Straw incorporation increases crop yield and soil organic carbon sequestration but varies under different natural conditions and farming practices in China: A system analysis

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Abstract. Loss of soil organic carbon (SOC) from agricultural soils is a key indicator of soil degradation associated with reductions in net primary productivity in crop production systems worldwide. Technically simple and locally appropriate solutions are required for farmers to increase SOC and to improve cropland management. In the last 30 yr, straw incorporation (SI) has gradually been implemented across China in the context of agricultural intensification and rural livelihood improvement. A meta-analysis of data published before the end of 2016 was undertaken to investigate the effects of SI on crop production and SOC sequestration. The results of 68 experimental studies throughout China in different edaphic conditions, climate regions and farming regimes were analyzed. Compared with straw removal (SR), SI significantly sequestered SOC (0–20 cm depth) at the rate of 0.35 (95% CI, 0.31–0.40) Mg C ha^{-1} yr^{-1}, increased crop grain yield by 13.4% (9.3%–18.4%) and had a conversion efficiency of the incorporated straw C of 16% ± 2% across China. The combined SI at the rate of 3 Mg C ha^{-1} yr^{-1} with mineral fertilizer of 200–400 kg N ha^{-1} yr^{-1} was demonstrated to be the best farming practice with crop yield increased by 32.7% (17.9%–56.4%) and SOC sequestrated by the rate of 0.85 (0.54–1.15) Mg C ha^{-1} yr^{-1}. Straw incorporation achieved higher SOC sequestration rate and crop yield increment when applied to clay soils under high cropping intensities, and in areas such as northeast China where the soil is being degraded. The SOC responses were highest in the initial starting phase of SI then subsequently declined and finally became negligible after 28–62 yr. However, crop yield responses were initially low and then increased, reaching their highest level at 11–15 yr after SI. Overall, our study confirmed that SI created a positive feedback loop of SOC enhancement together with increased crop production, and this is of great practical importance to straw management as agriculture intensifies both in China and other regions with different climate conditions.

1 Introduction

Around a quarter of China's land territory (or > 2 million km^2) is affected by soil degradation associated with the loss of net primary productivity equating to ~60 billion Mg carbon (C) over 23 yr (Bai et al., 2008). The considerable impact of soil degradation on crop production in China and worldwide points to the need for solutions appropriate to location-specific agro-ecological conditions and farming systems (Bindraban et al., 2012). Soil organic carbon (SOC) loss is a key indicator of soil degradation that is accelerated by land use (Erb et al., 2016; Liu et al., 2018) and is widely associated with cultivation (Dungait et al., 2012; Amundson et al., 2015). Thus, management to enhance SOC to potentially rejuvenate degraded agricultural soils, thereby improving soil fertility and increasing crop yield (Smith et al., 2012) while sequestering soil C to mitigate climate change (Meinshausen et al., 2009), is a win–win scenario that maintains the integrity of agricultural ecosystems (Power, 2010).

Like many degraded arable soils across the world, cropland soils in China commonly have low SOC (12.0–12.7 g kg^{-1} at 0–20 cm; Yan et al., 2011), which suggests a substantial potential for C sequestration (25–37 billion Mg C yr^{-1}) if management is changed to rebuild SOC stocks in cultivated soil (Lal, 2002). Since the start of the reform policies in 1978, China has experienced a rapid agricultural intensification process, which was characterized by farming practices mostly involving high mineral fertilization rate (e.g., > 400 kg N ha^{-1} yr^{-1}; Ju et al., 2004), frequent irrigation events (Kong et al., 2016) and popularized mechanization (Zhang et al., 2017b). This process greatly increased not only the grain yield but also straw yield to > 0.6 billion Mg straw yr^{-1} (Shi et al., 2014). Crop straw was once widely harvested for fuel but, with the improvement in rural livelihoods after the 1990s, farmers have tended to switch to electricity, liquid gas or coal (Zhang et al., 2017b), introducing challenges for managing large amounts of “waste” straw (Kong et al., 2014). The recently renewed recognition of SOC for soil health and quality has encouraged straw incorporation (SI) as a simple and environmentally friendly measure to effectively enhance cropland SOC levels (Pan et al., 2010; Liao et al., 2015) and to improve crop production (Zhao et al., 2015).

Differences in climatic and edaphic conditions (Bolinder et al., 2007), fertilization strategies (Khan et al., 2007), cropping regimes (Huang et al., 2012) and duration of SI (Lehtinen et al., 2014) have resulted in large spatial and temporal variations in the effects of SI on SOC and crop yield in China (Li et al., 2003; Yu et al., 2012). Extensive field experiments covering different regions and under various farming systems have been conducted since the 1980s to study the effect of SI (e.g., Cai and Qin, 2006; Gong et al., 2009; Zhang et al., 2014). Integration of the results of these studies assists an effective examination of the underlying mechanisms of SI on SOC (e.g., SOC conversion efficiency; Kong et al., 2005; Wang et al., 2015) and crop yield. This novel information could also provide scientific support for the development of sound policies for straw management at regional and governmental levels (Ministry of Agriculture–PRC., 2013, 2015).

We conducted a meta-analysis to test the hypothesis that SI increases SOC stocks and crop yields in China because it is an effective and proven statistical method to quantitatively integrate the results of numerous individual studies and subsequently draw general conclusions at a larger scale (Gurevitch et al., 2001; Chivenge et al., 2011). To date, several meta-analyses have reported on the effects of SI on SOC or crop yield in China’s arable soils (e.g., Lu et al., 2009; Tian et al., 2015; Wang et al., 2015; Zhao et al., 2015). For instance, Lu et al. (2009) reported that SI could sequester 9.76 billion Mg C yr^{-1} in China’s cropland and Zhao et al. (2015) found that SI improved crop yield by 7% across China. However, only a few of these studies presented the effects of SI in different climatic and edaphic regions (Lu et al., 2009; Zhao et al., 2015), or addressed both the responses of crop yield and SOC to SI (Wang et al., 2015). The poor reporting of straw C conversion efficiencies (Lu et al., 2009; Tian et al., 2015) also weakens the practicability of related conclusions in policy development. To overcome these limitations in previous meta-analysis studies, we conducted a new meta-analysis for field experiments carried out over the last 30+ yr in China. We aimed to: (i) quantify the responses of SOC and crop yield to SI at regional and national scales; (ii) calculate the conversion efficiency of straw C to SOC; and (iii) assess the effects of major factors of soil properties (e.g., texture and initial SOC content), climate conditions (temperature and precipitation) and farming practices (e.g., straw quantity and type, incorporation duration, N fertilizer and cropping system) on the efficacy of SI.

