

Article

Enhancing Sustainable Agriculture in China: A Meta-Analysis of the Impact of Straw and Manure on Crop Yield and Soil Fertility

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Abstract: As the main organic materials, straw and manure play a critical role in soil organic carbon (SOC) sequestration and crop yield in China. This meta-analysis evaluated the impact of straw and manure amendments, both individually and combined, on crop yield, SOC, and soil nutrients in China by collecting 173 studies. The findings of this study revealed that straw return and manure application increased crop yields by 14.4% and 70.4%, respectively, overall. Combined straw and manure application gained a better improvement effect than straw alone but was less effective than manure alone. Regarding the straw return results, rice straw and a 3000–6000 kg ha⁻¹ returning quantity improved crop yield, SOC, available phosphorus (AP), available potassium (AK), and total nitrogen (TN) the most; regarding the straw return form, straw incorporated into soil and biochar increased crop yield and SOC more, respectively; and <5 years and ≥5 years of straw return treatment increased crop yield and TN more, respectively. Regarding manure application, pig and chicken manure increased crop yield and TN more, respectively; a 50–80% substitution ratio and 10–20 years of duration were best for improving crop yield, SOC, AP, AK, and TN. This study highlights the importance of optimal organic amendment through straw or manure applications to achieve a win–win between crop yield and soil fertility under the requirement of sustainable agriculture.

Keywords: meta-analysis; organic amendment; China; carbon sequestration; management strategy



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1. Introduction

In the earth system, soil organic carbon (SOC) constitutes up to 75% of the terrestrial carbon pool, representing the largest carbon pool, which is approximately three times greater than the amount of carbon stored in the atmosphere or vegetation [1–3]. Findings have demonstrated that the sequestration of SOC could play an irreplaceable role in significantly reducing carbon emissions [4,5]. However, in China, long-term traditional agriculture management has induced soil deterioration from carbon sink to carbon source [6,7]. Meanwhile, the decrease in soil organic matter (SOM) and nutrients seriously threatens food security [8,9]. Consequently, the application of suitable management practices to increase SOC content and enhance crop yield is very important.

In agriculture, the practice of returning straw to the field is a feasible and promising strategy to sequester SOC without reducing yield [10–13]. A large number of studies have shown that returning straw to the field has a positive impact on crop yield, SOC, and soil nutrients [1,3,14,15]. China, as one of the world's largest crop straw producers, produces 800 to 1000 MT of crop straw every year, accounting for about 20% to 40% of the global aggregate (Table S1) [16–18]. In recent years, China has gradually shifted from incinerating crop straw to directly returning it to the field. The quantity of straw directly

returned can reach more than 40% of the total crop straw [19,20]. However, there are still many obstacles to directly returning straw to the field. For example, the difficult decomposition of straw and the fact that incompletely decomposed straw can impede crop growth have resulted in farmers preferring to dispose of the straw by burning it [21–24]. Moreover, there is a multitude of factors that can impact the effects of returning straw to the field (e.g., its duration, quantity, form, and category), which makes it difficult for farmers to ensure a proper strategy of straw return [21,25,26]. Due to these reasons, as well as the huge quantity of straw itself and its great potential in restoring soil and mitigating carbon emissions, it is, therefore, essential to apply appropriate straw return management methods in actual production practices to foster green development in China. Current meta-analyses related to returning straw to the field are limited in their investigation of the effects of different categories and forms of straw on SOC, crop yield, and soil nutrient content. Additionally, the categorization rules for research factors vary among different meta-analyses. Given the continuous updates to meta-analyses, a newly integrative and comprehensive meta-analysis should be conducted.

Apart from returning straw to the field, the strategy of replacing chemical fertilizers with organic ones can also effectively reverse the decrease in SOC caused by the excessive use of chemical fertilizers [27–30]. Currently, China has the largest production of manure, similar to crop residues, in the world, which is over twice the combined total of the United States and the European Union (Table S2) [31]. So far, except for increasing SOC content, a myriad of experiments have testified to the important role of manure in restoring soil nutrients and improving crop yield [32–36]. However, the excessive and sole use of manure can diminish its advantages compared with the proper combination of manure and chemical fertilizer, even leading to counterproductive outcomes such as lower yields than those achieved with chemical fertilizer due to its slow decomposition process [35]. Moreover, the difficulty and high labor cost of collecting manure are not seen as worthwhile or appropriate by farmers, thereby causing reluctance and resistance from farmers toward propaganda and promotion concerning the replacement of chemical fertilizer with organic fertilizer [37]. Therefore, it is both inevitable and crucial to analyze an effective management strategy for manure application. Based on our meta-analysis, the effects of manure application and its management strategies can be explained further. Likewise, the result can be regarded as a reference to manure application. In order to explore the impact of different manure management modes on the effectiveness of manure, we divided three groups: the source, substitution ratio, and duration of manure for the meta-analysis.

In addition to the development of a survey on returning straw and applying manure, the effects of combining straw and manure were explored to determine the specific role of integrating these two organic amendments.

In this context, this study carried out a meta-analysis including 2647 data derived from 173 eligible articles. The objectives were (1) to analyze the different effects of straw return management on crop yield, soil nutrients, and SOC; (2) to analyze the different effects of manure application management on crop yield, soil nutrients, and SOC; (3) to analyze the effects of manure application plus straw return on crop yield, soil nutrients, and SOC; and (4) to provide valid references for acquiring win–win management between crop yield and SOC.

2. Materials and Methods

2.1. Data Collection

In the rudimentary stage, we conducted a search and identified a total of 9320 relevant articles using the following keywords: “straw”, “manure”, “straw plus manure”, “crop yield”, “soil nutrient”, “soil organic carbon”, etc. Relevant articles published from 2013 to 2023 were gathered from the China National Knowledge Infrastructure (CNKI) and the Web of Science. In detail, the articles were collected without review and communication, the language of the articles is English or Chinese, and specific search strings were used (e.g., TS = soil organic carbon or SOC or soil nutrient or yield or crop production or crop

productivity and TS = crop residue or straw or stover or stalk or manure or organic fertilizer or slurry, etc.). The entire article search process is illustrated in a flowchart (Figures S1–S3). The data were sieved by conforming to the following rules: (1) The field experiment was conducted in China. (2) The article includes at least one of the following relevant indicators: crop yield, SOC, total nitrogen (TN), available phosphorus (AP), and available potassium (AK); to avoid confusion about the soil stock, the soil variables must be recorded as soil content, and all indicators must be observed or calculated. (3) The replication number must be ≥ 2 to ensure the function of the meta-analysis. (4) The treatments contained a control, namely no straw, manure, or chemical fertilizer application. (5) For crop data collection, only rice, wheat, and maize were considered. (6) SOC and soil nutrients were collected only from the 0–20 cm soil layer, regardless of crop category. (7) No other variables are present that may interfere with the analysis except for those necessary. For different amendments, the collection principles were distinct (Table S3). The details of these groupings are provided in the Supplementary Materials or the annotation under the following Figures.

An aggregate of 173 articles passed the standard screening process. We extracted the experiment location, soil and crop category, and replication number; straw return category, form, quantity, and duration; manure source, substitution ratio, and duration; nitrogen, phosphorus, and potassium fertilizer amount; and the mean and standard deviation (SD) of crop yield, SOC, TN, AP, and AK. GetData Graph Digitizer 2.26 was used to extract data in figures. We also used the function “refine category” of MetaWin 2.1 to deal with the missing data.

The collection of means and SDs was assisted by Formula (1) and Engauge Digitizer, Origin 2021. For the data that did not include the SD, if the standard error (SE) could be found, Formula (1) was used to obtain the SD; if the SD and SE could not be found in the article, we estimated the SD by calculating the 10% mean [38–40]. When only SOM could be found in the data, we used the method of multiplying SOM values with 0.58, a correction factor, to obtain the SOC values [41].

$$SD = SE \times \sqrt{n} \quad (1)$$

In Formula (1), n means replication number.

The collected data were classified to analyze the effect on crop yield, SOC, and soil nutrients of TN, AP, and AK contents after the classification of straw, manure, and a combination of straw with manure application using assorted management strategies, respectively (Table S4).

2.2. Meta-Analysis

The method used to calculate effect size and sampling variance was the natural logarithm of the response ratio (lnRR) by MetaWin 2.1 for this study. The calculation process was operated automatically by the intrinsic program of MetaWin 2.1, which was appropriate for the form of the data being extracted. Formulas (2) and (3) were used to calculate the effect size and sampling variance, respectively, in the lnRR.

$$\ln R = \ln (m_e / m_c) \quad (2)$$

In Formula (2), m_e and m_c are the sample means for the experimental and control groups.

$$\sigma_{\ln R}^2 = se^2 / n_e m_e^2 + s_c^2 / n_c m_c^2 \quad (3)$$

In Formula (3), n_e and n_c are the sample sizes, se^2 and s_c^2 are sample variances for the two groups, and m_e and m_c are the same as above.

Next, the random effect model was applied, which can simultaneously consider the within-case and cross-case variations in the effect size. Summary analysis was conducted by imposing acquired effect size and sampling variance, and categorical analysis was used for cumulative effect value and its 95% confidence interval (CI) in this process. If the 95% CIs

overlapped with 0, straw, manure, or straw plus manure application did not significantly influence the research indexes (crop yield, SOC, TN, AP, and AK); if the 95% CIs did not involve 0, the foregoing amendments had a positive (>0) or negative (<0) effect [38,42]. If the 95% CIs overlapped with the effect sizes at different levels of the same group in categorical analysis, there was no significant difference ($p < 0.05$) [43]. In order to ensure the reliability of the results, each category level can only be regarded as valid if the data volume is not less than 10 or if it comes from three different independent articles [44]. For results that meet the requirements, the sample size and effect value shown in brackets are presented in black on the plot; otherwise, the data are shown in red. Under this principle, we ensured the credence of these black-colored results; the red-colored results may possess little relevance but should still be further explored once sufficient samples are generated in the future. The effect value was present in the form of a percentage, which represented the improvement effects of different amendments; the percentage consisted of effect size and 95% CI. In crop yield, we used the following four different indicators: total yield, maize yield, wheat yield, and rice yield; the total yield means the average increase in crop yield without the consideration of crop type. Additionally, Q values for each group were displayed in each forest plot to demonstrate heterogeneity [45].

The forest plots and correlation were analyzed using GraphPad Prism 9.5 and SPSS Statistics 23. ArcGIS 10.8.1 was used to designate the experimental locations (Figure 1). Rosenberg's fail-safe number was used for testing the publication bias (Table S5) [46].

