How can straw incorporation management impact on soil carbon storage? A meta-analysis

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Abstract Straw incorporation (SI) is a common practice in China and has important implications for agricultural sustainability. This study aimed to quantitatively summarise the response of top soil (0–20 cm) carbon (C) to SI under different agricultural management regimes. Results indicated that compared with straw removal (SR), SI significantly increased soil C storage by 12 %. Moreover, incorporation of chopped straw with tillage treatment (ploughing and rotary tillage) increased C storage compared to unchopped straw without tillage treatment. SI implementation with upland cropping, in the northwest and northeast resulted in higher C storage compared with rice cropping, and in the northern and southern regions. Changes in soil C were observed based on SI variables, including tillage and straw amounts in fine-textured soils, however straw amount rather than tillage treatment exhibited a greater influence on soil C in coarse-textured soils. We concluded SI implementation with increased amounts of chopped straw for a longer duration was favourable to soil C sequestration in Chinese croplands. Furthermore, we estimated if SI was popularised across all of China's agricultural regions, soil C sequestration potential would reach 48.2~56.2 Tg C year⁻¹. SI practices should therefore be encouraged.

Keywords China · Meta analysis · Soil carbon (C) sequestration · Soil carbon storage · Straw incorporation

1 Introduction

Cereal crops (e.g. rice [*Oryza sativa*], maize [*Zea mays*], and wheat [*Triticum aestivum*]) produce substantial straw amounts, and it is estimated that cereal straw is responsible for 75 % of the total crop straw (Department of Science and Technology and Education, Ministry of Agriculture of the People's Republic of China, STEMOA 2010). Post-harvest straw management and utilisation, including burning, harvesting, and some degree of soil incorporation, are under increased scrutiny, and have complex social, economic and ecological implications (Gullett and Touati 2003; Powlson et al. 2011). In China, prior to the 1980s, crop straws were primarily used as cooking and heating fuels, or as forage and bedding for livestock. Since the 1990s, fossil fuels have replaced crop residues

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as the major energy source, and straw is commonly burned in fields following harvest, contributing to China's serious air pollution (Zhang 2000; Gullett and Touati 2003; Ye et al. 2010), and greenhouse gas emissions (Pan et al. 2011). Straw burning has recently been prohibited in China's major agricultural regions in the National Modern Agriculture Development Plan (2011–2015) (MOA 2011). Ministry of Agriculture (MOA) clearly encourages comprehensive utilisation of straws, including covering, burying, or returning straw to fields as organic fertilizer, rather than burning. Crop straws contain nutrients, such as N and organic C, therefore straw removal by burning reduces soil fertility and organic matter, resulting in declines in soil quality (Lu et al. 2010a, 2010b; Powlson et al. 2011), and C and N losses (Dobermann and Fairhurst 2000). Pan et al. (2011) reported biochar addition was an alternative approach to improve soil quality, however due to biochar technological limitations, direct straw incorporation is more commonly applied in China. Currently, local environmental protection authorities are in charge of straw burning prohibition with assistance from associated local government departments. In turn, agricultural administrations provide the efforts to popularize and optimise the utility of straw, particularly straw return, in agricultural communities. These cumulative governmental efforts continue as an important driving factor to implement straw incorporation protocols.

Numerous investigations into SI effects on soil C have been conducted across China, and included different climatic conditions (Li et al. 2003; Lu et al. 2009), and durations (Rui and Zhang 2010). In fact, notable differences occur not only in climate, and durations, but also geography, soil type, cropping system, and crop variety in Chinese agricultural lands, therefore, there are a great diversity of SI management in different regions (Liu et al. 2001; Bi et al. 2008). However, less attention, was paid to different straw management protocols, for example, SI type (chopped and unchopped), cropping systems (upland and rice paddies cropping), and tillage (no tillage, ploughing or rotary tillage). A numbers of studies have conducted meta-analysis of soil C storage change under different agricultural management protocols in meta-analysis (Rui and Zhang 2010; Huang et al. 2012), however, soil C sequestration potential was not estimated. Meta-analysis is a robust tool with the potential to synthesize data from multiple locations, temporal variability in results, and draw consistent conclusions across studies (Gurevitch and Hedges 1999). In the present study, our overall objectives were as followings: (1) investigate how certain factors (e.g., SI type and amount, tillage type, cropping system, and experimental duration) influenced SI effects on soil C storage; and (2) estimate soil C sequestration potential using meta-analysis results.

2 Materials and methods

2.1 Data collection

We collected data on soil C storage from studies where SI was compared with SR in side-by-side experiments. We performed an exhaustive literature survey in ISI-Web of Science, Google Scholar (Google Inc., Mountain View, CA, USA), and Chinese Journal databases (CNKI Databases and Wanfang Data, at www.cnki.net and www.wanfangdata.com.cn, respectively) for articles published before September 2013. Studies had to meet the following specific criteria: (1) soil C concentration or storage values were reported within the study; (2) field experiments were included: pot experiments, agroforestry systems or vegetable lands were excluded; (3) experimental periods were longer than 3 years; (4) only three crops were included in the analyses: rice, maize, and wheat, because these are the most common crops cultivated in China, and the amount of straw from these three crops account for 76 % of the

total straw (STEMOA 2010). Finally, Appendix lists 76 papers consisting of 159-paired soil C data met our inclusion criteria. The distribution of experimental field is shown in Fig. 1.