2 Materials and methods

2.1 Data source

A survey of peer-reviewed papers published before 31 December 2016 was conducted using two bibliographic databases: Web of Knowledge and Chinese Journal Databases (CNKI). The keywords “soil organic carbon”, “straw incorporation” and “straw return” were used. To be included in the meta-analysis, a study had to meet the following criteria: (i) the research was based on a field experiment lasting for more than 3 yr, with a known starting year; (ii) experimental treatments were replicated; (iii) experiments had paired treatments of both SI and SR; and (iv) cropping systems included at least one growing season for rice, maize or wheat. A total of 68 papers (Table S1), consisting of 70 long-term field experiment sites (Fig. 1) met the criteria for inclusion in our experiment.

Information on soil properties (texture, initial SOC content and bulk density (BD)), climate (temperature and precipitation), farming practices (land use, N fertilization, crop type, crop frequency, C and nutrient contents of straw and duration of SI) was also collected. The SOC content or stock and crop yields were obtained directly from tables and/or text of the papers or extracted from the figures using graph digitizing software (GetData Graph Digitizer V2.25; http://getdata-graph-digitizer.com/). For studies in which SOC content was reported with BD, SOC stock (Mg C ha^{-1}) was calculated using Eq. (1):

$$\text{SOC stock} = \text{SOC} \times \text{BD} \times H \times 0.1 \qquad (1)$$

where SOC is SOC content (g kg^{-1}), BD is the soil bulk density (g cm^{-3}), H is the thickness of the soil layer (0–20 cm) and 0.1 is a constant to adjust the units. The SOC stocks were computed to 20 cm depth. Soils were mineral soil at 0–20 cm depth at all sites examined in the 68 papers. In those studies that only reported soil organic matter content, we estimated SOC content as 58% of the soil organic matter. For the studies in which BD was not available, we estimated the BD for paddy or paddy-upland soil using Eq. (2) (Pan et al., 2003):

$$\text{BD} = -0.22 \times \ln(\text{SOC}) + 1.78 \qquad (2)$$

and for upland soil, the BD was estimated using Eq. (3) (Song et al., 2005):

$$\text{BD} = 1.377 \times \text{Exp}(-0.0048 \times \text{SOC}) \qquad (3)$$

For studies that did not report the quantity of incorporated straw-C, it was estimated by multiplying the straw-C content (39.9% for wheat, 44.4% for maize and 41.8% for rice; NATEC, 1999) by the amount of straw incorporated. A sensitivity analysis was conducted to test the robustness of our analysis. We undertook the same meta-analysis process using Eq. (2) for upland, and Eq. (3) for paddy, setting a constant C content (40%) for all the crop straws (wheat, maize and rice). The results showed that use of different estimation approaches for BD and straw-C did not have a major impact on the general findings of SOC responses to SI.

To distinguish between the sources of variation for the responses of SOC and crop yield to SI, the paired measurements were further subdivided into subgroups according to the categorical variables listed in Table 1. Annual fertilizer N input in the studies ranged from 0 to 720 kg N ha^{-1} yr^{-1} and was separated into three levels. The > 400 kg N ha^{-1} yr^{-1} and 200–400 kg N ha^{-1} yr^{-1} ranges represent typical farmer fertilizer N rate and the optimized fertilizer N rates, respectively, whereas < 200 kg N ha^{-1} yr^{-1} is the low N fertilization level (Ju et al., 2004; Zhang et al., 2017b). Mean annual precipitation (MAP) and mean annual temperature (MAT) ranged from 117 to 1788 mm and from 0.9 to 18.4 °C, respectively. The classifications of MAP and MAT in the meta-analysis were based on FAO guidelines for agro-climatic zoning (Fischer et al., 2002). Mainland China was divided into the following four regions according to the geographic location, climate conditions and farming practices: northeast China (NEC), north China (NC), northwest China (NWC) and south China (SC). Detailed information for each region is provided in Table 2. Other categorized variables were crop frequency (number of crops per year, i.e., single, double and triple crops), land-use type (paddy, upland and paddy-upland soils) and straw type (rice, wheat and maize straws).

2.2 Data analysis

2.2.1 Responses of crop yield to straw incorporation

Effect size is an index that reflects the magnitude of treatment (SI) effect in comparison with a reference treatment (SR) (Borenstein et al., 2009). The effect size of each observation (taken to be the comparison between SI and SR in our study) for crop yield was calculated as the natural log of the response ratio (ln*R*) (Rosenberg et al., 2000), as in Eq. (4):

$$\ln R = \ln \frac{X_e}{X_c} \qquad (4)$$

where *Xe* is the mean crop grain yield of the SI treatment and *Xc* is the mean grain yield of the control (SR). The relative change in crop yields following SI was also calculated as $(R - 1) \times 100\%$ (Chivenge et al., 2011). Positive values of relative change indicated a promotion effect of SI on crop production and vice versa.

2.2.2 Responses of SOC to straw incorporation

The effect size of SOC was expressed as an annual SOC sequestration rate (Mg C ha^{-1} yr^{-1}), which was calculated by Eq. (5):

$$\text{Annual SOC sequestration rate} = \frac{(\mathrm{D_{soct}} - \mathrm{D_{soci}}) - (\mathrm{D_{soct\prime}} - \mathrm{D_{soci\prime}})}{\text{duration}} \qquad (5)$$

where D_{soct} and $D_{soct'}$ are SOC stock for the terminal year of experimental SI and SR treatments, respectively; and D_{soci} and $D_{soci'}$ are SOC stock for the initial year of SI and SR treatments, respectively. A positive value of annual SOC sequestration rate indicates a SOC stock increase due to SI and a negative difference indicates the opposite effect.

2.3 Meta-analysis

A meta-analysis of the random effect model was performed and analyzed using MetaWin 2.1 software (Rosenberg et al., 2000). As standard deviations were rarely available in the selected literature, an unweighted analysis was adopted to include as many studies as possible (Hedges et al., 1999; Rosenberg et al., 2000). We used bootstrapping (4999 iterations) to generate the mean effect size and bias-corrected 95% confidence interval (95% CI) for each categorical variable. Mean effect sizes were considered to be significantly different if their 95% CIs did not overlap, and were considered to be significantly different from the control if their 95% CIs did not overlap with zero (Chivenge et al., 2011). We accepted the mean effect sizes of the categories to be significantly different between the levels of the factors if the P values of the between-group heterogeneity (Q_b) were less than the 0.05 level ($P < 0.05$).

2.4 Regression analysis

A stepwise regression analysis was applied to analyze the relationship between SOC contents, the input rate of total nutrients (N, P_2O_5 and K_2O) and crop yields. Regression analysis was also used to examine the SOC responses to experimental factors (i.e., straw-C input rate, experiment duration and initial SOC content). The relationship between yield response to SI and control yield was also examined. All regression analyses were performed using SPSS version 20.0 (SPSS Inc., Chicago, USA), and the results were considered statistically significant if $P < 0.05$.