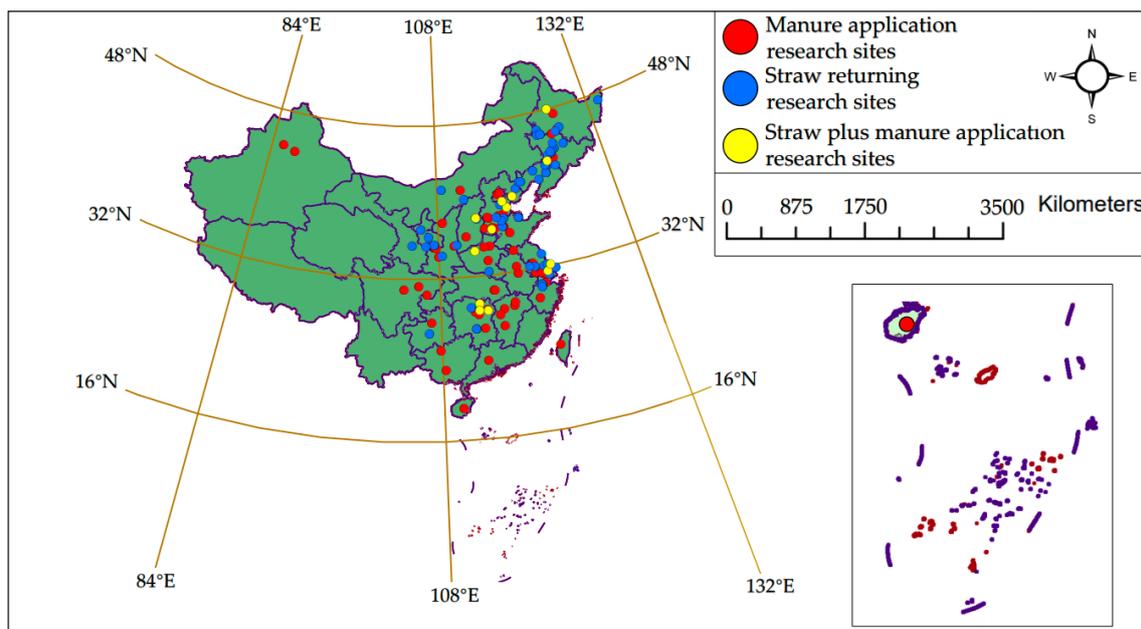


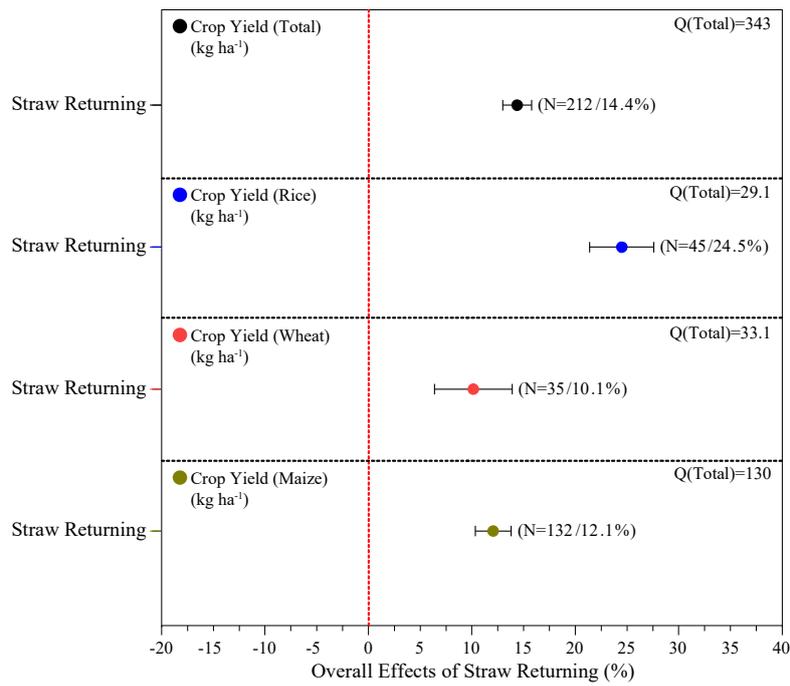
Figure 1. The research sites in China.

3. Results

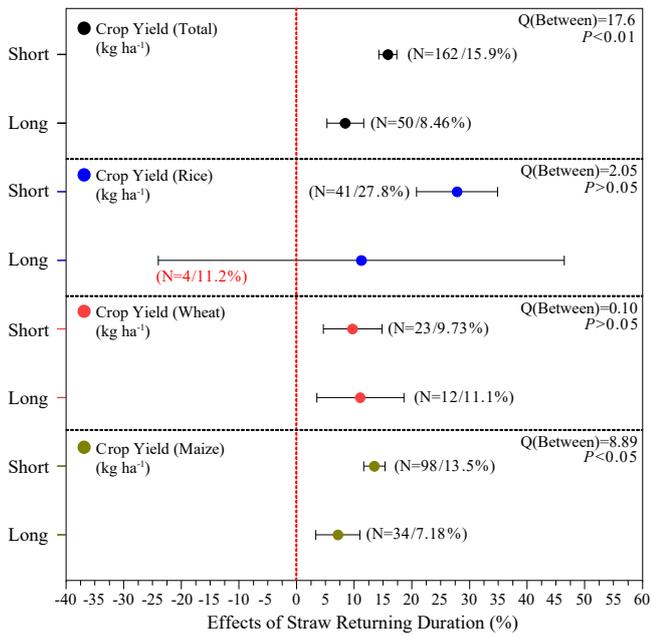
3.1. Overall Effects of Straw Return on Crop Yield, SOC, and Soil Nutrients

3.1.1. Straw Return Effects on Crop Yield

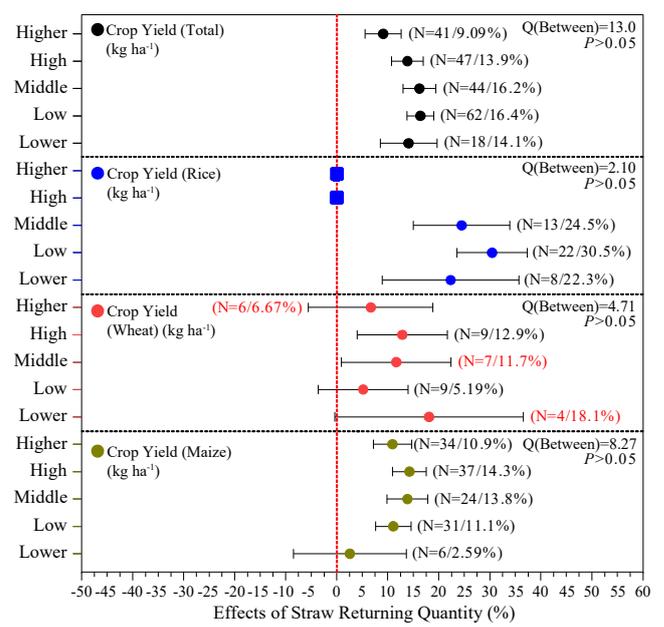
In Figure 2, the forest plots showed the overall effect on improving crop yield, duration effect, quantity effect, form effect, and category effect of straw return in turn. Overall, straw return increased the crop yield by 14.4%. The rice, wheat, and maize yield significantly increased by 24.5%, 10.1%, and 12.1%, respectively. Among them, the response degree of rice was significantly higher than maize and wheat (Figure 2a).



(a)



(b)



(c)

Figure 2. Cont.

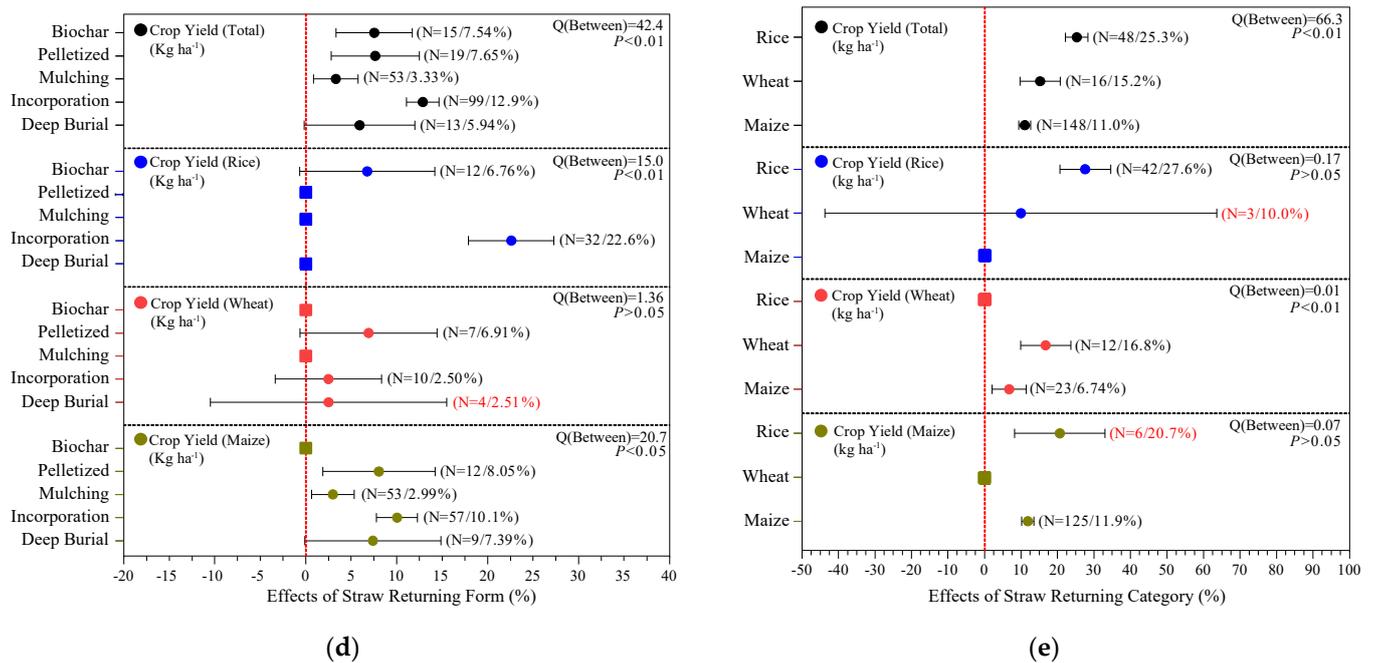


Figure 2. The forest plots of the effects of straw returning on yield. (a) Straw return overall effects on yield; (b) duration on yield; (c) quantity on yield; (d) form on yield; and (e) category on yield. In (b), long means ≥ 5 years, and short means < 5 years. In (c), higher, high, middle, low, and lower means $\geq 12,000$ kg ha⁻¹, 9000–12,000 kg ha⁻¹, 6000–9000 kg ha⁻¹, 3000–6000 kg ha⁻¹, and < 3000 kg ha⁻¹, respectively. Dot means effects values; black line means 95% CIs; square means void value; N means sample number; (%) means effect value; and all clusters were divided by different colors. Q (total) is the total heterogeneity, and Q (between) is the between-group heterogeneity; $p < 0.05$ indicates a significant difference in the group; $p < 0.01$ indicates a particularly significant difference in the group; and $p > 0.05$ indicates no significant difference in the group.