A meta-analysis requires every measurement is statistically independent (Gurevitch and Hedges 1999), therefore, multiple measurements conducted in single-field experiments using the same SI treatment were averaged. In addition, different SI treatment amounts within a single study were assumed to be independent cases (Curtis and Wang 1998). Furthermore, we restricted our analyses to the latest sampling dates.

Means and standard deviations and replications of soil C concentrations and storage in SR and SI were obtained from tables and text, or extracted from figures using digitizing software (Grafula 3 v.2.10, Wesik SoftHaus, St Petersburg, Russia). The ancillary information on bulk density, texture, tillage type, crop straw status and amount incorporated, cropping system, experimental region, and duration were also collected. Most studies provided bulk density (BD) values, but where it was not reported, we applied $BD = 1.377 \times e^{-0.0048 \times SOC}$ to estimate soil BD values (Song et al. 2005). Soil organic C concentration, BD and soil depth (20 cm) were multiplied to calculate soil C stock ($t\ ha^{-1}$) at a depth of 0–20-cm.

2.2 Meta-analysis

A meta-analysis was conducted to detect soil C storage response to SI. The response ratio $\ln R$ (1), was used to estimate the effect size of SI:

$$\ln(R) = \ln\left(\frac{\overline{X_{SI}}}{\overline{X_{SR}}}\right) \quad (1)$$

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

where, $\overline{X}_{SI}$ and $\overline{X}_{SR}$ are mean soil C storage values for SI and SR treatments, respectively. Meta-analysis results were reported as percentage changes, calculated as $(R-1) \times 100\%$ (Curtis and Wang 1998; Morgan et al. 2003; Feng et al. 2006; Wittig et al. 2007). Negative percentage changes indicate decrease mean soil C storage values based on SI application, and positive values indicated an increase in mean soil C storage values.

An unweighted meta-analysis was adopted because most of the collected papers did not provide a measure of variance for soil C storage (Gurevitch and Hedges 1999; Rosenberg et al. 2000). Meta-analysis was performed using a meta-analytical software package (METAWIN 2.1.3.4, Sinauer Associates, Inc., Sunderland, MA, USA) (Rosenberg et al. 2000) following the method reported by Curtis and Wang (1998). The variance of effect sizes were calculated using resampling techniques after 4,999 iterations, and the confidence limits around the effect sizes were calculated using a bootstrap method (Rosenberg et al. 2000). The cumulative effect sizes were considered significant if the 95 % confidence intervals (CI) did not overlap zero (Curtis and Wang 1998).

The variation in soil C storage response to SI was further explained by categorising, the paired measurements according to (1) SI type (chopped, unchopped); (2) tillage type (no tillage -NT, ploughing tillage -PT, and rotary tillage -RT); (3) cropping system (rice-rice, wheat-rice, wheat-maize, and single maize/wheat); (4) experimental duration (<5 years, 5–15 years, >15 years); (5) experiment region (northeast, north, northwest, and south); (6) soil texture (fine-textured soils, and coarse-textured soils); (7) SI amount (half, and full SI). Random effects models facilitate comparisons among groups in a framework similar to analysis of variance, and thus a random effect categorical summary analysis was used to compare the variance in effect sizes. We accepted the tests of between-group heterogeneity (Q_b) as statistically significant, if the P values were less than 0.05 level.

2.3 Annual soil C sequestration rates

The annual soil C sequestration rate (ΔD_{yr}) for soil C storage ($\text{t ha}^{-1} \text{ year}^{-1}$) in response to SI versus SR was calculated by the following equation (2):

$$\Delta D_{yr} = \frac{(D_{SI} - D_{SR})}{t} \quad (2)$$

where, D_{SI} and D_{SR} are the corresponding C storage values for the SI and SR variables, respectively, and t is the number of years SI had been implemented.

3 Results

In general, relative to SR, a significant increase ($CI > 95\%$) in soil C storage was detected following SI implementation (Figs. 2 and 3), as expected. Compared with SR, SI increased soil C storage by 12 % at 0 to 20 cm depths. Results indicated significant between-group heterogeneity (Q_b) among SI type, tillage, cropping system, experimental duration, and region for the soil C storage (Table 1). Mean soil C storage differences in SI compared to SR showed a 9 % increase in unchopped and 13 % increase in chopped straw (Fig. 2). RT and PT increased soil C storage following SI compared to NT. SI effects significantly increased soil C storage by respective averages of 9, 12, and 16 % in NT, PT, and RT. Soil C was also influenced by cropping system. Changes in soil C storage following SI treatment compared to SR was in the following order: single maize and wheat, wheat-maize > wheat-rice, and rice-rice (Fig. 2). Soil C storage following SI was higher in the northeast and northwest regions (average 55.22 and 63.67 $\text{kg C ha}^{-1} \text{ year}^{-1}$) than in northern and southern regions (average 38.35 and 56.05 $\text{kg C ha}^{-1} \text{ year}^{-1}$) (Fig. 3, Table 2). Annual soil C

Fig. 2 Response of soil organic C storage to SI under different SI types, tillage types, rotation types, and experimental duration. Dot and bar represent the mean and range at 95 % confidence intervals of percent response to SI as compared to straw removal. The values in parentheses represent independent sample size and percent response to SI

sequestration rates due to SI showed a linear increase with increasing straw amounts (Fig. 4). Experimental duration also exhibited a significant effect on C storage response to SI, with a progressive increase in the response as the experimental duration increased (over 15 years > 5–15 years > less 5 years) (Fig. 2). Results from the regression model revealed the majority of the increase in C storage occurred within the first 15 years (Fig. 4).

