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Effects of long-term straw return on soil organic carbon storage and sequestration rate in North China upland crops: A meta-analysis

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Abstract

Soil organic carbon (SOC) is essential for soil fertility and climate change mitigation, and carbon can be sequestered in soil through proper soil management, including straw return. However, results of studies of long-term straw return on SOC are contradictory and increasing SOC stocks in upland soils is challenging. This study of North China upland agricultural fields quantified the effects of several fertilizer and straw return treatments on SOC storage changes and crop yields, considering different cropping duration periods, soil types, and cropping systems to establish the relationships of SOC sequestration rates with initial SOC stocks and annual straw C inputs. Our meta-analysis using long-term field experiments showed that SOC stock responses to straw return were greater than that of mineral fertilizers alone. Black soils with higher initial SOC stocks also had lower SOC stock increases than did soils with lower initial SOC stocks (fluvo-aquic and loessial soils) following applications of nitrogen-phosphorous-potassium (NPK) fertilizer and NPK+S (straw). Soil C stocks under the NPK and NPK+S treatments increased in the more-than-20-year duration period, while significant SOC stock increases in the NP and NP+S treatment groups were limited to the 11- to 20-year period. Annual crop productivity was higher in double-cropped wheat and maize under all fertilization treatments, including control (no fertilization), than in the single-crop systems (wheat or maize). Also, the annual soil sequestration rates and annual straw C inputs of the treatments with straw return (NP+S and NPK+S) were significantly positively related. Moreover, initial SOC stocks and SOC sequestration rates of those treatments were highly negatively correlated. Thus, long-term straw return integrated with mineral fertilization in upland wheat and maize croplands leads to increased crop yields and SOC stocks. However, those effects of straw return are highly dependent on fertilizer management, cropping system, soil type, duration period, and the initial SOC content.

KEYWORDS
carbon sequestration, crop yield, cropping system, experiment duration, long-term experiment, meta-analysis, soil organic carbon stock, straw return

1 | INTRODUCTION

Globally, soil contains the largest carbon (C) pool of any terrestrial ecosystem, and soil organic carbon (SOC) is one of the most important C storage pools. The SOC pool represents a dynamic equilibrium of C gains and losses. Even small changes in SOC may potentially add up to significant changes in large-scale C cycling (Fang, Piao, & Zhao, 2001). In recent years, a number of studies and countries have paid attention to C sequestration and possibilities for mitigating SOC loss by optimizing appropriate crop rotation, proper application rates for organic and inorganic fertilizers, conservation tillage, and integrated soil fertility management (Srinivasarao et al., 2012; West & Post, 2002).

Increasing the accumulation of organic C in soils is a crucial challenge, both for soil fertility and for climate change mitigation (Gong, Hu, Wang, Gong, & Ran, 2008; Lu et al., 2009; Wang, Qiu, et al., 2008). The dynamics of SOC stocks and the role that the soil may play in long-term accumulation and sequestration of atmospheric CO_2 are of incredible concern because of their great potential for climate change mitigation, sustainability of crop productivity, and soil fertility (Kirchmann, Haberhauer, Kandeler, Sessitsch, & Gerzabek, 2004; Srinivasarao et al., 2012).

With a yield of 1.04 billion tons, China has a huge amount of crop straw, almost one-third of the global production in 2015 (Li, Cao, et al., 2017). But, China's croplands have relatively low SOC content because of their long cultivation history, low straw return rates (used instead as fuel and animal feed and burnt in fields), and other losses. Since abundant nutrients remain in crop residue (e.g., phosphorus [P], nitrogen [N], potassium [K]), intensified crop residue management in farmland helps maintain soil nutrient balance and soil quality and promotes soil microbial biomass and by-products (Kumar & Goh, 2000). Also, China now produces and consumes more chemical fertilizer than any other country (Sun et al., 2012). Consequently, the overuse of chemical synthetic fertilizers, coupled with straw removal, have led to soil quality degradation and heavy, adverse agricultural impacts (Liu & Diamond, 2005).

For example, a meta-analysis by Zhao, Sun, et al. (2015) determined that, compared with straw removal, incorporation of maize, wheat, and rice residues in Chinese croplands could increase soil C storage an average of 12%. Likewise, Wang et al. (2018) reported 5.7% higher SOC stock with straw addition compared to no straw addition after a 33-year-long experiment. Previous research has also shown that cropping duration has an influence: consistent straw return boosts SOC accumulation in early years, but that effect decreases after a decade. Liu, Lu, Cui, Li, and Fang (2014) reported that straw return enhanced SOC sequestration in a trial site during the first 3 years, but that effect was insignificant in the following 15 years. However, different results have also been reported (Pittelkow et al., 2015), possibly due to various ecological conditions, land management approaches, and soil types.

Cropping systems may play a critical role in the change of SOC stocks by influencing the balance between C inputs through litter additions and C losses through decomposition (Huang, Sun, & Zhang, 2012). Double and triple cropping systems are the principal cropping systems in China, and they have severely degraded China's agriculture (Dikgwatlhe, Chen, Lai, Zhang, & Chen, 2014). Therefore, while incorporation of crop straw into soil can be beneficial, it must be done immediately after harvest because straw's slow biodegradation can lead to unfavorable effects, such as undegraded straw interfering with subsequent crop growth, thus disrupting traditional crop management (Li, Dai, Dai, & Dong, 2018). Wang et al. (2018), in a long-term experiment using a double-cropping system in which straw was returned to the soil along with nitrogen-phosphorous-potassium (NPK+S), found that the SOC stock in the NPK+S treatment was 5.7% greater than with mineral NPK alone. However, in a single-maize cropping system, they found that SOC in the NPK+S treatment was not significantly different than that in the NPK treatment.

Previous studies have assessed changes in SOC stocks in Chinese soils and have focused mainly on single fertilizer management (Ji, Zhao, Li, Ma, & Wang, 2016); a specific crop (Tian et al., 2015); or a single-cropping system, particular duration period, and one soil type (Zha et al., 2015). However, uncertainties about the long-term effects of straw return on SOC stocks still exist. Therefore, additional factors, such as cultivation duration, soil types, cropping systems, and initial SOC levels, are critically needed to explain why certain soil C pools react differently to straw return.

Based on the uncertainties and variable reactions of SOC stocks to straw return under various management practices studied in an array of single investigations, we conducted a meta-analysis of SOC stock changes based on data obtained from long-term straw return and fertilizer management studies conducted in North China upland areas that grow wheat and maize crops. A meta-analysis is an effective statistical method to quantitatively summarize the results of numerous individual and independent studies and to draw general conclusions at regional and global scales to estimate the direction and magnitude of a treatment effect (Guo & Gifford, 2002). Therefore, the main objectives of this study were to (a) quantify the changes in SOC stocks under various fertilizer treatments and straw return, in different cropping durations, soil types, and cropping systems in 0–20 cm of the top soil; (b) compare crop yields in long-term fertilizer and straw return treatments; and (c) establish the relationships of SOC sequestration rates with the initial SOC stocks and annual straw C inputs.

2 | MATERIALS AND METHODS

2.1 | Data collection

We used keywords related to SOC stock or SOC content in farmlands using different fertilizer types and straw return to search peer-reviewed, English research articles available on Internet databases at the Northwest A&F University online library (http://www.sciencedirect.com, http://link.springer.com, http://apps.webofknowledge.com). To be included in the meta-analysis, a study had to meet the following criteria (Appendix S1): (a) Initial and final SOC content or stock with known years the study started and ended must be provided in the publication. (b) The work must have been published in peer-reviewed publications and not in conference proceedings or books. (c) The study must have been a field experiment and not a pot experiment or survey study. (d) The soil sampling depth must have been 0–20 cm but, in order to increase the study count, we included a few papers examining soil depths of 0–30 cm. (e) The experiment must have included at least one of the following treatments: Control (no fertilization [CK]); mineral NP or NPK fertilizers; mineral NP+S or NPK+S; and, to see the effect of fertilizer types, mineral NPK plus manure (NPK+M) was optional. Only those long-term studies that were conducted on upland fields in North China and that used conventional tillage practices were included in our analyses.

We compared the SOC response to straw and fertilizer management regimens among different cropping systems, soil types, and cropping durations. Cropping systems were categorized as annual double-cropped winter wheat–summer maize (DC), single-crop summer maize (SM), and single-crop winter wheat (SW). Experimental sites were categorized into following three soil types according to both the general soil classification of China and the Food and Agriculture Organization of the United Nations classification (in parentheses): black soils (Luvic Phaeozems), fluvo-aquic soils (Calcaric Cambisols), and loessial soils (Calcaric Regosols). Cropping duration was categorized into four intervals, namely 1–5, 6–10, 11–20, and greater than 20 years, with the minimum and maximum durations being 1 and 33 years, respectively. Necessary data from experimental sites, SOC content or stock, soil bulk density, soil sampling depth, cropping duration, cropping system, soil type, and fertilization regimens were obtained from texts and tables of the publications. If data were expressed as figures or charts, number values were extracted using GetData Graph Digitizer Version 2.26 (S. Federov).