3 Results

3.1 SOC and crop yield

For all the experiments studied, a significant positive linear regression was determined between SOC content and crop yield (Fig. 2; $R^2 = 0.42$, $P < 0.05$). If the fertilization variables were considered, a significant linear relationship between crop yield and SOC content revealed, i.e., Yield (Mg ha^{-1} yr^{-1}) = 0.933 + 0.267 × SOC (g kg^{-1}) + 0.008 × N (kg ha^{-1} yr^{-1}) + 0.010 × K_2O (kg ha^{-1} yr^{-1}) ($R^2 = 0.69$, $P < 0.01$, $n = 100$), in which the variable of fertilizer P_2O_5 was excluded by using the method of stepwise regression analysis. These results indicated that SOC content explained 42% of the yield variations while SOC content and fertilizer input altogether explained 69%. Overall, an increase of 1 g kg^{-1} SOC content could improve crop yield by 267–414 kg ha^{-1} yr^{-1}, or 101–157 kg ha^{-1} yr^{-1} of yield increase if converted to 1 Mg C ha^{-1} yr^{-1} of SOC stock increase (20 cm depth, with soil BD assumed to be 1.32 g cm^{-3}; Han et al., 2012).

3.2 Responses of crop yield to straw incorporation

Overall, SI significantly increased annual crop yield by 13.4% (95% CI, 9.3%–18.4%) relative to SR in China's cropland (Fig. 3a). The yield responses to SI were, however, different among the four regions of China (Fig. 3b). The greatest yield increment corresponding to SI was observed in NEC (mean 26.8%, 95% CI, 18.1%–38.2%), compared with SC (11.6%, 7.3%–17.7%) and NC (9.8%, 3%–26.7%), and the poorest response was found in NWC (7.3%, 1.8%–13.6%). Yield increase was positively related to the duration of SI for the first 15 yr. It then increased from 4.9% (3.0%–7.5%) after 3–5 yr to 12.3% (5.1%–20.7%) after 6–10 yr, and to 18.6% (12.4%–26.5%) after 11–15 yr. After 15 yr, the yield increase (12.6%, 5.1%–20.4%) tended to decline to a level similar to that reported for 6–10 yr (Fig. 3d). Grain yield responses to SI were greater in single and double cropping systems than in the triple cropping system (Fig. 3c), but there were no significant differences between single and double cropping systems (Fig. 3c). The effect of SI on crop yield varied among crops, i.e., 8.7% (4.1%–13.5%), 20.8% (12.8%–31.0%) and 10.4% (6.6%–15.3%) yield increase for wheat, maize and rice, respectively (Fig. 4). Yield increase above the control (SR) was greater when the control yield was low and, as the control yield increased, the yield responses to SI became smaller (Fig. 4).

Crop yield responses increased with the amount of straw incorporated, and the greatest response (28.4%, 18.6%–40.9%) was observed at the high level of straw input (> 3 Mg C ha^{-1} yr^{-1}) (Table 3). Crop yield responses generally increased in response to the combination of straw application with mineral N application, i.e., increasing from 11.5% (6.2%–18.0%) to 18.4% (11.9%–27.6%) when the N-application rate increased from 0–200 to 200–400 kg N ha^{-1} yr^{-1}. However, the highest level of N fertilizer (> 400 kg N ha^{-1} yr^{-1}) did not result in a significant additional yield increase (18.8%, 1.6%–54.2%; $P > 0.05$) relative to 200–400 kg ha^{-1} yr^{-1} (Table 3).

3.3 Responses of SOC to straw incorporation

Annual SOC sequestration in response to SI was enhanced with an average rate of 0.35 (95% CI, 0.31–0.40) Mg C ha^{-1} yr^{-1} in the experiments reviewed (Fig. 5a). A significant effect of Q_b was found for the categories of geographical regions, SI duration, crop frequency and soil texture (Fig. 5b, c, e, i; $P < 0.05$), but not for land-use type, straw type, MAT or MAP (Fig. 5d, f, g, h; $P > 0.05$). Compared with the SR treatments, the greatest SOC sequestration rates were recorded in NEC (0.57, 0.41–0.77 Mg C ha^{-1} yr^{-1}), followed by SC (0.36, 0.30–0.43 Mg C ha^{-1} yr^{-1}), NC (0.33, 0.25–0.40 Mg C ha^{-1} yr^{-1}) and NWC (0.19, 0.14–0.25 Mg C ha^{-1} yr^{-1}) (Fig. 5b). The annual SOC sequestration rates were significantly ($P < 0.05$) greater in the shortest time interval (3–10 yr) after SI began (0.53, 0.44–0.63 Mg C ha^{-1} yr^{-1}), compared with the medium term (10–20 yr; 0.29, 0.23–0.37 Mg C ha^{-1} yr^{-1}) or long term (> 20 yr; 0.17, 0.13–0.21 Mg C ha^{-1} yr^{-1}) (Fig. 5c). The effect of SI on SOC sequestration varied between different crop frequencies in the order: triple (0.51, 0.37–0.67 Mg C ha^{-1} yr^{-1}) > single (0.41, 0.31–0.53 Mg C ha^{-1} yr^{-1}) > double (0.28, 0.24–0.32 Mg C ha^{-1} yr^{-1}). The SOC sequestration after SI in clay soils was significantly ($P < 0.05$) higher than loam soil but was not significantly different to silt loam or sandy loam soils (Fig. 5i; $P > 0.05$). Rice straw and maize straw tended to sequester more SOC than wheat straw, but the difference was not statistically significant (Fig. 5f; $P > 0.05$).

The mean SOC sequestration rate was 0.20 (0.16–0.25) Mg C ha^{-1} yr^{-1} under the lowest straw-C input level (< 1.5 Mg C ha^{-1} yr^{-1}) but increased significantly to 0.70 (0.53–0.88) Mg C ha^{-1} yr^{-1} under the highest straw-C input (> 3 Mg C ha^{-1} yr^{-1}) (Table 3; $P < 0.05$). The N fertilizer input rate significantly increased the SOC responses to SI ($P < 0.01$). For example, the average annual SOC sequestration rate increased from 0.27 (0.22–0.32) to 0.69 (0.53–0.81) Mg C ha^{-1} yr^{-1} when the N application rates increased from 0–200 to > 400 kg N ha^{-1} yr^{-1}. Interestingly, we found that there was a significant positive interaction of SI with N fertilizer input on SOC accumulation (Table 3; $P < 0.05$).

3.4 Relationships between SOC sequestered and straw input or experiment duration

The meta-analysis revealed significant positive linear relationships between annual SOC sequestration rate and straw-C input across China (Fig. 6; $P < 0.05$). Based on the straw-C conversion efficiency derived from the regression equations (slope of the linear correlation equation; Kong et al., 2005), the conversion efficiency of straw-C to SOC was 16% ± 2% (mean ± standard error) for the whole of China and 30% ± 4% in NEC, 11% ± 3% in NC, 8% ± 2% in NWC and 13% ± 4% in SC (Fig. 6).

There was a significant logarithmic relationship between annual SOC sequestration rate and SI duration (Fig. 7; $P < 0.05$). A rapid decline in SOC sequestration rate was observed after the initial stage of SI, especially in NEC and SC, and then the SOC sequestration rate decreased to a steady state. The SOC increment diminished to negligible after 46, 26, 35, 63 and 55 yr of SI in the whole of China, NEC, NC, NWC and SC respectively (Fig. 7).

