Straw Incorporation Strategy on Cereal Crop Yield in China

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ABSTRACT

Straw incorporation (SI) is considered a valid agricultural measure for ameliorating soil quality and sequestering soil C. This study aimed to quantitatively summarize the response of cereal yield to SI management. Our results showed that compared with straw removal, SI could significantly enhance cereal yield by 7% over all of China across the 9-yr period. In all regions, SI in coarse-textured soils increased yields more than in fine-textured soils. Straw incorporation resulted in greater yield increases for upland crops compared with rice (*Oryza sativa* L.) cropping, and for rotary tillage compared with plowing and no tillage. Overall, SI-induced cereal yield increases were greater in areas with a lack of soil nutrients and soil water. The SI-induced increases of 1 t ha⁻¹ of soil organic C (SOC) storage could increase cereal yield by 44 kg ha⁻¹. If half or full amounts of cereal straw is returned across all of China's agricultural regions, cereal yields would increase by an average of 2.84 and 5.07 Tg yr⁻¹, respectively, which would contribute to achieving the increasing yield requirements of China.

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Abbreviations: AMP, annual mean precipitation; AMT, annual mean temperature; $\ln(R)$, response ratio; NBSPRC, National Bureau of Statistics of the People's Republic of China; NT, no tillage; PT, plowing tillage; RT, rotary tillage; SI, straw incorporation; SOC, soil organic carbon; SR, straw removal.

CHINA has 7% of the arable land, 6% of the water resources in the world, and feeds 22% of the world population (Zhang et al., 2011); therefore, food security is a top priority in China. It is estimated that the Chinese population will peak in 2033 at 1.47 billion. If annual per-capita food consumption requirement is at 400 to 450 kg (Feng, 2007), China will need 589 to 663 Tg of cereals to feed its population in 2033, equivalent to an increase of 0.81 to 1.46% per year from now. During the past five decades, China has adopted a series of agricultural practices and biotechnology methods to enhance cereal yield (Zhu and Chen, 2002; Zhou et al., 2007; Xue et al., 2013). Cereal production has increased 3.2-fold, with approximately 50% of this increase due to higher application rates of synthetic fertilizers (Wang and Xiao, 2008).

Nevertheless, due to many constraints, increases in crop production have lagged since the middle of the 1990s, with an annual increase of only 0.60% (Zhang et al., 2011). To maximize crop yields, synthetic fertilizer rates have greatly increased since the

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1990s, but, unfortunately, synthetic fertilizer application induced-yield enhancement has declined rapidly (Zhu and Chen, 2002). Generally, under high N fertilizer application, 5 to 15% of the N fertilizer is transformed into yield (Erisman et al., 2007) and the remaining N becomes either greenhouse gases (Smith et al., 2008) or pollution sources (Zhu and Chen, 2002; Bouraoui and Grizzetti, 2014). Additionally, the per-capita arable land area in China is only 0.1 ha, which is one-seventh of that in the United States and less than half of the world's average (Wang et al., 2009). Furthermore, the quality of the arable land has seriously degraded, with over 60% having some factors that limited yield increment (Zhao et al., 2006). Above all, an annual increase of 0.81 to 1.46% yield will be a great challenge in the next 20 yr, and in addition to synthetic fertilizers, China needs other valid methods to achieve greater production from the limited arable land to ensure food security.

China produces approximately 820 Tg of crop straw, which represents 1.3 times the total crop yield (Liu et al., 2008b; STEMOA, 2010). The cereal crops rice, maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.) are responsible for 75% of the total crop straw (STEMOA, 2010). It was estimated that 1 t of cereal straw contains 12 to 20 kg of N, 1 to 4 kg of P, 7 to 30 kg of K (Lal, 2004), and the burning of straw results in the loss of almost all the C and N (Dobermann and Fairhurst, 2000; Yadvinder-Singh et al., 2004). Although straw contains abundant nutrients, only 22% of straw is used as fertilizer in soils, and most is discarded or directly burnt in the field (Lu et al., 2010).