Accordingly, we collected 58 published articles with 268 and 139 observations for SOC stock and crop yield, respectively. About 54 of them contained complete SOC data and partial crop yield data, and the remaining four were articles we included for crop yield data only. The details of the selected studies and their references are in Appendices S2, S3, and S4 and site locations are in Figure 1. In addition, crop yields in the corresponding long-term experimental sites were collected to qualitatively evaluate the relationships between SOC stocks at 0–20 cm topsoil depth and crop yields after straw return and various fertilizer treatments. Using national average carbon concentrations (National Center for Agricultural Technology Service [NCATS], 1994), we converted aboveground straw into an equivalent amount of carbon, assuming 0.4 kg C/kg wheat or maize.

Studies in a meta-analysis are assumed to be independent (Gurevitch & Hedges, 1999). Therefore, to reduce dependency of observations, if any study contained duplicate results in different years for the same field plots, we included only the latest sampling date in our analysis (except for testing cropping duration effects). Fertilizer application rates and returned straw quantities were not considered in our study because of large variations in the amounts and types of fertilizer and straw used. Additionally, temperature and precipitation were not considered because of their collinearity with cropping systems. Therefore, we conducted a meta-analysis using CK, NP, NPK, NP+S, NPK+S, and NPK+M treatments, but only used the NPK+M treatment to compare SOC stock changes between different fertilizer treatments, because of a paucity of data for the other variables.

2.2 | Data analysis

The following equation was used to convert SOC concentration in the top 20 cm soil depth to SOC stock (Yang, Mohammat, Feng, Zhou, & Fang, 2007):

$$\mathrm{SOC_S} = \mathrm{SOC_C} \times \mathrm{BD} \times D \times 10^{-1}, \tag{1}$$

where $\mathrm{SOC_S}$ is soil organic C stock (Mg C/ha) and $\mathrm{SOC_C}$ is soil organic C concentration (g C/kg), BD is soil bulk density (g/cm^3), and D is the

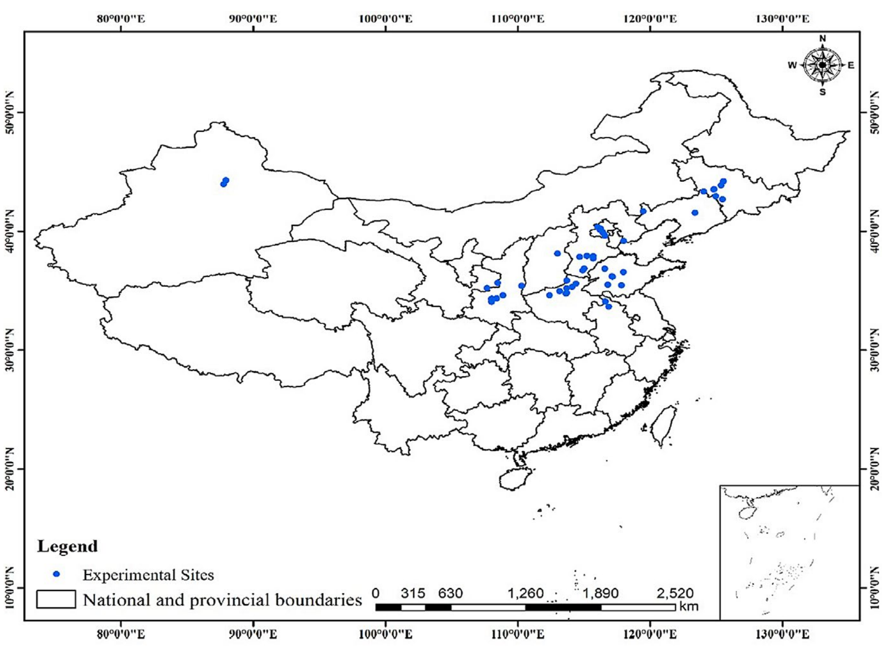

FIGURE 1 Map of China and its provinces with locations of selected long-term experimental sites in North China [Colour figure can be viewed at wileyonlinelibrary.com]

measured depth of soil (cm). If a study reported soil organic matter, it was converted to SOC concentration using the coefficient 0.58.

BD is a key parameter used in determining farmland SOC stocks. Unfortunately, when experimental studies did not report BD values, we had to use the following equation, developed by Song, Li, Pan, and Zhang (2005) for upland soils, to estimate BD for those sites:

$$\mathrm{BD} = 1.377 \times \mathrm{Exp}\left(-0.0048 \times \mathrm{SOC_C}\right). \tag{2}$$

Because BD changed due to long-term fertilizer use, we also calculated initial and final BDs using initial and final SOC_C, respectively, for each treatment in those experimental sites, if it was not provided in the pertinent publications.

The carbon sequestration rate (CSR, Mg C ha^{-1} year^{-1}) was calculated using the following equation:

$$\mathrm{CSR} = \frac{\left(\mathrm{SOC_f} - \mathrm{SOC_i}\right)}{t}, \tag{3}$$

where SOC_f and SOC_i are the mean SOC storage during the final year and in the initial year, respectively, of a specific treatment; and t (year) is the duration of the experiment.

2.3 | Meta-analysis

Given initial SOC stocks, studies with data including changes to SOC stocks with different fertilizer treatments, cropping systems, soil types, and experimental durations were analyzed using meta-analysis. The natural log of response ratio (R^+) was employed as effect size (Sanderman & Baldock, 2010). So, for each paired observation of SOC stocks at the initial and final experimental stages, we calculated the mean effect size using the following formula (Hedges, Gurevich, & Curtis, 1999).

$$\ln R^+ = \ln\left(X_f / X_i\right), \tag{4}$$

where X_f is the mean SOC stock (Mg C/ha) at the final stage, and X_i is mean SOC stock at the initial stage of each treatment.

To be easily understandable, we reported the results as percentage change, where these changes, influenced by various fertilizer treatments during long-term investigations, were calculated either by $(R^+ - 1) \times 100\%$ or with the following formula. Positive-percentage changes indicate an increase in SOC stocks, while negative values indicate a decrease.

$$\%\,\Delta\mathrm{SOC\ stock} = \left[\frac{\mathrm{SOC_f} - \mathrm{SOC_i}}{\mathrm{SOC_i}}\right] \times 100. \tag{5}$$

Means, standard deviations or standard errors, and the number of replicates are required for meta-analysis (Hedges et al., 1999; Luo, Hui, & Zhang, 2006), but in most of the studies we used, the standard deviations or standard errors that would allow us to calculate sample variances were not provided. Therefore, in order to include as many studies as possible, we used un-weighted meta-analysis. For that, the bootstrap resampling technique on MetaWin Version 2.1.4 (Rosenberg Software, Arizona State University) was used to generate bias-corrected 95% confidence intervals for each mean effect size (Adams, Gurevich, & Rosenberg, 1997). Means of the effect sizes of initial SOC stocks compared to means of their initial levels were considered significant if their 95% confidence intervals did not overlap zero (Huang et al., 2012; Zhao, Sun, et al., 2015).

2.4 | Statistical analysis

We used SPSS 22.0 for Windows (SPSS Inc.) for all statistical analyses and, before analyzing the data set, we performed data quality control and removed outliers. One-way analysis of variance was used to evaluate the effects that each long-term fertilizer regimen and cropping system had on crop yields and to compare the effects of cropping duration, soil type, cropping system, and fertilizers on SOC stock response ratios between treatments during long-term experiments. Linear regressions and logarithmic functions were used to compare the relationships between straw carbon input and SOC sequestration rates, and between initial SOC stocks and SOC sequestration rates.

3 | RESULTS

3.1 | Crop yields in different cropping systems

In the SM cropping system, mean annual maize yield over time and under different fertilizer regimens were not significantly different ($p > .05$) between the NP, NPK+S, NP+S, and NPK treatments. Except for NP, all treatments had significantly higher yields ($p < .05$) than did CK (Figure 2a). The additional straw return along with mineral fertilizers in the SM cropping system did not affect the result relative to mineral fertilizer applications alone.

In the SW cropping system, there was no difference between the average annual wheat yields of the NPK and NPK+S treatment groups, indicating that straw addition did not affect grain yield in this cropping system (Figure 2a). We did not include the other fertilizer treatments used in this cropping system because of too few available observations or data.