4 Discussion

The results of the meta-analysis suggest that SI increases SOC stocks and crop yields in experimental trials across China, regardless of the climate or land use. The SOC gains were significant in the short term, but the largest crop yield response was observed up to 15 yr after SI began. This conclusion is based on a wide range of soils and climate conditions and suggests that farmers across the world may use this simple management tool to increase their outputs by improving the quality of their soil, while mitigating climate change.

4.1 Increase of SOC by straw incorporation

The incorporation of straw unsurprisingly enhanced SOC stocks in China’s cropland at an average rate of 0.35 Mg C ha^{-1} yr^{-1}. This confirms the findings of previous meta-analyses of significant positive SOC responses to straw input (Lu et al., 2009; Lehtinen et al., 2014; Liu et al., 2014). Our result is comparable to the SOC sequestration rates of 0.1–0.3 Mg C ha^{-1} yr^{-1} in the croplands of the United States (Watson et al., 2000) and the global estimates of 0.3 Mg C ha^{-1} yr^{-1} (IPCC, 2000) but only half of the estimation for the EU (0.7 Mg C ha^{-1} yr^{-1}; Smith, 2004). Straw incorporation provides a direct C source for the formation of SOC (Mulumba and Lal, 2008; Blanco-Canqui and Lal, 2009), and the greater the annual straw-C input rate, the faster SOC sequestration increased (Table 3, Fig. 6). Significant linear relationships between SOC responses and organic C input were also reported in previous meta-analyses

(Liu et al., 2014; Maillard and Angers, 2014). Similarly, high crop frequency, which was accompanied by a large amount of above-ground crop residues, resulted in greater SOC sequestration (Fig. 5e; $P < 0.05$), supporting the findings of Luo et al. (2010).

Addition of N fertilization enhanced the effect of SI (Table 3), presumably because straw has a high C:N ratio and much of the N added at lower rates (up to 400 kg ha^{-1}) was immobilized when straw input was high (>3 Mg C ha^{-1}), at least in the short term (Singh et al., 1992). Furthermore, N fertilizer addition can enhance both above- and below-ground biomass production (Kuzyakov and Domanski, 2000; Neff et al., 2002; Ladha et al., 2011), leading to a greater SOC sequestration when the crop-derived C is incorporated (Gong et al., 2012). The effect of soil texture on SOC responses to SI was significant (Fig. 5i; $P < 0.05$); clay soils have a propensity to stabilize SOC by providing chemical and physical protection (Six et al., 2002), which supported the high sequestration rates in clay soils in the current study (Fig. 5i).

In NEC, where the initial SOC stocks are very high (Yu et al., 2012), a rapid decline of SOC stocks has been experienced since the 1970s (from 48.7 in the 1980s to 42.4 Mg C ha^{-1} in 2006; Pan et al., 2010), due to the large-scale land reclamation of wetland to cropland (Gao et al., 2015) and long-term low C input (Yu et al., 2012). At the same time, however, SOC stocks increased in the majority of croplands in other regions of China (Yu et al., 2012). In this context, a significant spatial variation in SOC responses to SI was observed (Fig. 5b; $P < 0.05$): 30% of the added 1 Mg C ha^{-1} yr^{-1} straw-C was sequestrated as SOC in NEC, compared with 8%–13% in other regions (Fig. 6). Additionally, the lower temperature (mean annual temperature of 0.9 °C–8.1 °C; Table S1) in NEC could also restrict SOC decomposition (Karhu et al., 2014) and favor the SOC accumulation. This supports the meta-analysis conducted by Tian et al. (2015), which also reported a greater SOC increment in northeast China from manure application compared with other regions. However, according to a farmer survey across China carried out by Zhang et al. (2017a), the percentage of SI by farmers was only 8.7% in NEC, while 32.7% of farmers burnt the straws in the field. Hence, there is an urgent need to encourage the local farmers to recycle the crop straw in NEC.

The impacts of land-use type on straw-induced SOC sequestration were not statistically significant (Fig. 5d; $P > 0.05$), in agreement with the previous meta-analysis of Liu et al. (2014). This may be because alternative wetting and drying has been widely applied as a common practice to improve crop yield in paddy soils in China (Zhao et al., 2013). This practice would stimulate microbial activity and increase organic matter mineralization during the mid-season drainage period (Mikha et al., 2005), thus leading to a less stable form of SOC in paddy soils (Cui et al., 2012). As arable cropping systems are complex ecosystems controlled by both natural factors and farming practices (Lohila et al., 2003; Song et al., 2005), the direct effect of MAT and MAP on SOC responses to SI might be dominated by farming practices (Fig. 5g, h; $P > 0.05$). Previous meta-analyses (Luo et al. 2010; Liu et al., 2014; Maillard and Angers, 2014) also reported similar results. Our results imply that improvement of SOC through SI might also be applicable to other regions in the world with different climate conditions or land uses.

Similar to Tian et al. (2015), we observed that the SOC stocks increased regardless of the initial SOC contents (data not shown). Moreover, a rapid SOC increase occurred in the first two decades rather than in later periods (26–63 yr) of SI (Fig. 5c, 7), which suggests that an equilibrium between C input and decomposition might occur at the decadal scale (West and Six, 2007). This supports the need for continued investment in long-term field experiments to provide robust support for policy development (Macdonald et al., 2015).

4.2 Increase of crop yield by straw incorporation

Straw incorporation significantly increased the overall crop yield by 13.4% compared with SR. This yield increase is similar in magnitude to a recent meta-analysis of global data (12%; Liu et al. 2014), but larger than other observations from China (up to 9% increase; Zhao et al., 2015; Wang et al., 2015; Huang et al., 2013; Xu et al., 2017) and the EU (6% increase; Lehtinen et al., 2014). The lower estimates reported in previous studies focused on more limited geographical zones, i.e., most studies in Lehtinen et al. (2014) were in the Mediterranean, only NC was considered by Xu et al. (2017) and only three sites from NEC were analyzed by Wang et al. (2015) and Huang et al. (2013). Shorter study durations, e.g., 8–12 yr in Zhao et al. (2015), might lead to a relatively low yield response, whereas our analysis shows that the greatest benefits of SI on crop yield were achieved after 11–15 yr of straw incorporation (Fig. 3d). According to the current cereal production in China (616 million Mg; NBSC, 2016), this straw-induced yield increment (13.4%) results in an additional 82.6 million Mg of agricultural products, which could feed 0.2 billion people or 15% of China's population at the current per-capita food consumption of 388 kg yr^{-1} (Central People's Government–PRC, 2008).

