Dear Prof. Kuzyakov,

Thank you very much for your comments and decision.

We have completely revised the MS considering all comments and suggestions from the reviewers. The uncertainty analysis has also been added in the MS. The paper has been improved on the language by our co-authors and a language service company.

Please kindly find the file of point-by-point responses to the reviewers, and the revised MS with changes marked and a clean version of the MS.

With best regards,

Xiao Han, Fanqiao Meng

on behalf of all co-authors

**Dear respected Referee #1 (R#1),**

**Thank you so much for your valuable comments and helpful suggestions. We have fully studied your review and revised the MS substantially. In your several comments, it seemed that "crop yield response" has been confused with "crop yield". In our study, "crop yield response" is the change of crop yield due to farming practice, such as straw incorporation.**

R#1: The authors present a meta-analysis about the effects of straw incorporation on crop production and SOC sequestration. The methods are technically sound. The authors also consider the effect of climate, straw carbon input, N fertilizer, and duration. This paper confirmed that straw incorporation did create a positive feedback loop of SOC enhancement together with increased crop production which is of great practical significance to agricultural management. However, I think that there is some part to be improved. Please edit closely for English. The sentences are often very long (even 5 lines) and, thus, difficult to follow and absorb immediately (i.e. P10 (line 21-26)). There were many repeats of results in the discussion section. I hope that authors could improve it.

**[Responses]: Thank you for the encouragement. We'll improve the Discussion section to avoid the repetitive sentences of results. The language will be further refined by our author, Professor Jennifer Dungait from Rothamsted and Professor Roland Bol from Juelich Center.**

R#1: 3.1 Why only consider the impact of N and K, how the effect of P fertilizer?

**[Responses]: Actually, we also considered the effect of P fertilizer in the study, which was stated in section 2.4. However, after the stepwise regression analysis has been finished, only the variables of SOC, N, and K were kept and P was excluded. We will clarify this in the MS.**

R#1: In the result part, I suggest that authors deleted the range (i.e. range 2.3%–14.5%)

**[Responses]: Agreed and will revise accordingly.**

R#1: P6 line 24-26 "with high levels of straw input corresponding to mean increases of 28.4% (range 18.6%......(mean 6.9%, range 2.3%–14.5%) straw input (Table 3)." 28.4% of what, I think it is of crop yield.

**[Responses]: Here, the "28.4%" refers to the crop yield response at the high level of straw input. We'll improve these sentences to avoid misunderstanding.**

R#1: P6 line 19-22 "Meanwhile, yield increases greatly varied between crops: 8.7% (range 4.1%–20 13.5%)……the yield response to straw incorporation became smaller (Fig. 4)." I don't understand the means of this sentence. Here, the yield increase refers to the straw incorporation or control? And could you explain it in the discussion part?

**[Responses]: The yield increase/response referred to the yield increase under straw**

**incorporation relative to the control (straw removal). The sentences will be revised as "Yield response to straw incorporation was greater when the yield of control (straw removal, or background crop yield) was low and, as the yield of control increased, the yield response became smaller (Fig. 4)". The discussion will be added as suggested.**

R#1: P6 line 26 Crop yield responses generally increase……, delete the "responses".

**[Responses]: As responded above, "responses" should be used instead of deleted, to reflect the interactive effect of straw×mineral N fertilization.**

R#1: P8 line 9-11: This yield increase is similar in magnitude to a recent global…… those of the EU (6% increase; Lehtinen et al., 2014)." Could you explain the reason for this differences?

**[Responses]: The reason might be the different climate zones in the EU and our study. Specifically, experimental sites in the Mediterranean, a typical climate zone of Europe, accounted for 25% of the database in the study of Lehtinen et al. (2014). These sites mostly exhibited a yield <u>decrease</u> under straw incorporation, thus lowered the mean yield responses of the EU. We'll address in the revised Discussion.**

**Lehtinen, T., Schlatter, N., Baumgarten, A., Bechini, L., Kruger, J., Grignani, C., Zavattaro, L., Costamagna, C., and Spiegel, H.: Effect of crop residue incorporation on soil organic carbon and greenhouse gas emissions in European agricultural soils, Soil Use Manage, 30, 524−538, doi:10.1111/sum.12151, 2014.**

R#1: P8 line 19 and the greater the annual straw-C input… Change "and" to "And"

**[Responses]: Agreed and will revise accordingly.**

P8 line 26-29: "Furthermore, N fertilizer addition can enhance both above and belowground biomass production (Ladha et al., 2011; Neff et al., 2002; Kuzyakov and Domanski, 2000), increasing the input of crop roots to stable SOC pools (Gong et al., 2012)." I think this sentence should be improved.

**[Responses]: Agreed. This sentence will be revised as "Furthermore, N fertilizer addition can enhance both above and belowground biomass production (Ladha et al., 2011; Neff et al., 2002; Kuzyakov and Domanski, 2000), which will result in a higher crop yield and the improvement of SOC (Gong et al., 2012)".**

R#1: P8 line 34 "…straw incorporation effect on SOC was observed between the four…" change "between" to "among"

**[Responses]: Agreed and will revise accordingly.**

R#1: P 9 line1-2 "compared to large-scale increases in SOC in the majority of croplands in NC, NWC, and SC." Here, the SOC means SOC stocks?

**[Response]: Yes, the SOC here means SOC stocks. We'll add this to the revised MS.**

R#1: P 9 line3: According to a farmer survey across China carried out by (Zhang et al.,2017), Change it to "According to a farmer survey across China carried out by Zhang et al. (2017)

**[Responses]: Thanks, and will revise accordingly.**

R#1: P 9 line6: "The impact of land use, MAT, and MAP on straw-induced SOC sequestration was not……and Huang et al. (2012)." to "The impacts of land use, MAT, and MAP on straw-induced SOC sequestration were not statistically significant (Fig. 5; $P > 0.05$), in agreement with the previous meta-analyses of Liu et al. (2014) and Huang et al. (2012)."

**[Responses]: Agreed and will revise accordingly.**

R#1: P 9 line9: "this wetting and drying cycles" change "this" to "these"

**[Responses]: Agreed and will revise accordingly.**

R#1: P 9 line8-11: "Since alternative wetting and drying has been wide……leads to a less stable form of SOC in paddy soils (Cui et al., 2012)." This is a long sentence, and change "increases", "leads" to "increase" and "lead".

**[Responses]: Agreed and we are going to refine all these long sentences.**

R#1: P 9 line 23-27: "The lower estimates reported in previous studies focused on shorter time periods......were included in the analysis by Wang et al. (2015) and Huang et al. (2013)." This is a long sentence.

**[Responses]: Same as above.**

R#1: P9 line 28: "result of" to "result in"

**[Responses]: Agreed and will revise accordingly.**

R#1: P9 line 35-36: Change "Straw incorporation does also reduce" to "Straw incorporation also reduces"

**[Responses]: Agreed and will revise accordingly.**

R#1: P10 (line 7-11) "Our analysis did observe a stro......(Fig. 4). This observation agrees.......those of wheat or barley." I think that these two sentences are repeated with each other.