In the DC system, unfertilized (CK) maize had significantly lower yields than maize in all other fertilizer treatments. But among fertilizer treatments, mean maize yields were not significantly different between NP+S, NPK, and NPK+S treatment groups. However, while there was a significant difference between yields in the maize NP and CK treatment groups, maize yield with the addition of straw in the NP+S treatment group was significantly greater than that with NP alone (Figure 2b). In the DC system, wheat yield differences between the NPK and NPK+S treatment groups were nonsignificant, but they were significantly higher than yields in the NP+S, NP, and

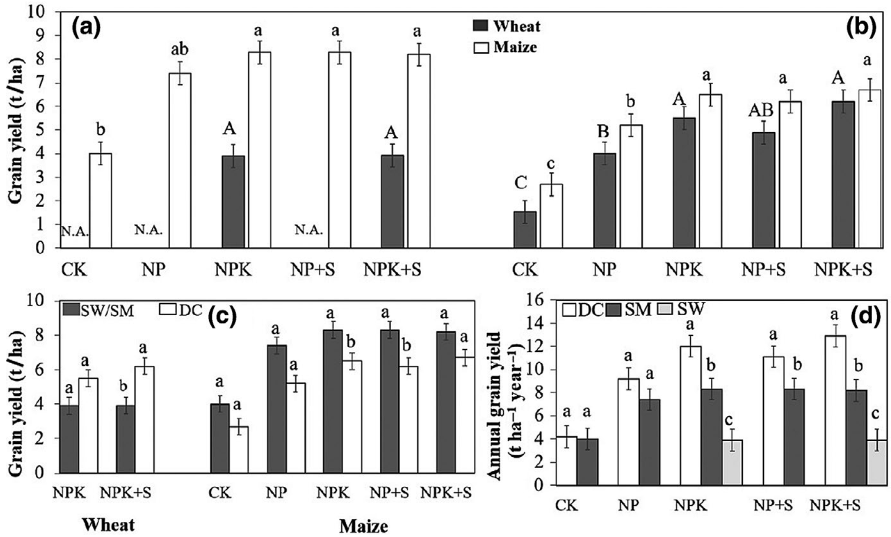

FIGURE 2 Comparisons of means (*SE*) of crop yields in different cropping systems (SM/SW and DC) and different fertilizer treatments (CK, control [unfertilized]; NP, mineral nitrogen and phosphorous fertilizer; NPK, NP plus potassium; NP+S, NP plus straw; NPK+S, NPK plus straw). (a) Different fertilizer treatments of SM (single-crop maize) and SW (single-crop wheat). (b) Different fertilizer treatments of double-crop (DC) winter wheat and summer maize. Between columns, means with different letters (upper case for wheat and lower case for maize) in (a) and (b) are significantly different (one-way ANOVA, $p < .05$). (c) Comparisons of yields for each crop in each cropping system and under various fertilizer treatments. Wheat means with different letters were significantly different and maize means with different letters were significantly different (one-way ANOVAs, $p < .05$). (d) Comparisons of annual total yields for each cropping system under each experimental treatment. Means with different letters were significantly different (one-way ANOVAs, $p < .05$). N.A., no available data

CK treatment groups. However, yields in the NPK and NP+S treatment groups were not markedly different (Figure 2b). In summary, only maize yield under NP fertilization in the DC system increased significantly with the addition of straw.

In cropping system comparisons (Figure 2c), mean maize yields with NPK application were significantly higher in the SM than in the DC systems ($p = .047$) and, likewise, between the SM and DC maize yields with the NP+S treatment ($p = .007$). However, we observed no significant differences in maize yields between the SM and DC systems in the other treatment groups (CK, $p = .396$; NP, $p = .07$; NPK+S, $p = .162$). Mean wheat yield under the NPK+S treatment was significantly lower in the SW system than in the DC system ($p = .034$); however, there was no significant difference between yields in the SW and DC systems for the NPK treatment ($p = .34$).

Overall, annual crop productivity was significantly greater in the DC system than in the SM system, regardless of fertilization treatment except for CK and NP treatments, and also for the NPK and NPK+S treatments in the SW system (Figure 2d). In the DC system, the addition of straw clearly increased annual grain yield over both NP alone (11.1 vs. 9.2 t/ha) and NPK alone (12.9 vs. 12 t/ha).

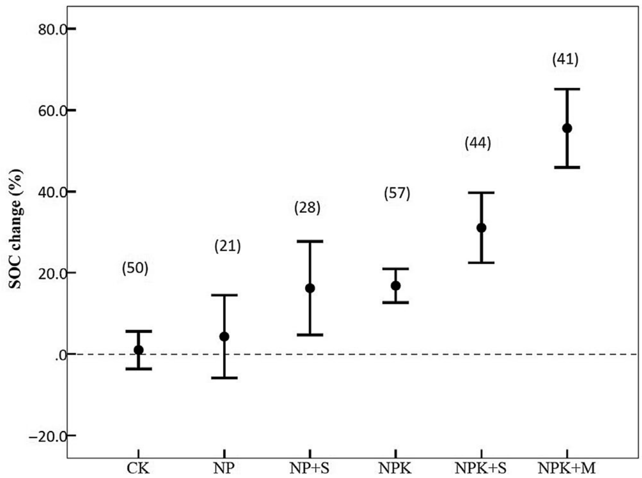

FIGURE 3 Increases in soil organic carbon (SOC) stock (mean, 95% confidence interval) between the beginning (0) and the end of experiments using different fertilizer treatments (CK, control [unfertilized]; NP, mineral nitrogen and phosphorous fertilizer; NPK, NP plus potassium; NP+S, NP plus straw; NPK+S, NPK plus straw; NPK+M, NPK plus manure). (*n*), number of input data points

3.2 | Response ratios of SOC stocks under different fertilizer treatments

We estimated the average response ratios of SOC stock to different long-term fertilizer treatments (Figure 3). The percentage change of SOC stock for the CK and NP treatments was 1% and 4%, respectively, indicating no significant change in SOC storage between the beginning and the end of long-term experiments (95% bootstrap confidence intervals of means overlap zero in Figure 3). For the NP+S, NPK, NPK+S, and NPK+M treatments, mean SOC stock changes were 16%, 16%, 31%, and 55%, respectively, thus showing a significant increase in SOC storage, compared to initial SOC stocks, by the end of the experiments.

Over all treatments, NPK+M, followed by NPK+S, had significantly higher increases in SOC storage than did the other treatments ($p < .05$). However, there was no significant difference between the NP+S and NPK treatments ($p > .05$), and NP and CK had the lowest and no responses, respectively, compared to the other treatments. Adding straw affected SOC level changes significantly, compared to SOC changes from NP and NPK fertilizer treatments alone ($p < .05$).

3.3 | Response ratios of SOC stocks in different soil types

Compared to initial levels, SOC stock levels in black soils after the NPK and NPK+S treatments increased significantly (11%, 95% CI [0.1, 0.23]) and (5%, 95% CI [0.005, 0.1], respectively, Figure 4). For fluvo-aquic soils, the responses under both NP and NP+S treatments were nonsignificant, with a 3% decrease following the CK treatment. However, SOC stock changes were significantly higher in the NPK (18%, 95% CI [0.12, 0.19]) and NPK+S treatments (35%, 95% CI [0.21, 0.35]) compared to initial SOC levels. Also, the mean SOC stock change following the NPK+S treatment was significantly higher than all other treatments ($p < .05$). Next, the SOC stock levels in loessial soils increased significantly, relative to initial levels, following NPK (21%), NP+S (20%), and NPK+S (34%) treatments, but not significantly in the CK (9.5%) and NP treatments (3.5%). The SOC stock increase following the NPK+S treatment was significantly higher than the increases following the NP and CK treatments, but not significantly different than the changes under the NPK and NP+S treatments ($p > .05$). Finally, black soils were not responded significantly to CK (0.3%) and NP (6%) treatments relative to initial SOC level. While NP+S treatment for black soils was not reported in our results due to limited data points.

Following both the NPK and NPK+S treatments, we observed no significant difference in SOC stock changes between fluvo-aquic and loessial soils ($p > .05$), and black soil had a significantly lower response ratio than the other soils ($p < .05$) following those treatments. Meanwhile, loessial soil following the NP+S treatment responded significantly relative to their initial SOC levels (Figure 4). However, there were no significant differences between fluvo-aquic and loessial soils under all fertilizer treatments, except that loessial soil had greater changes in SOC stock following the NP+S treatment than did the fluvo-aquic soil. In both black and fluvo-aquic soils, straw added to the NPK treatments (NPK+S) resulted in greater SOC stock increases than in the NPK treatment alone (11% vs. 5% and 35% vs. 18% for black and fluvo-aquic soils, respectively). However, we saw no significant effects from straw addition in loessial soil. Overall, the SOC stock response ratios in black soil were lower than those of the other soil types.

3.4 | SOC stock response in different cropping systems

Following both the CK and NP treatments, we observed no significant changes in SOC stocks in both DC and SM systems (significance occurs when confidence intervals do not overlap zero, Figure 5).