For the effect of straw return duration, except for the duration of ≥ 5 years, on increasing rice yield, all durations significantly increased crop yield. The duration of < 5 years improved crop yield significantly more than ≥ 5 years overall. Compared with ≥ 5 years, < 5 years significantly increased maize yield by 5.90% (Figure 2b).

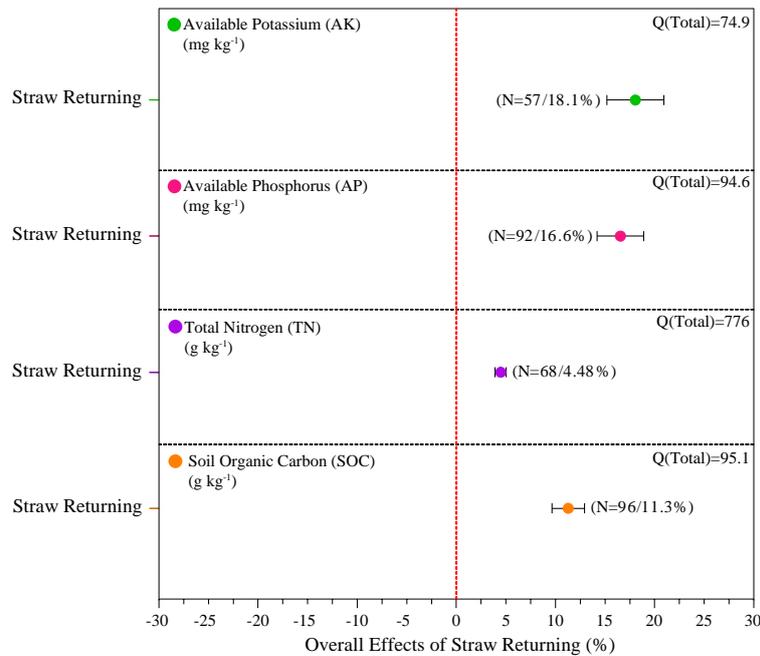
All the quantity degrees of straw return possessed significantly positive impacts on total crop yield. Compared with the straw return quantity $\geq 12,000$ kg ha⁻¹, 3000–6000 kg ha⁻¹ and 6000–9000 kg ha⁻¹ significantly increased crop yield by 6.70% and 6.52%, respectively. For individual crops, the quantity of < 9000 kg ha⁻¹ significantly increased rice yield; 6000–12,000 kg ha⁻¹ significantly increased wheat yield; and ≥ 3000 kg ha⁻¹ significantly increased maize yield (Figure 2c).

For the effects of form on crop yield, in the total crop yield, all forms significantly increased crop yield except deep burial of straw, and straw incorporation significantly enhanced crop yield by 9.26% compared with straw mulching. In terms of rice yield, straw incorporation significantly increased rice yield by 22.6%. Maize yield was significantly increased by pelletized straw, straw mulching, and straw incorporation; among them, straw incorporation significantly promoted maize yield by 6.90% compared with straw mulching (Figure 2d).

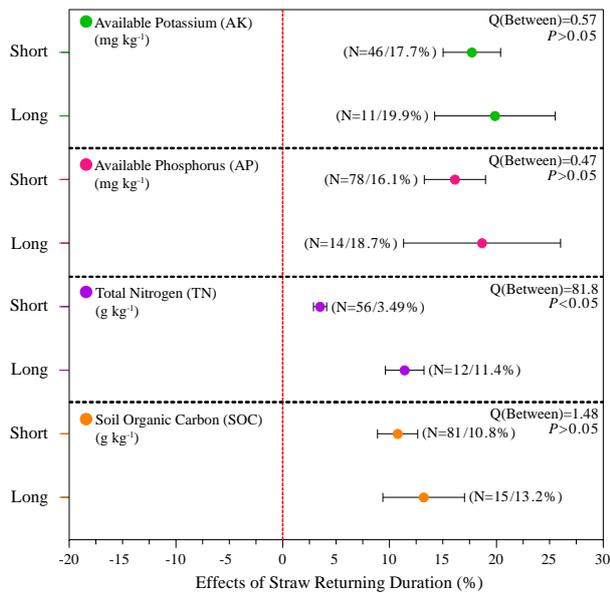
In terms of the relation of straw category to total crop yield, all straw categories significantly increased total yield, and rice straw significantly enhanced yield by 8.77% and 13.9%, respectively, compared with wheat straw and maize straw. Depending on the cultivation crop to classify, rice yield was significantly increased by rice straw; wheat yield was significantly increased by wheat and maize straw; and maize yield was significantly increased by rice and maize straw (Figure 2e).

3.1.2. Straw Return Effects on SOC and Soil Nutrients

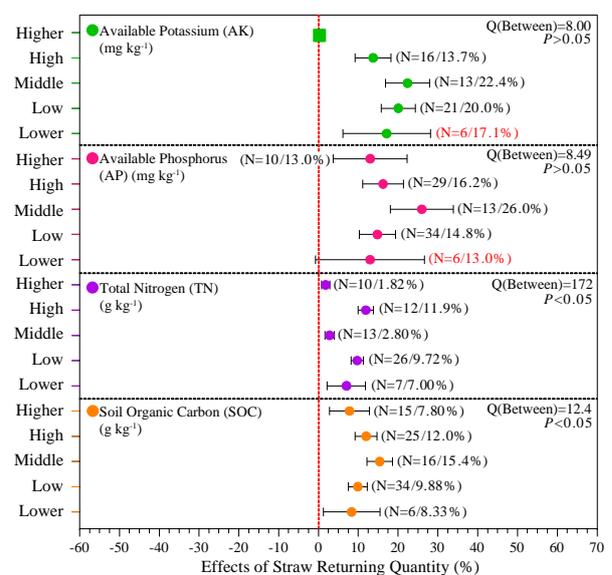
In Figure 3, the forest plots showed the overall effect on improving the SOC and soil nutrients, duration effect, quantity effect, form effect, and category effect of straw return in turn. Overall, the contents of AK, AP, TN, and SOC were significantly increased by straw return. Among them, the degree of response of TN content to straw return was significantly less than other elements; SOC response was significantly higher than TN but lower than AP and AK (Figure 3a).



(a)



(b)



(c)

Figure 3. Cont.

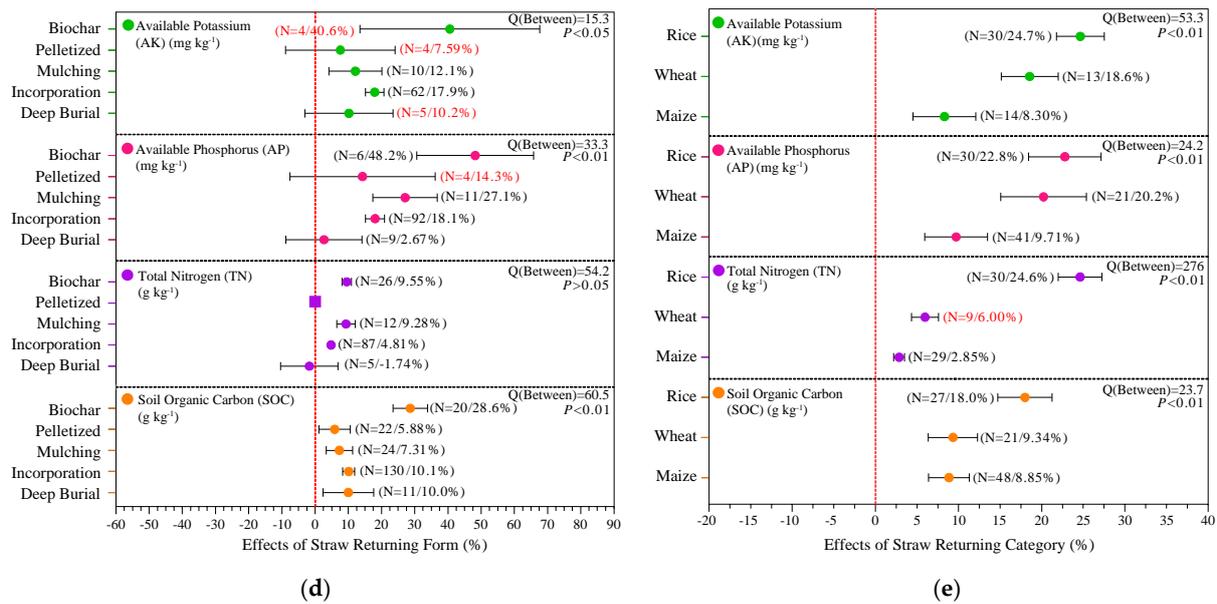


Figure 3. The forest plots of the effects of straw return on SOC and soil nutrients. (a) Straw return overall effects on SOC and soil nutrients; (b) duration on SOC and soil nutrients; (c) quantity on SOC and soil nutrients; (d) form on SOC and soil nutrients; and (e) category on SOC and soil nutrients. The rest of the notes are the same as in Figure 2 and were omitted for clarity.

Regarding the straw duration role in the content of SOC and soil nutrients, compared with the control, all durations significantly and positively affected the contents of AK, AP, TN, and SOC. Regarding increases in TN, compared with the straw return duration <5 years, ≥5 years significantly promoted TN by 7.64% (Figure 3b).

In terms of the effects regarding different straw return quantities, the quantity of 3000–12,000 kg ha⁻¹ significantly increased the contents of AK, AP, TN, and SOC. Compared with the quantities of 6000–9000 kg ha⁻¹ and ≥12,000 kg ha⁻¹, TN was increased by 3000–6000 kg ha⁻¹ and 9000–12,000 kg ha⁻¹ significantly (Figure 3c).

Among different straw return forms, straw biochar, straw incorporation, and straw mulching significantly increased the contents of AK, AP, and TN; all forms significantly enhanced SOC. Regarding the contents of AP, TN, and SOC, straw biochar significantly and positively affected AP more than straw incorporation and deep burial of straw; straw incorporation significantly decreased TN compared with straw mulching and straw biochar; and straw biochar significantly increased SOC compared with other forms. Namely, under equal conditions, these proper forms can increase the foregoing indicators with more efficiency compared with other forms (Figure 3d).