**[Responses]: Agreed and these two sentences will be revised as "The beneficial effect on yield response was more for maize (20.8%) than that for wheat (8.7%) (Fig. 4), which agrees with the study of Hijbeek et al. (2017).".**

R#1: P10 (line 10-12): Generally, the maize yields is the highest among the three types of the crop (wheat, rice, and maize). This is not only just because of the temperature and precipitation. What's more, the result in the paper found that climate has no significant effect on the response of SOC to straw incorporation.

**[Responses]: As mentioned above, here we discussed the relative increase of maize yield induced by straw incorporation, instead of the absolute maize yield. We found that under straw incorporation, yield increase was higher for maize than for wheat. This is most likely due to hotter and humid condition in the maize season than that in the wheat season (Tan et al., 2017). Hotter and humid condition stimulated the straw decomposition and released fast and more nutrients to crop production (Hartmann et al., 2014; Ladha et al., 2011). Here, we focused on crop yield responses, rather than the SOC responses.**

**Tan, Y. C., Xu, C., Liu, D. X., Wu, W. L., Lal, R., and Meng, F. Q.: Effects of optimized N fertilization on greenhouse gas emission and crop production in the North China Plain, Field Crop Res, 205, 135−146, doi:10.1016/jScr.2017.01.003, 2017.**

**Hartmann, T. E., Yue, S., Schulz, R., Chen, X., Zhang, F., and Müller, T.: Nitrogen dynamics, apparent mineralization and balance calculations in a maize–wheat double cropping system of the North China Plain, Field Crop Res, 160, 22–30, doi:10.1016/j.fcr.2014.02.014, 2014.**

**Ladha, J. K., Reddy, C. K., Padre, A. T., and van Kessel, C.: Role of nitrogen fertilization in sustaining organic matter in cultivated soils, J Environ Qual, 40, 1756−1766, doi:10.2134/jeq2011.0064, 2011.**

R#1: P10 (line 22) "In China, the areas where triple cropping was adopted usually received adequate rainfall (MAP > 1000 mm, Table S1)" I think the yield increase is due to the temperature and precipitation.

**[Responses]: We agreed that straw incorporation could improve crop yield by improving soil water retention as well as reducing abrupt fluctuations in soil temperature. The low soil water availability and low temperature are likely to be limiting factors for crop yield especially in the single cropping areas (MAP: 117~716 mm, MAT: 0.9~11.5 ℃; Table S1) compared with that in triple cropping areas (MAP > 1000 mm, MAT: 14.8~17.6 °C; Table S1). Thus, straw incorporation might contribute more benefits for crop production in the single cropping areas compared to that in triple cropping areas. We'll revise the manuscript.**

R#1: P11 (line 5) "crop yield responses increased and peaked at around 15-year and then declined." Delete "responses"

**[Responses]: As responded above, the crop yield response was the effect size to explore the effect of straw incorporation on crop yield. Here, it was the crop yield increment increased and peaked at around 15-year, so "responses" should be kept.**

R#1: P11 (line 7-8) Change "and the positive role of straw incorporation can play in China and global sustainable agriculture." to "and the positive role of straw incorporation playing in China and global sustainable agriculture."

**[Responses]: Agreed and will revise accordingly.**

R#1: Table 2 Add the information about the soil type of the different regions.

**[Responses]: Agreed and will add soil types in the revised Table.**

R#1: “Table 1:” to “Table 1.”

**[Responses]: Agreed and will revise accordingly.**

**Dear respected Referee #2 (R#2),**

**Your guiding comments and suggestions are highly appreciated. Our responses are listed below.**

R#2: The authors conducted a meta-analysis to examine the impact of straw incorporation on SOC sequestration in China. Their analysis identified the best combination of straw incorporation strategy and quantified the impact of different approaches. They also provided a general timeline for the response of SOC and crop productivity respectively.

The collected dataset has many missing values and the authors have made multiple assumptions to fill in the blanks, including using empirical functions and coefficients, it would be better if the authors can provide some kind of uncertainty analysis to ensure their results still holds under these noisy extrapolations.

**[Responses]: We agree with the reviewer that these assumptions indeed decrease the robustness and certainty of our study. Actually, during the MS preparation, we conducted an uncertainty analysis to test whether these estimations by using different empirical functions and coefficients would affect our results. We listed our results in the table below, which reported the comparison results of SOC responses with different BD (Table 1) and straw-C (Table 2) estimation approaches. The overall SOC response was 0.35 (95% CI, 0.31~0.40) Mg C ha$^{-1}$ yr$^{-1}$ in the Current scenario of BD estimation, while the SOC response was 0.33 (0.29~0.42), 0.35 (0.29~0.40), 0.35 (0.31~0.40) Mg C ha$^{-1}$ yr$^{-1}$ in scenario A, B and C, respectively. The relationship between SOC response and straw-C input in Current scenario was y=0.162x+0.067 ($R^2$=0.30 n=120 $P$<0.01), while the relationship was y=0.170x+0.059 ($R^2$=0.30 n=120 $P$<0.01) in scenario I of straw-C estimation. We did not report the findings in the 1st version of MS because the estimation approaches gave very similar results without significant differences (P >0.05). However, as the reviewer suggested, in the revised manuscript we will add the uncertainty analysis in the M&M and Discussion Sections.**

**Table 1. Comparison of the SOC responses using different BD estimation approaches.**

| Scenario | BD estimation approach | Annual SOC sequestration rate (Mg C ha$^{-1}$ yr$^{-1}$) | | | |
|---|---|---|---|---|---|
| | | All | Upland | Paddy | Paddy-Upland |
| Current | Eq. (1) for paddy or paddy–upland soil BD, Eq (2) for upland; | 0.35 (0.31~0.40) | 0.34 (0.28~0.41) | 0.30 (0.19~0.42) | 0.41 (0.33~0.51) |
| A | All the missed BD was estimated by Eq (1) | 0.33 (0.29~0.42) | 0.32 (0.26~0.38) | 0.30 (0.18~0.42) | 0.37 (0.26~0.51) |
| B | All the missed BD was estimated by Eq (2) | 0.35 (0.29~0.40) | 0.33 (0.26~0.40) | 0.32 (0.21~0.50) | 0.41 (0.27~0.54) |
| C | All the missed BD was estimated by Eq (3) | 0.35 (0.31~0.40) | 0.35 (0.28~0.42) | 0.29 (0.18~0.40) | 0.39 (0.31~0.49) |

Note: the estimation equations for BD:

Eq. (1): $BD = -0.22 \times \ln(SOC) + 1.78$ (Pan et al., 2003)

Eq. (2): $BD = 1.377 \times \mathrm{Exp}(-0.0048 \times SOC)$ (Song et al., 2005)

Eq. (3): $BD = -0.247 \times \ln(SOC) + 1.867$

Eq. (3) was derived from the empirical relationship between SOC content and BD based on 239 analytical samples in our database.