Overall, no significant Q_b for soil C storage among soil texture categories was observed (Table 1). However, in fine-textured soils, SI resulted in significant soil C storage variability under different tillage treatments (Fig. 5). PT treatment showed a greater increase in C storage (16 %) compared to NT and RT (5 %). In contrast, SI and tillage treatment had no significant effect on C storage in coarse-textured soils. Soil C storage was sensitive to SI amount, and progressively increased with SI amount, regardless of fine or coarse textured soil.

Fig. 3 Response of soil organic C storage to SI in different regions of China

4 Discussion

4.1 SI effects on soil C

Meta-analysis results from empirical cropland field study data derived from the literature showed SI generally resulted in increased soil C storage compared to SR treatments in surface (0–20 cm) soils (Kwabiah et al. 2003; Smith 2004; Wu et al. 2007; Saffih-Hdadia and Mary 2008; Powlson et al. 2011; Xu et al. 2011). SI provided large quantities of organic C inputs to cropland soils absent under SR, thereby promoting soil microbial biomass and its activity, and subsequently increasing soil organic matter (Dick 1992; Lal et al. 2007). Therefore, we conclude SI exhibited efficacy in increasing soil C storage.

Our results found SI effects on soil C storage were dependent on several factors, including type (chopped and unchopped) and amount of straw, tillage treatment (NT, PT, and RT), cropping system (rice-rice, wheat-rice, wheat-maize, and single maize/wheat), experimental region (northeast, north, northwest, and south), and duration (<5 years, 5–15 years, >15 years).

Table 1 Effects of SI on between-group heterogeneity for soil organic C storage

	Number	SI type	Tillage	Cropping system	Duration	Regions	Texture
Soil organic C storage	159	4.1*	7.3*	9.4*	11.6**	7.9*	1.2

* $P < 0.05$, ** $P < 0.01$

Table 2 Typical properties and mean annual change rate of soil C storage (AMC) after SI in different agricultural regions

Region	Number of crops sown per year	Major crops	AMC (kg C ha ⁻¹ year ⁻¹)
Northeast	Single crop	Maize, rice, wheat	55.22
Northwest	Single crop	Maize and wheat	63.67
North	Double crop	Maize and wheat	38.35
South	Double crop	Wheat and rice	56.05

Compared to unchopped straw, chopped straw exhibited a greater increase in soil C sequestration (Fig. 2). Chopped straw increases contact between the straw and soil microorganisms, which promotes the decomposition from straw into soil C. Alternatively, unchopped straw reduces contact between straw, soil, and soil microflora, decreasing decomposition and C sequestration. Therefore, chopped straw should be encouraged to enhance soil C sequestration.

NT treatment resulted in the absence of soil disturbance, with the straw remaining on the soil surface. In contrast, under RT and PT treatments, an excess of 90 and 60 % of incorporated straw might be buried at depths of 0–11 cm and 10–20 cm, respectively (Allmaras et al. 1996). Li et al. (2001) reported straw decomposition rates were closely related to SI depths, in decreasing order from 5 to 15 cm to the surface soil. Thus, compared with NT, tillage treatments have increased the potential to promote straw C conversion into soil C (Stemmer et al. 1999; Wingeyer et al. 2012). It is noteworthy that NT treatment generally results in greater soil C storage than PT and RT treatments at surface soil (Bossuyt et al. 2002; Dolan et al. 2006; Huggins et al. 2007; Hermle et al. 2008). Six et al. (2002) proposed C-saturation mechanisms where larger amounts of soil C accumulate when C is far from saturation. Therefore, we can conclude RT and PT management regimes were more favourable than NT to soil C accumulation under SI conditions.

Our results found SI adoption with upland cropping in northwest and northeast regions of China showed higher C storage increase compared with rice cropping in northern and southern regions. Furthermore, the C-saturated model (Six et al. 2002) might contribute to these observations. First, due to anaerobic conditions (Witt et al. 2000; Yu et al. 2009), rice-cropping systems (primarily located in the southern region) are generally associated with higher

Fig. 4 The relationship between soil C sequestration rate and different amounts of SI and years of cultivation