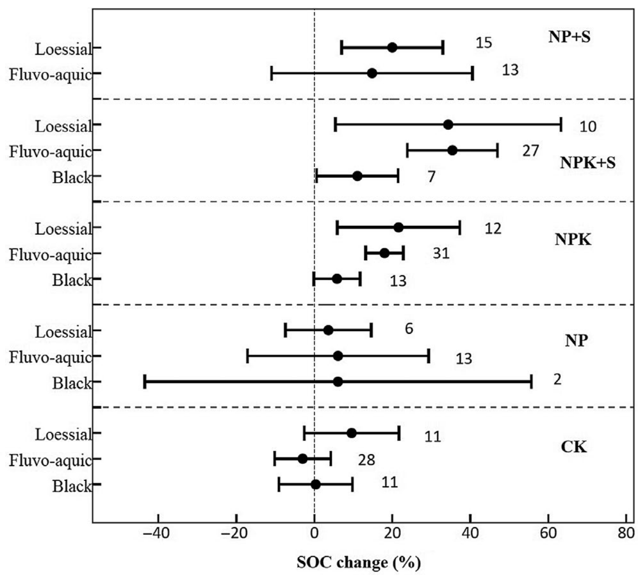

FIGURE 4 SOC (soil organic carbon) stock changes (mean, 95% confidence interval) under different fertilizer treatments (CK, control [unfertilized]; NP, mineral nitrogen and phosphorous fertilizer; NPK, NP plus potassium; NP+S, NP plus straw; NPK+S, NPK plus straw) in major soil types. Due to limited data, changes in the NP+S group in black soil was not used. The vertical-dashed line indicates the SOC levels' starting points before treatments began. Sample sizes are next to each bar

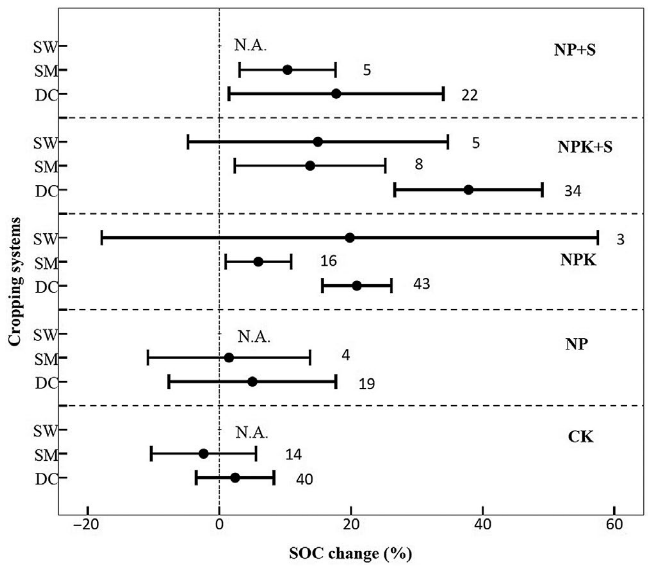

FIGURE 5 SOC (soil organic carbon) stock changes from initial levels in each fertilizer treatment in the three cropping systems. DC, double-cropped summer maize–winter wheat; N.A., no available data; SM, single-crop maize; SW, single-crop winter wheat. See the legend in Figure 2 for the definition of the three cropping systems and the five fertilizer treatments. The bars represent 95% confidence intervals. The sample size for each cropping system is shown next to the bar

Following the NPK treatment, the SOC response ratios of two cropping systems, SM and DC, increased significantly (6% and 21%, respectively) compared to their initial levels. But, for this treatment the increase in the SW system (20%) was nonsignificant relative to its initial SOC level. Overall, both the SW and DC systems had significantly greater increases than did the SM cropping system in NPK ($p < .05$). Compared to the initial levels in the NP+S treatment, mean SOC response ratios increased significantly in both the SM and DC systems (10%, 95% CI [0.05, 0.13] and 18%, 95% CI [0.012, 0.25], respectively) but there was no significant difference between those cropping systems ($p > .05$). For the NPK+S treatment, response ratios increased significantly compared to initial levels in the SM (14%, 95% CI [0.05, 0.2]) and DC (38%, 95% CI [0.22, 0.37]) systems, but the response in the SW system (15%) was nonsignificant (Figure 5).

In contrast, response ratios in the DC system were significantly higher than those in the SM system for both NPK and NPK+S treatments, with a 21% increase in the DC system and a 6% increase in the SM system following the NPK treatment ($p = .001$), and a 38% increase in the DC system and a 14% increase in the SM system for the NPK+S treatment ($p = .027$). However, SOC stock responses to the NPK treatment in the DC and SW systems were similar (21% and 20%, respectively), while the responses to the NPK+S treatment in the DC system increased more (38%) than it did in the SW system (15%), but the difference was not significant between the cropping systems. Because the SW system had small sample sizes, resulting in very large confidence intervals, the comparisons with that system were not as precise as they would have been with a larger sample. In the DC system, straw added to chemical fertilizer treatments resulted in greater SOC stock response increases than those following chemical fertilizer treatments alone: NP+S was markedly greater than NP alone (18% vs. 5%, $p > .05$) and NPK+S was significantly greater than NPK alone (38% vs. 21%, $p < .01$). However, in the SM system, only the NP+S treatment was significantly higher than NP (10% vs. about 1%, $p < .05$), and the SW system did not respond significantly to added straw (NPK+S treatment vs. the NPK treatment, $p > .05$).

3.5 | Effect of experiment durations on SOC stocks

We grouped each study's experimental periods into four duration ranges based on the amount of time that each study was conducted and then compared the response ratios of SOC stocks for each fertilizer treatment in each duration. In the CK, NP, and NP+S treatments, most duration groups showed nonsignificant SOC stock increases (Figure 6). The groups with significant increases included under 11- to 20-year groups in the NP (22%) and NP+S (53%) treatments, but in longer periods more-than-20 year groups lowered to 4% and 13%, respectively, in NP and NP+S. Moreover, in CK SOC increases were significantly greater than initial levels in the 1- to 5-year duration group (95% confidence intervals did not overlap zero).

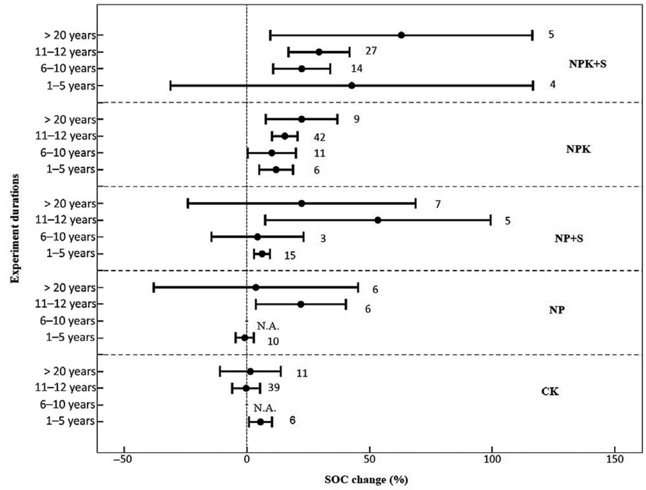

FIGURE 6 Changes in SOC (soil organic carbon) stocks from their initial levels (0) under different fertilizer treatments (CK, control [unfertilized]; NP, mineral nitrogen and phosphorous fertilizer; NPK, NP plus potassium; NP+S, NP plus straw; NPK+S, NPK plus straw) and across four experimental durations (mean, 95% confidence interval). The sample size for each duration range is shown next to the bar. N.A., no available data

Under the NPK treatment, response ratios increased significantly compared to initial levels (12% [1–5 years], 10% [6–10 years], 14% [11–20 years], and 22% [more-than-20 years]), but we observed no significant differences between the duration groups. Under the NPK+S treatment, the response ratios in three groups (6–10, 11–20, and more-than-20 years) increased significantly (22%, 29%, and 63%, respectively) compared to their initial levels. The changes between duration groups in the NPK+S and NPK treatments were significantly higher in the more-than-20-year group than in the 1- to 5-, 6- to 10-, and 11- to 20-year groups ($p < .05$) but not significantly different between the 1- to 5-, 6- to 10-, and 11- to 20-year groups. We observed no soil C saturation trends in any of the cropping durations in both the NPK and NPK+S treatments, thus indicating that carbon sequestration may have occurred in the fields of the studies with the longest duration (more-than-20 years). However, SOC stock changes increased in the 11- to 20-year duration group for both the NP and NP+S treatments but decreased in the more-than-20-years duration group. Additionally, only in the 1- to 5-year duration group was the SOC stock response in the NP+S treatment significantly greater than that in the NP treatment alone ($p < .01$), while the NPK+S treatment group's SOC stock increase was significantly greater than that of the NPK treatment group in the 11- to 20-year duration group ($p < .05$), but not in the other duration groups (Figure 6).