As previous meta-analyses (Wang et al., 2015; Liu et al., 2014) and the current study revealed, SI significantly increases SOC, which is a key determinant in crop production (Singh et al., 2002). Each increase of 1 Mg C ha^{-1} SOC in the root zone could improve crop yield by 30–300 kg ha^{-1} yr^{-1} in Asia (Lal, 2013). This is supported by our finding that 101–157 kg ha^{-1} yr^{-1} of crop yield increase could be achieved (Fig. 2). Straw contains various macro- and micro-nutrients, which can contribute to the nutrient budget of farms if returned to the soil (Lal, 2013). In the current study, the average annual N, P and K nutrients derived from straw residues were 35 kg N, 13 kg P_2O_5 and 78 kg K_2O ha^{-1} yr^{-1}, which accounted for ca. 15%, 11% and 52% of the average annual mineral N, P and K input, respectively. Similarly, Wang et al. (2015) reported a similar annual straw N input (39.6 kg N ha^{-1} yr^{-1}) and beneficial yield response. Singh et al. (2002) also suggested that crop residue recycling affects crop production substantially by maintaining the soil K balance. For the response to SI, maize crop achieved higher yield increase than wheat or rice crop (Fig. 4), which agrees with the study of Hijbeek et al. (2017). This may be because maize growth under higher temperature and precipitation (Tan et al., 2017), and these conditions favor faster straw decomposition and result in a rapid and complete nutrient release (Hartmann et al., 2014; Ladha et al., 2011).

Straw incorporation also reduces soil compaction (Soane, 1990), moderates soil temperature (Blanco-Canqui and Lal, 2009), retains soil water in the plow layer (Zhang et al., 2014) and immobilizes N for later release in the growing season (Hansen et al., 2015), all of which may promote crop production. In the triple cropping areas of China, promising climate conditions (MAP > 1000 mm, MAT: 14.8°C–17.6°C; Table S1) ensured a high land productivity, e.g., averaged 13.5 Mg ha^{-1} yr^{-1} of crop yield in our study. The low water availability and large temperature fluctuations in the single cropping regions are likely to be limiting factors for crop yield (MAP: 117–716 mm, MAT: 0.9 °C–11.5 °C; Table S1). Hence, straw-induced soil water retention and temperature moderation might contribute to better crop production in the single cropping system compared with that in the triple cropping system. The N immobilization of SI has potential environmental benefits, e.g., reduced losses by leaching and N_2O emissions (Meng et al., 2016) and improved N use efficiency (Yao et al., 2017). In our meta-analysis, under the fertilizer N levels of 200–400 and >400 kg N ha^{-1} yr^{-1}, which have been widely adopted in cropland in China (Ju et al., 2004), a 18% of yield increase due to SI was observed compared with SR (Table 3). This highlighted that SI is an effective measure for both improving crop yield and decreasing the risk of N leaching in intensive agricultural regions.

Our study found that yield responses tended to increase with time only when SI duration was <15 yr (Fig. 3d). This response indicates that long-term SI is necessary to achieve a high soil fertility and continuous yield sustainability (Bi et al., 2009). Indeed, the yield increase was relatively low in the initial stage (5% in the first 3–5 yr; Fig. 3d) but increased thereafter. However, unlike several other studies (Wang et al., 2015; Zhao et al., 2015), we observed that the yield increase tended to decline after a 15-yr timespan of SI (Fig. 3d), implying a potential saturation effect of SI on soil fertility. We also found that crop yield response to SI was greater when the control yield was low (Fig. 4), which highlights the importance of straw management in low-productivity regions (Chivenge et al. 2011).

4.3 Uncertainties of our study

Although meta-analysis is an effective statistical approach, our conclusions might be constrained by several uncertainties. Soil BD and straw-C input data were unavailable in some papers, which was resolved through estimation using empirical functions, although our sensitivity analyses found the errors due to these estimations were acceptable. For some categories, e.g., MAT and N fertilizer input, the available data set was small ($n < 10$) if divided into subgroups, which might hamper the estimation for SI effect under these subgroups. In addition, the lack of information on the SI methods (chopped or not) and tillage (non-tillage or tillage) might increase the deviation of SI in different natural contexts and using farming practices. Hence, further field experimental studies are needed to examine the effects of straw management in more details.

5 Conclusions

Our study found that SI significantly sequestered SOC at the rate of 0.35 Mg C ha^{-1} yr^{-1}, increased crop yield by 13.4% and had a SOC conversion efficiency of 16% across the whole of China. A coupled benefit of SI at 3 Mg C ha^{-1} yr^{-1} with the mineral N rate of 200–400 kg N ha^{-1} yr^{-1} was found to be the best combination for farmer use, with crop yield increased by 32.7% and SOC sequestrated by the rate of 0.85 Mg C ha^{-1} yr^{-1}. Soil texture and crop frequency were also recognized as the two factors significantly influencing the SI effects on SOC. The NEC region was identified as the region with greatest potential to simultaneously realize the SI benefit on SOC sequestration and yield improvement. As SI progressed, a rapid SOC increase occurred in the first two decades, and the crop yield increase peaked at around 15 yr. Our study confirmed the multiple beneficial effects of SI in sustainable intensive agriculture in China, which may also be applicable to other regions of the world.

6 Data availability

Data are available by direct request to the corresponding author.

7 Author contributions

Xiao Han and Cong Xu contributed equally to this work. Fanqiao Meng, Xiao Han, and Cong Xu conceived and designed the study. Xiao Han, Cong Xu, and Xiaojie Wang carried the data collection and analysis. Xiao Han and Cong Xu wrote the original draft. Jennifer A. J. Dungait, Roland Bol, Fanqiao Meng and Wenliang Wu reviewed and revised the draft.

8 Competing interests

The authors declare that they have no conflict interest.

9 Disclaimer

Funders had no role in conceiving the study, collection, and analysis of data or manuscript preparation.

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Table 1. Classification of categorical variables used as explanatory factors.

Categorical Variable	Level 1	Level 2	Level 3	Level 4
Soil texture	Clay	Loam	Silt loam	Sandy loam
Mean annual temperature (°C)	< 10	10–18	> 18	
Mean annual precipitation (mm)	< 600	600–1000	> 1000	
Experimental duration [a] (years)	3–10	11–20	> 20	
Experimental duration [b] (years)	3–5	6–10	11–15	> 15
Straw-C (Mg C ha^{-1} yr^{-1})	< 1.5 (Low)	1.5–3 (Middle)	> 3 (High)	
N fertilizer (kg N ha^{-1} yr^{-1})	0–200 (Low)	200–400 (Middle)	400–600 (High)	

[a] experiment duration for the response of soil organic carbon to SI.

[b] experiment duration for the response of crop yield to SI.

Table 2. Basic information on agricultural regions in the current analysis.

