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Replacing Synthetic Nitrogen Fertilizer with Different Types of Organic Materials Improves Grain Yield in China: A Meta-Analysis

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Abstract: Synthetic nitrogen fertilizer substitution (NSS) with different types of organic material is a cleaner agricultural practice for reducing the application of synthetic N input in farmlands while also relieving the environmental issues caused by the discharge of organic wastes. However, the effects of the NSS practice on crop yields, being the primary objective of agricultural activity, is still uncertain in China. This study conducted a meta-analysis to assess the impacts of the NSS practices with different types of organic materials on crop yields. Results showed that the average crop yield was increased by 3.4%, with significant differences under NSS, thereby demonstrating that this practice contributed to improving crop yields, especially of rice and maize. According to published reports, the NSS practices involving chicken manure, pig manure, and crop straw increased crop yields by 4.79, 7.68, and 3.28%, respectively, with significant differences, thus demonstrating the superior effects needed for replacing synthetic N fertilizer. Moreover, substitution ratios (SR) between 0% and 60% could be suggested when using the NSS practice, with the high SR recommended when the original soil fertility was adequate for crops. Considering the long-term effects of applied organic materials, improving the grain yield with the NSS practice should be expected in the long-term. By effectively applying the NSS, this study attempted to scientifically decide on the type of organic materials and the appropriate SR based on the conditions of the soil and the crop. The results provide research information for the development of clean agricultural production and food security in China.

Keywords: organic materials; synthetic N fertilizer; grain yield; meta-analysis; China

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1. Introduction

Nitrogen (N) is the main limiting factor of crop productivity. During the past fifty years, the grain yield per unit area in the world has increased by 130.34%, which the wide application of synthetic N fertilizer around the world has significantly contributed to [1]. At the same time, the excessive application of synthetic N fertilizer in agricultural production has caused to serious environmental issues, including soil acidification [2], N_2O emissions [3], water eutrophication [4], acid rain [5], etc. The environmental impacts are damaging the sustainability of crop farming systems and causing the possibility of declining crop yields [6]. Therefore, how to reduce the application of synthetic N fertilizer by using scientific approaches has been a hotspot of interest in global agricultural production and sustainable development.

In recent years, replacing synthetic N fertilizer with organic materials was proposed as a possible strategy for decreasing the synthetic N input in cropping systems, which was considered as an effective N fertilizer substitution (NSS) practice. On the one hand, the addition of organic materials could provide the N element required for crops when the original applied amount of synthetic N fertilizer was reduced. On the other hand, the NSS practice contributed to the relief of various environmental issues caused by the discharge of organic materials, such as animal manure, crop straw, etc. Thus, the NSS practice has been studied in different regions, analyzing its various aspects including N use efficiency [7], N_2O emission [8], soil nutrients [9,10], and crop yield [11].

China is one of the largest agricultural countries in the world with a population of 1.4 billion, thus ensuring that grain production and food security are very important to China. The production quantities of grain crops in China increased by 44.86% during the past twenty years [12]. However, the gap between the consumption and the production of grain in China could potentially reach 130 million tons by 2025 according to the "China Rural Development Report 2020", which also estimated that grain consumption in China would be about 651 million tons in 2025 [13]. Meanwhile, the environmental pressures derived from grain production in China have been increasing during the past decades. The quantity of consumed synthetic N fertilizer in China increased by 72.5% from 2000 to 2020 [14]. However, the N use efficiency in China was only 30−35%, which was far lower than the levels in developed countries [15]. Every percentage point increase in the application of synthetic fertilizer increased the grain yield by 0.32% but the environmental costs by 1.74% during 1983–2019 [16]. Clearly, the negative environmental impacts caused by the excessive application of synthetic N fertilizer has exceeded the positive benefits of increasing the crop yield in China.

Since 2016, the government of China has begun to implement the "zero growth policy" of synthetic fertilizer use. At the same time, large amounts of organic wastes, such as crop straw and animal manure, are generated in China each year, but the utilization rate is less than 40% [17]. In this context, the NSS practice was paid more attention by researchers for reducing synthetic N fertilizer use and disposing of organic wastes. The primary standard of evaluating the benefits of the NSS practice in China was if the advanced practice could ensure crop yield and even increase yield. So far, there have been many studies exploring the effects of the NSS in different areas in China [18–22]. For example, Yang et al. [23] showed that a 30% and 50% substitution of organic fertilizer increased grain yields by 10.4% and 12.4% in Hebei province, respectively. Tang et al. [24] showed that rice yield was increased with the added input of pig manure in Jiangxi province, China. Liu et al. [25] found that the NSS practice showed a slight increase in rice yield than that of the single application of synthetic fertilizer in Jiangsu. Ma et al. [20] found that the rice yields fertilized by pig manure with all proportions were higher than those of straw treatment. Clearly, the effects of the NSS practice on grain yields were affected by various factors, including the type of organic materials, the applied amount of the organic materials and the synthetic N, the experimental site, and so on [26–28]. The effect of the NSS practice on grain yield is still uncertain in China.