**Table 2. Comparison of the SOC responses to straw-C input from different straw-C estimation approaches.**

| Scenario | Carbon concentration (%) of crop straw | Relationship between SOC responses (y; Mg C $ha^{-1}$ $yr^{-1}$) and straw carbon input (x; Mg C $ha^{-1}$ $yr^{-1}$) for national scale |
|---|---|---|
| Current | Wheat: 39.9%; Maize: 44.4%; Rice: 41.8%; (NATEC, 1999) | y=0.162x+0.067, $R^2$=0.30 n=120 $P$<0.01 |
| I | 40% for all the straw type; (Liu et al., 2014) | y=0.170x+0.059, $R^2$=0.30 n=120 $P$<0.01 |

**Liu, C., Lu, M., Cui, J., Li, B., and Fang, C.: Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis, Glob Change Biol, 20, 1366-1381, doi:10.1111/gcb.12517, 2014.**

**National Agro-Tech Extension Center (NATEC): Chinese Organic Fertilizer Handbook, Chinese Agricultural Press, Beijing, China, 1999 (in Chinese).**

**Pan, G., Li, L., Wu, L., and Zhang, X.: Storage and sequestration potential of topsoil organic carbon in China's paddy soils, Glob Change Biol, 10, 79–92, doi:10.1111/j.1365-2486.2003.00717.x, 2003.**

**Song, G. H., Li, L. Q., Pan, G. X., and Zhang, Q.: Topsoil organic carbon storage of China and its loss by cultivation, Biogeochemistry, 74, 47−62, doi:10.1007/s10533-004-2222-3, 2005.**

R#2: The study focused on SOC changes in the top 20 cm soil, does this include organic horizon or is mineral soil only? Please make the distinction. Also it would be curious to see data for SOC below this depth.

**[Responses]: In our database, the SOC content of the top 20 cm ranged from 0.16% to 3.21%, i.e., mostly mineral soils. Even in northeast China, the studies adopted in our study are on agricultural soils which have been reclaimed more than 5 years, and with SOM low than 5%. We'll clarify this in the revised MS. Previous experiments conducted in China mostly are on 0-20 cm, although there several good studies revealing the significant value of deeper SOC. We will also address this in the revised MS.**

R#2: The language can be improved as well, and the text can be shortened and be more succinct if collapsing some of the results and discussions that are repetitive.

**[Responses]: Thank you for this good advice. Our revised MS will also be further refined by our authors of Jennifer Dungait and Roland Bol, considering of your advice.**

R#2: Overall, the study explores an interesting topic and provided quantitative proof of the impact of straw incorporation on SOC sequestration of soils. The analysis approach is appropriate. Some implications of these findings are lacking in the current version, it would be good to expand on.

**[Responses]: Agreed. The important implications will be added to the Discussion and Conclusion Sections.**

# Straw incorporation increases crop yield and soil organic carbon sequestration but varies under different natural conditions and farming practices in China: ~~a~~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. ~~Simple technical~~Technically simple and locally appropriate solutions are required for farmers to increase SOC and to improve cropland management. In the last 30 ~~years~~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 ~~under different~~ farming regimes were analyzed. Compared with straw removal~~, straw incorporation~~ (SR), SI significantly sequestered SOC (0–20 cm depth) at the rate of 0.35 (~~range~~95% CI, 0.31–0.40) Mg C ha$^{-1}$ yr$^{-1}$, increased crop grain yield by 13.4% (~~range~~ 9.3%–18.4%) and had a conversion efficiency of the ~~applied~~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 ~~combination for farmers to use~~farming practice with crop yield increased by 32.7% (~~range~~ 17.9%–56.4%) and SOC sequestrated by the rate of 0.85 (~~range~~ 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 ~~like Northeast~~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 ~~straw incorporation did create~~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 more than≥ 2 million km$^2$) is affected by soil degradation associated with the loss of around 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 carbonC 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 poorlow SOC concentrations (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 series of rapid agricultural intensification processesprocess, which werewas characterized by a main farm managementfarming 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 intensification ofpopularized 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$^{-1}$ from three crops of maize, wheat, and rice$^{-1}$ (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 the importance 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 straw incorporationSI (Lehtinen et al., 2014) have resulted in large spatial and temporal variations in the effects of straw incorporationSI 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 straw incorporationSI (e.g., Cai and Qin, 2006; Gong et al., 2009;  and these have helped to achieve a more systematic understanding of the benefits of straw incorporation.Zhang et al., 2014). Integration of the results of these studies covering different regions and under varied farming practices also assistassists an effective examination of the underlying mechanisms of straw incorporationSI 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 basic support for the development of sound policies for straw management at regional and governmental levels (Ministry of Agriculture–PRC., 2013, 2015).

We selectedconducted a meta-analysis to test the hypothesis that straw incorporationSI 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 ~~from that to~~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 ~~straw incorporation~~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 ~~straw incorporation~~SI could sequester 9.76 billion Mg C $\text{yr}^{-1}$ in China's cropland and Zhao et al. (2015) ~~reported~~found that ~~straw incorporation~~SI improved crop yield by 7% across China. However, only a few of these studies presented the effects of ~~straw incorporation~~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 ~~straw incorporation~~SI (Wang et al., 2015~~), which commonly are interactively influenced by many environmental factors and also farming management measures (Pan et al., 2009; Loveland and Webb, 2003).~~). The poor reporting of straw C conversion efficiencies (Lu et al., 2009; Tian et al., 2015) also weakens the practicability of ~~some of the management~~ 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 ~~straw incorporation~~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~~, rainfall~~ and precipitation) and farming practices (e.g., straw quantity and type, incorporation duration, N fertilizer and cropping system) on the efficacy of ~~straw incorporation~~SI.

## 2 Materials and methods

### 2.1 Data source

A survey of peer-reviewed ~~research~~ papers published before 31 December 2016 was conducted ~~in~~ 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 ~~straw incorporation~~SI and ~~straw removal~~SR; and~~,~~ (iv) cropping systems included at least one ~~crop of~~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 ~~straw incorporation~~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 ~~where~~in which SOC content ~~were~~was reported with BD, SOC stock (Mg C $\text{ha}^{-1}$) was calculated using Eq. (1):

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

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):

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

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

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

For studies that did not report the quantity of incorporated straw-C, it was ~~calculated~~estimated by multiplying the straw-C content (39.9% for wheat, 44.4% for maize and 41.8% for rice~~) with~~; 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 ~~straw incorporation~~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 ~~the current~~typical farmer~~'s~~ fertilizer N ~~practices~~rate and the optimized fertilizer N rates, respectively, whereas < 200 kg N $ha^{-1}$ $yr^{-1}$ ~~a~~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 (~~crop straw~~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 ~~straw incorporation~~SI and ~~straw removal,~~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 ~~straw incorporation~~SI treatment and *Xc* is the mean grain yield of the control (~~straw removal~~SR). The relative change in crop yields following ~~straw incorporation~~SI was also calculated as ($R$-–1) × 100% (Chivenge et al., 2011). Positive values of relative change indicated a promotion effect of ~~straw incorporation~~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):

