Balancing straw returning and chemical fertilizers in China: Role of straw nutrient resources

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ABSTRACT

Currently, large-scale farmland degradation resulted from the overuse of chemical fertilizers has become a major issue in China. Meanwhile, a large sum of straw nutrient resources have been lost from the farmland due to the straw removal from fields, which in return aggravated the degradation in farmland quality and long-term productive capacity of soil resources. Whether current straw management practices represent rational utilization and how straw can be used more efficiently have become the most important but least studied problems for China’s green agricultural development. Based on the China’s Official Statistics, we first collected a large number of data on the annual crop yields, crop sown areas and chemical fertilizer consumption of different crop types in 31 China’s mainland provinces from 1998 to 2014. Straw yields and straw nutrient resources were calculated to assess the potential contribution of straw resources to chemical fertilizers. Our estimation demonstrates that straw returning to farmlands could counterbalance all of the K₂O, the majority of the P₂O₅, and a portion of the N in chemical fertilizers. Promoting the return of straw to field has a great potential to reduce the use of chemical fertilizer, air pollutant emission and environmental burden. Thus, we propose that the Chinese government should adjust the policies to take promoting straws returned to field as priority, instead of greatly encouraging straw removal from field. Innovative straw decomposing technologies and returning practices are also needed to assure China’s green agricultural development and reduce environmental pollution in the future.

1. Introduction

China is one of the largest agricultural countries in the world. In 2015, the total crop yield and sown area in China amounted to 621.44 million tons (hereafter Mt) and 11,3340.5 thousand hectares, respectively [1]. Accompanied by the constant increase in crop production, the crop straw yield has grown dramatically [2]. China is now one of the most abundant countries in terms of straw resources in the world (fig. 1) [3], and the average annual increase in the rate of crop straw production was about 4% in China over the last several decades [4]. As a source of bioenergy, livestock forage and other sources of loss (including open field burning, being throwing aside, etc.), crop straws in China have long been removed from the field, which has led to a large sum of straw nutrient losses from the fields. Meanwhile, straw resource utilization policy will further be encouraged in China’s 13th Five-Year Plan Period (2016–2020), and the comprehensive utilization efficiency of straw will be up to 85% by applying new advanced technologies [5]. This will further aggravate straw nutrient losses from the fields.

At the same time, China is now the largest producer and consumer of synthetic fertilizers, accounting for ca. 35% of the global total consumption [6]. A tremendous amount of inorganic fertilizers (nitrogen, phosphorous and potassium) have been applied to the farmland to boost food production, despite the fact that China’s agronomic nutrient use efficiency (i.e., the ration of crop yield to the amount of fertilizer applied) has gradually increased over the past 10 years [7]. As a consequence, both straw removal and the overuse of chemical fertilizers have led to soil quality degradation (i.e., the loss of soil organic matter, low soil fertility, inefficient nutrient-use, and subsequently low-yielding land) and heavy environmental impacts (i.e., agricultural non-point pollution) [8]. Policy makers are challenged by the dilemma of resource competition/allocating among various straw users to balance the economic benefits and environmental effects [9]. As one of the renewable resources with high efficiency and rationality, straw resource utilization not only meets the demands for resources as the economy grows (i.e., saving the scarce natural resources and substitution for...
depleted resources), but also provide a basis for environmental protection and sustainable development of society in China [3]. Consequently, people are paying more attention to the social and economic advantages of straw utilization, and less attention to the ecological consequences of removing straw from the fields on farmland quality. In fact, the excessive removal of straw from the fields has greatly resulted in field nutrient depletion and the decrease in soil organic matter content [10], and thus degraded the long-term productive capacity of soil resources [11]. From an ecosystem mass balance perspective, however, straw removal greatly disrupts the nutrient cycling of agricultural systems, and degrades the long-term productive capacity of soil since a large amount of nutrient resources are taken away from the fields [12,13]. Whether current straw management practices represent rational utilization and how straw can be used more efficiently have become the most important but least studied problems for China’s green agricultural development. In this paper, we assessed the potential contribution of straw resources to chemical fertilizer consumption based on the official Chinese data of crop yield, straw yield and chemical fertilizer consumption from 1998 to 2014. The bioenergy content and pollutant emission from straw combustion were also calculated to evaluate the environmental impact of straw use for biofuel.