Regarding the impact of the straw category on SOC and soil nutrients, all categories significantly increased the contents of AK, AP, TN, and SOC. Rice and wheat straw significantly enhanced AK, AP, and TN compared with maize straw; rice straw significantly increased TN by 17.5% and 21.1% compared with wheat and maize straw, respectively; and wheat and maize straw significantly increased SOC less than rice straw (Figure 3e).

3.2. Overall Effects of Manure Application on Crop Yield, SOC, and Soil Nutrients

3.2.1. Manure Application Effects on Crop Yield

In Figure 4, the forest plots show the overall effect on improving crop yield, source effect, substitution ratio effect, and duration effect of manure application in turn. Overall, manure application increased the crop yield by 70.4%. The rice, wheat, and maize yield significantly increased by 47.0%, 78.0%, and 76.9%, respectively. Among them, the response degree of rice was significantly lower than maize and wheat (Figure 4a).

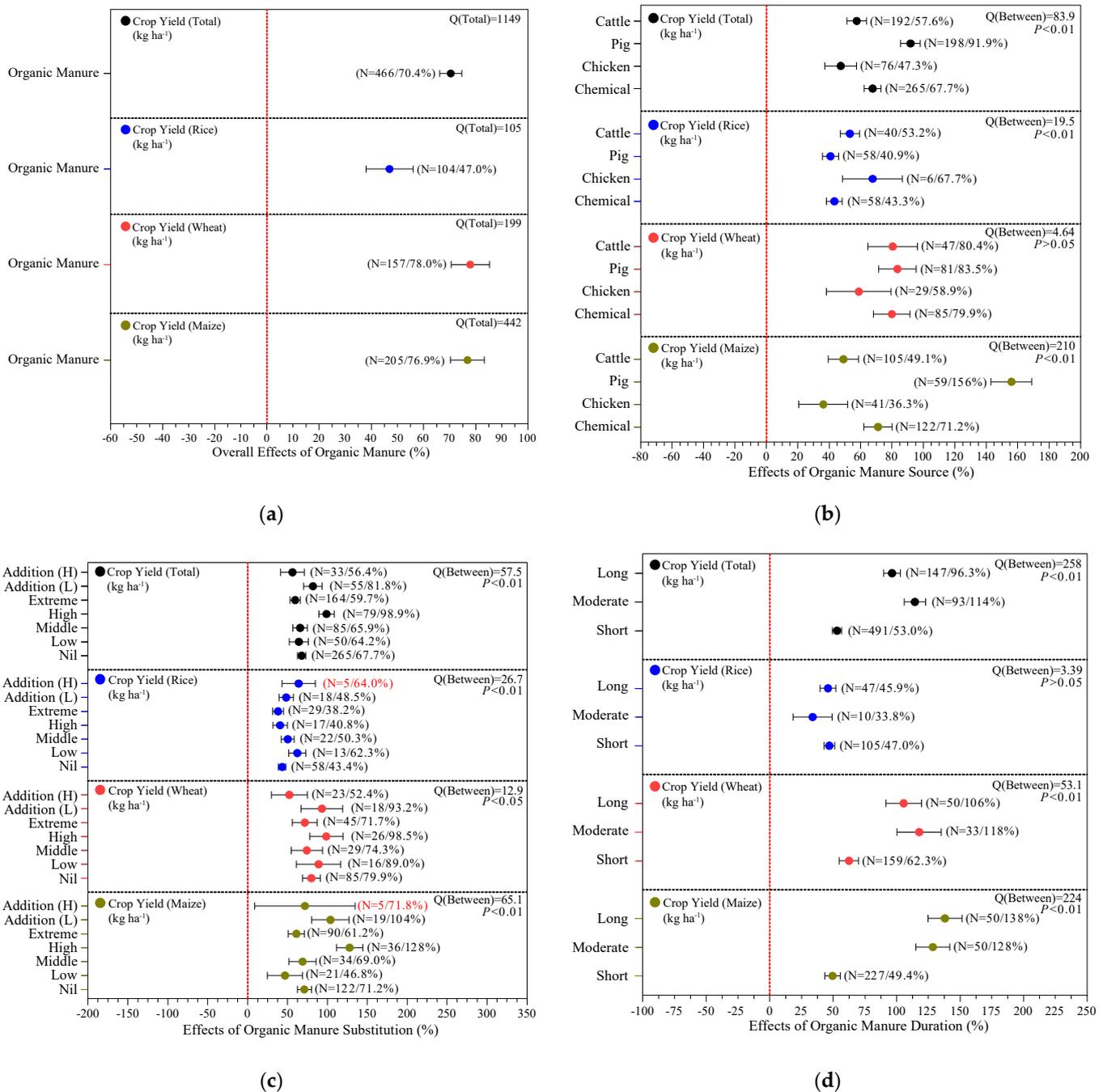


Figure 4. The forest plots of the effects of organic manure on yield. (a) Manure application overall effects on yield; (b) source on yield; (c) substitution ratio or additional replenishment on yield; and (d) duration on yield. In (c), nil, low, middle, high, extreme, addition (L), and addition (H) mean 0%, 0–30%, 30–50%, 50–80%, 80–100%, <30 t ha⁻², and ≥30 t ha⁻², respectively. In (d), long means ≥ 20 years, moderate means 10–20 years, and short means < 10 years. The rest of the notes are the same as in Figure 2 and were omitted for clarity.

For the effects of different manure sources, all sources significantly increased crop yield. In the total crop yield, compared with chemical fertilizer, pig manure significantly increased crop yield by 14.4%, but chicken manure significantly decreased crop yield by 12.2%. For individual crops, pig manure significantly increased rice yield less than cattle and chicken manure, but pig manure significantly increased maize yield more than other

sources; moreover, chemical fertilizer significantly increased maize yield compared with cattle and chicken manure (Figure 4b).

Regarding increases in crop yield, the forest plot was made to determine the impacts of substitute proportion change. Compared with the control, all substitution ratios significantly and positively increased crop yield; except in the case where $<30 \text{ t ha}^{-2}$, the substitution ratio 50–80% significantly increased total crop yield compared with other ratios. Under crop categorization, the substitution ratio $<30\%$ significantly increased rice yield more than the 0% substitution ratio; the wheat yield was significantly increased by the ratio of 50–80% compared with $\geq 30 \text{ t ha}^{-2}$; and the substitution ratio 50–80% significantly promoted maize yield by 40.5% and 41.4% compared with $<50\%$ and $>80\%$, respectively (Figure 4c).

Finally, the impacts of different durations of manure application on yield were determined, and all durations significantly increased crop yield. The duration of 10–20 years significantly increased total crop yield by 9.02% and 39.9% compared with ≥ 20 years and <10 years, respectively; the duration of ≥ 20 years also significantly increased total crop yield by 28.3% compared with <10 years. In terms of wheat and maize yield, the duration of <10 years decreased yield compared with 10–20 years and ≥ 20 years significantly (Figure 4d).

3.2.2. Manure Application Effects on SOC and Soil Nutrients

In Figure 5, the forest plots showed the overall effect on improving the SOC and soil nutrients, source effect, substitution ratio effect, and duration effect of manure application in turn. Overall, the contents of AK, AP, TN, and SOC were significantly increased by manure application. Among them, the response degree of AP content to manure application was significantly higher than other elements; AK responded significantly more than TN and SOC but less than AP (Figure 5a).

In terms of the effects of manure sources on SOC and soil nutrients, all sources significantly increased the contents of AK, AP, TN, and SOC. Regarding increases in AP, pig manure significantly increased AP by 59.7% and 63.7% compared with cattle manure and chemical fertilizer, respectively. Chicken manure significantly increased TN content compared with other sources; cattle and pig manure significantly and positively affected TN more than chemical fertilizer but less than chicken manure. All manure sources significantly increased SOC content compared with chemical fertilizers (Figure 5b).

Regarding the effects of the substitution ratio on SOC and soil nutrients, AK was significantly enhanced by the ratios except $<50\%$; all ratios significantly increased the contents of AP, TN, and SOC. For individual elements, the ratio of 50–80% significantly increased AK by 54.0% and 36.2% compared with $<30\%$ and $>80\%$, respectively; AP was significantly promoted by 68.6% and 52.4% through the ratio of 50–80% compared with $<50\%$ and $>80\%$, respectively; and compared with 0%, except when $<30\%$, all ratios significantly increased TN and SOC (Figure 5c).

Under the impact of duration variation, all durations significantly increased the contents of AK, AP, TN, and SOC. Compared with the duration of <10 years, 10–20 years and ≥ 20 years significantly increased the contents of AK, AP, and SOC; regarding TN, the duration of ≥ 20 years significantly enhanced TN by 11.4% (Figure 5d).