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

where $D_{soct}$ and $D_{soct'}$ are SOC stock for the ~~final~~terminal year of experimental ~~straw incorporation~~SI and ~~straw removal~~SR treatments, respectively; and $D_{soci}$ and $D_{soci'}$ are SOC stock for the initial year of ~~straw incorporation~~SI and ~~straw removal~~SR treatments, respectively. A positive value of annual SOC sequestration rate indicates ~~the~~a SOC stock increase due to ~~straw incorporation~~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 ~~intervals~~interval (95% ~~CIs~~CI) for each categorical variable. Mean effect sizes were considered to be significantly different if ~~the~~their 95% CIs did not overlap~~ with each other~~, 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~~ that~~ 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 ~~straw incorporation~~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~~–~~

~~A~~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~~, in which the factor of fertilization was considered, –~~ 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

~~Straw incorporation~~Overall, SI significantly increased annual crop yield by 13.4% (~~range~~95% CI, 9.3%–18.4~~%, 95% CI)~~%) relative to ~~straw removal~~SR in China's cropland (Fig. 3a). The yield responses to ~~straw incorporation~~SI were, however, different ~~in~~among the four ~~different~~ regions of China (Fig. 3b). The greatest yield ~~increase~~increment corresponding to ~~straw incorporation~~SI was observed in NEC (mean 26.8%, ~~range~~95% CI, 18.1%–38.2%), compared with SC (~~mean~~ 11.6%, ~~range~~ 7.3%–17.7%) and NC (~~mean~~ 9.8%, ~~range~~ 3%–26.7%), and the poorest response was found in NWC (~~mean~~ 7.3%, ~~range~~ 1.8%–13.6%).

_Yield increase was positively related to the duration of ~~straw incorporation~~SI for the first 15 ~~years, and~~yr. It then increased from 4.9% (~~range~~ 3.0%–7.5%) after 3~~–~~_5 ~~years,~~yr to 12.3% (5.1%–20.7%) after 6~~–~~_10 ~~years~~yr, and to 18.6% (~~range~~ 12.4%–26.5%) after 11~~–~~_15 ~~years~~yr. After 15~~-year~~ yr, the yield increase (12.6%, 5.1%–20.4%) tended to decline to a level similar to that reported for 6~~–~~_10 ~~years~~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 ~~increases greatly~~ varied among crops, i.e., 8.7% (~~range~~ 4.1%–13.5%), 20.8% (~~range~~ 12.8%–31.0%) and 10.4% (~~range~~ 6.6%–15.3%) yield increase for wheat, maize and rice, respectively (Fig. 4). Yield ~~response~~ increase above the control (SR) was greater when the control ~~(straw removal)~~ yield was low and, as the control yield ~~of control~~ increased, the yield ~~response~~responses to ~~straw incorporation~~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% (~~range~~ 6.2%–18.0%) to 18.4% (~~range~~ 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 (~~mean~~ 18.8%, ~~range,~~ 1.6%–54.2%; $P > 0.05$) relative to 200–400 kg ha$^{-1}$ yr$^{-1}$ ~~yr$^{-1}$ (mean 18.4%, range 11.9%–27.6%)~~ (Table 3).

**3.3 Responses of SOC to straw incorporation**

Annual SOC sequestration in response to ~~straw incorporation~~SI was enhanced~~,~~ with an average rate of 0.35 (~~range~~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 ~~(Fig. 5b; $P < 0.05$), and between different straw incorporation~~, SI duration, crop frequency and soil texture (Fig. ~~5c~~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 ~~to~~with the ~~control~~SR treatments ~~(straw removal),~~, the greatest SOC sequestration ~~rate~~rates were recorded in NEC (~~mean~~ 0.57, ~~range~~ 0.41–0.77 Mg C ha$^{-1}$ yr$^{-1}$), followed by SC (~~mean~~ 0.36, ~~range~~ 0.30–0.43 Mg C ha$^{-1}$ yr$^{-1}$), NC (~~mean~~ 0.33, ~~range~~ 0.25–0.40 Mg C ha$^{-1}$ yr$^{-1}$) and NWC (~~mean~~ 0.19, ~~range~~ 0.14–0.25 Mg C ha$^{-1}$ yr$^{-1}$) (Fig. 5b). The annual SOC sequestration rates were ~~significant~~ significantly ($P < 0.05$) greater in the shortest time interval (3–10 yr) after ~~straw incorporation~~SI began (~~mean~~ 0.53, ~~range~~ 0.44–0.63 Mg C ha$^{-1}$ yr$^{-1}$), compared ~~to~~with the medium-term (10–20 yr; 0.29, ~~range~~ 0.23–0.37 Mg C ha$^{-1}$ yr$^{-1}$) or long-term (> 20 ~~years; mean~~yr; 0.17, ~~range~~ 0.13–0.21 Mg C ha$^{-1}$ yr$^{-1}$) (Fig. 5c).

The effect of ~~straw incorporation~~SI on SOC sequestration varied between different crop frequencies in the order: triple (~~mean~~ 0.51, ~~range~~ 0.37–0.67 Mg C ha$^{-1}$ yr$^{-1}$) > single (~~mean~~ 0.41, ~~range~~ 0.31–0.53 Mg C ha$^{-1}$ yr$^{-1}$) > double (~~mean~~ 0.28, ~~range~~ 0.24–0.32 Mg C ha$^{-1}$ yr$^{-1}$). The SOC sequestration after ~~straw incorporation~~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 ~~overall~~ SOC sequestration ~~rates were~~rate was 0.20 (~~range~~ 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 (~~range~~ 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~~). Nitrogen~~; $P < 0.05$). 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 (~~range~~ 0.22–0.32) to 0.69 (~~range~~ 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 ~~relationship~~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.

~~6a, b, c, d, e~~6).

There was a significant logarithmic relationship between annual SOC sequestration rate and ~~straw incorporation~~SI duration (Fig. 7; $P < 0.05$). A ~~quick~~rapid decline in SOC sequestration rate was observed after the initial stage of ~~straw incorporation~~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 ~~years~~yr of ~~straw incorporation~~SI in the whole ~~nation and~~of China, NEC, NC, NWC~~,~~ and SC respectively (Fig. ~~7a, b, c, d, e~~7).

## 4 Discussion

The results of the meta-analysis suggest that ~~straw incorporation increase~~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 ~~years~~yr after ~~straw incorporation~~SI began. This conclusion is based on a wide range of soils and climate conditions and suggests that farmers across the world may ~~be able to~~ use this simple management tool to increase their outputs by improving the quality of their soil, ~~whilst~~while mitigating climate change.