2. Methodology

2.1. The main crop production in China

China is one of the biggest crop production countries, producing large amounts of crop straw annually. The crops grown in China include rice, wheat, maize, soybean, peanut, canola, cotton, potato, sesame, jute, sugarcane, sugarbeet, tobacco, etc. The first 7 of these crop types comprise 96.4% of the total grain, oil-bearing, cotton, fibre, sugar, and tobacco straw yields of China in 2014. Detailed information on the chemical fertilizer consumption or straw nutrient contents of other crop types is not available in the Chinese official statistics. Hence, the main Chinese field crops selected in this study were rice (Oryza sativa L.), wheat (Triticum spp.), maize (Zea mays L.), soybean (Glycine max (L.) Merr.), peanut (Arachis hypogaea L.), canola (Brassica spp.), and cotton (Gossypium spp.). These 7 crops were chosen to evaluate the status of main straw resource in China.

Since Hong Kong and Macao possess limited areas of farmland and their negligible crop yields are not recorded in China’s official statistics, the regions we covered in the current work contained China’s 31 mainland provinces. The crop yields (10^8 t) and crop sown areas (10^3 ha) of the 31 provinces were obtained from the China Rural Statistical Yearbook [14]. The sown areas of the 7 main crops in China during 1998–2014 varied from 99.27 to 114.7 million hectares (Table S1). Among the provinces, Henan Province exhibits the largest crop yields of China, followed by Heilongjiang, Shandong and Anhui (Table S2). The detailed data on crop yield, crop sown area, straw yield and chemical fertilizer consumption for each crop type and province can be collected after 1998. However, the chemical fertilizer consumption (N, P, K) for each crop type cannot be obtained from the Chinese official statistics before 1998. Thus, the period investigated in this study ranges from 1998 to 2014.

2.2. Crop yield (CY)

The total CY in China was calculated based on the sum of the CY values of 7 crop types in the 31 provinces using the following equation:

$$CY_{\text{total}} = \sum CY_i$$
The chemical fertilizer consumption across China from 1998 to 2014 are shown in Table S2. The mean annual chemical fertilizer consumption per hectare (FCPH) of the different crops in China was derived from the Compendium of National Agricultural Products Cost-benefit [15]. The FCPH values found in Table [15], were the net contents of N, P2O5 and K2O per hectare.

(1) The net contents of N, P2O5 and K2O in nitrogen, phosphorus and potassium fertilizers were calculated using the following equations:

\[ N_C = \sum FCPH_{N,C, i} \times CSA_{i} \]

\[ N_{P2O5} = \sum FCPH_{P2O5,C, i} \times CSA_{i} \]

\[ N_{K2O} = \sum FCPH_{K2O,C, i} \times CSA_{i} \]

where \( N_C \), \( N_{P2O5} \) and \( N_{K2O} \) are the net contents of N, P2O5 and K2O in nitrogen, phosphorus and potassium fertilizers, respectively, \( FCPH_i \) \((10^6 \text{ t hectares}^{-1})\) is the chemical fertilizer consumption per hectare of crop type-\( i \) in China, and \( CSA_{i} \) \((10^{3} \text{ ha})\) is the crop sown area of crop type-\( i \).

(2) For the net contents of N, P2O5 and K2O in the compound fertilizers, it was reported that a range of 10–23% for N, 10–20% for P2O5 and 8–25% for K2O has been used for the different fractions of compound fertilizer types in China [16]. According to the data from the China Phosphate Fertilizer Industry Association, the 15-15-15 common type compound fertilizer (N, P2O5, and K2O in equal proportions) was the main compound fertilizer used in China, with 54% of the market share [16]. In addition, this compound fertilizer (15-15-15) is regarded as the most widely used fertilizer type of China, which has been representatively utilized by many researchers to calculate the quantities of N, P2O5, and K2O in compound fertilizers. Hence, the net contents of N, P2O5, K2O in in compound fertilizer (\( N_{\text{compound-N}} \), \( N_{\text{compound-P2O5}} \), \( N_{\text{compound-K2O}} \), \( 10^6 \text{ t} \)) were formulated as:

\[ N_{\text{compound-N}} = \frac{\sum FC_{\text{compound-N}, i} \times CSA_{i}}{3} \]

\[ N_{\text{compound-P2O5}} = \frac{\sum FC_{\text{compound-P2O5}, i} \times CSA_{i}}{3} \]

\[ N_{\text{compound-K2O}} = \frac{\sum FC_{\text{compound-K2O}, i} \times CSA_{i}}{3} \]