Fig. 5 Response of soil C to SI under different tillage types, and straw amount in fine and coarse textured soils. The unit of straw amount is t ha^{-1} . Different *lowercase letters* indicate significant difference of soil C storage between min tillage (no tillage and rotary tillage) and ploughing tillage after adoption of SI, different *capital letters* present significant different of soil C storage among different SI amount ($P < 0.05$)

soil C storage than upland-cropping soils in China (Xie et al. 2007; Pan et al. 2010; Yu et al. 2012). Huang et al. (2012) conducted a national scaled meta-analysis that compared no fertiliser treatment and initial soil C values, and reported rice-rice rotation promoted a slight gain in soil C under the absence of fertiliser and straw treatments. Second, intense cropping systems might cause increased soil C storage compared to fallow soil (West and Post 2002; Álvaro-Fuentes et al. 2009), therefore single maize or wheat cropping systems corresponded to lower soil C storage due to decreased C input. Third, considerable evidence confirmed northwest and northeast regions of China are still experiencing considerable C losses (Yu et al. 2009, 2012; Wang et al. 2013), with some soil types in the northwest region exceeding over 50 % C loss during a short time (Wu et al. 2004). Based on these studies, we concluded that soils suffering from C loss, or further from C saturation have greater potential for soil C sequestration following SI implementation. Moreover, rice-cropping systems were associated with a warmer climate and anaerobic conditions, which accelerated CH_4 emissions and straw decomposition (Devêvre and Horwath 2000), therefore less C was accumulated than colder upland cropping.

Our results also indicated increased SI duration resulted in higher soil C sequestration (Fig. 2), however annual soil C sequestration rate gradually decreased over the experimental period (Fig. 4). C-saturation mechanisms (Six et al. 2002) might be responsible for these results, i.e. increased soil C diminished over time as a steady state was achieved (West and Post 2002; Kimetu et al. 2009; Luo et al. 2010). Therefore, SI implementation enhanced soil C storage only over periods of approximately 20 years (Luo et al. 2010; Rui and Zhang 2010). Although soil C sequestration rate decreased with experimental duration, long-term SI was still encouraged to increase soil C sequestration.

Lal (2004) reported optimum soil C stock could maintain water and nutrient levels, and improve soil structure, therefore we deduced that SI not only enhanced soil C storage, but also had an integral affect on crop yield (Lal 2004; Lal et al. 2007; Pan et al. 2009). Fifty-five paired measurements, including changes in crop yield due to SI were analysed in this study. Results showed SI increased crop yield by $0.143 \text{ t ha}^{-1} \text{ year}^{-1}$. Linear regression indicated annual soil C sequestration rate ($Y, \text{ kg C ha}^{-1} \text{ year}^{-1}$) was positively related to the annual crop yield rate, i.e. $X, \text{ t ha}^{-1} \text{ year}^{-1}$, $Y = 30.44 + 206.2X$ ($R^2 = 0.44$, $P < 0.01$).

Table 3 Two potential scenarios of SI in China

Scenario	Northeast	Northwest	North	South
I	100 % SI	100 % SI	SI for one of the two crops	SI for one of the two crops
II	100 % SI	100 % SI	SI for both of the two crops (i.e. 100 % SI)	SI for both of the two crops (i.e. 100 % SI)

4.2 Response of soil C to SI under different textured soils

Compared with coarse-textured soils, it is widely regarded that fine-textured soils contain more soil C (Li et al. 1994; Franzluebbers et al. 1996; Wang et al. 2008), because fine-textured soils are favourable to C protection, and reduce in C decomposition rates (Sukkariyah et al. 2007). In practice, a strong interaction between tillage management and soil texture has been observed. Previous studies reported reduced tillage resulted in greater soil organic C accumulation than PT treatment in fine-textured soils, whereas in coarse-textured soils, tillage practices had no affect on soil C content (Needelman et al. 1999; Chivenge et al. 2007; Melero et al. 2009). These findings combined with the C-saturated model (Six et al. 2002) are a viable explanation for our results regarding tillage effects on different textured soils. Additionally, our results showed that irrespective of soil texture, soil C progressively increased with increasing SI amounts. This finding was inconsistent with Chivenge et al. (2007), who reported straw management was of substantial importance to increase soil C in coarse-textured but not fine-textured soils, which might reflect lower overall levels of soil C in Chinese croplands.

4.3 Estimates of soil C sequestration under SI in China

Based on the Second Soil Survey and China Landcover 2010 database, we estimated total surface soil organic C in cropland soils was 4.05 Pg C. SI could sequester 405 Tg C during the first 5 years, with an average of 81 Tg C year⁻¹ according to our current data. Over a longer period (20 years), soil C sequestration could potentially reach 688 Tg C, with an average of

Table 4 Estimates of potential carbon sequestration by SI

Region	Scenarios	C sequestration rate (Tg C year ⁻¹)	Potential of C sequestration (Tg C)	Source
Global	100 % SI	200		Lal 1997
USA	50 % SI	11.2–22.4		Follett 2001
EU15	100 % SI	14.02	1400	Smith et al. 1997
Europe	2 t ha ⁻¹ year ⁻¹	1.09		Smith et al. 2000
	10 t ha ⁻¹ year ⁻¹	6.49		
Australia	SI over 25 years		31 %	Luo et al. 2010
China	100 % SI	36.8–52.1		Sun et al. 2010
	50 % SI	23.2	231.8	Yan et al. 2007
	100 % SI	57.1	1146.2	
	30 % SI	9.76		Lu et al. 2009
	100 % SI	34.4		
	Scenario I	48.2	531	In this study
	Scenario II	56.2	618	