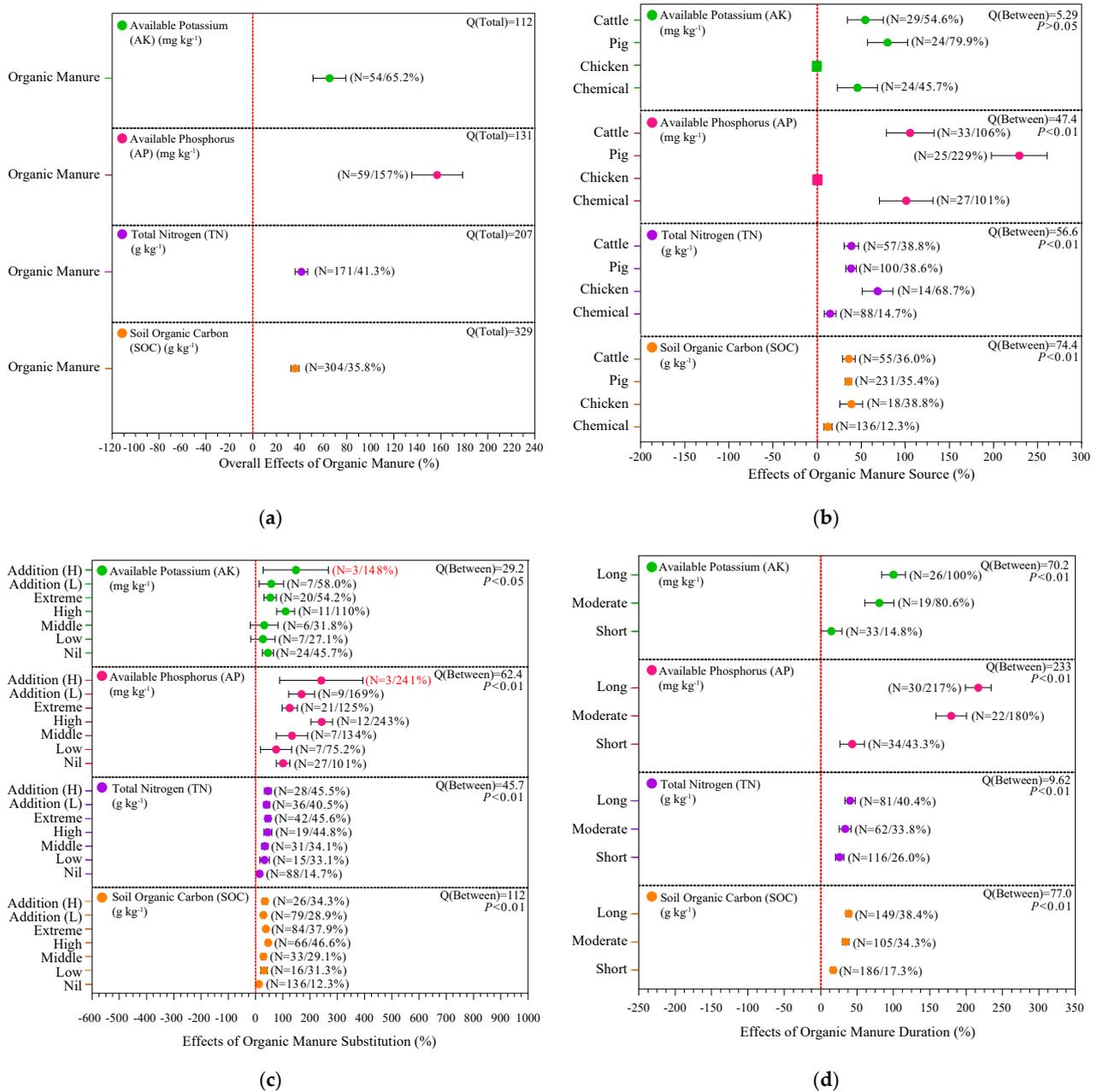


Figure 5. The forest plots of organic manure on SOC and soil nutrients. (a) Manure application overall effects on SOC and soil nutrients; (b) source on SOC and soil nutrients; (c) substitution ratio on SOC and soil nutrients; and (d) duration on SOC and soil nutrients. The rest of the notes are the same as in Figure 4 and were omitted for clarity.

3.3. Overall Effects of Straw Plus Manure on Crop Yield, SOC, and Soil Nutrients

Compared with the control, straw returning plus manure application significantly increased the crop yield of total, rice, wheat, and maize by 35.0%, 40.8%, 37.2%, and 27.9%, respectively (Figure 6a).

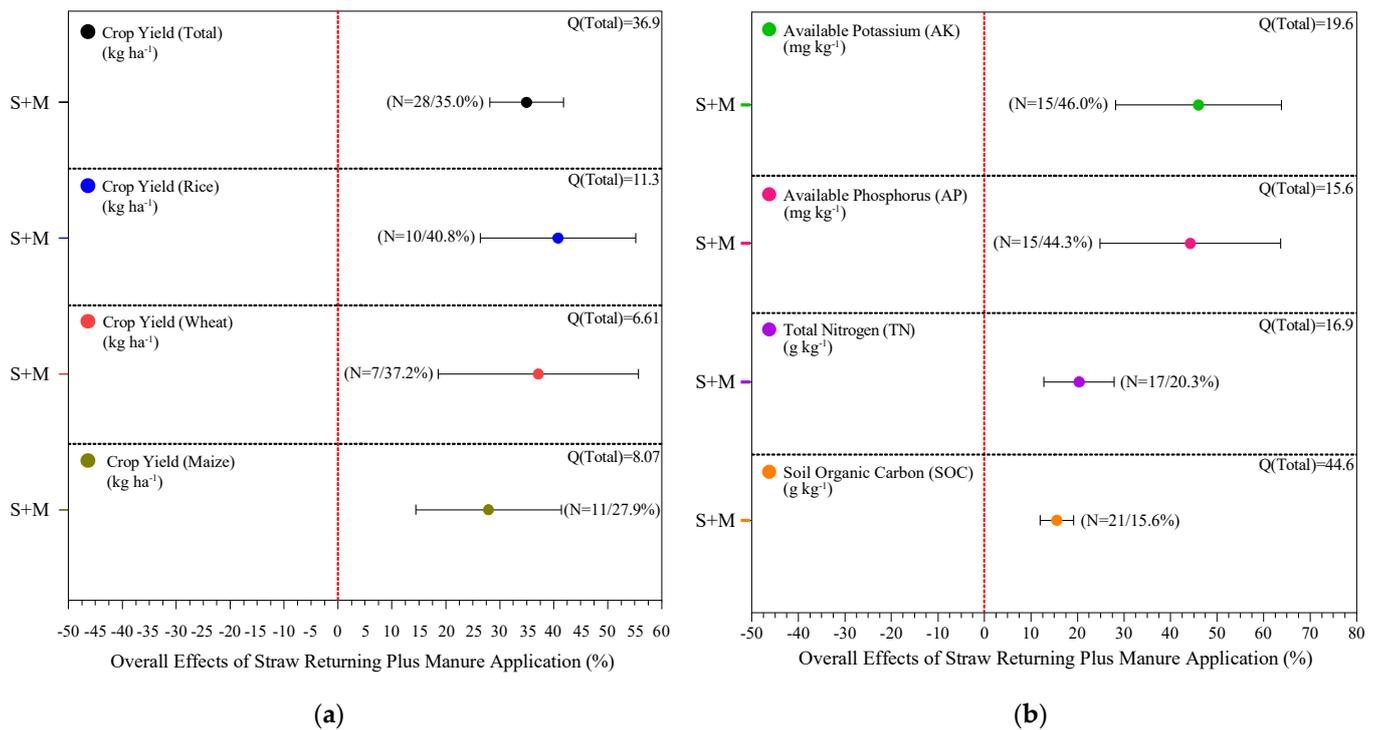


Figure 6. (a) The forest plot of straw returning plus manure application to yield; (b) SOC and soil nutrients. S + M means straw plus manure. The rest of the notes are the same as in Figure 2 and were omitted for clarity.

Comprehensively, compared with the control, straw returning plus manure application significantly increased the contents of AK, AP, TN, and SOC by 46.0%, 44.3%, 20.3%, and 15.6%, respectively. The response degree of SOC content to straw returning plus manure application was significantly lower than for AK and AP; moreover, AK significantly responded more than TN (Figure 6b).

3.4. Correlation Analysis

The correlation coefficients between the net increase in crop yield and net increase in SOC, TN, C/N, AP, and AK were calculated and divided into straw return (Figure S4) and manure application groups (Figure S5).

In the straw return group, SOC and soil nutrients had significant and positive effects on the net increase in crop yield. The correlation coefficient of net-increased SOC, TN, C/N, and AK were more than 0.42, while AP was the lowest (0.22) (Figure 7a).

In terms of manure application, the net-increased C/N was irrelevant to crop yield. The correlation coefficients of the net-increased SOC and TN both were significantly positive to the net-increased crop yield, which reached 0.35 and 0.33, respectively. The biggest correlation was 0.40 of the net-increased AK (Figure 7b).

Overall, the significance and coefficients of different factors regarding crop yield under straw return or manure application were determined. Under the straw return treatment, the increase in SOC and soil nutrients was more closely related to yield.

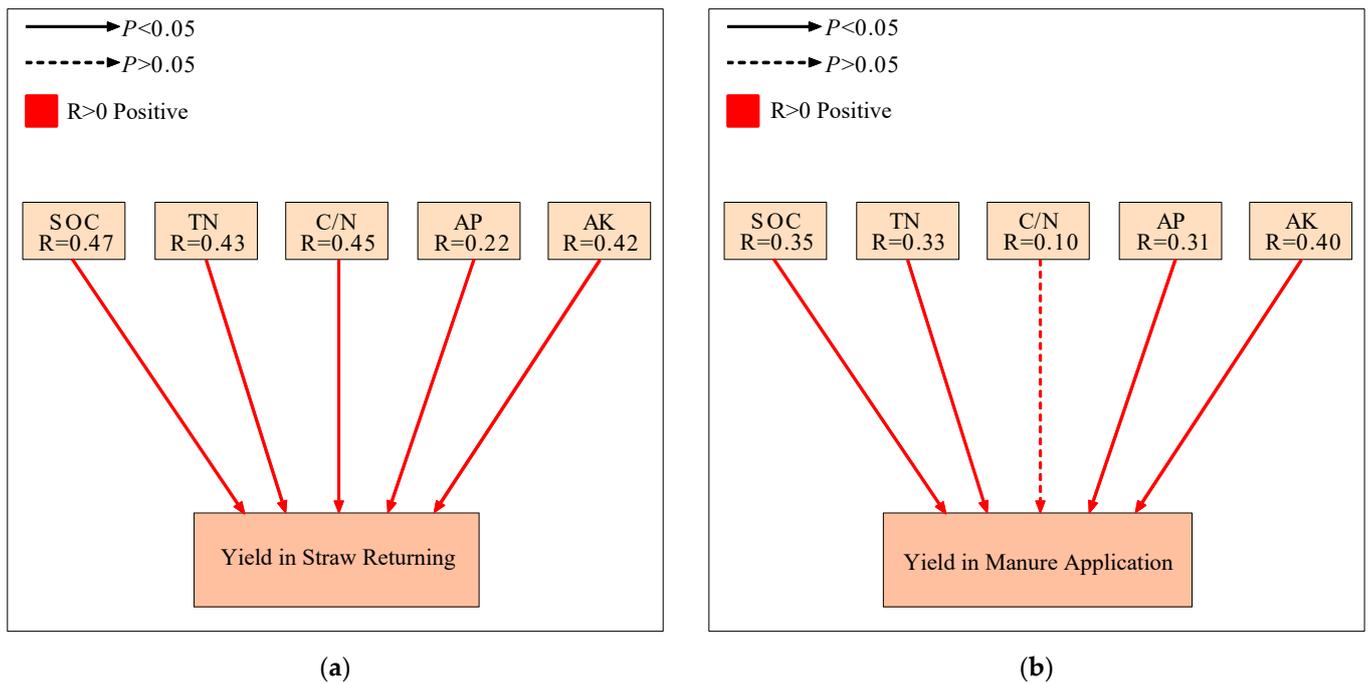


Figure 7. (a) The correlation between different factors and crop yield under the straw return application and (b) under the manure application. Full line and dashed line, respectively, mean the correlation was significant ($p < 0.05$) and not significant; the red color means positive effect; and R means correlation coefficient.

