal. On the other hand, the cost of straw return (1350 per ha in Northeast China, Wang et al. (2021b)) usually exceeds its benefit from soil nutrients, and these factors influence farmers' decision-making on straw utilization.

Profit maximization is the only concern for BCP, and if merely considering the profit in straw supply chain, full straw removal is the cheapest way. So, there would be a conflict in balancing the benefits of companies' operation and the environment. In the future, it is suggested that straw utilization should be integrated into a comprehensive framework, including straw retention and straw removal for other proposes. The 3E (Economy, Environment, and Ecology) evaluation is required to provide the contingent value of different straw utilization modes in the future. Not only monetary return is estimated, but also ecoefficiency ratio should be concerned, from the perspective of achieving greater economic value with lower environmental impacts (Palmieri et al., 2020). With the participation of BCP (optimal amount of straw removal from farmland), the comprehensive 3E benefits could be better than single straw utilization modes (straw open burning, full straw retention, full straw removal).

The lower the amount of straw feedstock that could be supplied from farmland, the larger the straw feedstock collectable area, and accordingly the higher the raking and transportation-related costs. Therefore, more straw utilization options could reduce the potential risk of straw open burning, but require higher straw feedstock supply cost. Balancing the trade-off between raking and transportation costs and the benefit of comprehensive straw utilization would be important for an efficient design of straw feedstock supply chain. The results obtained from 3E evaluation could support BCP to apply for circular economy projects, so as to seek more funds to compensate for the increased operational cost. Another possible expected way is the upturn of carbon market. Apart from conventional CDM to trade carbon credit from bioenergy production, the optimization of straw feedstock supply chain could earn more carbon abatement. Kongchouy et al. (2021) explored that, if the proportion of straw feedstock removed could raise from 50% (baseline case) to 75%, the estimated greenhouse gas emission could reduce by about 1.5 times greater than the baseline case, and such reduction could bring higher revenue for bioenergy producers, if the quota of abatement could be traded in the carbon market.

3.3. Hiring machines

To estimate the depreciation of machines under hiring circumstance, the units-of-production depreciation method (the actual usage hour) is used instead. The unit straw supply cost could be saved by 18% when machines are hired during straw supply period. The findings from the modelling support that, cross-regional operation of agricultural machine, could not only reduce the cost of agricultural machinery service acquisition (Huang and Luo, 2020), but also reduce the cost of straw supply, which is seldom discussed in previous studies.

While giant state-owned energy companies might afford to equip with all the necessary machines, there is a need to find technological and institutional solutions to enable mechanization for private enterprises and brokers, who play a crucial role in straw-based bioenergy development. Without such options, the high amount of investment for machine procurement would bring financial burden on the stable operation of straw feedstock supply. The Transaction cost in the machine hiring market should be noticed. The results from StrawFeed model do not consider the Transaction cost, because it is uneasy to estimate. Coase (1937) argued that the cost of acquiring service through the market is more than just the price of service itself. Other costs, including search and information costs, as well as negotiation costs, should be added to the cost of purchasing something with a market. An information asymmetry existed between farmers and owners of agricultural machines. The time for harvesting is short and precious, but neither farmers nor owners had effective apparatus to contact each other (Zhang et al., 2018, 2020). In view of information asymmetry, the convenience of the development of communication via Internet could reduce the Transaction cost significantly. In developing countries like India and Nigeria, the popularization of digital tools (“Uber for tractors” model) could reduce Transaction costs for service providers and enable farmers to access tractor hire services (Daum et al., 2021). In China, the construction of cloud platform encourages application design. With the development of mobile applications and agricultural machinery intelligent acquisition terminals, the supply and demand of agricultural machines could be connected (Zhang et al., 2020).

3.4. Subsidy policy in machine procurement

Taking the advantage of farmers’ identity from brokers, buying balers and tractors could be cheaper. The subsidies for hayrakes, balers and tractors (for dragging hayrakes and balers) are 4800, 40190, 15410, and 96430 respectively, which is estimated the financial saving could reach 8.6 CNY/ton (5% reduction). Hence, this is another advantage of selecting broker acquisition mode instead of self-acquisition in China, which has rarely been mentioned and discussed in previous studies. Straw feedstock supply chain is not a winner-take-all system, and it is important to learn how to cooperate with other partners, thereby maximizing the benefit with comparative advantage.

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Chapter 7

General discussion, conclusion and policy implication

Adapt from:

Wang, S., Yin, C., Jiao, J., Yang, X., Shi, B., Richel, A., 2022. StrawFeed model: An integrated model of straw feedstock supply chain for bioenergy in China. Resour. Conserv. Recy. 185, 106439.

Wang, S., Yin, C., Li, F., Richel, A., 2023. Innovative incentives can sustainably enhance the achievement of straw burning control in China. Sci. Total Environ. 857, 159498.

Wang, S., Yin, C., Yang, X., Richel, A., 2023. Barter mode: The institutional innovation for affordable and clean energy (SDG7) in rural China. Biomass Bioenerg. 106725.