34.4 Tg C year⁻¹. Chinese croplands are catalogued into single and double crops. The northeast and northwest regions harvest a single annual crop, while the northern and southern regions produce double annual crops (Table 2). In practice, due to labour costs and energy-consumption for SI practices, a number of regions implement single-crop SI (Zhang et al. 2007), particularly in the north and south (i.e. the double-crop regions). We propose the following two Scenarios: in Scenario I, if single-crop SI was implemented in croplands across all of China's agricultural regions (Table 3), the potential soil C sequestration could reach 531 Tg C, with an average 48.2 Tg C year⁻¹; in Scenario II, full utilisation of single- and double-crop straw (Table 3) could further enhance the potential soil C sequestration to 618 Tg C, with an average 56.2 Tg C year⁻¹. The soil C sequestration amounts in Scenarios I and II could respectively account for 2.43 % and 2.83 % of the C emissions from fuel use in China in 2010 (2.18 Pg C, IEA 2011). Soil C sequestration following adoption of SI in our results was slightly higher than in other reports from China (Table 4), because straw inputs were underestimated in previous reports (Yan et al. 2007; Lu et al. 2009; Sun et al. 2010). Overall, soil C sequestration rates in China were higher than in Europe and the United States (Table 4), which might be attributable to the relatively larger initial soil organic C content in the other countries (Li et al. 2003).

5 Conclusions

The results of our meta-analysis demonstrated that straw incorporation (SI) has considerable potential to sequester surface soil C in Chinese croplands, and SI effects on soil C storage are highly dependent on the type and amount of straw, tillage treatment, cropping system, experimental region, and duration of SI. The application of larger chopped straw amounts over a longer duration was more favourable to soil C sequestration. Furthermore, soils with serious C loss, such as soils in the northwest and northeast regions, and soils experiencing tillage treatments and upland cropping, exhibited increased potential to sequester soil C following SI implementation. Following data analysis, we estimated during the first 5 years, SI could sequester 81 Tg C year⁻¹, and approximately 34.4 Tg C year⁻¹ in the long term. If single- and double-crop straw were fully utilised, then soil C sequestration potential could reach a respective 48.2 and 56.2 Tg C year⁻¹, equivalent to 2.43 and 2.83 % of the C emissions from fuel combustion in China in 2010.

China is currently experiencing notable societal and economic transitions, and agriculture is sharing in the rapid changes occurring in the country. The popularisation of electric power, fossil fuel use in rural areas, and increased labour costs for collecting straw has limited or eliminated its use for fuel and forage. China has become the world's largest producer of CO₂ emissions, and simultaneously subject to substantial soil C loss. As a single agricultural management which shows concurrently increase in both carbon storage and crop yield, returning crop straws to the soil may be a promising option for the enhancement of C sequestration in cropland.

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Appendix

Table 5 Experimental data of SI

Regions	Site	Periods years	Crop	Tillage	Straw amount t ha ⁻¹ year ⁻¹	Straw status	Carbon storage g m ⁻²		Carbon sequestration rate kg C ha ⁻¹ year ⁻¹	Reference
							SR	SI		
Northeast	Zhangwu, Liaoning	6	Maize	NT	7	Chopped	256	336	132.6	Hu et al. 2009
	Changchun, Jilin	6	Maize	PT	2.5	NA	339	352	21	Jia et al. 1992
		6	Maize	PT	5	NA	339	378	65	
		6	Maize	PT	2.5	NA	346	354	14.2	
		6	Maize	PT	5	NA	346	392	76.3	
	Dongning, Heilongjiang	8	Rice	NA	8	NA	394	435	51.6	Jin et al. 1993
	Hailun, Heilongjiang	14	Wheat	PT	7.5	Chopped	603	725	243.8	Liang et al. 2011
		14	Maize	PT	7.5	Chopped	603	740	274.8	
	Gongzhuling, Jilin	20	Maize	PT	7.5	Chopped	366	489	61.8	Liu et al. 2008
	Lishu, Jilin	4	Maize	PT	2.5	Unchopped	323	341	44.2	Peng et al. 2013
Northeast		4	Maize	PT	5	Unchopped	323	341	43	
		4	Maize	PT	7.5	Unchopped	323	346	55.2	
		4	Maize	NT	2.5	Unchopped	337	341	9.8	
		4	Maize	NT	5	Unchopped	337	341	8.5	
		4	Maize	NT	7.5	Unchopped	337	346	20.8	
	Mishan, Heilongjiang	9	Wheat	PT	2.2	Chopped	469	582	125.1	Tian et al. 2004
	Dehui, Jilin	6	Maize	PT	7	Chopped	391	448	93.8	Wang et al. 2007
	Shenyang, Liaoning	12	Maize	NA	2.6	NA	245	254	7.6	Yan et al. 2004
	Mishan, Heilongjiang	18	Wheat	PT	4	Chopped	549	656	59.3	Zeng et al. 2004
		18	Maize	PT	8	Chopped	416	628	117.6	
	Hailun, Heilongjiang	14	Maize	PT	2.5	Chopped	660	679	134.3	Zhao et al. 2005

Table 5 (continued)