### 4.1 Increase of SOC by straw incorporation

The ~~straw~~ incorporation ~~in the experimental systems reviewed across China significantly~~of straw unsurprisingly enhanced SOC stocks in China's cropland at an average rate of 0.35 Mg C ha~~$^{-1}$ yr$^{-1}$ (relative~~$^{-1}$ yr$^{-1}$. This confirms the findings of previous meta-analyses of significant positive SOC responses to straw ~~removal; Fig. 5a) regardless of the straw type (i.e. source crop) ($P > 0.05$), also observed by (Wang~~input (Lu et al., 2009; Lehtinen et al., 2014; Liu et al., 2014). ~~2016). This estimate~~Our result is comparable to the SOC sequestration rates ~~reported after reviews for~~ of 0.1–0.3 Mg C ha$^{-1}$ yr$^{-1}$ in the croplands of the ~~USA (0.1–~~United States (Watson et al., 2000) and the global estimates of 0.3 Mg C ha$^{-1}$ yr$^{-1}$~~;~~ (IPCC, 2000~~),~~) but only half ~~that~~of the estimation for the EU (0.7 Mg C ha$^{-1}$ yr$^{-1}$; Smith, 2004). ~~Like Tian et al. (2015), through meta-analysis we observed that SOC contents increased regardless of the initial SOC contents (data not shown), and that a rapid increase in SOC density occurred in the first two decades rather than in later periods (26–63 years) of straw incorporation (Fig. 5c, 7), which suggest that an equilibrium between C input and decomposition had been reached but only after decades. This supports the need for continued investment in long-term field experimentation to provide robust information about the impact of management in agroecosystems to inform farmer decision-making and policy (Macdonald et al., 2015).~~

Straw incorporation provides a ~~C~~ 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), as previously described (Kong et al., 2005~~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 ~~; Liu et al., 2014). Sequestration rates were increased where greater amounts of annual~~ above-ground crop residues ~~were input under double and triple cropping regimes (Fig.~~, resulted in greater SOC sequestration (Fig. 5e; $P < 0.05$), ~~also observed by (West and Post, 2002; Blanco-Canqui and Lal, 2009).~~supporting the findings of Luo et al. (2010).

Addition of N fertilization enhanced the effect of ~~straw incorporation~~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$^{-1}$~~) was immobilized,~~), at least in the short term (Singh et al., ~~1999~~1992). Furthermore, N fertilizer addition can enhance both above- and ~~belowground~~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~~ roots to stable SOC pools~~-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 ~~study wherein sequestration rates in clay were greater than in loam soils (Fig. 5i).~~

~~A~~context, a significant spatial variation in ~~straw incorporation effect on SOC was observed between the four regions of China defined for analysis (Fig. 5b; $P < 0.05$). Straw conversion efficiency (30%; Fig. 5b;) and annual SOC sequestration rate (0.57 Mg C ha$^{-1}$ yr$^{-1}$; Fig. 6) were notably~~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 ~~in NEC~~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~~., 2017~~. (2017a), the percentage of ~~straw residue retention~~SI by farmers was only 8.7% in NEC, while 32.7% of farmers burnt the straws in the field. ~~Our results highlight the~~Hence, there is an urgent need to encourage the local farmers to ~~incorporate~~recycle the crop straw~~ to maintain SOC stocks~~ in NEC. The ~~impact~~impacts of land~~-~~use~~, MAT, and MAP~~ type on straw-induced SOC sequestration ~~was~~were not statistically significant (Fig. ~~5~~5d; $P > 0.05$), in agreement with the previous meta-~~analyses~~analysis of Liu et al. (2014~~) and Huang et al. (2012). Since~~). 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 wetting and drying cycles~~). This practice would stimulate microbial activity and ~~increases~~increase organic matter mineralization during the mid-season drainage period (Mikha et al., 2005~~) and leads~~), 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 ~~largely overwhelmed and overridden~~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~~; Pei et al., 2016). For instance,~~

the MAP only ranges from 455 to 821 mm in NC (Table S1), much less than the variations of irrigation (0 to 667 mm yr$^{-1}$; Liao et al., 2015).) also reported similar results. Our results imply that improvingimprovement of SOC through straw incorporationSI might be also be applicable to other regions in the world with different climate conditions or land useuses.

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 to straw removal.with SR. This yield increase is similar in magnitude to a recent global meta-analysis of global data (12%; Liu et al. 2014), but larger than previous meta-analyses of published dataother observations from China (up to 9% increase; Zhao et al., 2015; Wang et al., 2015; Huang et al., 2013; Xu et al., 2017) and those of the EU (6% increase; Lehtinen et al., 2014). The lower estimates reported in previous studies focused on shorter time periods, e.g. 8–12 years in Zhao et al. (2015), with this new analysis showing the greatest benefits of straw incorporation for crop yield after 11–15 years (Fig. 3d); or more limited geographical spread, e.g.zones, i.e., most studies in Lehtinen et al. (2014) were in the Mediterranean, only NC was considered in (by Xu et al., . (2017) and only three sites from NEC were included in the analysisanalyzed 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 level in China (616 million Mg; NBSC, 2016), this straw-induced yield increment (13.4%) results ofin an additional 82.6 million Mg of agricultural products. At the current per capita food consumption of 388 kg yr$^{-1}$ (Central People's Government–PRC, 2008), this, 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 discussed above, straw incorporation significantly increases SOCprevious 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). In the current meta-analysis, regression analysis revealed that eachEach increase of 1 Mg C ha$^{-1}$ SOC in the root zone could improve crop yield by 101–157 kg ha$^{-1}$ yr$^{-1}$ (Fig. 2), which fell within the range of 30–30–300 kg ha$^{-1}$ yr$^{-1}$ obtained forin Asia region by (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, incorporated from the soil and foliar applications of fertilizer during plant growth, 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 ha$^{-1}$ yr$^{-1}$, 13 kg $P_2O_5$ ha$^{-1}$ yr$^{-1}$ 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 ~~that the estimated~~a similar annual straw N input ~~rate~~ (39.6 kg N ha$^{-1}$ yr$^{-1}$) ~~significantly~~ and ~~positively contributed to the crop~~beneficial yield ~~increase. Similarly,~~response. Singh et al. (2002) also suggested that crop residue recycling ~~determines the soil K balance and thus~~ affects crop production substantially~~. Our analysis did observe a strong indication that~~ by maintaining the soil K balance. For the response to SI, maize ~~yields benefited more (20.8%) from straw incorporation~~ crop achieved higher yield increase than ~~those of~~ wheat ~~(8.7%)~~or rice crop (Fig. 4~~). This observation~~), which agrees with the study of Hijbeek et al. (2017~~), who found that~~ ). This may be because maize ~~benefits significantly from organic inputs than those of wheat or barley. The most likely reason for this difference was that, compared to wheat, maize is mostly grown require with~~growth under higher temperature and precipitation (Tan et al., 2017), and these conditions favor ~~a fasten~~faster straw decomposition and ~~also~~ result in a ~~more~~ rapid and ~~abundant~~complete nutrient release (Hartmann et al., 2014; Ladha et al., 2011).