1. General discussion

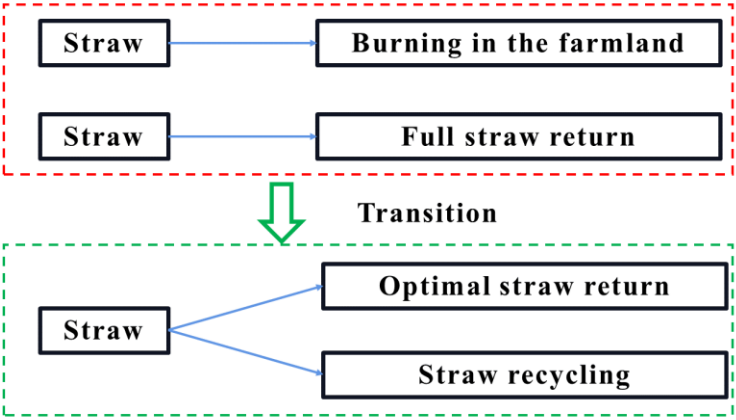

Figure 7-1: The major goal of this thesis: elaborating on the transition from conventional straw management (straw burning in the farmland or full straw return) to sustainable straw management.

Sustainable straw management is the ultimate goal that should be pursued for maximizing the greatest potential and value of straw feedstock, by achieving the transition (**Figure 7-1**). On one hand, as an alternative to fossil feedstock, which is not renewable and exhaustible over time, straw-based biomass can be considered as a green and sustainable raw material for various utilized forms, including forage, biofuel, substrate or material. On the other hand, if straw feedstock can be fully utilized, then straw burning phenomenon can be genuinely eliminated, whereas the whole society can be free from the hazardous environmental effects of air pollutants, smog as well as fire risk. Although it has many difficulties and challenges in front of the transition from conventional straw management to sustainable straw management, it is still worthwhile with economic, environmental and societal benefits. A discussion of each chapter is presented below.

1.1. The potential abatement of carbon emission with sustainable straw management

1.1.1. The emission factors in each straw utilization mode

(1) Emission factor of optimal corn straw return

The annual corn yield in Northeast China in 2018 is on average 6546 kg per ha. Straw-grain ratio of corn and available coefficient for straw collection are 1.83 and 0.85 respectively. Assuming that for optimal corn straw return half of the straw is incorporated into farmland. Therefore, the total amount of straw can be returned to farmland is around 5.09 tons per ha. Carbon sequestration from straw return is one of the great contributions to carbon emission abatement. Berhane et al. (2020) conducted a meta-analysis that assessed the effects of long-term straw return on soil organic carbon storage and sequestration rate in North China's upland crops, and they provided the relationships between annual straw carbon inputs and annual soil organic carbon sequestration rates. Assuming that the carbon content of corn straw is 48.62% (Yang et al., 2017), it can be further estimated that the straw carbon input is 2.48 tons per ha and soil organic carbon sequestration rate is 0.48 ton CO_2 eq. per ha. A typical mode of corn straw return with agricultural machine in NEC showed that cost could reach 1350 CNY/ha (**Figure 7-2**). Assuming that the fuel cost is 6 CNY/Liter, then it can be estimated that the fuel consumption and carbon emission in corn straw return is 96 kg per ha as well as 0.35 ton CO_2 eq. per ha (Carbon emission factors of diesel is 3.7 ton CO_2 eq., Chen et al., 2021). The GHG emission in straw return is 0.35 ton CO_2 eq. per ha. Then, the final emission factor for optimal corn straw return with plowing tillage is -24 g CO_2 eq./kg straw.

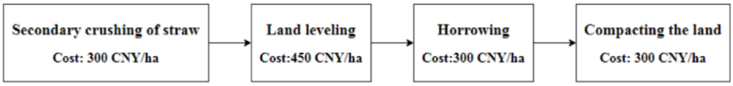

Figure 7-2: A typical mode of corn straw return with agricultural machine in NEC and its cost components. Data are from field survey and (Zheng and Chi, 2012; Zhang, 2017; Wang et al., 2019a; Wang, 2019).