4. Discussion

4.1. Overall Effects of Straw Return on Crop Yield, SOC, and Soil Nutrients

4.1.1. Straw Return Overall Effects

Straw return can significantly improve crop yield, SOC, and soil nutrients [14,47–50]. Through our meta-analysis, the ranks of the overall effect of straw return on improving the yield of different crops and the content of different soil indicators were as follows: rice (24.5%) > maize (12.1%), wheat (10.1%); AK (18.1%), AP (16.6%) > SOC (11.3%) > TN (4.48%). It is important to note that the ranking pertains to the magnitude of improvement attributed to straw return across various parameters. The ranking of straw return's overall effect on enhancing the yield of different crops and the levels of various soil indicators is based on significant differences.

The yield-increasing effect of rice was significantly greater than maize and wheat after straw return, which possibly resulted from the cultivation conditions. The pH of paddy soil pH is 5.5–6.5, presenting slight acidity. The increased yield effect of straw return in acidic soils may be higher because crop straw is an alkaline material, and its return to the field reduces soil acidity, enhancing the retention capacity of soil to fertility [48]. Moreover, straw return increased maize yield slightly more than wheat yield, which was mainly affected by different growth seasons. Wheat is cultivated in winter or spring, which possess lower precipitation and temperature compared with the growth season of maize—summer. Lower precipitation and temperature are not beneficial to the acceleration of straw decomposition, thus impacting the release of straw nutrients [39]. AK and AP increased more compared with the SOC under straw return, which may be attributed to the quickly released minerals contained within straw; the release of available nutrients mainly occurs through chemical decomposition and microbial activity, and the processing is comparatively faster than SOC accumulation. In terms of the difference between SOC and TN, the high C/N of straw could be one major reason. When straw is added to soil, microorganisms use up available nitrogen to decompose the straw, temporarily slowing the short-term increase in TN [51]. This shows that the improvement effect of straw return on different indicators is influenced

by their characteristics. However, the improvement effect is also affected by changes in environmental and management factors. For instance, the effectiveness of straw return on increasing SOC is significantly influenced by the initial SOC levels, with soils having lower initial SOC showing greater response ratios [52]. Proper use of nitrogen fertilizer can optimize soil C/N and boost microbial activity, thereby facilitating the nutrient release of straw [38]. Moreover, compared with no-tillage practices, tillage could mix straw into the deeper soil layer, making soil nutrients well distributed and improving the straw decomposition rate [53]. In practical production, these factors should also be considered under straw return.

4.1.2. Straw Duration

Our meta-analysis found the straw return of <5 years significantly increased crop yields compared with ≥ 5 years. This was mainly because of the high C/N of straw [17]. Continuous straw return results in relatively more exogenous carbon and less nitrogen inputs [38]. In order to maintain growth, the soil microbe will begin to compete with crops for nitrogen, which impacts crop yields [7]. Regarding soil nutrients, ≥ 5 years was more effective in enhancing soil nutrient levels, particularly TN. The net-increased TN was possibly generated from the remaining straw after long-term straw return treatment. In terms of SOC, there was no significant difference between <5 years and ≥ 5 years in improving its content. This result for SOC could be attributed to the soil gradually reaching a carbon threshold with extended periods of straw return, which may limit further increases in SOC [38]. Moreover, long-term straw return can enhance the potential for carbon decomposition. In contrast, only a small proportion of carbon remains in the soil as stable carbon, reducing the carbon sequestration effect [20].

From our meta-analysis, a universal conclusion could be found. Namely, the duration < 5 years increased crop yield more, and the duration ≥ 5 years increased soil nutrients more. However, the determination of the optimal duration always needs to consider the local environment. Many studies have waged an exploration based on their local environment [25,38,39]. Under long-term straw return, Goran et al. and Wang et al. discovered the content of TN significantly increased [14,25], which was similar to our outcome. One study suggested that long-term straw returning over 20 years could considerably increase SOC content by two or three times compared with short-term straw returning [52]. However, the SOC will decrease rapidly once the continuous straw return stops due to the introduction of numerous labile carbon compounds and the acceleration of “priming effects” [41]. In a rain-fed upland, the practice of long-term rice straw return was used to increase maize productivity; although compared with the control, straw return significantly increased maize yield, a year-on-year comparison within the straw return group showed a decline over the years [51]. Jiang et al. and Wang et al. found that straw return significantly increased crop yield after continuous return for 5 years [54,55]. Altogether, and based on other experiments, the regulation of straw returning duration needs to also consider the local conditions of soil properties and meteorology to determine the most suitable duration.

4.1.3. Straw Quantity

As an important index and controllable variable of weighing crop residue return effects, the quantity of straw is one of the most popular topics in the subject of returning straw to the field. The change in returning straw quantity can always significantly affect crop yield, SOC, and soil nutrient content [14,20,56,57]. Many studies have revealed that a higher quantity of straw return has an improvement role [7,49,56]. However, theoretically, there is no linear relationship between crop yield, SOC, soil nutrients, and straw returning quantity [15,47]. Moreover, in terms of the economic dimension, an excessive returning straw quantity can decrease the potential economic benefit of farmers. Therefore, the most vital crux is to identify a proper quantitative level for straw return based on the premise of balancing improvement and economy.

Based on the data that we compiled, the alteration of straw return quantity significantly affected TN content and crop yield. Initially, the increase in straw return quantity could significantly improve TN content and crop yield. After arriving at a limitation, there was no significant increment; furthermore, there was even a reduction in the increasing rate with superfluous straw quantity. In the meta-analysis, the return of 3000–6000 kg ha⁻¹ of straw to the field significantly increased the total crop yield and TN content compared with the higher returning quantity. Regarding the improvement in other indicators, no significant difference among different quantities was found. Similar to the continuous straw return, when an excessive amount of straw is returned to the field, it induces competition between microbes and crops for available nitrogen [7,38]. This may be the main reason why the returned straw amount of 3000–6000 kg ha⁻¹ could best increase the total crop yield. In conclusion, following the collection of an enormous amount of data, a universal returning quantity was gained from our meta-analysis. The quantity of 3000–6000 kg ha⁻¹ could effectively increase crop yield and TN while arriving at the same effect and saving straw resources compared with other quantities on the improvement for all indicators. Therefore, the quantity of 3000–6000 kg ha⁻¹ of straw return could be recommended based on the premise of balancing improvement and economy.

However, in specifically local conditions, the best straw quantity always varies with the cultivation environment. As the temperature decreased and SOC content increased in the experimental area, the applicable quantity of straw return also decreased. For example, research results from Ustals, an area in a warm temperate zone with low SOC content, revealed that the highest maize straw return of 13,500 kg ha⁻¹ resulted in the most marked increase in TN and SOM [14]. In the cultivation system of a calcareous, subtropical zone, returned maize straw treatments of 5000 kg ha⁻¹ and wheat straw treatments of 6000 kg ha⁻¹ enhanced the content of SOC more than other lower quantitative treatments [56]. In the results of research conducted in Chinese semiarid areas, warm temperate zones, and low SOC content areas, treatment with 13,500 kg ha⁻¹ of maize stalk incorporation accomplished the most effective boost in the contents of SOC and TN under the maize–millet rotation system [57]. The conditions of maize monoculture, cold monsoon climate, and treatment with the 2500 kg ha⁻¹ of maize straw on farmland can significantly enhance the relative abundance of fungi under the no-tillage condition, which benefits the increase and immobilization of SOC [15]. In terms of saline–alkali paddy soil in a cold monsoon climate, the treatment of 7300–7500 kg ha⁻¹ of rice straw decreased crop yield compared with the 5475–5625 kg ha⁻¹ treatment [47]. Ultimately, because of China's complicated terrain and climate conditions, soil type varies in China [58]. The effect of increasing straw return quantity should also incorporate a range of factors, including soil physicochemical characteristics and meteorological and management conditions [38].

4.1.4. Straw Form

A change in returning form can considerably affect the improvement in straw return on crop yield, SOC, and soil nutrients [21,42,59–63]. Different straw return forms each have their unique advantages. Compared with other forms, straw mulching has shown superiority in reducing water evaporation and increasing soil moisture, thereby enhancing crop yield and water use efficiency [50]. Furthermore, straw mulching has been observed to lower soil temperature, which is beneficial for ensuring crop growth and soil moisture during the high temperatures of the summer [51]. In contrast to mulching, straw incorporation increases the contact area between straw and soil microorganisms when the straw is buried at the soil layer of 0–20 cm, which accelerates the decomposition rate of straw [7]. One study has suggested that due to its water conservation capabilities, straw mulching may be more suitable for areas with insufficient precipitation, while straw incorporation might be better suited for regions with sufficient precipitation [38]. Deep straw burial enhances subsurface microbial activity, boosting microbial metabolism and SOM formation compared with straw mulching; comparatively, straw mulching leaves straw on the surface in a semi-dry status, resulting in more carbon and nitrogen loss through gas during decom-

position [64]. Straw biochar significantly enhances soil nutrient effectiveness through its high adsorption capacity, engaging in nutrient cycling by adsorbing key nutrients (nitrogen, phosphorus, and potassium) and facilitating ion exchange [21]. Pelletized straw disrupts the original structure and cuticle of straw, enhancing the contact area with soil and improving decomposition rates by increasing microbial biomass [65,66]. Moreover, after straw is processed into pellets, its release of carbon and nitrogen from the straw is enhanced due to the pelletization process breaking down the original adhesive structure of the straw [67]. It also helps preserve fine straw particles by forming soil aggregates, reducing carbon loss; the pelletized straw boosts SOC more effectively than unprocessed straw [68]. However, although one study discovered that the pelletized straw was observed to significantly increase grain yield in the short term more than incorporation, straw incorporation showed a long-term, slow-release benefit in enhancing SOC levels over the years [69].

Based on the results of our meta-analysis on the increase in total crop yield and maize yield, straw incorporation significantly and positively affected the yield compared with straw mulching. The possible reason for this difference is that straw mulching decomposes slower than straw incorporation, making the straw less available to crops; this may result in nutrient deficiencies and crop yield decrease [50,70,71]. The straw biochar and the pelletized straw possessed a similar effect value on each other; the effect of straw biochar on improving crop yield is contingent on a lot of external factors such as the category of soil and environmental conditions [72]. In SOC and soil nutrients, straw biochar had the biggest effect value on SOC, but there was no significant difference with straw mulching on TN, AP, and AK. Straw biochar can significantly uplift the contents of available soil nutrients and SOC sequestration due to its physicochemical characteristics [72,73]. Compared with straw incorporation, straw mulching significantly increased TN, but there was no significant difference between straw incorporation and straw mulching in improving AP, AK, and SOC. Different forms have varying impacts, each with its own best improvement in different indicators (SOC, AP, AK, TN, maize yield, wheat yield, and rice yield). Through a comparison, our findings show that straw incorporation boosted crop yield more effectively, while straw biochar enhanced SOC more efficiently compared with other forms.