~~Our study found that only when straw incorporation duration~~ 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 ~~might be related to~~ indicates that ~~for the greater~~long-term SI is necessary to achieve a high soil fertility and continuous yield sustainability ~~to be achieved, a long term adoption of straw incorporation in arable cropping management is required~~ (Bi et al., 2009). Indeed, the yield increase was relatively low in the initial stage (5% in the first 3~~-~~–5 ~~years~~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-~~year timespan of the adoption of straw incorporation (Fig. 3d). The crop yield response was lower under the triple cropping system compared with that under the single or double cropping systems (Fig.~~ 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).~~ In China, the areas where triple cropping was adopted usually received adequate rainfall (MAP >~~

~~1000 mm, Table S1) supporting good rates of crop production (i.e. 13.5 Mg ha$^{-1}$ yr$^{-1}$ versus 9.2 and 4.9 Mg ha$^{-1}$ yr$^{-1}$ in double and single cropping, respectively, in our database); thus straw-induced soil water retention might contribute little benefit for crop production in the region (Raffa et al., 2015) compared with the drier regions.~~

~~The probable N immobilization effect of straw incorporation discussed above has potential benefits for the crop and environment (e.g. reduced losses by leaching and $N_2O$ emissions; Meng et al., 2016) through improved nitrogen use efficiency (Yao et al., 2017). In the current meta-analysis, under the N fertilizer level of 200–400 and > 400 kg N ha$^{-1}$ yr$^{-1}$, which was widely adopted in arable land in China (Ju et al., 2004), 18% of yield increase due to straw incorporation was observed (Table 3). This emphasized that straw incorporation is an effective measure for both improving crop yield, as well as having the potential to decrease the risks of polluting N leaching in areas of intensive agriculture.~~

## 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

~~This study presents the responses of SOC and crop yield to straw incorporation under different farming management practices in various edaphic and climate regions in China. Compared with straw removal, straw incorporation~~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 ~~straw incorporation~~SI at 3 Mg C ha$^{-1}$ yr$^{-1}$ with the mineral N rate of 200–400 kg N ha$^{-1}$ yr$^{-1}$ was ~~exhibited~~found to be the best combination for ~~farmers to~~farmer use, with crop yield increased by 32.7% and SOC sequestrated by the rate of 0.85 Mg C ha$^{-1}$ yr$^{-1}$. ~~Straw incorporation achieved a higher~~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 ~~rate and crop yield increment in clay soils under high cropping intensities and in cold and humid area like Northeast China.~~and yield improvement. As ~~straw incorporation~~SI progressed, ~~the~~a rapid SOC ~~accrual rate declined~~increase occurred in the first two decades, and ~~then stabilized;~~the crop yield ~~responses increased and~~increase peaked at around 15-~~year and then declined.~~ yr. Our study confirmed ~~that straw incorporation did create a positive feedback loop of SOC enhancement together with increased crop production, and the positive role of straw~~

~~incorporation can play in China and global~~ 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.

**10 Acknowledgements**

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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 straw incorporationSI.
[b] experiment duration for the response of crop yield to straw incorporation.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: Northeastnortheast China; NC: Northnorth China; NWC: Northwestnorthwest China; SC: Southsouth China.
MAP: Meanmean annual precipitation (mm); MAT: Meanmean annual temperature (°C°C).

**Table 3. Responses of soil organic carbon (SOC; Mg C ha$^{-1}$ yr$^{-1}$) and crop yield (%) to ~~straw incorporation~~SI over ~~straw removal~~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.

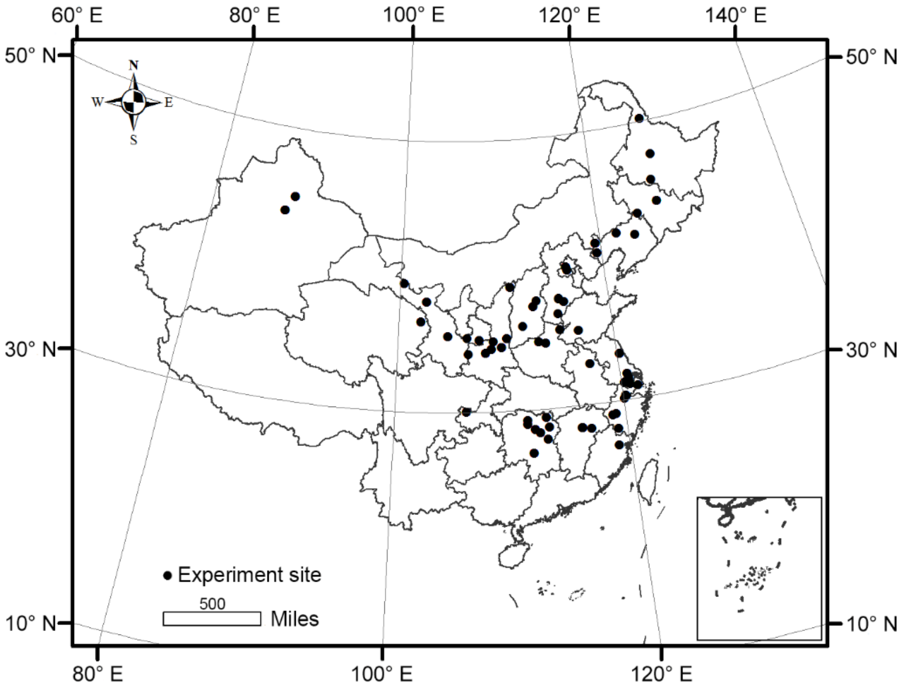


**Figure 1:. Locations of the long-term experiment sites in China.**

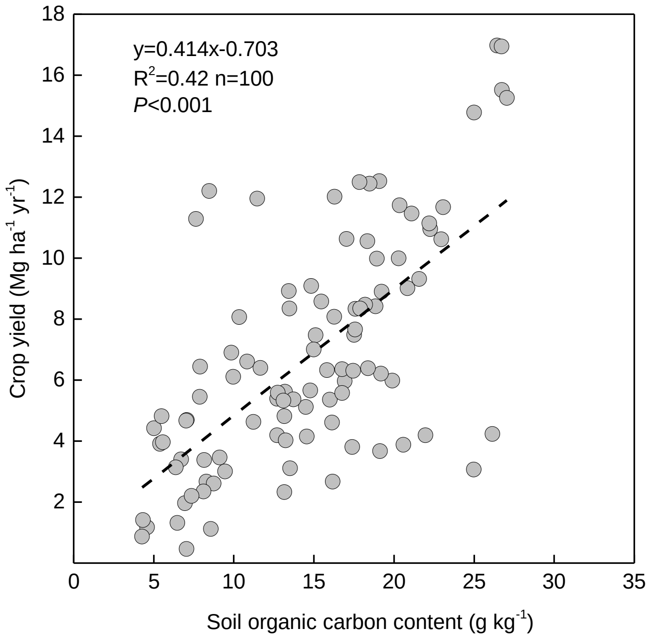


**Figure 2:. Relationship between crop yield and soil organic carbon content.**

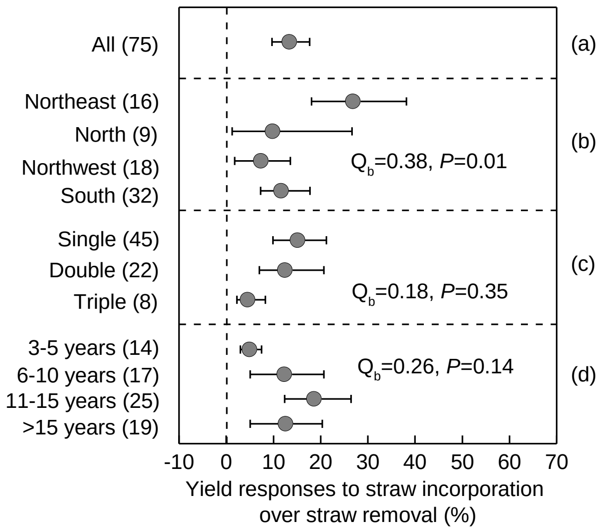


**Figure 3~~:~~. Responses of crop yield to ~~straw incorporation~~SI compared with ~~straw removal~~SR (a), categorized into (b) region, (c) crop frequency and (d) experiment duration. Yield responses are expressed as the relative increase (%) compared with control (~~straw removal~~SR) with 95% ~~confidence intervals~~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.**