China's cropland has characteristic double-cropping systems (on 70% of the arable land), and repetitively harvesting crops can decrease soil quality. Thus, the National Modern Agriculture Development Plan, 2011–2015 (Ministry of Agriculture–PRC, 2011) stressed comprehensive use of straws to protect the soil environment and increase crop yield. There have been numerous recent investigations about SI effects on cereal yield across China, with both positive and negative effects observed (Tan et al., 2009; Zhang et al., 2014). Up to now, only the response of yield to SI in rice paddies has been systematically investigated on a large scale (Dawe et al., 2003; Huang et al., 2013). Wheat and maize account for 60% of China's total cereal yield, and feed 730 million of the population, nevertheless, few papers have synthesized assessments of how these yields respond to SI. China has a great diversity of climates, soil types, and cropping systems, and meta-analysis can synthesize such data from multiple locations, with temporal variability in results, and draw consistent conclusions across studies (Gurevitch and Hedges, 1999). Thus, our overall objectives in this study are to (i) investigate how certain factors (e.g., SI amount, tillage type, and cropping system) influence the response of cereal (maize, wheat, and rice) yield to SI and (ii) estimate cereal yield increase with adoption of SI management in China.

MATERIALS AND METHODS

Data Collection

An exhaustive literature survey was performed by searching the ISI-Web of Science, Chinese Core Journal databases (CNKI and Wanfang databases) and Google Scholar (Google Inc.) for peer-reviewed articles published before June 2014 and containing the keywords straw, yield, rice, maize, wheat, and their combinations. Studies had to meet the following specific criteria: (i) annual cereal yield values were reported within the paper; (ii) field experiments were included, but pot experiments, agroforestry systems, or vegetable land were excluded; (iii) experimental periods were >3 yr; and (iv) rice, maize, and wheat were included because they are the most common crops cultivated in China and they produce 75% of the total straw (STEMOA, 2010). A total of 64 papers (Supplemental Table S1), consisting of 142 paired cereal yield data met our inclusion criteria. The experimental field distribution is shown in Fig. 1.

The means, standard deviations, and replications of cereal yields for straw removal (SR) and SI were taken from the published literature, including tables, texts, and figures. The data from figures were extracted by using digitizing software (GRAFULA 3 v.2.10, Wesik SoftHaus). Ancillary information on the soil basic chemical and physical properties of the experimental sites (0–20 cm depth) was collected. Additionally, the agricultural management combined with SI such as tillage treatment, straw amount, cropping system, experimental site, and duration were also extracted from the articles.

To explain the variations in response of cereal yield to SI, the paired measurements were further categorized according to (i) tillage type: no tillage (NT), plowing tillage (PT), and rotary tillage (RT); (ii) cropping system: rice–rice, wheat–rice, wheat–maize, and single maize, wheat, or rice (single); (iii) experiment region: northeast (lower annual mean temperature [AMT], with single cropping), north (warm, with double upland cropping), northwest (warm and dry, with single cropping), and south (hot and moist, with double cropping); (iv) soil texture: fine- and coarse-textured; (v) experimental duration (<10 and >10 yr); and (vi) straw amount: half and full amounts of SI management.

Analysis

A meta-analysis was conducted to detect the response of cereal yield to SI. A response ratio, $\ln(R)$, or the natural log of the ratio of the mean value of a concerned variable in SI management to that in SR, was used to represent the magnitude of the effects of SI as below (Rosenberg et al., 2000):

$$\ln(R) = \ln\left(\frac{\overline{X_{SI}}}{\overline{X_{SR}}}\right)$$

Where, $\overline{X_{SI}}$ and $\overline{X_{SR}}$ are the mean yield values of SI and SR treatments, respectively. This method estimates the effect as a proportionate change resulting in SI manipulation, and calculated as $(R - 1) \times 100\%$ (Curtis and Wang, 1998; Feng et al., 2008). Negative percentage changes indicate an inhibitory effect of SI, and positive values indicate an increase of a variable in response to SI.

Figure 1. The distribution of experimental straw study sites in China.

An unweighted meta-analysis was adopted, as most of the collected papers did not provide a measure of variance for cereal yield (Gurevitch and Hedges, 1999; Rosenberg et al., 2000). Following the techniques of Curtis and Wang (1998), the meta-analysis was conducted using a meta-analytical software package METAWIN 2.1.3.4 (Rosenberg et al., 2000). Random-effects models allow comparisons among categories in a framework similar to ANOVA, and thus we adopted a random-effects categorical summary analysis to compare the variances of the different categorical groups. We defined statistical significance as $p < 0.05$ under between-group heterogeneity (Q_b). Confidence limits around the effect size were calculated using a bootstrap method with 4999 interactions (Rosenberg et al., 2000). In cases where 95% confidence intervals did not overlap zero, a significant SI-induced response was considered (Curtis and Wang, 1998).