3.6 | Relationships between SOC sequestration rates and annual C inputs from straw

When measuring straw C inputs to soils, we examined only the estimated aboveground C inputs retained by the soil and those

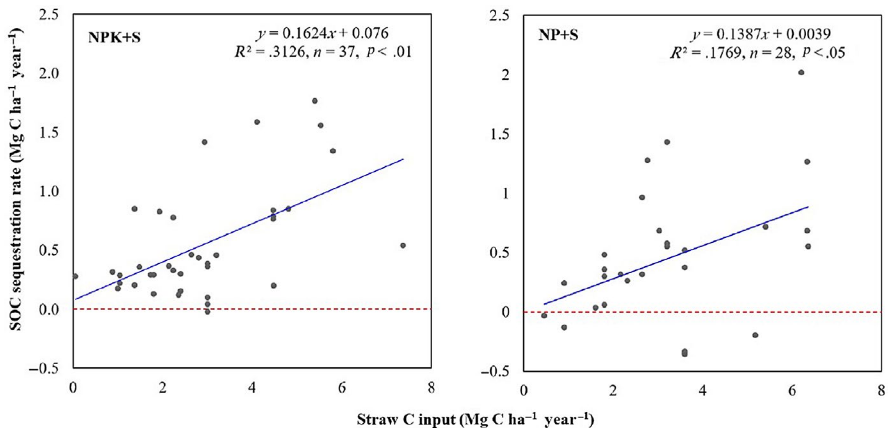

FIGURE 7 Relationships between annual straw carbon (C) inputs and annual SOC (soil organic carbon) sequestration rates in the (NP+S, mineral nitrogen and phosphorous fertilizer plus straw; NPK+S, NP plus potassium plus straw) treatments of different studies using various crop types [Colour figure can be viewed at wileyonlinelibrary.com]

amounts ranged from 0.05 to 7.36 Mg C ha^{-1} year^{-1} and 0.45 to 6.36 Mg C ha^{-1} year^{-1} in the NPK+S and NP+S treatments, respectively. In examining the long-term experiments, we observed significantly positive linear relationships between annual soil C sequestration rates and the annual straw carbon inputs to the soils experiencing both straw addition treatments: NP+S (SOC sequestration rate = 0.13 × annual straw C input + 0.004) and NPK+S treatments (SOC sequestration rate = 0.16 × annual straw C input + 0.08; Figure 7). This implies that the soil in those treatments still had the capacity to store external carbon. Similar linear relationships were detected in meta-analyses (Wang, Wang, Xu, Feng, Zhang, & Lu, 2015; Zhao, Sun, et al., 2015) and in observations from Northwest China (Shuo et al., 2016). Moreover, the slope of the linear equation was lower for NP+S (0.17) than for NPK+S (0.31), thus demonstrating that about 17% and 31%, respectively, of annual straw C input into the soil was transformed to SOC. We attributed those SOC sequestration increases to the C supplied by the returned straw.

4 | DISCUSSION

4.1 | Straw and fertilizer management effects on SOC stocks

Our meta-analysis specifically examined multiple year observations of upland grain crops of northern China, focusing on winter wheat and summer maize. However, differing sample sizes may have affected significance levels, especially when 95% confidence intervals of small sample sizes are much wider than those derived from large sample sizes, an effect experienced in similar studies (Han, Zhang, Wang, Sun, & Huang, 2016; Tian et al., 2015). With that said, we found that NP+S, NPK, NPK+S, and NPK+M treatments significantly increased SOC sequestration, thus indicating that adequate fertilization with balanced chemical and organic fertilizers sequestered SOC better than did unbalanced fertilizers (NP) and no fertilization (CK) during long-term experiments (1–33 years). Potassium is an essential plant nutrient, second in importance only to N, that increases crop yield, improves crop quality, and is required in large amounts by plants for proper growth. In our results, crops grown with added K fertilizer produced more biomass that was returned to the soil than did crops grown without K fertilizer. Therefore, SOC levels increased more in those soils that received K fertilizer than in those that did not. The largest SOC increases, NPK+M (55%) followed by NPK+S (31%; Figure 3), were likely associated with the added C input of long-term manure and straw additions. Indeed, a global meta-analysis conducted by Han et al. (2016) revealed that balanced chemical fertilizers combined with manure or straw resulted in greater SOC stocks than with chemical fertilizers alone. A similar result was reported by Liang et al. (2019), and Han et al. (2016) claimed that a substantial C sequestration potential of applying mineral fertilizer with straw and with manure is very important for either improving or maintaining current SOC stocks across all agro-ecosystems. Liu et al. (2010) also reported that manure application in combination with mineral fertilizers more effectively improves soil organic matter than do mineral fertilizers alone. Synthetic fertilizers integrated with manure (e.g., NPK+M) further mediated adverse effects of both soil acidification and reduction in base saturation caused by chemical fertilizer inputs alone (Zeng et al., 2017). Thus, supplying enough nutrients to soil through organic fertilizers is preferred for both soil fertility improvement and C sequestration enhancement.

Soil nutrients are depleted gradually during continuous cropping with no fertilizer, which affects SOC dynamics and stability (Banger, Kukal, Toor, Sudhir, & Hanumanthraju, 2009; Zhang et al., 2010). We determined that no fertilizer application (CK) and application of NP over the long-term did not significantly change SOC stocks (their 95% confidence intervals overlapped zero), as the stocks stayed at initial levels (Figure 3). This static result in the CK group was likely due to relatively high-atmospheric N deposition (Wang, Zhang, et al., 2008). Later, Zha et al. (2015) showed, in a 19-year experiment without fertilizer, that SOC content decreased by 7%. The difference between our analysis and that finding may be because only one soil type (fulvo-aquic) in that small-scale study with only one cropping system (wheat–maize cropping system) was examined versus our study, which averaged results of different soil types (black, fluvo-aquic, and loessial) and different cropping systems (SM, SW, and DC). Our result is supported by Chen, Zhao, Feng, Li, and Sun (2015) who reported that long-term unfertilized soils maintain their initial SOC content. Incorporating organic matter (e.g., crop stubble and root biomass) into agricultural soils compensates for SOC losses through decomposition, especially with double cropping every year. Thus, soil requires organic C input to increase SOC content.

Our analysis also found that long-term addition of straw, along with inorganic fertilizers, significantly increased SOC stocks over that of inorganic fertilizer applications alone. That is, compared to their initial SOC stock levels, NPK+S and NP+S treatment groups had greater increases in SOC stocks (31% and 16%, respectively) than did the NPK and NP treatment groups (16% and a negligible percent, respectively). The same increasing effect was observed in a meta-analysis conducted on long-term paddy crops (Tian et al., 2015) in which the NPK+S treatment group sequestered about 1.9 times more SOC than did the NPK group. Because mineral fertilizers may enrich C inputs only through increasing root and stubble biomass, they did not directly contribute organic matter into the soil like straw does. Straw addition provides large amounts of organic C to cropland soils, thereby promoting soil microbial biomass and activities, hence increasing soil organic matter (Lal, Follett, Stewart, & Kimble, 2007). Therefore, we concluded that the addition of crop residues results in greater C storage than does the application of mineral fertilizers alone.

A global scale meta-analysis (Han et al., 2016) and observations from other studies conducted in upland areas of central China (Zha et al., 2015) reported SOC increases following straw incorporation. Those studies had broad differences in climate, soil type, study duration, and rotation systems, yet the results of SOC increases following straw addition fell in a narrow range (19.4%–25.2%, Table 1). The results from our study using data from upland areas of North China agreed with the above studies since the relative change of SOC (23.5%) with long-term straw incorporation fell within the range of those studies (Figure 3, Table 1). In contrast, relative increases in SOC stocks with straw addition in our study were slightly lower than those of studies conducted in sub-Saharan croplands (Powlson, Stirling, Thierfelder, White, & Jat, 2016) and in China (Zhang et al., 2016) in which the combined range of SOC increases was 26%–38%. However, our observed increases were greater than those found by a global scale meta-analysis of upland areas (Liu et al., 2014), a meta-analysis conducted on a national scale of Chinese croplands (Zhao, Sun, et al., 2015), and one of European and North American upland soils (Powlson, Glendining, Coleman, & Whitmore, 2011), with a combined range of 11%–13.3% (Table 1). The differences between those studies and ours were probably due to variations in crop types (from winter wheat in Europe and North America to rice, wheat, and maize in sub-Saharan Africa to winter wheat and summer maize in our study), durations (6–56 years in Europe and North America, 20–30 years in China, and 5.7 years in sub-Saharan Africa vs. 1–33 years in our study), coverage of the study (from global and national scale meta-analyses to regional meta-analysis and single-site studies), and climatic conditions of the various sites (Han et al., 2016; Liu et al., 2014; Powlson et al., 2011, 2016; Zha et al., 2015; Zhang et al., 2016; Zhao, Sun, et al., 2015). This array of differing variables can produce results that disagree with one another, including the amounts that SOC increases due to straw addition. So, our study's conclusions suggest that we need to consider many factors that contribute to variations in outcomes (e.g., crop rotation, study duration, soil type, initial C concentrations, and climatic conditions) in future studies. Furthermore, another study (Reicosky et al., 2002) also found no increases in SOC stock after long-term straw returns, and a study in North China by Wang et al. (2018) demonstrated that long-term straw application maintained, and sometimes increased, SOC compared to the initial SOC level. Perhaps, soil carbon sequestration is limited by certain aspects of initial soil quality associated with low inputs of C, initial SOC content, pH, or the total carbon and nitrogen ratios (Wang, Wang, Xu, Feng, Zhang, Yang, et al., 2015). In addition, we observed significant linear relationships between straw C inputs and SOC sequestration rates (Figure 7), indicating that the increase in SOC stocks in the straw-added treatments was directly correlated with the amount of straw C inputs to the soil.