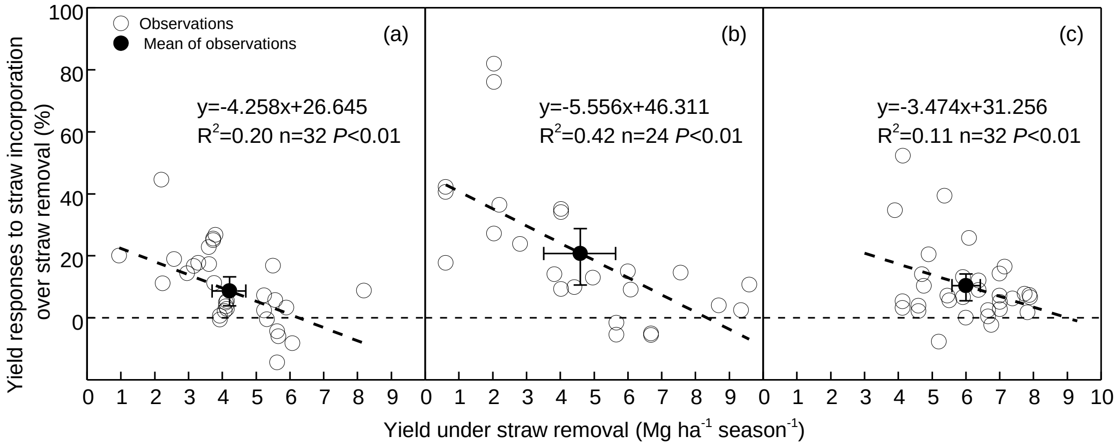


**Figure 4~~:~~. Relationship<u>s</u> between crop yield responses to ~~straw incorporation~~<u>SI</u> and control yield under ~~straw removal~~<u>SR</u> for~~ the crop of~~ (a) wheat, (b) maize and (c) rice. Yield responses are expressed as the relative increase (%) compared with control (~~straw removal~~<u>SR</u>). Error bars in horizontal and vertical directions represent 95% ~~confidence intervals~~<u>CIs</u> of the control yield and yield responses, respectively.**

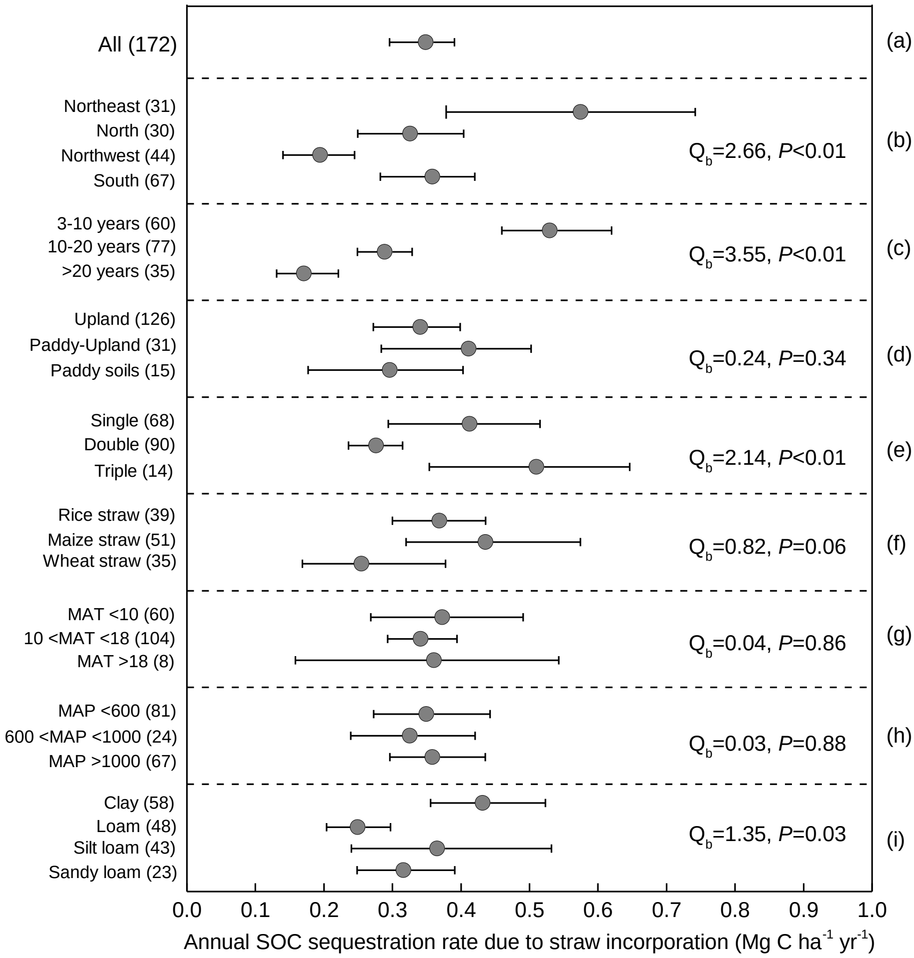


**Figure 5~~:~~. Responses of soil organic carbon (SOC) to ~~straw incorporation~~SI compared with ~~straw removal~~SR (a), categorized into (b) region, (c) experiment duration, (d) land use, (e) crop frequency (season yr$^{-1}$), (f) straw type, (g) mean annual temperature (MAT), (h) mean annual precipitation (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% ~~confidence intervals~~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.**