However, the choice of straw return form should also be based on different objectives and environmental conditions. For instance, under cultivation conditions with limited soil moisture, opting for straw mulching might be more beneficial for ensuring crop growth compared with straw incorporation, pelletized straw, or deep burial of straw. Moreover, many experiments also explored the best form based on their local conditions. For example, straw mulching has been found to enhance SOC levels, leading to improved soil fertility and nutrient availability, particularly in dryland regions and under no-till systems [21,74,75]. In the rice–wheat system, straw incorporation can lead to the retention of SOC from farmyard manure or crop straw, limiting nutrient loss and increasing SOC sequestration [61]. The outcome of a study on Argiudolls suggested that deep straw burial can increase SOC and TN contents compared with other straw incorporation methods [64]. In the paddy soils of northeast China, biochar treatment was superior to straw in terms of SOC accumulation and increasing soil fertility [76]. Except for the foregoing forms, pelletized residue return was salutary to the rapid increment in soil nutrients, SOM, and crop yield of cultivated hibernal wheat [68]. In a warm temperate continental monsoon climate, under the winter wheat–summer maize rotation system or monoculture maize cultivation, pelletized straw significantly increased crop yield and SOC content [69,77].

4.1.5. Straw Category

As three of the most predominant crops in China, rice, maize, and wheat constitute more than three-fourths of China's total crop residues [38], which is why these crops are the major subjects of straw returning research [37,78,79]. The effects of straw return vary with the change in straw category. Under the rice–wheat rotation system, a 10-year experiment indicated rice straw was better than wheat straw in improving SOC and other nutrient properties of soil [80]. In the wheat–maize rotation system, the combination of wheat

and maize straw return diversified the abundance of soil bacteria and fungi before wheat cultivation; compared with the combination, the sole application of maize straw led to the decrease, which was regarded as unfavorable toward the sequestration of SOC [81]. The disposal of blending maize and wheat stalk return could reinforce the formation of soil aggregate, finally boosting internal SOC storage and crop yield under the integrated application of controlled-release nitrogen fertilizer [1].

In our meta-analysis, the improvement effect of the three categories of straw presented a tendency: rice straw > wheat straw > maize straw overall. Upon comparing the obtained results, it was found that the rice straw possessed the optimal effect for improving crop yield, SOC, and soil nutrient content. This distinction could possibly be attributed to their different physicochemical characteristics. In the results of the nutrients of crop residues, it was found that the rice, wheat, and maize straw were similar in carbon content but significantly different in the content of nitrogen, phosphorus, and potassium. Many articles pointed out that rice straw contained more potassium and phosphorus compared with wheat and maize straw [17,82]. Crops could ingest and assimilate the nutrients generated in the decaying process of rice straw better; rice straw could also foster the activity of microbes, releasing more nitrogen than wheat straw [80]. Moreover, the decomposition of rice straw was quick, and its nutrients were liable to be mineralized easily; thus, the employment of rice straw was conducive to the recovery of soil fertility [47]. The maize straw represented the lowest effect value in our study, which may be due to the slow decomposition. According to previous research, maize straw decomposed slower than wheat straw [83]. A study found that maize straw decreased the diversity of soil fungi compared with wheat straw; theoretically, fungi tend to decompose complex organic matter [81]. In the physical structure, the internal structure and pore characteristics of crop residues such as rice straw, wheat straw, and maize straw differ significantly. This leads to variations in their specific surface area, pore volume, average pore size, cumulative pore volume, total pore area, porosity, etc. These characteristics also influence their compactness, which is reflected in different bulk densities. The bulk density of maize straw is greater than that of wheat straw, which means greater compactness; however, greater compactness may not be conducive to decomposition [17].

4.2. Overall Effects of Manure Application on Crop Yield, SOC, and Soil Nutrients

4.2.1. Manure Application Overall Effects

The employment of manure could significantly increase soil fertility, crop yield, and SOC sequestration [84–86]. Based on the results of our meta-analysis, the ranks of the overall effect of manure application on improving the yield of different crops and the contents of different soil indicators were as follows: wheat (78.0%), maize (76.9%) > rice (47.0%); AP (157%) > AK (65.2%) > TN (41.3%), SOC (35.8%). Similar to the straw return, the ranking is based on the improvement role of manure and significant differences.

The results convey that the wheat yield increased more than the maize yield, and the possible reason could be the difference in growing season and fertilization management. The response of rice yield to manure application was lower than that of maize and wheat, which was similar to the results of a previous study [87]. This result implies that the rice yield increased under the treatment of organic manure plus chemical fertilizer but decreased under the full employment of manure. The high requirement of soil nutrients in rice growth and the sluggish process of manure nutrient release were inferred as the possible causes. In terms of the content of SOC and soil nutrients, the results of our meta-analysis were similar to the results of the previous study [88]. The difference among various elements may be because of their different characters and different manure constitutions.

4.2.2. Manure Source

Different types of organic manure can have varying nutrient contents and physical properties, which can affect their impact on soil and crops. In acidic paddy soil, the additional replenishment of cattle manure on chemical fertilizer significantly enhanced

the rice yield, TN, AP, AK, and SOC storage, which was conducive to increasing soil fertility and SOC sequestration [89]. Under rice–wheat rotation cultivation, pig manure plus chemical fertilizer could significantly increase SOC content and AP more than chemical fertilizer alone, but no significant difference in TN and AK was found [90].

In our meta-analysis, compared with the chemical fertilizer, pig manure had significantly greater effects on increasing the crop yield of total and maize indicators and the contents of AP, TN, and SOC; cattle and chicken manure significantly enhanced TN and SOC. The group of cattle, pig, and chicken manure contained treatments that partially substituted the chemical fertilizer via the corresponding manure source, which was the main reason why the pig source acquired a better effect value than the chemical fertilizer. The effect of pig manure plus chemical fertilizer was also similar to the results of the precedent study [91], which indicated that manure plus chemical fertilizer achieved a better effect value. Since the precedent study lacked classification of the manure category, it reported different effect values compared with our study. The difference in effect values among different manure categories could possibly be attributed to the difference in physical and chemical characteristics regarding cattle, chicken, and pig manure.

According to the results of the present study, pig manure could be regarded as the suitable manure source for the crop yield of total and maize indicators and the content of AP; however, chicken manure was effective in enhancing the content of TN compared with other manure sources. Since the organic manure treatments included different replacement degrees of chemical fertilization, partial manure treatment attained more remarkable effects than chemical fertilizer in terms of improving yield. However, the analysis results convey that it is not apt to recommend the total substitution of chemical fertilizers with manure; instead, the content of chemical fertilizer could be reasonably reduced after optimization and then substituted by manure to increase the crop yield. Namely, the use of a manure source could be better than using chemical fertilizer provided a proper substitute is used; therefore, the results of our meta-analysis of the use of manure sources demonstrate that pig, cattle, and chicken manure are not conclusively better than chemical fertilizer without the consideration of proportion between manure and chemical fertilizer.

4.2.3. Manure Substitute Ratio of Chemical Fertilizer

Depending on a multitude of data, the partial substitution of organic fertilizer with chemical fertilizer could acquire a higher crop yield and considerably increase SOC content and sequestration and soil fertility [35,36,92]. For example, in the rice inter-row planting experiment, partial use of organic fertilizer instead of chemical fertilizer significantly improved soil quality and accelerated soil fertility recovery [32]. In addition, under the maize cultivation system, organic fertilizer replaced 50% of chemical fertilizer, which significantly improved soil fertility and crop yield [92]. The ramifications from northern China clarified that the combination of 50% organic fertilizer and 50% chemical fertilizer can uplift the labile organic and mineral nitrogen pool while decreasing the risk of nitrogen loss, which increases the stability of soil fertility under intensive cultivation conditions [33].

The results from our meta-analysis displayed that the substitution ratio of 50–80% could significantly increase the crop yield of total and maize indicators and the contents of AK, AP, TN, and SOC compared with the ratio of 0%, namely chemical fertilizer application alone. In contrast to other substitution ratios, the substitution ratio of 50–80% significantly increased most of the indicators compared with chemical fertilizer. However, the ratio of 50–80% performed worse than the ratio <30% in the group of rice yield, and it did not possess a significant increasing role compared with other ratios in the group of TN, which showed similarity with the earlier results [93,94]. The results from the wheat–maize rotation system showed that the 25-year substitution ratio of 50–80% of organic manure to chemical fertilizer increased AP, AK, and wheat yield by 23.2%, 186.5%, and 19.0%, respectively, and decreased SOC and TN by 6.84% and 31.3%, respectively [93]. In acidic paddy soil, the substitution ratio of 50–80% increased the foregoing indicators more when compared with the ratio of <30% and 30–50% [94]. As seen from the correlation analysis, the net increases

in AK, AP, TN, and SOC were significantly relevant to the net increase in crop yield. The ratio of 50–80% significantly increased AK, AP, TN, and SOC, which could be positive for crop yield increase. Thus, although the ratio of 50–80% cannot increase rice yield better than the ratio <30%, it increases other indicators more than the rest of the ratios compared with chemical fertilizer. Therefore, a ratio of 50–80% is recommended as the suitable ratio. The specific ratio used should be based on the soil and crop types.

4.2.4. Manure Duration

As one of the critical ingredients in soil amendments, the duration of manure application could influence the effects of manure, which further affects crop yield, SOC sequestration, and soil nutrients [95]. So far, many studies have demonstrated the effects of long-term manure application on crop yield and soil [88,90,95,96]. However, a study discovered that inordinately long-term manure application decreased the effect of manure application on the improvement in SOC content compared with shorter application durations [91]. Therefore, the determination of manure application duration is very important to the optimal performance of organic amendments.