Incorporation of crop residue is not only a major source of C input, but it also helps to control air pollution by returning carbon-based material into the soil rather than burning it and sending it into the

TABLE 1 Studies of soil organic carbon (SOC) changes with straw addition

Study region	Duration (years)	Land use type	Relative change of SOC stock (%)	Reference
Global	10.2	Cropland	19.4	Han et al. (2016)
	Short to long-term	Upland	13.3	Liu et al. (2014)
China	Short to long-term	Cropland	12	Zhao, Sun, et al. (2015)
	20–30	Cropland	26–38	Zhang et al. (2016)
Sub-Saharan Africa	5.7	Cropland	34.2	Powlson et al. (2016)
Europe and North America	6–56	Upland	11	Powlson et al. (2011)
Central China	19	Upland	25.2	Zha et al. (2015)
North China	Short to long-term (12.8)	Upland	23.5	This study

atmosphere. As chemical fertilizers are the main source of nutrients used for crops in China, their excessive use with a relatively low efficiency contributes to environmental problems (Zhang, Wu, & Dai, 2004). Many findings that agreed with our results also concluded that the application of organic materials, combined with chemical fertilizer, is the best approach for increasing SOC content (Meng, Ding, & Cai, 2005; Wang, Li, & Qiu, 2004). Farm management practices greatly influence biomass productivity by changing SOC content, thus influencing crop yield while possibly increasing atmospheric CO_2 concentrations, which leads to climate change (Wang, Qiu, Tang, Li, & Li, 2007). Generally, the effect of chemical fertilizers combined with straw not only decreases the required amounts of chemical fertilizers, but also improves SOC content and, by extension, contributes to very efficient and environmentally friendly farm management. Thus, carbon sequestration could be attained through long-term crop residue application or straw return, especially in our study area in China.

4.2 | Response ratios of SOC stocks in different soil types

Changes in SOC stock levels probably depend on initial levels in farmlands (Stewart, Paustian, Conant, Plane, & Six, 2007). In our meta-analysis, we observed a lower SOC stock response ratio in the long-term duration experiments (range 1–33 years) in cropland soils that had greater initial SOC stocks, regardless of soil types. Black soils had the highest initial SOC stock in our results (Figure 8); however, its SOC stock response ratio was the lowest of the three soils measured in most of the fertilizer treatments (Figure 4). This is consistent with the result of a meta-analysis by Li, Shi, et al. (2017) of a

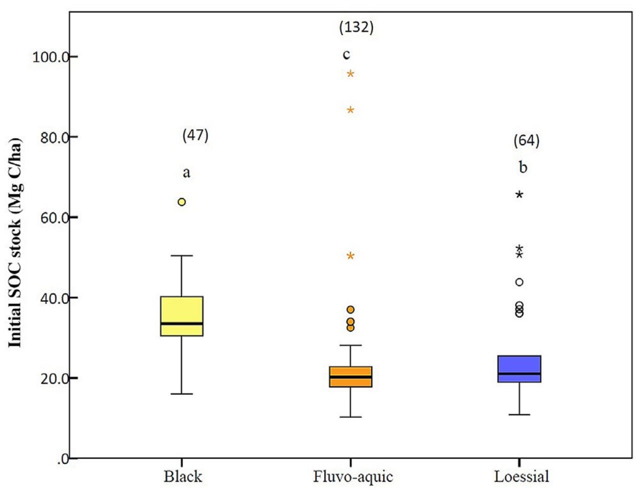

FIGURE 8 Initial SOC (soil organic carbon) stocks (Mg C/ha) in the top 20 cm of soil in the selected studies of major agricultural soil types in North China. The thick lines within the boxes represent medians. Vertical bars show minimum and maximum values and * and ° denote outliers. Numbers in parentheses are numbers of input data points and the bars with different letters indicate significant differences (one-way ANOVA, $p < .05$) [Colour figure can be viewed at wileyonlinelibrary.com]

long-term experiment looking at fertilizer treatments and different upland and paddy (rice fields) soil types. It shows that, for both upland and paddy fields, SOC stock change depends on the initial SOC stock. In our study, higher response ratios in fluvo-aquic and loessial soils (Figure 4) may be attributed to initial SOC stock levels (22.5 and 26.2 Mg C/ha, respectively), which were lower than those of black soils (35.1 Mg C/ha). The lower the initial C content, the farther a soil is from C saturation level (Stewart et al., 2007).

In addition, we used a logarithmic function to describe the relationship between annual SOC sequestration rates and initial C stocks (Figure 9). SOC sequestration rates in all treatments were weak, with R^2 ranging from .11 to .19, but significantly negatively correlated with initial SOC stock amounts, except in the NP+S treatment in which there was a positive, but weak and nonsignificant, correlation. These results were mainly due to large differences in C sequestration rates caused by differences in C inputs, fertilizer rates and types, durations of fertilizer regime, and cropping systems (Appendix S2). A meta-analysis by Li, Shi, et al. (2017) revealed a significant negative correlation between SOC sequestration rates and initial SOC stocks in upland soils planted in maize and wheat and in paddy soils planted in rice. However, another meta-analysis in China paddy soils using single-cropped rice, double-cropped rice, and double-cropped rice–wheat found no apparent relationship (Tian et al., 2015). The differences in similar meta-analyses may be due to climatic conditions and cropping system variations between upland and paddy soils, especially since decomposition in anaerobic paddy soils is low, even if initial SOC contents are high (Li, Shi, et al., 2017). Moreover, initial SOC levels probably control the sequestration of soil C in farmlands (Sun, Huang, Zhang, & Yu, 2010). Initial soil C concentrations influence the stabilization of added C, and perhaps soils having lesser C stocks have the greatest potential and ability to sequester C because they are farther from their saturation levels than are soils with greater C stocks (Stewart, Puastian, Conant, Plane, & Six, 2008). Thus, SOC sequestration rates will likely depend on initial SOC stocks.

4.3 | Crop rotation systems, SOC stocks, and crop yields

In this study, greater SOC sequestration occurred in all cropping systems under the NPK, NP+S, and NPK+S treatments than in the CK and NP treatments (Figure 5), mostly because of greater C inputs resulting from higher crop productivity in the fields treated with adequate fertilizer and straw return (Mandal et al., 2007). This indicates that soils that received sufficient nutrients from either fertilizers or both fertilizers and straw return experienced enhanced SOC changes, due mainly to greater C inputs. These inputs arose from crop residues and root-related C, and from straw addition resulting from higher crop productivity in the NPK, NP+S, and NPK+S treatments than in the CK and NP treatments. In comparison, SOC changes in the DC system were significantly higher than those in the SM system, compared to their initial levels, using both NPK and NPK+S fertilization, with increases of 21% in DC versus 6% in the SM systems