Regions	Site	Periods years	Crop	Tillage	Straw amount t ha ⁻¹ year ⁻¹	Straw status	Carbon storage g m ⁻²		Carbon sequestration rate kg C ha ⁻¹ year ⁻¹	Reference
							SR	SI		
Northeast	Weitun, Liaoning	14	Maize	PT	4.5	Chopped	660	680	138.6	Zhao et al. 1998
		10	Maize	RT	2.5	NA	186	250	44.4	
		10	Maize	RT	3.8	NA	200	375	58.4	
	Zhangtun, Liaoning Fanjiatun, Jilin	7	Maize	NA	2.5	NA	172	186	19.9	Zheng et al. 2006
		5	Maize	PT	2.8	Chopped	384	446	124.4	
North	Quzhou, Hebei	5	Maize	PT	2.8	Unchopped	384	433	98.8	Ludwig et al. 2010
		19	Wheat-maize	PT	2.3	NA	319	335	8.4	
		19	Wheat-maize	NT	4.5	NA	300	325	13.2	
	Hengshui, Hebei	25	Wheat-maize	RT	2.25	Chopped	212	236	9.4	Du et al. 2009
		25	Wheat-maize	RT	4.5	Chopped	212	228	6.1	
		25	Wheat-maize	RT	9	Chopped	212	244	12.7	
		25	Wheat-maize	RT	4.5	Chopped	207	261	22	
		25	Wheat-maize	RT	9	Chopped	207	280	29.3	
	Hengshui Dengzhuang, Hebei	6	Wheat-maize	RT	6.75	Chopped	168	186	30.1	Fan and Liu 2005
	Fengqiu, Henan Xiping, Henan Luoyang, Henan	18	Wheat-maize	PT	1.4	Chopped	150	190	22.6	Gong et al. 2009
		4	Wheat-maize	PT	13	NA	158	187	72.5	
		6	Wheat-maize	NT	3.8	Unchopped	190	238	79.8	
	Yucheng, Shandong	6	Wheat-maize	PT	3.8	NA	202	242	66.5	Jiang et al. 2012
		7	Wheat-maize	NT	10	Chopped	225	283	82.7	
		7	Wheat-maize	RT	10	Chopped	221	283	88.3	
	Tianjin Beijing AAS	25	Wheat-maize	PT	6	NA	346	396	20.1	Jin 2006
		3	Wheat-maize	PT	12	Chopped	312	328	51.3	
										Li et al. 2002

Table 5 (continued)

Regions	Site	Periods years	Crop	Tillage	Straw amount t ha ⁻¹ year ⁻¹	Straw status	Carbon storage g m ⁻²		Carbon sequestration rate kg C ha ⁻¹ year ⁻¹	Reference
							SR	SI		
North	Shandong AAS	5	Wheat-maize	NT	6	NA	190	205	29.6	Li et al. 2009a
	Changping, Beijing Quzhou, Hebei	5	Wheat-maize	RT	6	NA	190	225	71	Liu 2007
		15	Wheat-maize	PT	3	Chopped	194	212	11.9	
		8	Wheat-maize	PT	7.3	Unchopped	202	223	26.8	Meng et al. 2010
		8	Wheat-maize	PT	7.3	Chopped	202	204	2.5	
	Zhengzhou, Henan Xinji, Hebei	8	Wheat-maize	NT	7.3	Unchopped	202	208	7.6	
		8	Wheat-maize	NT	7.3	Chopped	202	207	6.4	
		18	Wheat-maize	PT	5.5	NA	222	255	18.33	Wang et al. 2010
		3	Wheat-maize	RT	7.5	NA	262	276	46.7	Xing et al. 2010
		3	Wheat-maize	RT	7.5	NA	199	210	35.7	
		3	Wheat-maize	RT	7.5	NA	271	294	77	
Shouyang, Shanxi		3	Wheat-maize	RT	7.5	NA NA	205	228	75.3	Yan et al. 2010
		5	Maize	PT	3	Chopped	277	280	6	
			Maize	RT	1	Chopped	277	276	-3.8	
			Maize	NT	3	Unchopped	277	312	69.4	
		4	Wheat-maize	NT	13	NA	155	189	86	
		7	Wheat-maize	PT	3.4	Chopped	262	240	-30.5	Zhao and Lu 2009
	Luancheng, Henan	7	Wheat-maize	RT	3.4	Chopped	262	287	36.8	
		7	Wheat-maize	NT	3.4	Unchopped	262	281	27.8	
Zunhua, Hebei		8	Wheat-maize	RT	4.5	Chopped	246	302	70.5	Zhang et al. 1999
		8	Wheat-maize	RT	4.2	Chopped	246	299	66	
		8	Wheat-maize	RT	4.5	Chopped	182	215	41.4	
		8	Wheat-maize	RT	4.2	Chopped	182	211	35.9	

Table 5 (continued)