Compared with the duration < 10 years of manure application, the results from our meta-analysis revealed that the durations ≥ 20 years and 10–20 years significantly increased the crop yield of total, wheat, and maize indicators, but there was no significant difference in the rice yield. In terms of SOC and soil nutrients, the duration ≥ 20 years significantly increased SOC, TN, AP, and AK; the duration of 10–20 years was insignificantly positive in promoting TN; and the result was similar to the previous study [88]. The increment performed as a regular tendency, which gradually increased with the advance of time. As seen in our correlation analysis, the increase in SOC and soil nutrients positively affected the increase in crop yield, which can explain the promotion of maize and rice yields with the rise in SOC and soil nutrient content [55]. The rice, wheat, and maize yield was not significantly increased by the duration ≥ 20 years compared with the duration of 10–20 years. The main possible reason is that after long-term cumulation, soil nutrients and SOC are less crucial than climate, water availability, etc. [7,55]. In terms of the results of this study and other relevant previous studies, since the duration 10–20 years significantly increased the yield of the total indicator compared with the duration ≥ 20 years and there was no other significant difference between these two durations, the duration 10–20 years could be suitable.

4.3. Overall Effects of Straw plus Manure on Crop Yield, SOC, and Soil Nutrients

As a kind of plentiful source of carbon, straw could be provided for stock-raising as fodder and then transformed into manure via livestock digestion [97]. Practically, some experiments have tried to compare the improvement effect between straw and manure [97–100]. In terms of the difference between straw and manure, straw has a higher C/N (approximately 55:1) and a compact structure that is recalcitrant to decomposition [17], whereas manure has a lower C/N (approximately 25:1), which facilitates the decomposition of exogenous carbon by soil microbes, thereby accelerating the mineralization speed of soil nutrients [101]. Most manure undergoes composting and fermentation before use, a process that not only increases the content of lignin and polyphenols in the manure but also enhances the SOC content [102]. A study comparing the effects of straw return and manure application on crop yield found that manure application significantly increased crop yield by 49%, while straw return only resulted in an 8% increase [103]. This indicates that due to the significant yield-increasing effect of manure, more crop roots remain in the soil, indirectly increasing the input of exogenous carbon [104]. Therefore, compared with straw return, manure application more effectively improves soil nutrients because of its characteristics. With the increase in soil nutrients, crop yield and SOC increased mutually.

Based on their characteristics, we found that straw return can sustain soil moisture and regulate soil temperature [50,51], and manure could provide more nutrients to crops [101]. By compromising their C/N, the combined application of straw and manure may offer a

more effective method to leverage the complementary benefits of the two amendments. In terms of individual experiments, lots of studies have experimented with the combination of straw and manure. In the summer maize–winter wheat system, compared with no fertilizer application, the combined application of crop straw and manure increased SOM, soil nutrients, crop biomass, and yield [97]. Based on the results from the monoculture condition of maize, the unification of crop straw and farmyard manure could sharpen the circulation of soil nutrients and carbon storage without generating a negative impact on yield. Furthermore, compared with the chemical fertilizer, the organic fertilizer was able to immobilize surplus TN, preventing its loss [98]. In dryland farming, the combination of organic fertilizer with straw can boost soil microbial quantity, soil enzyme activity, and crop yield under maize cultivation [99]. In the results of a study on Andisols, the application of crop residues with manure could attain the biggest yield among respective treatments in both no-tillage and tillage systems [100]. However, there is no meta-analysis concentrated on the integrative effects of straw plus manure on crop yield, SOC, and soil nutrients; the specific effect of it is still not clarified well. The lack of data and the complexity of it may be regarded as the main reasons. Although the combination of straw and manure has been noticed by numerous scientists, the number of relevant articles on the subject is still obviously lower than the articles regarding the sole use of straw or manure, as the combination has always been designed as a secondary treatment rather than the primary subject. Moreover, the variables of the combination of straw and manure are excessive; for example, the quantity of straw and the substitution ratio of manure should be considered simultaneously. For these reasons, we made a meta-analysis to analyze its approximately increasing effect on crop yield, SOC, and soil nutrients that did not involve its variables.

From the results of our meta-analysis, the effect values of straw plus manure were higher than the effect values of straw return, while the values were lower than the effect values of manure application. Their combined application does not gain the anticipated synergistic benefit. The decrease in crop yield under the combination of straw plus manure application might be due to an excess of nitrogen in this treatment, which led to the production of ineffective tillers in crops [97,105]. Moreover, since a portion of manure (e.g., cattle manure) has a relatively high C/N ratio compared with others, combining them with straw might not effectively neutralize the C/N. The ratio of C/N and the amount of exogenous carbon input in the combination of straw plus manure are higher compared with the treatment with manure alone, which can affect the mineralization activity of microbes. Generally, a C/N ratio of 25:1 is considered suitable for the decomposition rate of organic matter; when the C/N ratio exceeds 25:1, the decomposition rate of organic matter decreases [106]. At the same time, most of the manure used in current experiments or production practices is composted in high-temperature fermentation tanks, resulting in a product that contains few microbes after composting, which has a negligible effect on enhancing the decomposition rate of straw.

However, considering the scarcity of present research articles on the aspect of combined application between straw return and organic manure, its specific impacts on the foregoing indexes cannot be concluded well; therefore, further research still should be conducted. Notwithstanding, economically, it is predictable that utilizing straw for livestock breeding to alleviate stock-raising costs, meanwhile producing manure through animal digestion, may become a gradually popular trend in the future. An attempt to combine straw with manure to notably enhance the efficiency of straw returning while vigorously developing manure application could potentially emerge as a major direction in sustainable agriculture practices.

4.4. Vista of Straw Return and Manure Application in China

By comparing the overall effects of straw return, manure application, and straw plus manure application, a hypothesis could be assumed. If we conduct these organic amendments to cover the major farmland of China completely, under the employment of

straw, manure, or straw plus manure, how much SOC will be in sequestration? How much crop yield could be increased?

According to the data of the Chinese National Bureau of Statistics, in 2022, the sown areas of three staple crops were collected; the calculation results are shown in Table 1. The computation was based on the mean density of SOC in China [107], and the harvest yield of three major crops in China was taken from the dataset of the Chinese National Bureau of Statistics. We determined that the generalization of straw return and manure application will benefit the development of Chinese sustainable agriculture considerably.

Table 1. The mock computation of yearly increased SOC content and crop yield in China.

Crop	Sown Area (Hectare) In 2022	Expectedly Boosted SOC (MT)	Expectedly Boosted Yield (Kg)
Maize	$43,070 \times 10^3$	Straw: 389	Straw: $36,781,780 \times 10^3$
		Manure: 1234	Manure: $23,434,387 \times 10^4$
		Straw plus manure: 537	Straw plus manure: $85,020,180 \times 10^3$
Wheat	$23,520 \times 10^3$	Straw: 213	Straw: $13,970,880 \times 10^3$
		Manure: 674	Manure: $10,732,176 \times 10^4$
		Straw plus manure: 293	Straw plus manure: $51,132,480 \times 10^3$
Rice	$29,450 \times 10^3$	Straw: 266	Straw: $51,066,300 \times 10^3$
		Manure: 843	Manure: $97,862,350 \times 10^3$
		Straw plus manure: 367	Straw plus manure: $85,051,600 \times 10^3$

4.5. Scientific Implication, Current Limitations, and Future Prospects

As a country with a large population, agriculture is the critical artery of China. In turn, the rational management of organic amendments is very important to agriculture, which impacts the development of the whole country indirectly. Under the meta-analysis based on a multitude of published articles, we confirmed the specific duration, quantity, form, and category of straw returning and the specific source, substitution ratio, and duration of manure application that possess the optimal improvement effects. This result is helpful to foster the proper utilization of organic matter returning and accelerate the achievement of the “Zero Increase Action of Chemical Fertilizer and Pesticide Usage” proposed by the Chinese government [108]. Meanwhile, precise and appropriate use of straw returning or organic manure can not only play a better role in improving soil but also reduce costs, which is conducive to reaching a harmonious balance among ecological, social, and economic benefits [109].

However, our meta-analysis did not consider the factors of original soil physicochemical characteristics (SOC, TN, soil bulk, soil moisture, etc.) and meteorological conditions (temperature, precipitation, etc.), which can affect the response of crop yield, SOC, and soil nutrients to straw returning and manure application. Moreover, the meta-analysis could be conducted under specific conditions (e.g., nitrogen use amount and temperature), which will further explore sustainable organic amendment management in the specific condition. As the impact of different management methods on straw returning and manure application improvement has been researched in this study, the suggested solution should combine this study’s results and productive practice.

Some researchers presented results demonstrating that microbes impacted the improvement in straw returning and manure application significantly [15,35]. Thus, except

to consider the foregoing limitations, further research is also needed on processes (biochemical, microbiological, and biogeochemical) that occur in the soil after straw and manure application.

5. Conclusions

This meta-analysis researched the effects of straw return, manure application, and their combination on crop yield, SOC, and soil nutrient content in China. It also evaluated the impact of different management methods for these amendments, including the category, form, quantity, and duration of straw, as well as the source, substitution ratio, and duration of manure. The main objective was to identify optimal strategies for straw and manure application. The key findings include the following:

- (1) In terms of effect values, the rank of the three organic amendments could be described as straw return < the combination of straw and manure < manure application. All significantly increased the crop yield, SOC, and soil nutrient content; however, manure application resulted in the greatest increase.
- (2) In straw return, the optimal duration varied: <5 years was beneficial to improve crop yield, while ≥ 5 years increased TN the most. The optimal quantity was the low quantity of 3000–6000 kg ha⁻¹. The optimal form varied: incorporation was beneficial to improve crop yield; biochar increased SOC more; and the optimal category was rice straw.
- (3) In manure application, pig manure was beneficial in improving crop yield, while chicken manure increased TN the most. The optimal substitution ratio was the high ratio of 50–80%, and the optimal duration was 10–20 years.

Overall, this study is fit for the development policy of China. In productive practice, the research presented in this study allows farmers to apply straw or manure precisely and decrease waste. At present, the theory of green development is prevailing around the world; this study not only provides benefits to sustainable agriculture in China but also complies with the trend of global development. On a global scale, the comprehensive and proper use of straw and manure will positively solve the problems of food crisis, soil deterioration, and global warming. However, the further exploration of straw plus manure and the consideration of microbial effects in the returning process should be researched in the future.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriculture14030480/s1>, Figure S1: A flowchart of article selection regarding straw returning; Figure S2: A flowchart of article selection regarding organic manure; Figure S3: A flowchart of article selection regarding straw returning plus organic manure; Figure S4: The correlation between yield and other variables of straw returning; Figure S5: The correlation between yield and other variables of manure application; Figure S6: Frequency distribution diagrams of different organic amendments to SOC; Table S1: Brief circumstance of annual crop residue production between China and global aggregate; Table S2: Succinct profile of annual livestock manure production in China; Table S3: The selection qualification of articles in this meta-analysis; Table S4: Data grouping of the management strategies in this meta-analysis; Table S5: Rosenberg's fail-safe number; Table S6: The correlation between crop yield and other variables in two different groups.

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