(2) Emission factor of energy use

For straw pellet fuel, the necessary parameters are selected from Wang et al., (2017), which is the study for life cycle assessment on corn straw pellet fuel in China. The carbon emissions of straw pellet fuel are 11 g CO_2 eq./MJ. The lower heating value of corn straw pellet fuel is about 13.9 MJ/kg. Concerning that the straw-to-pellet ratio is 92.92% (5381 tons of straw feedstock can produce 5000 tons of straw pellet), and the carbon emission of corn straw pellet fuel is 142 g CO_2 eq./kg straw. The referenced energy of Wang et al., (2017) is coal, and its emission factor is 146 g CO_2 eq./MJ. Hence, after adding the substitution of coal, the final emission factor of using corn straw pellet fuel is -1744 g CO_2 eq./ kg straw. For electricity, the necessary parameters are selected from Wang et al., (2020), which is the study of sustainability assessment of straw direct combustion power generation in China from the environmental and economic perspectives of straw substitute to coal. The final emission factor of using straw-based electricity is -890.3 g CO_2 eq./ kg straw. For straw-based biogas, the necessary parameters are selected from Wang et al. (2016), which is a study for life cycle assessment on biogas production from straw in China. The function unit of this study is defined as 1 ton of pre-dried straw. The global warming potential of the whole process is 281 kg CO_2 eq. for 100 years, which is equivalent to 281 g CO_2 eq./kg straw. The output of straw-based biogas production is 0.36 m^3 LNG per ton of straw, and its low heating value is 50179 KJ/m^3. Carbon emission of commercial LNG is 67 g CO_2 eq./MJ, then it can be estimated that the final emission factor of using straw-based biogas substituted LNG is -926 g CO_2 eq./kg straw. For straw-based liquid fuel, the necessary parameters are selected from Li et al. (2012), which is the study for life cycle implication of the potential commercialization of stover-based E85 in China. The carbon emission of 1000 liter straw-based ethanol is 7.04 tons CO_2 eq. After excluding the carbon emission of equivalent gasoline and avoided grid electricity, the emission factor of straw-based ethanol is 3.63 tons CO_2 eq. per 1000 liter. Because the production of 1000 liter straw-based ethanol requires 5.6 tons of corn straw feedstock. Hence, it can be estimated that the final emission factor of using straw-based ethanol-substituted gasoline is 648 g CO_2 eq./kg straw.

(3) The explanation of feed, material and substrate modes

For straw-feed utilization modes, the necessary parameters are selected from Huo et al. 2022), which involve the carbon emissions of manure return (132.0 g CO_2 eq./kg straw), straw feedstock supply chain (27.53 g CO_2 eq./kg straw), straw processing for feed (21.04 g CO_2 eq./kg straw) as well as manure composting (25.65 g CO_2 eq./kg). Hence, the final emission factor of using straw feed is -57.8 g CO_2 eq./kg straw. As for material utilization mode, although using straw for paper production is gradually becoming popular in China, the major type of straw feedstock used for paper production is wheat straw (Singh and Arya, 2021; Ma et al., 2019; Man et al., 2020; Sun et al., 2018). As for substrate mode, the major types of straw feedstock of substrate are rice straw (Nguyen-Van-Hung et al., 2019; Gummert et al., 2020), wheat straw (Dorr et al., 2021; Ullah et al., 2015) or corncob (Leong et al., 2022). The use of corn straw for mushroom cultivation is rare. In addition, the horticultural experiments conducted by Atila (2019) demonstrated that corn straw is unrecommended as a basal substrate for mushroom cultivation because of its low yield and biological efficiency, in comparison with chickpea straw, alfalfa hay and sunflower head residue. Hence, material and substrate modes are excluded from assessing the corn straw comprehensive utilization in Northeast China. The emission factors are summarized in **Table 7-1**.

Table 7-1: The emission factor (g CO_2 eq./kg straw) of straw utilization for fertilizer, feed and bioenergy.

Mode	Sub-component	Emission factor
Fertilizer	Plowing tillage	-24
Feed	Dry straw feed	-58

Energy	Direct combustion for electricity	-890
Energy	Biogas	-926
Energy	Pellet fuel	-1744
Energy	Liquid fuel: ethanol	648

1.1.2. The carbon emission abatement of straw comprehensive utilization in the corn belt

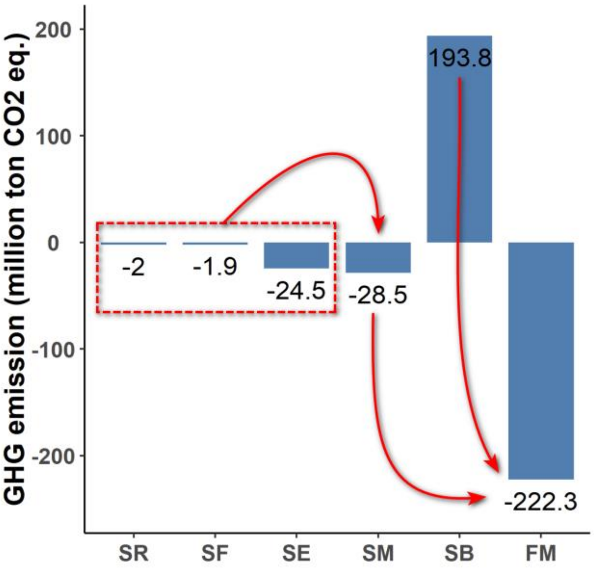

Figure 7-3: The estimation of carbon emission mitigation potential of corn straw utilization in Northeast China. SR: straw return; SF: straw feed; SE: straw-based bioenergy; SM: straw utilization mitigation; SB: straw burning in the field; FM: final straw utilization mitigation.