(3) The total net contents of N, P2O5 and K2O in all chemical fertilizers: the total net contents of N, P2O5 and K2O (\( TNC_N \), \( TNC_{P2O5} \), \( TNC_{K2O} \), \( 10^6 \text{ t} \)) and the sum of the total net contents of nutrients (\( TNC_{\text{sum}} \), \( 10^6 \text{ t} \)) in all chemical fertilizers were calculated using the following equations:

\[ TNC_N = N_{\text{compound-N}} + N_{\text{P2O5}} \]

\[ TNC_{P2O5} = N_{\text{P2O5}} + N_{\text{compound-P2O5}} \]

\[ TNC_{K2O} = N_{\text{K2O}} + N_{\text{compound-K2O}} \]

\[ TNC_{\text{sum}} = TNC_N + TNC_{P2O5} + TNC_{K2O} \]

All the \( TNC \) and \( TNC_{\text{sum}} \) values of the 7 main crops in China during 1998–2014 are presented in Table 1.
2.4. Variations in crop yields and chemical fertilizer consumption from 1998 to 2014

To compare the variations in the increasing percentages (IP) of crop yields (CY) and net contents of nutrients in all chemical fertilizers (TNC) in China from 1998 to 2014, two calculation methods were used:

\[
IP1(CY_n + 1) = \frac{CY_n + 1 - CY_{1998}}{CY_{1998}} \times 100\%; \quad IP1(TNC_n + 1)
\]

\[
IP2(CY_n + 1) = \frac{CY_n + 1 - CY_n}{CY_n} \times 100\%; \quad IP2(TNC_n + 1)
\]

where \( IP1 \) and \( IP2 \) represent the increasing percentage considering 1998 as the base year and between two adjacent years, respectively. \( CY_{n+1} \) and \( TNC_{n+1} \) are the total crop yields and total net nutrient contents in all chemical fertilizers in year-\( n+1 \) (n = 1998–2013), respectively.

2.5. Straw yield

The straw yield (SY) analyzed in this study refers to the quantity of residues after the crop is harvested, including stalks, stubbles, and leaves [17]. Additionally, process residues from the harvesting crops, such as rice hulls, maize cobs, and peanut husks, were not included. The sum of straw yield (\( SY_{\text{sum}} \), \( 10^4 \) t) in China was estimated on an air-dried basis by multiplying the crop yield (CY) by the Field Residue Index (FRI) based on the following equation [17]:

\[
SY_{\text{sum}} = \sum CY_i \times FRI_j
\]

where \( i \) is the crop type, and \( j \) is the province. The FRI values of the different crop types were originated from Refs [17,18], which were different among the 31 provinces due to varied climate, soil fertility levels, and management [19]. Table S3 lists the residue indices for the main Chinese crops. The calculated SY and \( SY_{\text{sum}} \) values of the 31 provinces in China are shown in Table S4.

2.6. Nutrient resource of straw

Straw nutrient (SN) resources are indicated by the net quantity of N, P\(_2\)O\(_5\) and K\(_2\)O (\( 10^6 \) t). Here, we calculated the SN amount for each crop type to obtain the total SN\(_{\text{sum}}\), SN\(_{\text{P2O5}}\) and SN\(_{\text{K2O}}\) in China:

\[
SN_N = \sum CY_i \times C_{N,i}
\]

\[
SN_{P2O5} = \sum CY_i \times C_{P,i} \times 2.29
\]

\[
SN_{K2O} = \sum CY_i \times C_{K,i} \times 1.2
\]

where \( i \) is the crop type, \( C_N \), \( C_P \) and \( C_K \) are the nutrient content coefficients of N, P and K in straws, respectively. The coefficients were collected from the Organic Fertilizer Nutrient in China [20] and presented in Table S5. The two conversion coefficients (2.29 and 1.2) represent the ratios of P\(_2\)O\(_5\) and K\(_2\)O to P and K, respectively [21].