Region	Province	Crop frequency (season yr^{-1})	Major crop	MAP (mm)	MAT (°C)	Soil texture
NEC	Heilongjiang, Jilin, Liaoning	Single	Maize, Soybean, Wheat	450–716	0–8.1	Clay, Loam, Silt loam
NC	Beijing, Hebei, Henan, Shandong, Shanxi, Anhui (north region)	Double	Maize, Wheat	455–821	7.3–14.8	Clay, Loam, Sandy loam
NWC	Shanxi, Gansu, Qinghai, Xinjiang	Single/Double	Maize, Wheat	117–632	5.7–13	Clay, Loam, Silt loam
SC	Jiangsu, Anhui (central and south region), Hubei, Hunan, Zhejiang, Shanghai, Guangxi, Chongqing, Sichuan, Jiangxi, Fujian	Double/Triple	Maize, Wheat, Rice, Rapeseed	1038–1795	14.8–19.5	Clay, Loam, Silt loam, Sandy loam

NEC: northeast China; NC: north China; NWC: northwest China; SC: south China.
MAP: mean annual precipitation (mm); MAT: mean annual temperature (°C).

Table 3. Responses of soil organic carbon (SOC; Mg C ha^{-1} yr^{-1}) and crop yield (%) to SI over SR under different levels of straw C and N fertilizer input.

	N input rate (kg N ha^{-1} yr^{-1})	Straw-C input rate (Mg C ha^{-1} yr^{-1})								Impact		
		< 1.5	n [a]	1.5–3	n	> 3	n	Mean	n	S	N	S × N
Annual SOC sequestration rate (Mg C ha^{-1} yr^{-1})	0–200	0.18 (0.14~0.23)	34	0.27 (0.21~0.34)	17	0.52 (0.42~0.61)	10	0.27 (0.22~0.32)	61			
	200–400	0.23 (0.16~0.32)	19	0.42 (0.31~0.56)	15	0.85 (0.54~1.15)	14	0.46 (0.35~0.59)	48			
	> 400	0.18	1	0.83 (0.72~0.94)	5	0.64 (0.51~0.77)	4	0.69 (0.53~0.81)	10			
	Mean	0.20 (0.16~0.25)	54	0.41 (0.33~0.49)	37	0.70 (0.53~0.88)	28			*	**	*
Year-around crop yield increment (%)	0–200	14.0 (6.5~23.6)	20	1.8 (-3.2~7.2)	12	24.3 (13.0~37.8)	6	11.5 (6.2~18.0)	38			
	200–400	12.1 (6.9~17.7)	9	15.7 (6.1~34.6)	8	32.7 (17.9~56.4)	6	18.4 (11.9~27.6)	23			
	> 400	71.2	1	5.2 (1.4~12.9)	3	–	0	18.8 (1.6~54.2)	4			
	Mean	15.0 (9.1~22.5)	30	6.9 (2.3~14.5)	23	28.4 (18.6~40.9)	12			*		

[a] the number of observations.

* and ** represent 0.05 and 0.01 significance levels, respectively.

S, N and S × N represent straw-C input rate, N input rate and their interaction, respectively.

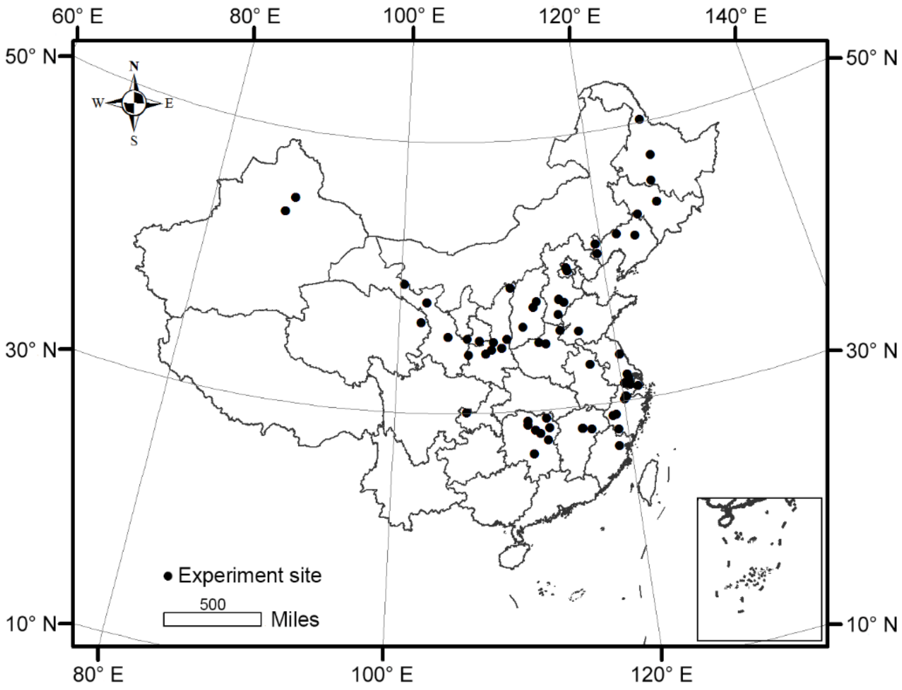

Figure 1. Locations of the long-term experiment sites in China.

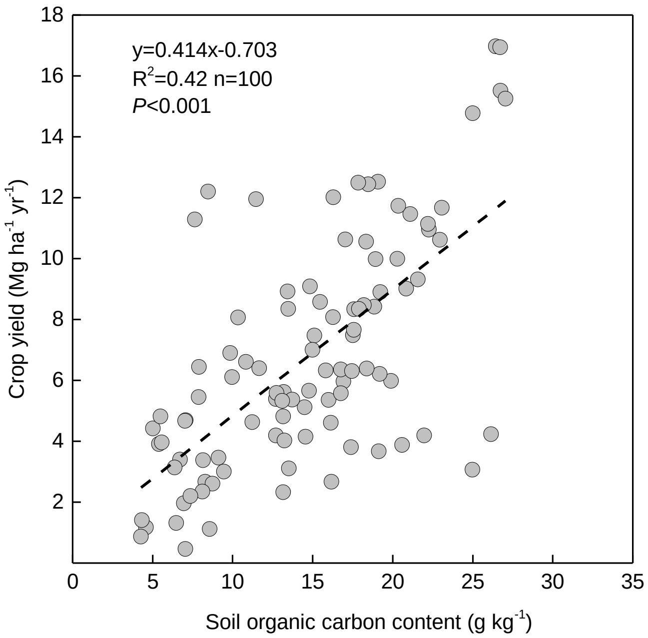

Figure 2. Relationship between crop yield and soil organic carbon content.