To sum up, it can be further estimated that, the carbon emission mitigations for straw return to farmland as organic fertilizer (SR), straw used for feeding animals (SF), as well as straw used for bioenergy (SE) are -2, -1.9 and -24.5 million tons CO_2 eq. respectively, based on the straw utilization scheme (**Figure 7-3**). The overall corn straw utilization (SM) in Northeast China can achieve the -28.5 million tons CO_2 eq. mitigation. Concerning the direct GHG emission from straw burning in the farmland (SB) instead of being utilized properly (which could bring about around 193.8 million tons CO_2 eq.), the final carbon emission mitigation from corn straw utilization in

Northeast China has the potential of 222.3 million tons CO_2 eq. eventually. Concerning the major contribution made by straw-based bioenergy production, for straw recycling utilization (removing straw from field for other purposes), straw-based bioenergy industry will be analyzed emphatically.

1.2. The potential solutions for practicing innovative incentives

Instead of increasing burden on government finance, it is suggested that, transferred payment from other stakeholders (people with healthy demand and tourism) and carbon trading can be the new sources of income for compensating farmers' loss in straw burning ban. For future study, the "2T rule" (transparent and traceable) should be drawn to attention to turn the idea into practice. How to make sure that straw burning is banned genuinely? How money is collected from benefactors (stakeholders)? How money is transferred to farmers? How do measure the actual quantity of carbon emission abatement? These questions should be addressed in future research. China's unique experiences, cross-regional transferred payment mechanism of eco-compensation and application of mobile device, should be the potential solutions for addressing the crucial concerns in innovative incentives.

1.2.1. Cross-regional transferred payment mechanism of eco-compensation

In China, it is a similar experience of cross-regional transferred payment mechanism of eco-compensation that can be learned from. The water quality of the Yellow River Basin harasses the relationship between upstream and downstream regions. In order to motivate upstream region to adopt strict water-quality-control management, Shandong province (downstream region) set up an agreement with Henan province (upstream region) that, the improvement of water quality will be subsidized, whereas the decline of water quality will be penalized (Qilu Evening Paper, 2022). This transferred payment mechanism encourages Henan province to control water quality voluntarily, and in 2022 Shandong province is delighted to provide 126 million CNY for subsidizing the effort that Henan province made (Guangming Net, 2022). Such experience can also enlighten the design of transferred payment mechanism for straw burning control. Based on the expenditure of respiratory disease and the pain of suffering from straw burning, the subsidy standard can be set up. After that, the entities can be identified (the couples like 'Rural-Urban' or 'pollution creator-victim') and the air quality standard can be determined. With the endorsement from government, the transferred payment mechanism can be implemented. If the straw burning region could reduce air pollution (below reference level they negotiate), then the downstream region could pay for the effort made for straw burning ban. Correspondingly, if the straw burning region fails to control and even raises air pollution, then straw burning region should be penalized. It requires further research to determine the detail of this transferred payment mechanism.

1.2.2. Application of mobile device

Furthermore, with the development of mobile internet technology in China, the behaviours of donation, payment, and transfer can be implemented on mobile devices, which can be useful for the implementation of carbon trading as well as encouraging public participation. For example, a new Ant Forest mobile gaming application was launched in China by Ant Financial Service Group in cooperation with Alipay (Ashfaq et al., 2021). It can collect personal information about adopting low-carbon behaviours, such as using public bicycles and electronic payments, and using carbon credits for planting more trees. It is further estimated that, at the end of 2019, Alipay Ant Forest had reduced carbon emissions by 7.9 million tons by attracting over 500 million users and planting 122 million trees in China (Business Wire, 2020). Apart from using these carbon credits to support tree planting and afforestation, straw burning control is also a meaningful way to make and world better and improve the living conditions of farmers in rural areas. It could be good enlightenment and breakthrough that transferred payment and carbon trading in straw burning ban can be achieved in a similar way.

1.3. The extension of StrawFeed model

1.3.1. Integrating StrawFeed model with techno-economic models

StrawFeed model is flexible and adaptable for integrating with existing techno-economic models. It provides a cradle-to-gate solution for straw feedstock supply, where techno-economic modes have better performance and higher accuracy in filling the knowledge gap in bioenergy production stage. Many researchers have established techno-economic models to assess straw-based bioenergy products, such as electricity in Egypt (Abdelhady et al., 2018), Bolivia (Morato et al., 2020), and bioethanol in Japan (Roy et al., 2012b), Sweden (Ljunggren et al., 2011), Brazil (Pratto et al., 2020) and Malaysia (Kristianto et al., 2017). Apart from technical or chemical concerns, the feedstock supply chain also has a strong influence on the eventual outcome. StrawFeed model can be assembled as a submodel to be integrated with other techno-economic models, and it can be useful for providing sound results in feedstock supply chain, or checking the reliability of existing results. Better still, the integration of StrawFeed model can benefit techno-economic model to clarify geographical difference to some extent, thus making the results more comparable.