2.7. Potential contribution of straw to chemical fertilizer

Straw nutrients returned to soil can greatly contribute to soil fertility and reduce the consumption of chemical fertilizers in China. The average straw nutrient resources and total chemical fertilizer consumption in recent 5 years (2010–2014) are compared to investigate to what extent the straw nutrients can counterbalance fertilizer consumption, and provide suggestions for the green development of agriculture during the China’s 13th Five-Year Plan Period (2016–2020). Considering that chemical fertilizers cannot be entirely utilized by crops, we used two calculation methods to analyze the contribution of straw nutrients to chemical fertilizers:

\[
P_1 = \frac{SN \times PR}{TFC \times RE}
\]

\[
P_2 = \frac{SN \times PR}{TFC}
\]

where \( P_1 \) is the percentage of straw nutrients accounting for the net N, P\(_2\)O\(_5\) or K\(_2\)O contents (i.e., effectively utilized by crops) in all chemical fertilizers, \( RE \) is the apparent recovery efficiencies of the net N, P\(_2\)O\(_5\) or K\(_2\)O contents in fertilizers, \( PR \) is the percentage of straw returning to the field (0–100%), and \( P_2 \) is the percentage of straw nutrients accounting for the total N, P\(_2\)O\(_5\) or K\(_2\)O contents in all chemical fertilizers. As found in the Research Report on Fertilizer Utilization Efficiency of Three Major Grain Crops in China [7], the average \( RE \) values of N, P\(_2\)O\(_5\) or K\(_2\)O fertilizers (\( RE_N, RE_{P2O5} \) and \( RE_{K2O} \)) for the 3 major crops (rice, wheat, and maize) were 33%, 24% and 42%, respectively. The chemical fertilizer consumption of the 3 crops in 2014 comprised 84% of the 7 crop types, according to the fertilizer data in Table 1. Therefore, the \( RE \) values of the 3 major crops were used to represent the average \( RE \) values of the 7 main crops in this study (Fig. 1).

2.8. Potential energy value within the crop straw

The potential energy values of different crop straws as biofuel were represented by computing the standard coal equivalent (SCE) [22]. The average SCE value for each crop straw was formulated as:

\[
SCE_i = SY_i \times CF_i
\]

\[
CF_i = \frac{H_{\text{coal}}}{H_{\text{crop}}} \times 100\%
\]

where \( i \) is the crop type, \( SY \) is the straw yield \((10^4 \) t), CF is the conversion factor of standard coal equivalent for crop straw, \( H \) is the heating value of crop straw \((\text{MJ} \text{kg}^{-1})\), and \( H_{\text{coal}} \) is the heating value of standard coal \((29.31 \text{MJ} \text{kg}^{-1})\) [22]. The \( H \) and CF values of different crop straws in China are shown in Table S1.

2.9. Emission of gas pollution and particle number from crop straw burning

The calculation processes of potential emissions (PE) of gas pollutions \( (PE_{\text{gas}}) \) and particle number \( (PE_{\text{particle}}) \) from the three major agricultural crop straws (rice, wheat, maize) were given below:

\[
PE_{\text{gas}} = EF_{\text{gas}i} \times SY_i \times 50.02\%
\]

\[
PE_{\text{particle}} = EF_{\text{particle}i} \times SY_i \times 50.02\%
\]

where \( i \) is the crop type, \( EF_{\text{gas}} \) is the emission factor of gas pollution \((\text{g} \text{kg}^{-1})\), \( EF_{\text{particle}} \) is the emission factor of particle number \((\text{particles} \text{kg}^{-1})\), \( SY \) is the straw yield \((10^4 \) t), and 50.02% is the potential straw percentage for biofuel production [23]. The \( EF_{\text{gas}} \) and \( EF_{\text{particle}} \) values of rice, wheat and maize straws in China are shown in Table S3, which were evaluated using a self-built burning stove and an aerosol chamber in a previous study [24].