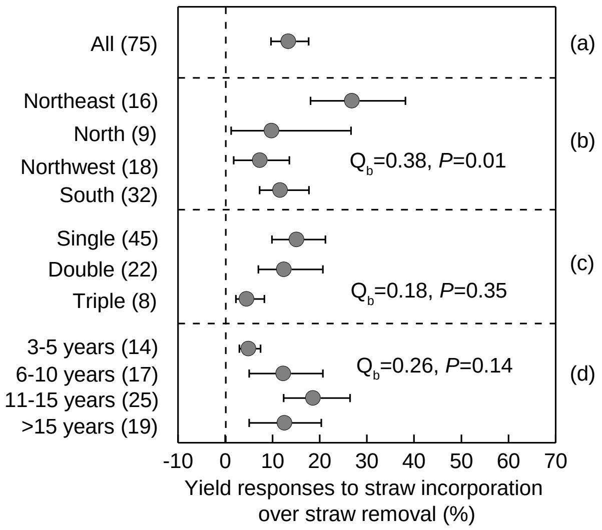

Figure 3. Responses of crop yield to SI compared with SR (a), categorized into (b) region, (c) crop frequency and (d) experiment duration. Yield responses are expressed as the relative increase (%) compared with control (SR) with 95% CIs represented by the error bars. Numbers of paired observations are in parentheses. Between-group heterogeneity (Q_b) and the probability (*P*) were used to describe statistical differences in yield responses between different levels of the categorized factors.

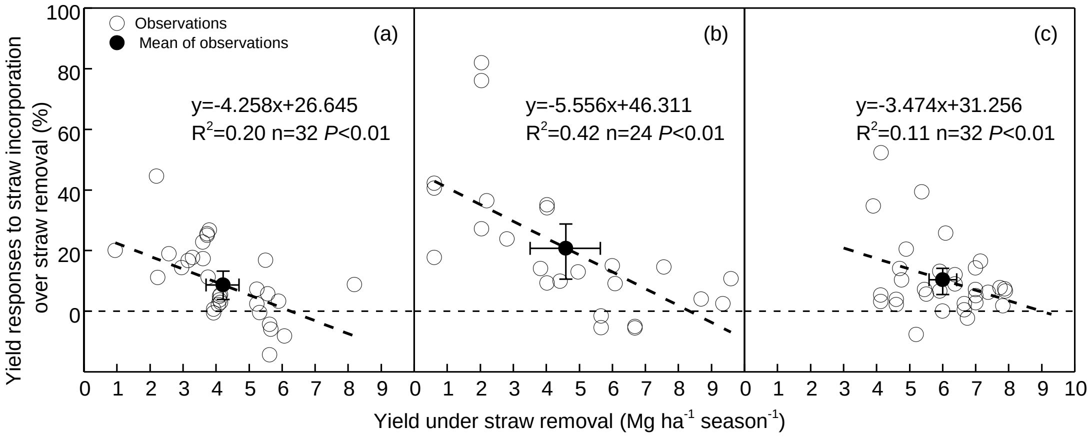

Figure 4. Relationships between crop yield responses to SI and control yield under SR for (a) wheat, (b) maize and (c) rice. Yield responses are expressed as the relative increase (%) compared with control (SR). Error bars in horizontal and vertical directions represent 95% CIs of the control yield and yield responses, respectively.

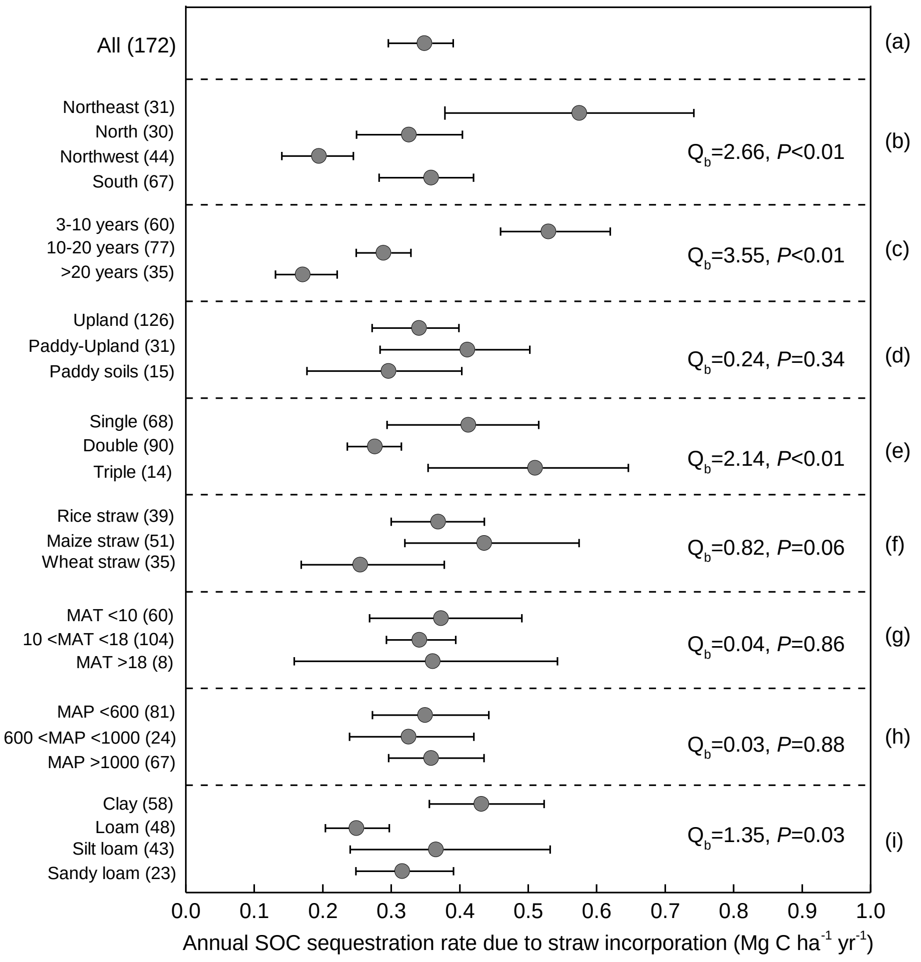

Figure 5. Responses of soil organic carbon (SOC) to SI compared with SR (a), categorized into (b) region, (c) experiment duration, (d) land use, (e) crop frequency (season yr^{-1}), (f) straw type, (g) mean annual temperature (MAT), (h) mean annual precipitation (MAP) and (i) soil texture. The SOC responses are expressed as the average annual SOC sequestration rate (Mg C ha^{-1} yr^{-1}) with 95% CIs represented by the error bars. Numbers of paired observations are in parentheses. Between-group heterogeneity (Q$_b$) and the probability (*P*) were used to describe statistical differences of SOC responses between different levels of the categorized factors.