1.3.2. Integrating StrawFeed model with agricultural production management

Combined with crop calendars and precipitation records, the crop growing season could be analysed via crop growth models (APSIM, DSSAT, etc.). With the help of these models, the crop harvesting season could be predicted in advance, and the appropriate straw harvesting schedule could be designed in accordance with weather forecasting. Furthermore, in assistance with local government and agricultural organizations, the grant arrangement of harvest time varieties in a specific region should also consider the request from straw feedstock supply. The diversification strategy of harvest time varieties could avoid intensified straw harvesting activity. The accomplishments of these works require cooperation with agronomic experts, and it is a good opportunity to strengthen the connection between agricultural and bioenergy production.

2. Conclusion

This thesis systematically summarizes the reason, hazard and persistence of straw burning behaviour in China. Straw has dual characters: waste and resource. After crop harvesting season, enormous straw is generated. If straw cannot be disposed of properly, it will seriously affect next-season cropping. Hence, for developing countries (e.g., China, and India), straw burning in the farmland is the cheapest and most convenient way to get rid of it. Concerning the harmful environmental hazards from straw burning as agricultural waste, straw comprehensive utilization is turning waste into a valuable resource, and it can achieve the triple-win solution from agriculture, environment and energy simultaneously. This is one of the crucial advantages that the government designs and promulgates the comprehensive straw utilization scheme, and strongly supports the development of related straw-based biomass industry.

And then, this thesis depicts the current problematic issues that hinder the realization of sustainable straw management: (1) weak capacity of straw disposal by dominant smallholder farmers; (2) the uncertainty of optimal straw return scheme; (3) the unreliability of straw feedstock supply chain modelling; (4) lacking sustainable safeguard mechanism. In front of these problems, corresponding potential solutions are given.

In chapter 3, taking China's corn belt (Northeast China) as an example, an integrated regional evaluation with meta-analysis and system dynamics is conducted to explore the effect of corn straw return on corn production. The results illustrate that, in comparison with corn straw removal, corn straw return has positive effect on corn yield increase in general, and with the lower soil nutrients and higher pH, such benefit will also increase correspondingly. Also, an excessive amount of corn straw return would hinder the goal of yield increase achieves. With the help of n-fold cross-validation method, the optimal scheme of corn straw return in Northeast China is proposed. Furthermore, system dynamics with MC simulation are used to estimate potential net profit of corn straw return earned by farmers on the hypothetical ordinary and extreme scenarios. The simulation indicates that under the ordinary scenario, the cost of corn straw return is unaffordable. Reversely, under the extreme scenario, corn straw return could be profitable. With flexible adjustment of subsidy, such profitability could become the motivation for measurement adaptation. It could be concluded that, optimal scheme of corn straw return is the sustainable safeguard that can promote corn production in Northeast China, thus to China's food security on the long run.

In chapter 4, due to the divergence of farmers' endowments, some smallholder farmers are in weak capacity for straw disposal, and thus they have to choose to burn the straw in the farmland. Therefore, straw burning ban policy should be improved from pure deterrent administrative measurement to a comprehensive 'carrots and sticks' mechanism: the integration of coercive force as well as monetary incentives. As for monetary incentives, the limitations of subsidy policy have been discussed. Instead of increasing burden on government finance, it is suggested that, transferred payment from other stakeholders (people with healthy demand and tourism) and carbon trading can be the new sources of income for compensating farmers' loss in straw burning ban. For future study, the "2T rule" (transparent and traceable) should be drawn into attention to turn the idea into practice. How to make sure that straw burning is banned genuinely? How money is collected from benefactors (stakeholders)? How money is transferred to farmers? How do measure the actual quantity of carbon emission abatement? These questions should be addressed in future research.

In chapter 5, this thesis presents a comprehensive solution tool, StrawFeed model, to overcome the challenges of straw feedstock supply chain planning, which is beneficial for both academic research and commercial bioenergy projects. The unique feature of this model is the integration of remote sensing technology as well as electronic navigation application by using an open-source programming platform. Taking Nongan county, one of the highest corn yield regions in Northeast China as the case study area, the provision of 200 thousand tons corn straw feedstock for bioenergy production is estimated.

In chapter 6, this thesis elaborates the sustainable safeguard mechanism for securing the long-term stable operation of straw feedstock supply chain. Benefit-sharing mechanism is that the cooperation between farmers, brokers and straw utilization companies can not only secure the reliability of straw feedstock supply chain, but also can increase farmers' income from selling straw. In addition, considering the realistic circumstances of agricultural production and bioenergy production, as well as policy intervention in China, two potential obstacles and two improvements in straw feedstock supply are discussed in accordance with four contrived scenarios. Weather (rain and snow, etc.) would shorten the available working period, thus increasing the supply cost remarkably. An optimal straw utilization scheme could achieve environmental and ecological benefits, and is favoured by the public and government, but it also increases the supply cost by prolonging collection radius. The extra expenses burdened by straw consumers are neglected by previous research. Due to the seasonal availability and restricted working period of straw feedstock, hiring machines are cheaper than owning machines, when the cross-regional machine operation could be fully achieved. On the contrary, if straw consumers apprehensive about the competition for hiring services, instead of purchasing machines by themselves, it is suggested to cooperate with brokers to grasp the proprietary machine purchasing subsidy for farmers. The scenario analysis and optimization provide enlightenment for future research directions. The experiences and lessons learned from straw feedstock supply chain in China could enlighten countries around the world and inspire their individual practice and management, which is especially applicable to developing countries facing similar circumstances to China.