Regions	Site	Periods years	Crop	Tillage	Straw amount t ha ⁻¹ year ⁻¹	Straw status	Carbon storage g m ⁻²		Carbon sequestration rate kg C ha ⁻¹ year ⁻¹	Reference
							SR	SI		
Northwest	Qinhuangdao, Hebei	8	Wheat-maize	PT	4.2	Chopped	245	302	71.6	Zhang et al. 2004
	Dingxi, Gansu	8	Wheat-maize	PT	4.5	Chopped	245	303	71.7	Cai et al. 2009
		6	Wheat	PT	6.6	Chopped	222	234	20.1	
	Heyang, Shanxi	6	Wheat	NT	6.6	Chopped	222	239	25.7	Cai et al. 2012
		4	Maize	PT	4.5	Chopped	382	394	29.7	
		4	Maize	PT	9	Chopped	382	434	129.3	
		4	Maize	PT	13.5	Chopped	382	475	233.5	
	Pengyang, Ningxia	3	Wheat-maize	NT	3	NA	272	275	9	Gao et al. 2011
		3	Wheat-maize	NT	6	NA	272	300	90.7	
		3	Wheat-maize	NT	9	NA	272	309	123.3	
	Yangling Toudaoyuan, Shanxi	12	Wheat-maize	NA	4.5	NA	214	221	6.4	Gu et al. 2004
		18	Wheat-maize	NA	3.7	NA	262	286	13.3	
	Yangling, Shanxi	21	Wheat-maize	PT	5.6	Chopped	210	267	26.8	Li et al. 2012
		13	Wheat-maize	PT	6.3	Chopped	222	258	27.9	
	Wulumuqi, Xinjiang	3	Maize	PT	4.5	Chopped	228	257	98	Liu 2007
		3	Maize	PT	4.5	Chopped	228	257	98	
	Northwest Agriculture & Forestry University	3	Maize	PT	9	Chopped	228	282	182	Lu et al. 2011
		3	Maize	PT	13.5	Chopped	228	290	207	
		9	Maize	RT	9.8	Chopped	132	237	118.8	
	Pingliang, Gansu	30	Wheat	PT	3	NA	95.8	106.2	3.5	Mu et al. 2012
	Fukang, Xinjiang	4	Wheat	RT	3.5	Chopped	110	133	58.7	Rong et al. 2012
	Linze, Gansu	4	Whea	PT	3.5	Chopped	105	117	30.5	Su et al. 2012

Table 5 (continued)

Regions	Site	Periods years	Crop	Tillage	Straw amount t ha ⁻¹ year ⁻¹	Straw status	Carbon storage g m ⁻²		Carbon sequestration rate kg C ha ⁻¹ year ⁻¹	Reference
							SR	SI		
Northwest	Xining, Qinghai	12	Wheat	PT	6.4	Chopped	288	330	35.5	Tan et al. 2009
	Changwu, Shanxi	5	Maize	PT	8.5	Unchopped	201	202	3	Yang et al. 2009
		5	Maize	NT	8.5	Unchopped	195	208	25.8	
	Qingyang, Gansu	6	Wheat-maize	PT	4.5	Chopped	182	205	37.7	Yang et al. 2010a, b
		6	Wheat-maize	NT	4.5	Chopped	200	246	77.8	
	Weiwu, Gaoping	18	Wheat-maize	PT	10.5	Chopped	311	358	25.7	Zeng et al. 2011
South	Jiayang, Sichuan	18	Wheat-maize	PT	5.3	Chopped	322	351	15.9	
		4	Wheat-rice	RT	11.6	Unchopped	475	554	196.5	Chen et al. 2008
		4	Wheat-rice	NT	11.6	Unchopped	475	487	28.5	
	Jiayang, Sichuan	4	Wheat-rice	RT	11.6	Unchopped	334	396	156	
		4	Wheat-rice	NT	11.6	Unchopped	334	358	60.5	
	Jiangle, Fujian	5	Rice-rice	PT	4.5	NA	479	492	25.9	Chen 2000
		5	Rice-rice	PT	4.5	NA	400	412	24.3	
		5	Rice-rice	PT	4.5	NA	479	484	11.4	
		5	Rice-rice	PT	4.5	NA	466	474	15.5	
	Nanning, Guangxi	4	Rice-rice	PT	6	Unchopped	531	582	128.7	Chen 2012
		4	Rice-rice	NT	6	Unchopped	508	548	99.5	
	Taihe, Jiangxi	11	Rice-rice	NA	4.5	NA	262	287	23.1	Dong et al. 2012
	Nantong, Jiangsu	4	Wheat-rice	NT	7.2	Chopped	248	278	75.5	Duan et al. 2009
		4	Wheat-rice	RT	7.2	Chopped	266	309	109.5	
		4	Wheat-rice	PT	7.2	Chopped	288	320	79.2	
	Changsha, Hunan	4	Rice-rice	PT	4.5	Chopped	427	543	38.2	Ji et al. 2012
		4	Rice-rice	NT	4.5	Chopped	517	524	15.7	

Table 5 (continued)