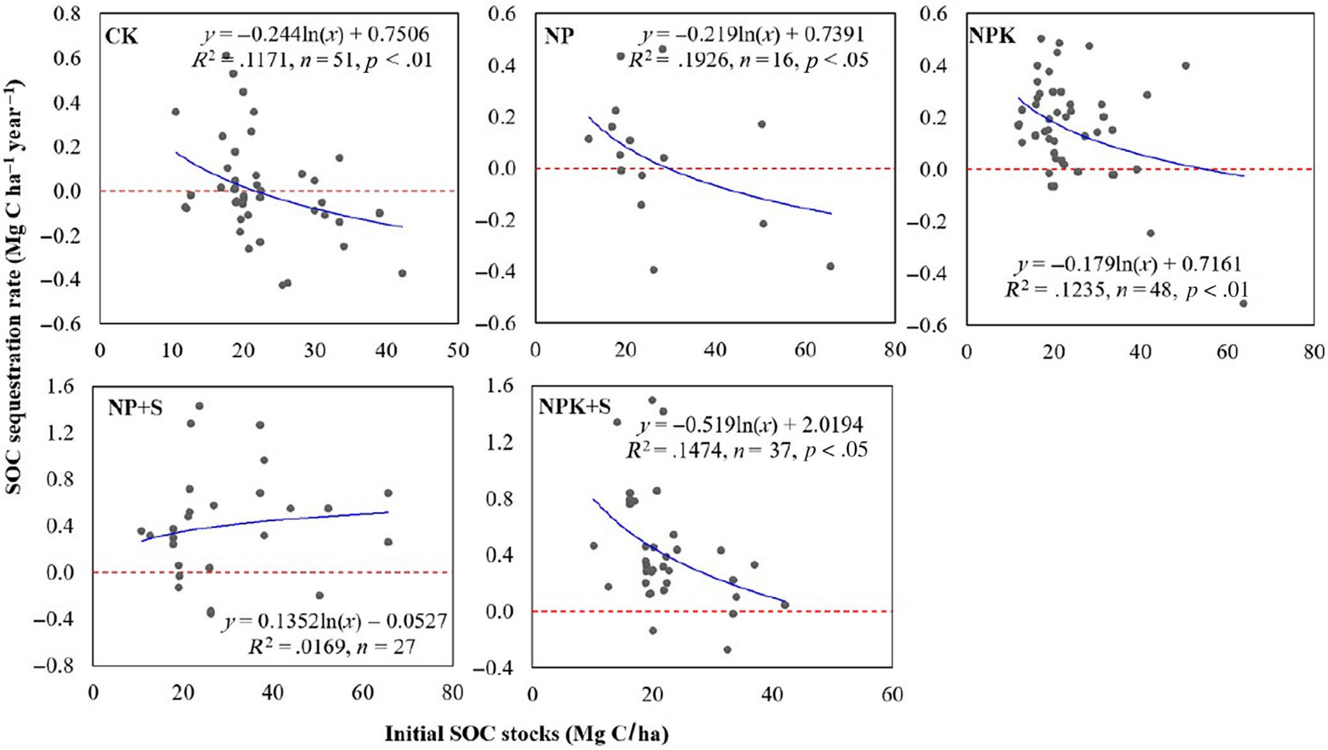

FIGURE 9 Correlations between the annual soil organic carbon (SOC) sequestration rates and initial SOC stocks in each of the five fertilizer treatments (CK, control [unfertilized]; NP, mineral nitrogen and phosphorous fertilizer; NPK, NP plus potassium; NP+S, NP plus straw; NPK+S, NPK plus straw) [Colour figure can be viewed at wileyonlinelibrary.com]

under the NPK treatment (p = .001), and up 38% in DC versus 14% in the SM systems under the NPK+S treatment (p = .027). This can be partially explained by the lower whole-year crop productivity and less plant-derived C input in a single-cropping system (Huang et al., 2012). Moreover, under NPK treatments, the SW system response was significantly higher than that of the SM system, but nonsignificant under the NPK+S treatment. This indicates that SM cropping responds less to SOC than do the other cropping systems. Wang et al. (2018) compared data from different experimental sites in northeast China and suggested that the continuous, single-cropping maize system is less efficient at sequestering C from added C inputs than are systems that include two crops per year. Single cropping provides less stored SOC, even in paddy crops, as Huang et al. (2012) found in a national scale meta-analysis of different cropping systems used in paddy fields in China. They observed lower SOC sequestration in the rice single-cropping system than in the double-cropping system using rice–wheat and rice–rice. Our result was also supported by the linear relationships between the SOC sequestration rates and the straw C inputs (Figure 7), and Wang, Wang, Xu, Feng, Zhang, Yang, et al. (2015) reported a significant correlation between changes in SOC and the amount of C input. This implies that SOC stock responses to cropping systems, in paddies as well as in uplands, depend on the amount of C input supplied to the soil throughout the year. In addition, Mandal et al. (2007) suggested that SOC stocks could be enhanced in cropping systems that provided more C than the critical value of C losses. In contrast, the SM system experienced lower SOC stock increases than did the SW system, perhaps because the decomposition rates of wheat and maize residues differ because of their different climatic conditions. The high temperatures of the maize-growing season foster a faster decomposition rate of organic materials generated by maize root systems than the decomposition rate during the cooler wheat-growing season, resulting in a lower retention coefficient for the maize season than for the wheat season (Wang, Wang, Xu, Feng, Zhang, Yang, et al., 2015; Zheng et al., 2009). So, while SOC increased in both the DC and SW systems under both the NPK and NPK+S treatments, the increase for the SW system was statistically nonsignificant (p > .05), possibly because the SW system's small sample size resulted in large confidence intervals (Gurevitch & Hedges, 1999; Han et al., 2016).

Adding straw to the fertilizer regimes of the DC system clearly resulted in significantly greater SOC stock responses, compared to initial SOC levels, than those with chemical fertilizers alone. While single-cropping systems responded slightly to straw return, except in the SM system in which the SOC increase under NP+S (10%) was significantly greater than the NP treatment increase (1%). The significant SOC stock increases in the DC system was most likely due to the higher annual amounts of straw returned to the soil from double crops. Therefore, both straw addition and cropping system affected SOC stock change. Because of low C inputs, single-cropping systems (SM and SW) had less stored soil C than did the DC system (Zhao, Sun, et al., 2015 in a previous meta-analysis conducted at a national level).

We also examined grain yields in different fertilizer treatments and cropping systems. We found that the yields of both the wheat and maize crops in the DC system fertilized with either NPK, NP+S, or NPK+S were greater than the yields of crops with NP fertilization and no fertilization (CK; Figure 2). Similarly, examining a wheat–maize rotation system, Zhao et al. (2014) reported lower grain yield in NP treatments compared to NP treatments combined with K fertilizer or returned straw. That yield difference was associated mostly with the essential nutrients in the balanced chemical fertilizers and the returned straw compared to the insufficient nutrients in the NP and CK systems. However, we saw no yield differences between treatments in the SM systems, except that the CK yield was significantly lower, even though SOC stocks varied with treatments. Partially in line with our results, Chen et al. (2015) found that all fertilizer treatments significantly enhanced crop production compared to unfertilized crops, but the yield difference between fertilized treatments was not significant for both the wheat and maize crops. They suggested that inorganic fertilizers, straw, and manures, when N, P, and K are applied at equivalent rates, have similar effects on crop yields. In our meta-analysis, due to a large range in the quantities of applied fertilizer or returned straw in the selected studies, we did not consider the total amounts of nutrients applied for each treatment. Therefore, the total nutrients applied in these treatments may be similar and may have resulted in similar grain yields. When comparing cropping systems, maize yield in the SM system was significantly higher than it was in the DC system with NPK ($p < .05$) and NP+S ($p < .01$) applications. Most likely, productivity was lower than in a single-season system because of the moisture lost by tilling twice per year and the intensive cropping and high nutrient utilization in the DC system. However, the mean yield of wheat in the NPK+S treatment was significantly lower in the SW system (3.92 t/ha) than in the DC system (6.2 t/ha, $p < .05$). This difference in wheat yields may have been because the DC system benefited from two seasons, cold and warm, in which the mobilization of available nutrients from fertilizers and soils differed (Wang, Wang, Xu, Feng, Zhang, & Lu, 2015 in a previous meta-analysis). Therefore, the higher wheat yield in the DC system might be attributed to two seasons of applied nutrients and tillage frequency.

In the DC system, the combination of straw and chemical fertilizers resulted higher grain yields than those produced with chemical fertilizers alone: NP+S yield (11.1 t/ha) was higher than the NP yield (9.2 t/ha) and NPK+S yield (12.9 t/ha) was higher than the NPK yield (12 t/ha). These overall yield increases under straw return may have been due to additional nutrient inputs and improvements in the soils' biophysical and physicochemical properties (Liu et al., 2014). During the past few decades, huge amounts of chemical fertilizers have been used to maximize crop yields, thus improving food security throughout the world (Savci, 2012). However, those methods can degrade soil through compaction and acidification, leading to crop yield reduction (Horrigan, Lawrence, & Walker, 2002). Use of chemical fertilizers has also decreased soil bacteria community richness and diversity and has significantly changed soil bacteria community structure (Ramirez, Craine, & Fierer, 2010; Sun et al., 2016). Similar to our results, Zhao, Jiang, et al. (2019), in their eight-consecutive-year field experiment using the wheat–maize cropping system in northwest China, observed significantly higher crop yields in a combined straw and chemical fertilizer treatment than with no straw addition. Integrated application of chemical fertilizer and crop straw is an important field management practice that can help maintain both soil quality and productivity (Bhattacharyya, Kundu, Prakash, & Gupta, 2008; Shuo et al., 2018; Zhao, Ning, et al., 2019). It improves the physical, biological, and chemical properties of the soil (e.g., porosity, moisture, and constituent substrates), thus aiding the activity and community structure of soil bacteria (Zhao, Wang, & Jia, 2015). Straw return likely produces increased plant-derived C, sequesters SOC, and, at the same time, achieves optimum crop productivity (Shuo et al., 2016). Similar to the results obtained in our study, a meta-analysis of upland and paddy crops in China compared crop yields and SOC stock changes with and without straw returns and found that long-term, continuous straw return leads to overall increases in both yields and SOC (Wang, Wang, Xu, Feng, Zhang, & Lu, 2015).