Meta-analysis is a comprehensive statistical analysis method for multiple independent experiments or studies under the same subject. The method can be used for the quantitative analysis of large sample data from a macro-regional scale. In the agricultural research field, meta-analysis is mainly used for the comprehensive study of controlled trials to explore the response characteristics of the main treatments and the influence mechanisms of other key factors [29]. In recent years, meta-analysis has been widely used to explore the effects of different agricultural practices, including straw turnover [30,31], conservation tillage [32,33], and deficit irrigation [34–36]. However, information on the grain yield caused by the different NSS practices in China and the key influence factors have still been lacking.

Therefore, this study conducted a meta-analysis to quantitatively assess the impacts of the NSS practices with different types of organic materials on grain yields in China, including crop straw, animal manure, biogas residue, and biochar. The considered organic materials were the main types of organic materials applied in croplands in China at present, which were the typical representatives of the organic wastes derived from the planting, livestock rearing, and the bioenergy sectors, respectively. The results provide the theoretical basis for the rational application of the NSS practice in China, and new research information for the development of clean agricultural production in the world.

2. Materials and Data

2.1. Data Sources

The data used in this study were published peer-reviewed papers which were collected from the Web of Science (From 1985 to January in 2021, http://apps.webofknowledge.com/) and the China Knowledge Resource Integrated Database (Before January 2021, http://www.cnki.net/). The type of literature was the "article". The search terms that referred to yield, organic materials type, and reduced N fertilizer input were used in various combinations. The Boolean operators "AND" and "OR" were used to combine three separate searches and contained optional search terms. Specific search terms were set out in supplementary material (Table S1).

The filtering criteria for the collected data retrieval were as follows: (1) the experimental data were collected from field trials of wheat, maize, and rice cultivation systems in China; (2) the number of replicates in the control group (CK) and the treatment groups were not less than three; (3) the dosage of N input between the CK and the treatment groups were equal, and the CK only applied synthetic N fertilizer while the treatment groups applied organic fertilizer replace synthetic N fertilizer in different ways; (4) grain yield and standard deviation (SD) could be obtained directly from the papers or by indirect calculation; (5) the N doses of synthetic fertilizer and/or organic materials were reported for the substitution ratio (SR), defined as the N input from the organic materials that are from different sources divided by the total N input in each treatment. If more than one publication presented the results from the same field plots, we collected the experimental data from the articles that were recently published in the journals with higher impact factors. Finally, we collected a total 263 comparisons from 78 publications that met the selection criteria for meta-analysis (Figure 1). The distribution of collected test sites in the study was presented in the Figure 2.

2.2. Data Aggregation

This study summarized the results of grain yield, SD, and the number of replicates reported in the articles. At the same time, the information on the experimental site, soil type, fertilization treatment, experimental period, and regional distribution were considered. All the information forms a database in supplementary material (Table S2). For analyzing the key factors of affecting the grain yield under the NSS practice, this study divided all the collected datasets into different subgroups based on the standard of maximizing group homogenization (Table 1). Differences in regional environmental characteristics were shown in Table 2.

Figure 1. Filtration process for selection of peer-reviewed journal papers.