In conclusion, this thesis is an important contribution to improving the understanding of the implication, mechanism and motivation of sustainable straw management and straw burning ban in China. The state-of-the-art ideas and concepts raised, such as transfer payment as well as carbon trading for farmers, are new and attractive for researchers and policymakers who intend to implement straw burning ban in the future, especially for developing countries. With the improvement of technology and institution, it can be foreseen that, straw burning phenomenon will soon be eliminated in China, and farmers can be beneficial from adopting sustainable straw management.

3. Policy implication

Straw comprehensive utilization in China aligns with the concept of sustainable and circular management and use of natural resources to unlock the potential of the bioeconomy through deployment of practical utilization modes. This thesis aims to ensure its impact at different levels: scientific, societal and economic. Thus, to track the project's impact, the following impact pathways have been established:

From a scientific point of view, this thesis has contributed to the promotion of excellent scientific research by introducing the five major straw utilization modes in China, with the new statistical data description. Furthermore, this thesis can foster diffusion of knowledge by establishing the open-source & GIS-based tool that can be exploited its potential for upscaling, adaptation and replication in other regions in China.

Regarding the societal impact perspective, this thesis addresses several China policies and priorities as well as global challenges. In particular, more related policies in China are straw burning ban, subsidy policy for farmers in straw return practice as well as subsidy policy and supportive policy for straw feedstock supply chain and straw-based biomass industry. In addition, consumers' acceptance and needs for straw-based products have been raised and should be further considered to ensure societal benefits, especially with high value-added chain. Not only people who dwelled in rural areas but also citizen in urban areas can also enjoy renewable straw-based products.

With regard to economic impact, this thesis indicates that, with proper business operation, straw feedstock supply chain can become a major profit-maker, and the benefit of farmers, brokers and the straw-based biomass industry can be increased. Additionally, it is expected a significant reduction in the external dependency on certain products (e.g., fertilizer, fossil fuels, wood, grass). Finally, the deployment of straw-based biomass industry, which provides solutions to agricultural waste will contribute to the creation of job and business opportunities in rural areas.

In addition to the influences reached such levels, it is worth mentioning the overall environmental impact that is underlying sustainable straw management. For example, if the corn straw comprehensive utilization scheme can be implemented in Northeast China, it will be translated into an overall reduction in a total 28.5 million tons of CO_2 eq. GHG emission. This is explained by the sustainable use of straw feedstock related to waste management and replacement of imported products with high carbon footprints by others locally produced from recycled waste (reduction in supply chain optimization). Many environmental issues are resulted from or related to the production, conversion as well as consumption of energy and resource. Conventional fossil fuel is a finite resource and its continued consumption leads to a remarkable environmental burden. The most globally significant environmental issues, in which energy plays a crucial role, are global climate change, stratospheric ozone depletion and acid precipitation (Dincer and Rosen 2021). The hazard caused by these environmental issues threatens the life of human-being and property. Therefore, mitigating the reliability and dependency of fossil fuels, reducing the consumption of a non-renewable resource, and promoting is crucial. McGlade and Ekins (2015) estimated and suggested that more than 80% of coal, 50% of gas, and 33% of oil reserves should not be consumed from 2010 to 2050, in order to restrict average global warming to 2 ◦C. In front of the global crisis, the power and force of every nation should be united together, and the UN has made the most prominent effect in proposing sustainable development goals (SDGs), which require all UN members to adopt. In total, 17 SDGs are proposed to protect the planet, end poverty and ensure prosperity (Toro and Alzate, 2021; Matharu et al., 2016; Asadikia et al., 2021) and this thesis has also contributed directly to the following SDGs:

SDG 2: Zero hunger. The application of straw return with optimal scheme could be regarded as an effective measurement to promote crop production in China, and thereby making contribution to national food security.

SDG 3: Good health and well-being. Using straw-based bioenergy products (straw pellet, biogas e.g.) instead of coal can reduce indoor air pollution and improve health circumstances.

SDG 7: Affordable and clean energy. Using straw-based bioenergy products can reduce rural familys' expenditure for energy consumption, and it could be cleaner than using conventional fossil fuels or using straw directly.

SDG 8: Decent work and economic growth. Straw comprehensive utilization can create new business models to promote economic growth and create more job opportunities in rural areas.

SDG 11: Sustainable cities and communities. The objective is to improve the global sustainability of straw from agricultural sector, thereby enhancing its positive impact on rural areas, soil and the environment.