A stepwise regression analysis was used to analyze the relationship between $\ln(R)$ and soil nutrients, AMT, and annual mean precipitation (AMP), using SPSS version 10 (SPSS Inc, 2011). Regression equations were regarded as significant, if $p < 0.05$.

RESULTS

Response of Cereal Yield to Straw Incorporation across Different Soil Environments

Of 142 comparisons, cereal yields were enhanced in 92% (131 comparisons) and reduced in 8% (11 comparisons) of locations under SI management. Overall, cereal yields

were significantly higher (7%) for locations under SI management compared with SR management (Fig. 2). Results showed significant between-group heterogeneity among experimental regions, soil texture, and cropping systems (Table 1). Averaged annual yield differences in SI compared with SR indicated a 12 and 8% increases in the northwest and north regions, respectively, which are significantly higher than those in the south (6%) and northeast (4%) regions (Fig. 2). The yield increase with SI was significantly greater in coarse-textured (9%) than in fine-textured soils (6%). Wheat–maize, single, and wheat–rice rotations resulted in higher yield increments than for rice–rice (3%). Experimental durations of <10 and >10 yr resulted in cereal yield increase with SI of 6 and 8%, respectively, but with no significant difference between them (Table 1). The $\ln(R)$ across all the studies exponentially decreased with increases in initial soil chemical properties in the top 20 cm of soil (crop available N and total K; Fig. 3a,b). In the northwest region, there was a positive relationship of $\ln(R)$ with AMT (Fig. 4b-1) and with AMP (Fig. 4b-2). In other regions, there was no pronounced relationship between $\ln(R)$ and AMT and AMP (Fig. 4a-1, a-2, c-1, c-2, d-1, d-2).

Figure 2. Response of annual cereal crop yield to straw incorporation under different experimental regions, soil texture types, and cropping systems. The square and the horizontal line represent the mean and range of cereal yield response to straw incorporation at 95% confidence interval; the number and percentage value in parentheses indicate the number of paired trials and the percentage increase.

Table 1. Effects of straw incorporation on between-group heterogeneity for cereal yield.

	<i>n</i>	Tillage	Cropping system	Regions	Texture	Experiment duration	Straw amount
Yield	142	6.60*	6.35*	7.63*	3.62*	3.31	3.66*

* Significant at the 0.05 probability level.

Response of Cereal Yield to Straw Incorporation under Different Agricultural Management Practices

Overall, the effects of SI on cereal yield varied significantly with different tillage treatments and straw amount (Table 1). For SI compared with SR, the enhancement of cereal yield in RT (12%) was significantly higher than that for PT (7%) and NT (6%), and the full amount of SI management (9%) resulted in a greater cereal yield increment than the half amount (6%). The response of cereal yield to straw amount also varied in different regions (Fig. 5a–d); the greatest difference between full and half amounts of SI was for the northwest region, with 18 and 6% of the yield increases, respectively (Fig. 5a).

DISCUSSION

How Would Straw Incorporation Increase Cereal Yield in China?

In China, an average 7% increase in cereal yield after adoption of SI could be induced by the following several mechanisms. First, SI could significantly improve SOC (Lu et al., 2009; Zhao et al., 2014), and SOC is of fundamental importance to soil fertility and directly affects crop yield (Lal, 2004, 2010). In the present study, of a total of 142 comparisons of cereal yield, 88 paired comparisons included SOC storage due to SI management. Regression analysis revealed a significant linear relationship between $\ln(R)$ of cereal yield and $\ln(R)$ of SOC storage [$\ln(R)_{\text{cereal_yield}} = 0.03 + 0.35[\ln(R)_{\text{SOC_storage}}]$; $R^2 = 0.38$; $p < 0.01$]. According to the ratio of SOC change to cereal yield change after adoption of SI management, we found 1 t ha⁻¹ of SOC

Figure 3. The relationship between response ratio and initial crop available N and total K (0–20 cm depth).