Regions	Site	Periods years	Crop	Tillage	Straw amount t ha ⁻¹ year ⁻¹	Straw status	Carbon storage g m ⁻²		Carbon sequestration rate kg C ha ⁻¹ year ⁻¹	Reference
							SR	SI		
South	Guangde, Anhui	4	Rice-rice	NT	4.5	Chopped	517	530	30.2	Li et al. 2003
		4	Wheat-rice	PT	1.5	NA	206	304	107.8	
		4	Wheat-rice	PT	3	NA	206	330	175	
	Fuzhou, Fujian	12	Rice-rice	NA	11	NA	268	283	11.7	Li 2011
	Taoyuanpantang, Hunan	6	Wheat-rice	PT	12.6	NA	213	228	25.3	Li et al. 2009b
		4	Wheat-maize	NT	3	Chopped	276	287	38.5	
		4	Wheat-maize	NT	4	Chopped	276	296	45.7	
	Wuxue, Hubei	4	Wheat-rice	NT	6	Chopped	276	297	45.8	Li et al. 2011
		18	Rice-rice	PT	5.3	Chopped	540	567	14.9	
		10	Rice-rice	NA	9	NA	363	395	31.3	
	Shunchang, Fujian	10	Rice-rice	NA	9	NA	415	442	27.3	Liao et al. 2009 Lin and Lin 1994
		15	Rice-rice	PT	2.3	Unchopped	150	191	270	
			Rice-rice	PT	4.5	Unchopped	150	184	223	
	Xinhua, Hunan	25	Rice-rice	NA	9	Chopped	446	495	19.8	Luo et al. 2013
		17	Rice-rice	PT	7.7	Chopped	448	569	70.9	
		17	Rice-rice	PT	9	Chopped	481	602	71.4	
	Yangzhou, Jiangsu	5	Wheat-rice	PT	9	Chopped	276	287	23.4	Nie 2007
		5	Wheat-rice	PT	6	Chopped	276	280	9	
		5	Wheat-rice	NT	9	Chopped	276	300	49	
	Suzhou, Jiangsu	5	Wheat-rice	NT	6	Chopped	276	289	27.2	Shen et al. 2007
		5	Wheat-rice	PT	4.5	Chopped	429	438	18.6	
		5	Wheat-rice	PT	4.5	Chopped	392	455	125.8	
	Changshu, Jiangsu	15	Wheat-rice	PT	2.3	Chopped	485	535	337	Sun et al. 2008a, b

Table 5 (continued)

Regions	Site	Periods years	Crop	Tillage	Straw amount t ha ⁻¹ year ⁻¹	Straw status	Carbon storage g m ⁻²		Carbon sequestration rate kg C ha ⁻¹ year ⁻¹	Reference
							SR	SI		
South	Jinxian, Jiangxi	15	Wheat-rice	PT	4.5	Chopped	485	550	435	Sun 2008
		24	Rice-rice	NA	4.5	Chopped	551	619	28.3	
	Suzhou, Jiangsu	5	Wheat-rice	PT	2.3	Chopped	392	417	49.4	Sun et al. 1994
		5	Wheat-rice	PT	2.3	Chopped	392	424	64	
	Chongqing	6	Rice	PT	7.5	Chopped	392	457	108.5	Wang et al. 2005
		6	Rice	PT	7.5	Chopped	403	463	100.2	
		6	Rice	PT	7.5	Chopped	408	469	102	
		3	Wheat-rice	PT	5	Unchopped	405	434	96	
	Yanyingyujiang, Jiangsu	3	Wheat-rice	NT	5	Unchopped	414	449	116	Wang et al. 2011
		3	Wheat-rice	PT	3	Chopped	463	488	83.7	
	Feidong, Anhui	3	Wheat-rice	PT	3	Chopped	463	493	99	Wu 2012
		19	Wheat-maize	PT	4.5	NA	211	219	3.7	
	Qiyang, Hunan	4	Rice-rice	PT	3	NA	492	514	18	Xie 2011
		18	Wheat-rice	NT	7.5	NA	465	494	16.3	
	Hangzhou, Zhejiang	4	Wheat-rice	PT	7.5	NA	469	543	41.1	Xu et al. 2009
		18	Wheat-rice	PT	7.5	NA	469	543	41.1	
	Jurong, Jiangsu	4	Rice-rice	PT	12.5	Chopped	689	731	105	Xu et al. 2007
		4	Rice-rice	RT	12.5	Chopped	689	733	109.5	
	Niangxiang, Hunan	4	Rice-rice	NT	12.5	Chopped	689	744	136.7	Xu et al. 2011
		6	Wheat-rice	NT	2.3	Chopped	183	230	77.8	
	Nanjing, Jiangsu	6	Wheat-rice	PT	2.3	Chopped	183	243	100	Yu et al. 2007
		11	Wheat-rice	NT	11.5	Chopped	445	509	58.4	
	Beipei, Chongqing	4	Wheat-rice	PT	6.8	Chopped	337	355	44	Zhang et al. 2002
		4	Wheat-rice	PT	13.5	Chopped	337	410	180	

Table 5 (continued)

Regions	Site	Periods years	Crop	Tillage	Straw amount t ha ⁻¹ year ⁻¹	Straw status	Carbon storage g m ⁻²		Carbon sequestration rate kg C ha ⁻¹ year ⁻¹	Reference
							SR	SI		
Wujing, Jiangsu		17	Rice-rice	RT	2.5	Chopped	399	408	5.5	Zhou 2007
		17	Rice-rice	NT	2.5	Chopped	399	415	9.7	
		17	Rice-rice	RT	4.5	Chopped	399	420	12.5	

SR and SI is straw removal and straw incorporation treatment, respectively. PT, RT, and NT is ploughing tillage, rotary tillage, and no tillage, respectively. NA is not available data, and do not include in meta-analysis

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