3. Results and discussion

3.1. Overuse of chemical fertilizers

China has achieved twelve consecutive years of growth in crop production since the Chinese government implements a series of policies and management measures (i.e., protecting crop procurement prices, agricultural tax relief, and planting structure adjustments, etc.)
to guarantee food security after the 1990s. The total crop yields of the 7 main agricultural crops increased from 481.23 Mt in 1998 to 597.95 Mt in 2014, which represented an increasing percentage of 24.25% from 1998 to 2014 (Fig. 2, Table S2). Although China’s grain output has dramatically increased, tremendous chemical fertilizers have been overused to boost crop production from a limited area of cropland [25]. China’s total consumption of chemical fertilizers increased from 29.66 Mt in 1998 to 39.54 Mt in 2014, with an increasing percentage of 33.31% (Fig. 2, Table 1). From 1998–2014 (17 years), China’s crop yield and chemical fertilizer consumption showed an increasing trend in total, with the exception of 1999–2003, during which the crop production and the consumption of chemical fertilizers in China were generally lower compared to all the other years listed in the Fig. 2, mainly due to the lower crop sown area [26].

China had implemented a number of mature technology mode (i.e., formula fertilization by soil testing) to improve the fertilizer use efficiency over the past decade, and by 2015 that the fertilizer comprehensive use efficiency in China had risen up to 35.2% [7]. However, the increases in both the use of chemical fertilizers and crop yields, and the increasing rate of chemical fertilizer consumption are generally higher than that of crop yield in China. For example, the average growth percentage in the chemical fertilizer consumption based on 1998 was 9.42%, whereas the average growth percentage in crop yield was 3.84% during the period of 1998–2014 (Fig. 3a). As a whole, the increase rates of chemical fertilizer consumption from 1998 to 2014 maintained a sustained upward trend, except for the period of 1999–2003. Similarly, the average growth percentage in chemical fertilizer consumption between each of the two adjacent years from 1998 to 2014 was higher than that of crop yield (Fig. 3b). As a result, excessive levels of chemical fertilizers had been applied to farmlands in order to maintain the increasing rates of crop yields in China for a long time. The long-term overuse of chemical fertilizers, especially for nitrogen fertilizers, has not only reduced soil fertility via driving the loss of soil organic matter, the deterioration of soil structure (i.e., enhancing condensation degree, aromaticity, aging function, etc.), the decrease in the energy level of soil humus, microbial biomass content and enzyme activities due to the acidify effect of N fertilizer application [27–29], but also has led to serious environmental degradation, such as enhanced nitrogen deposition [30] and agricultural non-point pollution (i.e., nitrate pollution of groundwater, eutrophication of surface waters, and soil acidification).

3.2. Straw nutrient resource

China’s crop straw production has dramatically increased with the increase of crop yield. Total straw yields averaged 559.28 and 703.30 Mt in 1998 and 2014, respectively, which represent an increase of 9.00 Mt/yr, or a total increasing percentage of 25.75% (Fig. 2, Table S4). The vast majority of straw is used for bioenergy and livestock forage, or is lost through other ways, whereas only a small amount (14.78%) of the total straw resources are directly returned to the field [23], which is far below the average returning percentage (approximately 70%) in Europe, the United States and other developed countries [31]. Straw contains rich nutrient resources such as N, P and K, and their contents in straw range between 0.65–7.00% and 0.08–0.196% and 1.02–1.82%, respectively (Table S5). Although current straw management practices address the resource needs and economic benefits, the far-reaching ecological effects from removing the straw from the field are often underestimated. Straw removal from the field has greatly aggravated the environmental burdens and soil fertility degradation in farmlands.

3.3. Potential contribution of straw to fertilizer

Since straw contains rich N, P and K resources, we analyzed to what extent returning the straw nutrients to the filed can theoretically counterbalance chemical fertilization consumption of these nutrients. Considering that crops can only partially utilize the applied chemical fertilizers, we analyzed the potential contribution of straw nutrients to chemical fertilizers under two scenarios: (I) the efficiently used
chemical fertilizer and (II) the total chemical fertilizer consumption. The straw yield and chemical fertilizer consumption in recent 5 years was adopted to better provide management implications for China’s 13th Five-Year Green Agriculture Development Plan. The annual mean straw yield was up to 674.91 Mt, including 19.52 Mt of total nutrient resources, 6.11 Mt of N, 2.00 Mt of P2O5, and 11.41 Mt of K2O during 2010–2014. Furthermore, the 5-year average chemical fertilizer consumption of N, K2O and P2O5 were 21.25 Mt, 8.26 Mt and 7.85 Mt, respectively.