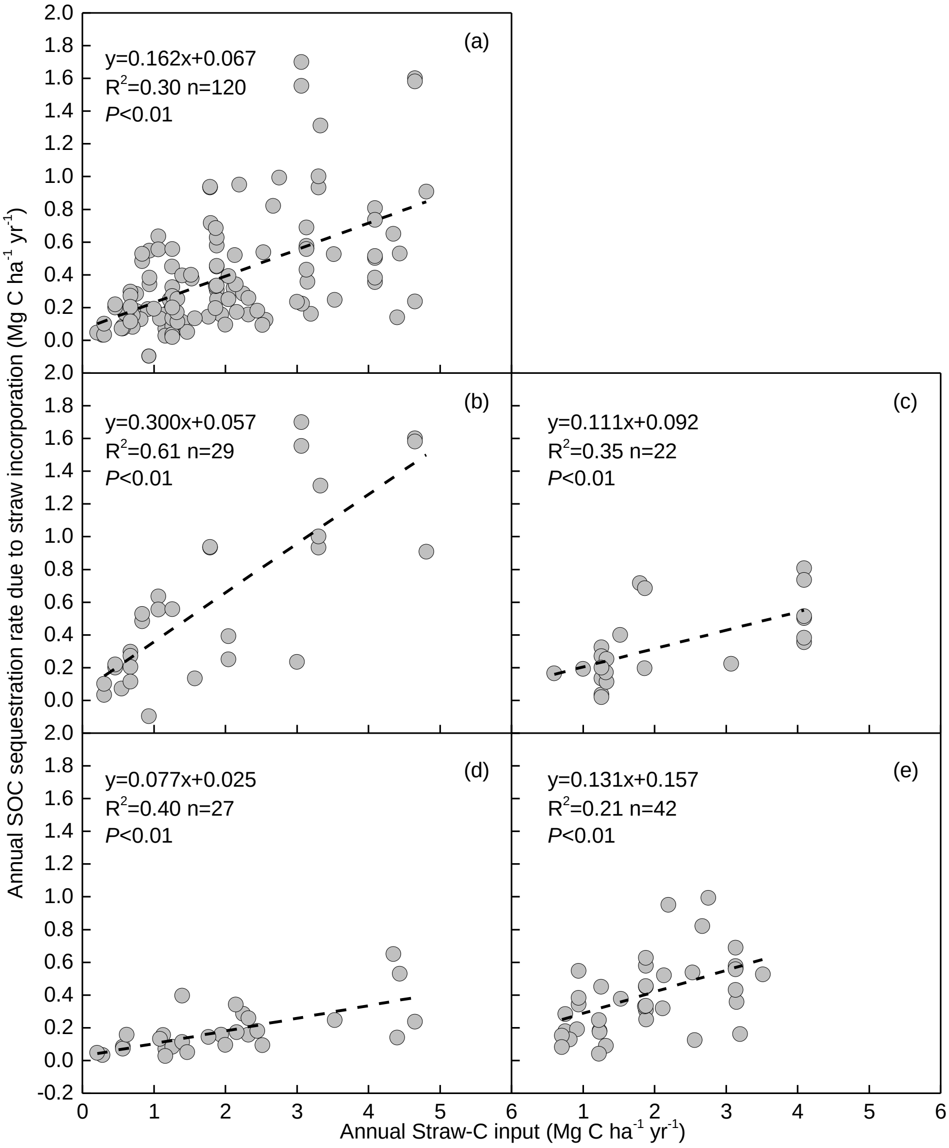

Figure 6. Relationships between annual soil organic carbon (SOC) sequestration rate and straw carbon input for (a) national scale, (b) northeast China, (c) north China, (d) northwest China and (e) south China.

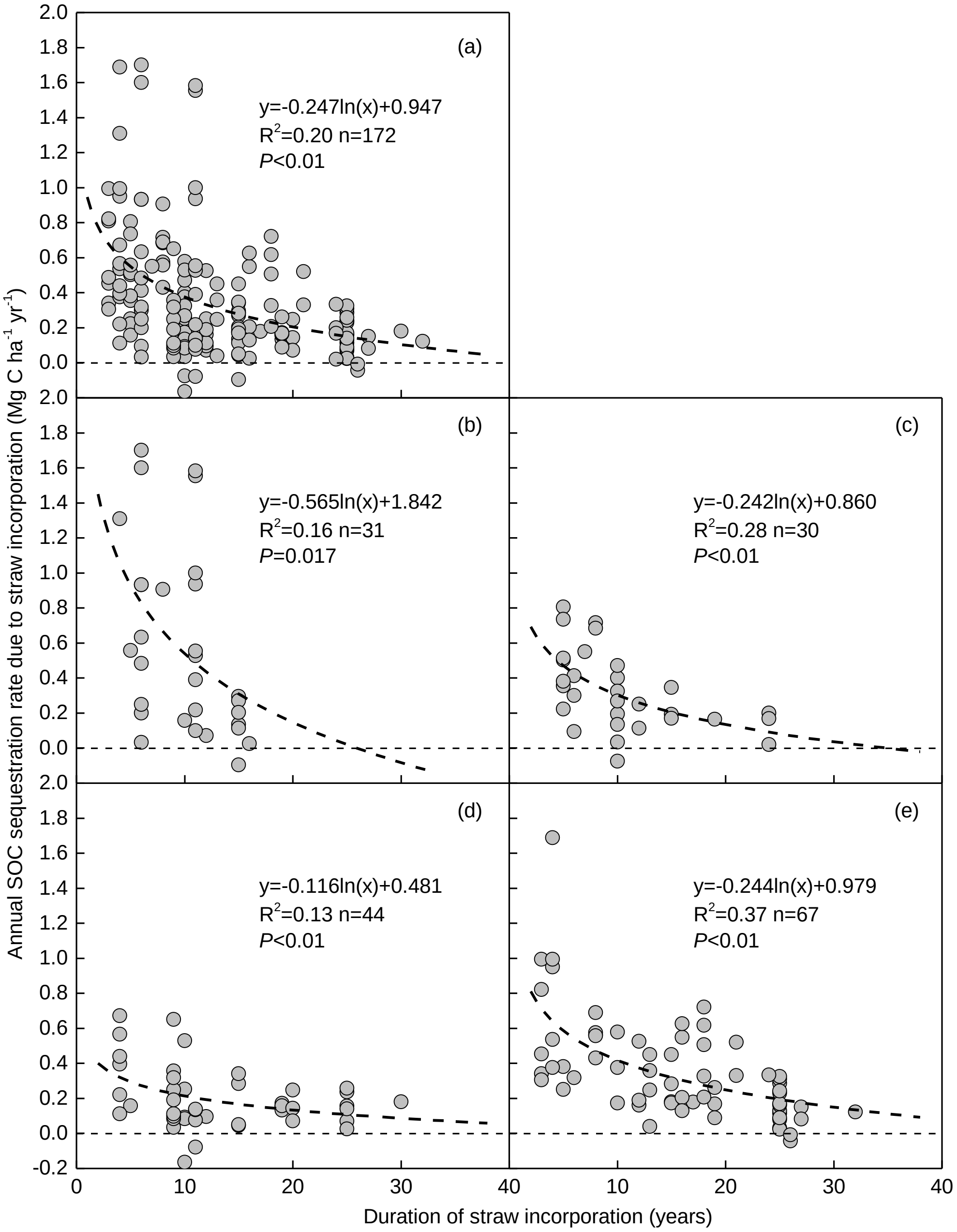

Figure 7. Relationships between annual soil organic carbon (SOC) sequestration rate and SI duration for (a) national scale, (b) northeast China, (c) north China, (d) northwest China and (e) south China.