SDG 12 & 13: Responsible consumption and production & climate action. The consumption of straw-based biomass products with lower impact can be helpful for GHG emission reduction as well as resource conservation, thereby assisting with the environmental and ecological protection as well as mitigation of global warming.

SDG 15: Life on land. The recycling of straw feedstock for comprehensive utilization can alleviate the dependency on firewood or energy crops, thereby reducing deforestation, land degradation as well as desertification.

SDG 17: Partnerships for the Goals. The experience and lessons learned in China can also be helpful for developing countries (India, Vietnam, Thailand, e.g.) with similar circumstance and similar challenges.

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Chapter 8

Supplementary material

Scientific publications

[1] **Shu Wang**, Xianlei Huang, Yang Zhang, Changbin Yin, Aurore Richel, 2021. The effect of corn straw return on corn production in Northeast China: An integrated regional evaluation with meta-analysis and system dynamics. Resources, Conservation and Recycling, 167:105402.

[2] **Shu Wang**, Xianlei Huang, Changbin Yin, Aurore Richel, 2021. A critical review on the key issues and optimization of agricultural residue transportation. Biomass and Bioenergy, 146:105979.

[3] **Shu Wang**, Changbin Yin, Jian Jiao, Xiaomei Yang, Boyang Shi, Aurore Richel, 2022. StrawFeed model: An integrated model of straw feedstock supply chain for bioenergy in China. Resources, Conservation and Recycling, 185, 106439.

[4] **Shu Wang**, Changbin Yin, Fuduo Li, Aurore Richel, 2023. Innovative incentives can sustainably enhance the achievement of straw burning control in China. Science of the Total Environment, 857, 159498.

[5] **Shu Wang**, Changbin Yin, Xiaomei Yang, Aurore Richel, 2023. Barter mode: The institutional innovation for affordable and clean energy (SDG7) in rural China. Biomass and Bioenergy, 106725.

The procedure for selecting the literature with PRISMA 2009 Flow diagram

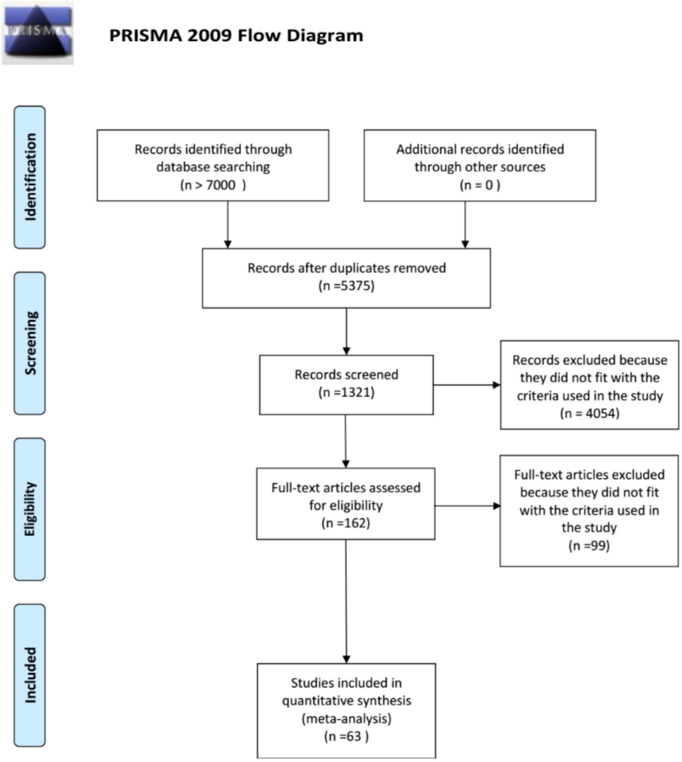

Figure. S1. PRISMA 2009 Flow diagram of the process used to obtain the literature data to build a database for the study.

List of publications used in the meta-analysis

Table S1 List of publications used in the meta-analysis with specific variables extracted. AP, annual average precipitation from each reference; AT: annual average temperature from each reference; StD: year of study duration included in meta-analysis. NA was missing value. For missing values in AP and AT, they were filled in with data from same reported areas or corresponding statistical yearbook.