(I) The efficiently-used chemical fertilizer (i.e., obtained through multiplying the amount of specific fertilizer consumption by its utilization efficiency) for N, K2O and P2O5 were about 7.01 Mt/yr, 3.30 Mt/yr and 1.98 Mt/yr, respectively (Fig. 4a). Assuming that the straw nutrient resources can completely be translated into soil fertility after returning to the field, only 28.92% and 98.86% of the straw returned to the field can theoretically counterbalance the amounts of efficiently-used chemical fertilizers of K2O and P2O5, respectively. Although the full return of straw can’t completely counterbalance the current consumption rate of N fertilizers, the N nutrient resources in straws can replace approximately 87.22% of the total N fertilizer consumption when all straw was returned to the field.

(II) When considering the potential contributions of the straw nutrients to the total chemical fertilizer consumption, only 68.80% of the straw returned to the field can fully counterbalance the total chemical fertilizer consumption of K2O (Fig. 4b). Meanwhile, the full return of straw nutrients can take up 28.77% and 24.25% of N and P2O5 fertilizer consumption, respectively.

Overall, promoting the return of straw to the field has a great potential to reduce the use of chemical fertilizer despite neglecting the actual straw nutrient utilization efficiency in the field and thus slightly overestimating the contribution of straw nutrient resources to chemical fertilizer consumption.

3.4. Straw bioenergy and pollutant emission

Crop straws contain rich bioenergy, and had traditionally been used as one of the most important energy sources in China, especially in the rural areas [23]. The total straw yields in China were equivalent to 255.4–373.3 Mt of standard coal equivalent (SCE) from 1998 to 2014 (Table 2). The amount of total SCE was mainly contributed by rice (77.2–98.5 Mt), maize (61.8–129.6 Mt) and wheat (60.4–88.4 Mt). Soybean, peanut, canola and cotton together provided less than 20% of the total SCE (Table 2). The straw percentage for biofuel production was approximately 50.02%, which was the sum of the straw burned for cooking food/warming, or burned directly in fields and that used for biofuel combustion [17]. Hence, the potential energy derived from part of the straw yield was 186.7 Mt of SCE in 2014.

With improved living conditions in rural areas, the dwellers and farmers tend to rely more on commercial fuel, which leads to even more open field burning or accelerated comprehensive utilization of straw resource removed from the field. Thus, we further evaluated the pollutant emission derived from straw burning to assess its potential

![Image](https://via.placeholder.com/150)

**Table 2**

Standard coal equivalent (SCE, Mt) of the 7 main crop straws in China from 1998 to 2014. The SCE value of specific crop straw was estimated by multiplying straw yield (SY) by conversion factor (CF) of standard coal equivalent.

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<tbody>
<tr>
<td>SCE_Rice</td>
<td>96.2</td>
<td>95.8</td>
<td>90.5</td>
<td>85.6</td>
<td>84.1</td>
<td>77.2</td>
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<td>66.7</td>
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Table 3: Potential emission of gas pollution (PEgas, Tg) derived from crop straw combustion in China from 1998 to 2014. The fci crop straw was calculated by multiplying straw yield (SY) by emission factor of gas pollution (EFgas).

<table>
<thead>
<tr>
<th>Year</th>
<th>Rice</th>
<th>Wheat</th>
<th>Corn</th>
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<tbody>
<tr>
<td>1998</td>
<td>6.68</td>
<td>5.36</td>
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**Note:** The values are in Tg. The table shows the potential emission of gas pollution from crop straw combustion in China from 1998 to 2014. The potential emission was calculated by multiplying the straw yield (SY) by the emission factor of gas pollution (EFgas).
fields is a major barrier to popularizing straw-returning practices. Appropriate policy interventions and guidance should be established to increase the public’s awareness and knowledge regarding the important significance of straw-returning practices in terms of sustainable agricultural and environmental protection. Third, another main barrier to the effective application of straw-returning practices in China is the high cost. The government needs to offer much more incentives (i.e., agricultural subsidies) to motivate farmers to adopt and popularize straw-returning practices.

Green agriculture has already become a major theme in China. Consequently, theories on ecosystem mass cycling should be introduced for the sustainable development of agriculture and the protection of environment. We should take full advantage of straw returning to improve farmland soil quality while applying chemical fertilizers to maintain the demand for crop production in the short term. We argue that efficiently balancing chemical fertilizer consumption and straw returning practices is imperative and the foundation of both sustainable agricultural development and steady increases in crop production.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2017.06.076.

References