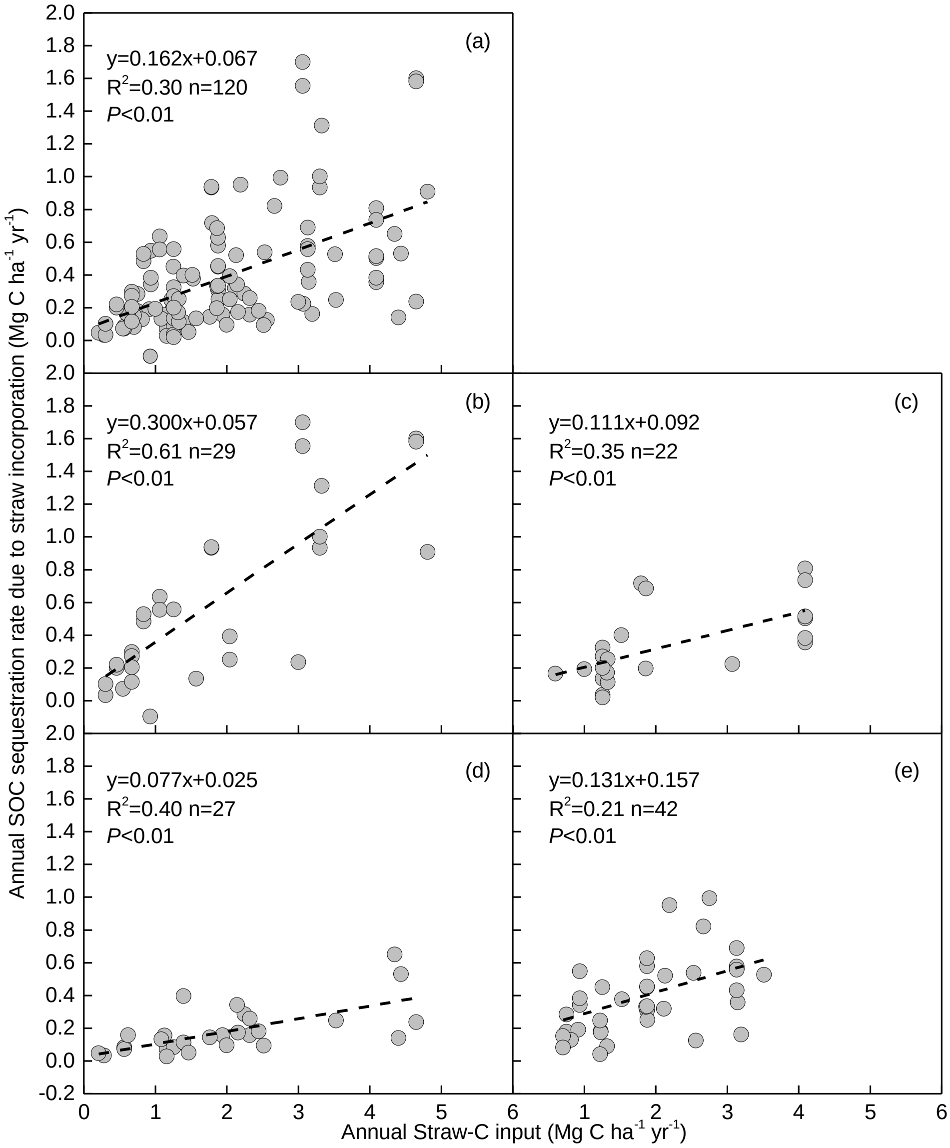


**Figure 6~~:~~. Relationships between annual soil organic carbon (SOC) sequestration rate and straw carbon input for (a) national scale, (b) ~~Northeast~~northeast China, (c) ~~North~~north China, (d) ~~Northwest~~northwest China and (e) ~~South~~south China.**

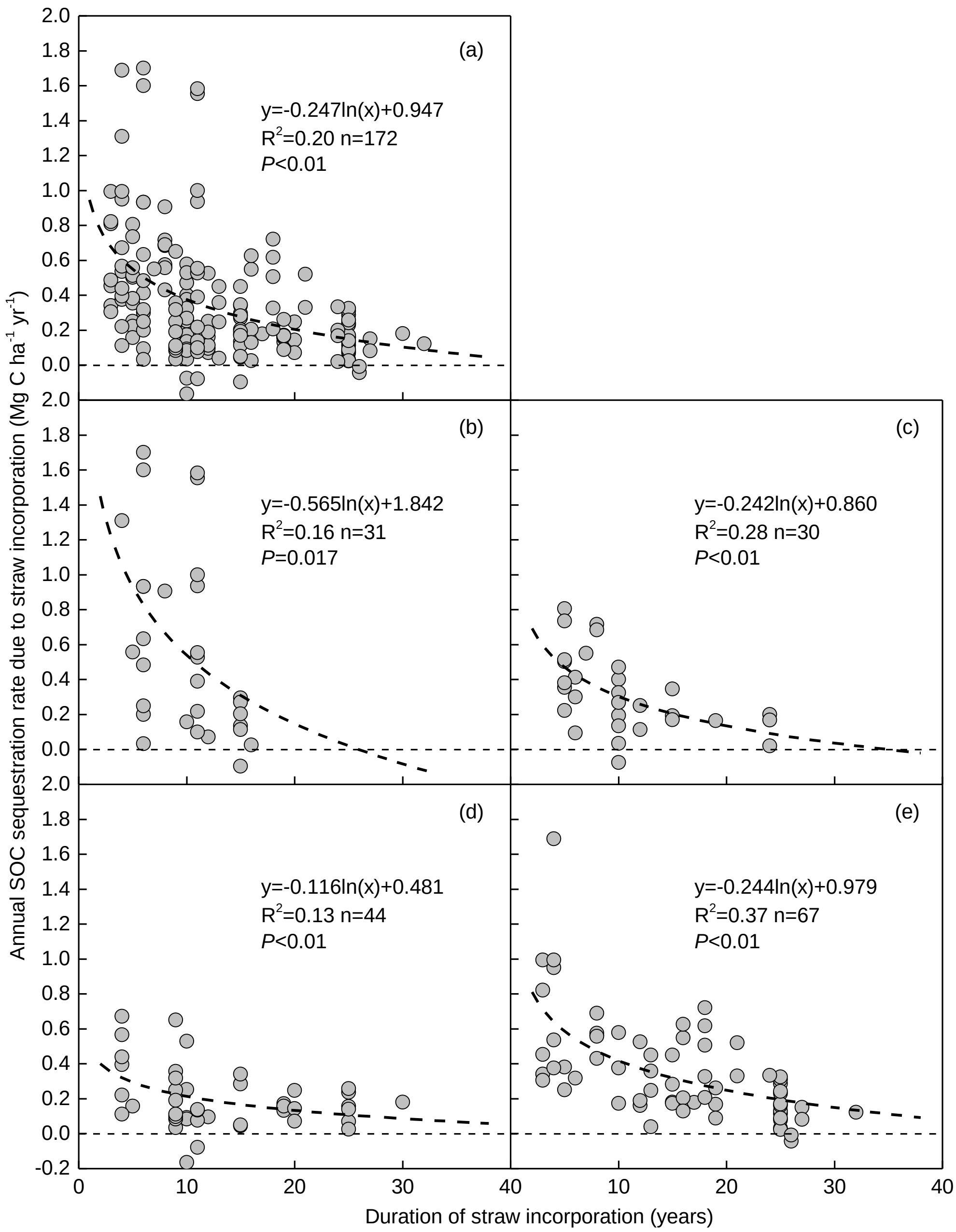


**Figure 7. Relationships between annual soil organic carbon (SOC) sequestration rate and SI duration for (a) national scale, (b) northeast China, (c) north China, (d) northwest China and (e) south China.**