Reference	Location	Tillage	StD (year)	AP (mm)	AT (°C)	Soil type
[1]	Changtu, Liaoning	plowing	3	596	7	Brown
[2]	Fuxin, Liaoning	plowing	4	475	7.35	Meadow
[3]	Liaozhong, Liaoning	plowing	1	629	7.55	Meadow
[4]	Shenyang, Liaoning	plowing	3	629	7.55	Meadow
[5]	Lishu, Jilin	no	1	577.2	5.8	Black
[6]	Baoqing, Heilongjiang	plowing/no	1	541.7	4	Albic
[7]	Siping, Jilin	NA	1	577.2	5.8	Black
[8]	Chaoyang, Liaoning	plowing	1	400	7.9	Cinnamon
[9]	Jianping, Liaoning	plowing	10	450	6.5	Hapli-Ustic Cambosol
[10]	Jianping, Liaoning	plowing	10	450	6.5	Hapli-Ustic Cambosol
[11]	Haicheng, Liaoning	plowing/rotary	1	700	10	Brown
[12]	Fuxin, Liaoning	plowing	1	475	7.35	Cinnamon
[13]	Yanbian, Jilin	plowing	1	549.3	6.2	NA
[14]	Jinzhou, Liaoning	plowing	1	610	8.7	Meadow
[15]	Shenyang, Liaoning	plowing	3	629	7.55	Meadow
[16]	Linghai, Liaoning	NA	3	446.9	8.7	Meadow
[17]	Linghai, Liaoning	NA	2	610	8.7	Meadow
[18]	Hailun, Heilongjiang	plowing	1	550	1.5	Black

[19]	Harbin, Heilongjiang	plowing	1	500	3.6	Loam
[20]	Gongzhuling, Jilin	plowing	1	567	5	Black
[21]	Gongzhuling, Jilin	plowing	3	567	5	Black
[22]	Qingyuan, Liaoning	plowing	1	1148.6	6.5	Meadow
[23]	Linghai, Liaoning	plowing	2	610	8. 7	Meadow
[24]	Jinzhou, Liaoning	plowing	2	610	8.7	Meadow
[25]	Lishu, Jilin	no	2	573	5.9	Silty clay loam
[26]	Changtu, Liaoning	rotary	1	596	7	Brown
[27]	Shenyang, Liaoning	plowing	1	629	7.55	Brown
[28]	Changtu, Liaoning	rotary	1	607	7	Brown
[29]	Fuxin, Liaoning	rotary	3	500	7. 2	Cinnamon
[30]	Fuxin, Liaoning	rotary	2	520	7. 2	Aeolian sandy
[31]	Fuxin, Liaoning	plowing	2	400	7.5	Cinnamon
[32]	Fuxin, Liaoning	NA	2	400	7.5	Cinnamon
[33]	Jilin, Jilin	plowing	1	700	3.9	Black
[34]	Gongzhuling, Jilin	plowing/no	1	600	5.6	Black
[35]	Gongzhuling, Jilin	no	1	600	5.6	Black
[36]	Shenyang, Liaoning	rotary	1	700	7.4	Brown
[37]	Suihua, Heilongjiang	plowing	1	477	2.5	Chernozem
[38]	Tieling, Liaoning	plowing	2	600	6.3	Brown
[39]	Harbin, Heilongjiang	plowing/no	1	500	3.6	Black
[40]	Tieling, Liaoning	rotary	2	600	6.3	Brown
[41]	Fuxin, Liaoning	rotary	1	500	7. 2	Cinnamon

[42]	Shenyang, Liaoning	NA	1	730	8.5	Brown
[43]	Haicheng, Liaoning	rotary	1	700	10	Brown
[44]	Tongliao, Inner Mongolia	plowing/rotary	2	385	6.8	Meadow
[45]	Shenyang, Liaoning	NA	5	520	7.5	Alfisol
[46]	Shenyang, Liaoning	rotary	2	629	7.75	Fluvo
[47]	Gongzhuling, Jilin	NA	1	550	5.5	Black
[48]	Tieling, Liaoning	plowing/no/rotary	1	600	6.3	Brown
[49]	Changtu, Liaoning	plowing	4	655	7	Brown
[50]	Tieling, Liaoning	plowing	2	600	6.3	Brown
[51]	Changtu, Liaoning	plowing	4	655	7	Brown
[52]	Changchun, Jilin	plowing/no	2	331.9	9.8	Chernozem
[53]	Tieling, Liaoning	rotary	2	675	6.3	Brown
[54]	Qiqihar, Heilongjiang	plowing/no/rotary	1	273.7	5	Chernozem
[55]	Shenyang, Liaoning	plowing	4	500	7.5	Brown
[56]	Harbin, Heilongjiang	plowing	2	500	4	NA
[57]	Mudanjiang, Heilongjiang	plowing/no	2	647.4	5	Meadow
[58]	Qiqihar, Heilongjiang	plowing	1	273.7	5	Black
[59]	Changchun, Jilin	plowing	1	507.5	4.7	Black
[60]	Gongzhuling, Jilin	plowing	4	600	5.6	Black
[61]	Lingyuan, Liaoning	plowing	5	479.4	8.7	Cinnamon
[62]	Tongliao, Inner Mongolia	rotary	1	387	6.9	Meadow
[63]	Gongzhuling, Jilin	plowing	5	600	5.6	Black

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Sensitivity analysis of StrawFeed model

Table S2 Sensitivity analysis of StrawFeed model

Item\variability	+25%	-25%
fuel price	7.56%	-7.56%
labor cost	6.4%	-6.4%
idle time	3.49%	-3.49%
speed	-3.49%	5.81%
working hour	-8.14%	13.37%