Figure 4. The relationship between response ratio and annual mean temperature and precipitation in different experimental regions.

Figure 5. Response of annual cereal crop yield to different straw amounts in different experimental regions. The square and vertical line represent the mean and range of cereal yield response to straw incorporation at 95% confidence interval; the number and percentage value in parentheses indicate the number of paired trials and the percentage increase. Half amount, and full amount in the horizontal line, respectively, represent the incorporation of half amount of the straw in each hectare of cropland and incorporation of full amount of the straw in each hectare of cropland. Overall in the x-axis represents the overall cereal yield increase between half and full amount.

storage increment could increase cereal yield by 44 kg ha⁻¹. Second, SI can substantially improve soil physical properties (e.g., soil aggregation and bulk density) (Powelson et al., 2011) and soil temperature (Ramakrishna et al., 2006) and increase soil water retention, especially in dry areas and dry years (Malhi et al., 2011a; Zhang et al., 2014). Third, cereal straw contains abundant essential nutrients required for crop growth. Using the cereal production data from 2010 (National Bureau of Statistics of the People's Republic of China [NBSPRC], 2010), straw/grain ratio (Han et al., 2002) and straw nutrient content (National Center for Services and Popularization of Agricultural Techniques, 1999), we estimated that cereal straw in China produced (all in Tg) 230 of C, 5 of N, 0.72 of P, and 10 of K. The N and P amounts in cereal straw account for 21 and 9% of the application of chemical N and P fertilizers, respectively, while the amount of K in cereal straw is 1.8 times that in K fertilizer applied in China (NBSPRC, 2010). Straw incorporation management could improve the N-supplying power of soil (Malhi et al., 2011a,b). Relevant studies showed that increasing SI amounts in China from 15 to 90% would

increase the N mineralization rates by 10 to 25% in the following year, thus reducing the need for synthetic N fertilizers (Li et al., 2003). Straw K could even substitute for the same amount of synthetic K fertilizers (Lao et al., 2003).

Of 142 data pairs, 11 data pairs showed cereal yields were suppressed by SI compared with SR management; all of the 11 data pairs were distributed in the regions with rich SOC and soil nutrient. Additionally, this might be due to weed infestation or insect damage under SI (Liu et al., 2010b). However, no consensus has yet been reached on whether SI generally stimulates or suppresses weed infestation and insect damage (Ramakrishna et al., 2006; Liu et al., 2010b; Huang et al., 2014). Furthermore, SI technology has been researched for 30 yr in China, and a series of sound SI techniques have been formed in different climate zones and cropping systems (Liu et al., 2001; Bi et al., 2008; Liu et al., 2008a). Moreover, previous studies showed that SI promoted cereal yield over the long rather than the short term (Takahashi et al., 2003); therefore, SI should be an effective practice to enhance crop yield in China in the long run.

Table 2. Cereal yield increase potential in different experimental regions and whole China.

Experimental region	Total cereal yield in 2010	Scenario I (half amount of straw incorporation)			Scenario II (full amount of straw incorporation)		
		Yield increase ratio	Yield increase	Mean experimental duration	Yield increase ratio	Yield increase	Mean experimental duration
	Tg	%	Tg	yr	%	Tg	yr
Northeast	86.16	4	3.44	9	8	6.89	9
Northwest	32.69	6	1.96	12	18	5.88	8
North	152.84	7	10.69	10	9	13.76	9
South	224.69	6	13.48	9	8	17.97	10
Whole China	496.38		29.57			44.51	

Meta-Analysis for Cereal Yield Response to Straw Incorporation

This study analyzed the response of cereal yield to SI, which varied greatly with experimental region, cropping system, soil nutrient level, soil texture, straw amount, climate, and tillage type. The critical contributing factors can be summarized in two capacities of SI: retaining soil water (Ramakrishna et al., 2006; Li et al., 2012; Zhang et al., 2014) and increasing SOC (Lu et al., 2009; Malhi et al., 2011b; Zhao et al., 2014).