Average, year-round, overall crop yields were higher in the DC system under all treatments than in both the SM and SW cropping systems. So next, we considered the effect of cropping system on both SOC change and annual total crop yield, and found that the DC system is preferable to both single-cropping systems per year. The winter wheat–summer maize cropping system is the most common and important cropping system in the North and North-Central China Plain. Double-cropped fields in this region cover 16 million ha and account for about 25% of the national grain yield (Zhang et al., 2015). Because China's agricultural production is so large, especially of wheat, it not only feeds its own population but also exports wheat beyond its borders. Our study area in North China is very important for that production and, interestingly, this study has revealed that when straw was combined with chemical fertilizers, SOC stock increases in the DC system were greater than those in both single-cropping systems, an effect mainly associated with greater amounts of crop residue being returned to the soil in double cropping compared to that returned from just one crop per year. Abundant nutrients (e.g., N, P, K) remain in crop residues and by intensifying management of those residues, farmers can help maintain soil nutrient balance and quality and can promote soil microbial biomass and beneficial microbial by-products (Kumar & Goh, 2000). Thus, straw return is an effective way of promoting agricultural production and, along with annual double-cropping wheat and maize, is an advantageous and recommended method that can enhance both soil fertility and annual crop yields. In general, we observed lower responses of grain yield to different fertilizer treatments and cropping systems than to SOC response. North China is a dryland area that receives low annual rainfall, hence crop productivity and fertilizer effect on grain yield are highly limited by precipitation and the low productivity response is linked to dry weather (Fan, Xu, Song, Zhou, & Ding, 2008). Finally, all fertilizer treatments in our study included mineral N fertilizer, which decreases decomposition of organic matter, thus leaving greater amounts of undecomposed crop residues than in soils without mineral N fertilization. This, in turn, increases the efficiency of SOC sequestration in the soil (Li, Jia, et al., 2017).

4.4 | SOC stock responses and experimental durations

The SOC response ratios of four experimental cropping duration periods (1–5, 6–10, 11–20, and more-than-20 years) varied among fertilization treatments and were slightly time-dependent. SOC stock response ratios in the CK treatment did not change significantly in longer durations but did increase by 6% in the 1- to 5-year period. Declines in SOC stock over time may be due to the lack of C inputs and supplementary fertilizers, which would both compensate for C losses during nutrient consumption by growing crops. For the NP and NP+S treatment groups, SOC stock responses were higher, relative to the initial SOC stock levels, in the 11- to 20-year period (22% and 53%, respectively), but the responses in the more-than-20-year periods were only 4% and 13%, respectively (Figure 6). Similar to our NP+S results, a meta-analysis across major agricultural zones of China (Wang, Wang, Xu, Feng, Zhang, & Lu, 2015) observed that long-term straw return increased SOC stocks during the 10- to 20-year duration period, but then the increases declined in longer periods. This result indicates that SOC enhancement decreases after 20 years of fertilization without K. This persistent lack of K may eventually adversely affect plant growth, thus reducing C input from stubble, roots, and rhizodepositions. In contrast, the annual average straw C input following the NP+S and NPK+S treatments was 3.21 and 2.84 Mg C ha^{-1} year^{-1}, respectively, with average annual SOC sequestration rates of 0.4 and 0.7 Mg C ha^{-1} year^{-1}, respectively (Figure 7). That indicated a higher C input but less sequestration potential in the NP+S than in the NPK+S treatment. Moreover, SOC enhancement in longer periods may be influenced by higher than average, initial SOC stocks in the NP and NP+S treatments compared to those in NPK and NPK+S treatments (Figure 10). However, the relationship between the C sequestration rate and the initial C content in the NP+S treatment (Figure 9) was weak (R^2 = .01) and differed from other treatments, possibly because the NP+S treatment had a smaller sample size than did the NPK+S treatment. According to the soil C saturation hypothesis, changes in SOC stocks may be affected by the initial soil C content levels: the lower the initial C content, the farther from saturation (Stewart et al., 2007). Considering that hypothesis and the upland fields included in our meta-analysis, it seems that SOC sequestration in longer duration periods was influenced by the initial soil C levels.

In NPK and NPK+S treatments, the SOC stock response ratio increased incrementally in almost all duration periods (Figure 6). For the NPK treatment group, the highest SOC stock mean response ratio occurred in the more-than-20-year duration period, but there was a slight difference between duration periods. A study in North China by Gao, Yang, Ren, and Hailong (2015) determined that application of balanced inorganic fertilizers, with or without added manure or straw, can significantly increase SOC content over long periods. Similarly, our NPK+S treatment group had a significantly higher response

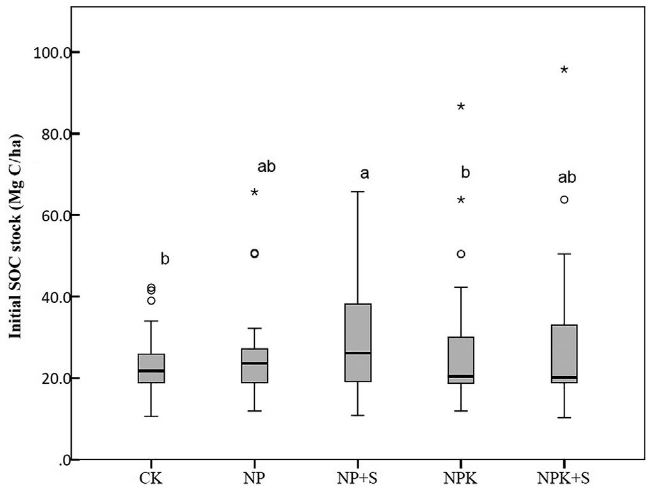

FIGURE 10 Initial SOC (soil organic carbon) stocks in the top 20 cm of soil in selected studies based on different fertilizer treatments in North China (CK, control [unfertilized]; NP, mineral nitrogen and phosphorous fertilizer; NPK, NP plus potassium; NP+S, NP plus straw; NPK+S, NPK plus straw). The thick lines within the boxes represent medians, the vertical bars show minimum and maximum values, and * and ° denote outliers. Treatments with different letters are significantly different (one-way ANOVA, p < .05)

ratio (63%; p < .05) in the more-than-20-year duration period than in periods less than 20 years. A meta-analysis by Tian et al. (2015) also suggested that application of mineral NPK plus straw increased the decomposition and mineralization rates of crop residues. This resulted in greater C storage, compared with the application of NPK only, as applications continued through time before reaching a new equilibrium. This increase in SOC in their NPK treatment group was due mostly to high C input from crop stubble and remaining roots, whereas in the NPK+S treatment group, the increase was most likely due to high C input from returned straw, as well as from crop residue resulting from higher crop productivity (Tian et al., 2015).

In the long-term experiments, we observed no C saturation trend in all cropping duration periods in the NPK and NPK+S fertilizer treatment groups, indicating that soils in those treatment groups required more C input from balanced chemical fertilizer in order to sequester C continuously over the long-term. In addition, the positive relationship between SOC sequestration rate and straw C input in the NPK+S treatment in the included studies indicates that soil has the potential to sequester C for at least 33 years. Our findings are supported by a long-term study of the effects of chemical fertilizers combined with straw and organic manure (Fan et al., 2008). Those researchers found, during their 26-year experiment, that dryland soils had not reached their C sequestration upper limit. Moreover, we analyzed the relationship between clay content and SOC storage for the two treatments with straw return and found a significant positive correlation (y = 0.733x + 16.29, R^2 = .24, p < .01) for the NPK+S treatment, but the NP+S correlation increased to some extent and then declined (Appendix S5). However, due to limited studies reporting clay content, the sample size for the NP+S was likely too small to analyze effectively. Soils with high clay content may experience greater SOC storage than soils with less clay content (Jagadamma & Lal, 2010). This is because organic C molecules adsorb to clay surfaces because of clay's large surface area and the presence of polyvalent cations that form organo-mineral complexes that protect SOC from microbial and enzymatic decay. But, the clay content in our study was low, 10%–32%, indicating that North China soils may best sequester SOC if kept under balanced fertilizer management and straw return (NPK+S) programs. However, the relationships between SOC sequestration rates and the corresponding initial SOC stock levels were negative in almost all treatments, thus suggesting the possibility of SOC saturation in the study area in the future. Thus, our study indicates that balanced fertilizers with straw return could be very important for both crop yields and SOC stock increases over longer periods in dryland areas.

Overall, we found straw return to be an effective practice for sustaining soil fertility and crop productivity. Our regional and climate specific study revealed that fertilizer management, cropping duration, cropping system, initial SOC levels, and soil types all influenced SOC dynamics in relation to straw return. However, we found very few studies spanning periods greater than 30 years, regardless of whether straw return was examined and especially in dryland areas. Future research considering many factors in managed experiments are required to fully understand the benefits of straw return to agricultural fields. Such factors might include different fertilizer rates, more soil types, climatic conditions, straw types and quantities, and different durations. Continued experimental study would help resolve uncertainties observed in meta-analyses. This knowledge can aid future cropland management and study, especially for upland crops in North China.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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