Retaining soil water led to increases in cereal yields mainly in areas with low water availability. The northwest region is the driest area in China, with an average AMP of 200 to 600 mm, and over 90% of the cropland receives no irrigation (Liu et al., 2010a). A field experiment in the Loess Plateau of the northwest revealed that SI showed the same capacity for storing soil water, as did mulching with plastic film or biodegradable film (Li et al., 2012). Due to rapid drying in coarse-textured soils, Arora et al. (2011) demonstrated that SI management would result in greater yield increments in coarse-textured compared with fine-textured soils, which was consistent with our results.

Soil organic C is the foundation and core of soil fertility, and increasing SOC results in enhancing of cereal yields mainly in areas with depleted soil nutrients and SOC (Lal, 2004). Unlike other upland cropping regions (northwest and north regions), the northeast region is associated with higher SOC, lower AMT, and single cropping (Pan and Zhao, 2005; Lu et al., 2009). The power of SI to increase yield was not evident under lower straw decomposition rates and SOC-rich northeast soils. Fine-textured and rice–rice cropping soils generally have greater SOC compared with coarse-textured and other cropping (i.e., wheat–rice, wheat–maize, and single) soils (Plante et al., 2006; Huang et al., 2012); therefore, they have lower capacity to enhance production (Lal, 2010). Recent reports verified that, due to improving soil physical structure, RT combined with SI management resulted in increased cereal yields (Zhao et al., 2013; Guan et al., 2014). In the present study, there was a decreasing $\ln(R)$ of cereal yield with increases in initial crop available N and total K. This might

suggest that in originally nutrient-poor regions, SI management benefited uptake of nutrient elements (Sheldrick et al., 2003; Guan et al., 2014) and caused greater yield increases. At an Asia-scale, Dawe et al. (2003) concluded that organic amendments might not improve grain yield in rice–rice and rice–wheat cropping systems but would be profitable as complements to synthetic fertilizer. Therefore, SI might not always increase cereal yield, especially in soils containing higher levels of SOC and nutrients.

Estimated Cereal Yield Increase in China

In recent years, the Chinese government has made great efforts to prohibit straw field burning and encourage SI (Lu et al., 2010). As a result, the techniques of full amount of crop SI are popularized across the whole of China, especially in the northwest and north regions, for keeping soil water content (Li et al., 2012). However, taking into account the labor costs and straw decomposition rate for SI practices, a number of regions still implement half amount of crop SI (Bi et al., 2008), particularly in the north, south (the double-crop regions), and northeast regions. Therefore, two scenarios were considered in the present study: incorporation in each hectare of cropland of half- of the amount of the straw (Scenario I) and full amount of the straw (Scenario II). By multiplying the yield increase ratio by total cereal yield in 2010, the cereal yield increase potential in different experimental regions could be obtained (Table 2). It could be expected that on the national scale, total cereal yield across the 9-yr period (as the data was drawn from the field experiments that lasted for 8 to 12 yr with an average of 9 yr) would increase by 29.59 and 44.51 Tg (Table 2), or 2.84 and 5.07 Tg yr⁻¹, respectively, if half amount (Scenario I) or full amount of SI (Scenario II) management is implemented. These increase potentials correspond to 0.57 and 1.02% of the total cereal yield in 2010 (NBSPRC, 2010). However, it is noteworthy that, as for SOC saturation mechanisms (Six et al., 2002; Zhao et al., 2014), SI-induced yield increase is not constant, especially in nutrient-rich regions. Despite this, SI is still a valid management for ameliorating soil quality and providing guarantees for yield security (Powlson et al., 2011), especially in China. Feasible management strategy

and policy that ensure stable cereal yield improvement are needed in the future.

CONCLUSIONS

This study demonstrated that, compared with SR, SI significantly increase cereal yield by 7% over all of China across the 9-yr period. When evaluating the magnitude of the effect of SI on cereal yield, it is critical to consider such factors as experimental site, cropping system, straw amount, soil circumstances, climate, and tillage type. Our results revealed that response of cereal yield to SI was greater in areas experiencing water deficits and low levels of nutrient elements and SOC. Additionally, we estimated that an increase of 1 t ha⁻¹ of SOC storage could increase cereal yield by 44 kg ha⁻¹. If half or full amount of SI is implemented, there would be a respective 2.84 and 5.07 Tg yr⁻¹ of cereal yield increase, corresponding to 0.57 and 1.02% of the cereal yield in 2010. Therefore, SI management should be encouraged for its contribution to increasing cereal yield in China.

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