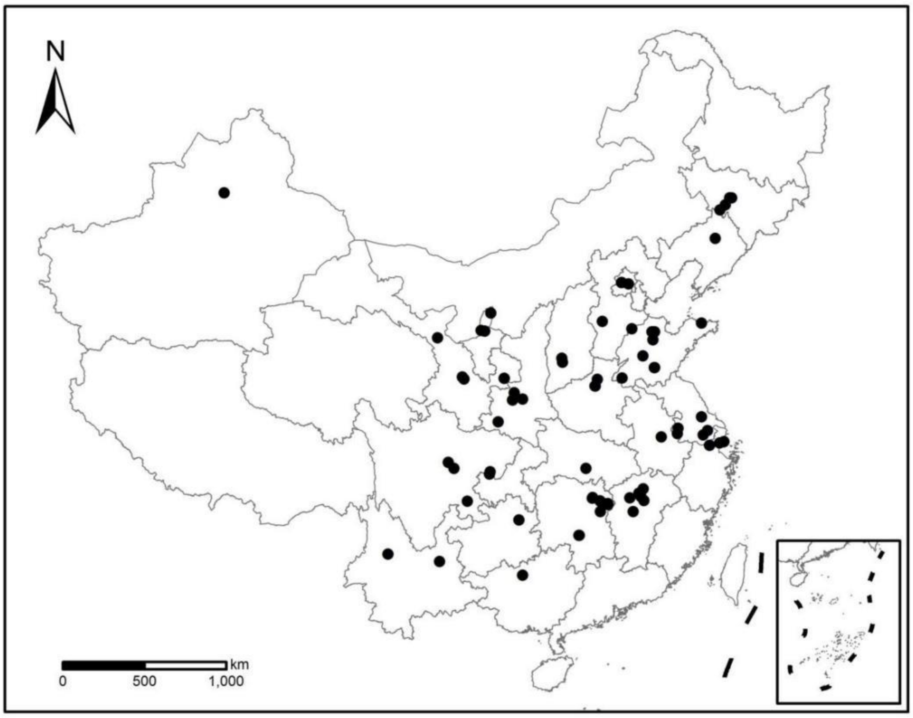

Figure 2. Distribution of test sites analyzed in the study.

Table 1. Data grouping for regional distribution, nutrients, and experimental duration.

Item	Regional Distribution	Type of Organic Materials	Substitution Ratio (SR)	Grain Type
Grouping	East China North China Southwest China Northeast China Northwest China Center South China	Cow dung Chicken manure Pig manure Straw Biochar Biogas residue	$0 < SR \leq 20\%$ $20 < SR \leq 40\%$ $40\% < SR \leq 60\%$ $60\% < SR < 100\%$	Maize Wheat Rice

Note: substitution rate (SR) is defined as the ratio of manure N input and total N input (%).

Table 2. Regional environmental characteristics [1].

Regional Distribution	Prevailing Soil Type	Prevailing Climate	Summary Soil PH	Soil Carbon
East China	Medium loam	Subtropical humid monsoon climate, temperate monsoon climate	5.39–8.56	medium
North China	Medium loam	Temperate continental monsoon climate	11.9–21.50	medium
Southwest China	Sandy loam	Subtropical monsoon climate	5.59–7.57	super
Northeast China	Clay loam	Monsoon climate of medium latitudes	6.01–7.60	super
Northwest China	Medium loam	Temperate continental monsoon climate	6.58–8.79	medium
Center South China	Loam	Subtropical humid monsoon climate	5.10–8.05	super

[1] The data were collected from the retrieved articles in the study.

2.3. Data Preparation

In this study, all of the units of grain yields in the publications were converted into kg/ha. For studies providing only standard error (SE), this study calculates SD by the following formula:

$$\mathrm{SD} = \mathrm{SE} \times \sqrt{\mathrm{n}} \tag{1}$$

where the n was the number of repetitions. If the SD and SE values were both not reported in the publications, the overall SD values were estimated in the present study based on the proportion of the mean of the SD values across all collected data. For the study of presenting data in graphic form, the software Get Data Graph Digitizer 2.26 was used in this study to extract the required mean values and SD.

2.4. Data Analysis

Meta-analysis quantifies the main indicators emerged in research results (data) through effect indicators and summarizes the different results of similar studies through weighted integration, for directly and briefly expressing the objective laws [30]. In meta-analysis, the effect value is the most basic and critical existence. The reasonable selection of the effect value is also related to the scientific and reasonable final results. Effect values can be combined, compared, and analyzed with data from different independent studies [37]. In this study, the ratio of the treatment group to the CK was used as a response ratio (R). Based on the collected results and the statistical assumptions, this study selected the natural logarithm (*lnR*) as the effect value index to reflect the impact of treatments on the corresponding indicators compared to the CK. The *lnR* was calculated based on Equation (2):

$$lnR = ln\frac{\overline{X_t}}{\overline{X_c}} = ln\overline{x_t} - ln\overline{x_c} \tag{2}$$

where the x_t and x_c were the mean values of the grain yield of the treatments and the CK groups, respectively.

The overall effect value of the treatment groups was obtained by adding the weights of the different research data pairs, which was calculated based on Equation (3):

$$lnR_{++} = \frac{\sum(lnR_i \times w_i)}{\sum w_i} \tag{3}$$

where the i was the ith observation, and the lnR_i and w_i were the effect values and weights of the ith pair of data.

The weight (w) of each data pair was the inverse of the variance (v) of the corresponding effect value. The v referred to the variance of the effect values in an independent study. The w and v were calculated based on Equations (4) and (5):

$$w = \frac{1}{v} \tag{4}$$

$$v = \frac{(S_t)^2}{n_t(x_t)^2} + \frac{(S_c)^2}{n_c(x_c)^2} \tag{5}$$

where the S_t and S_c were the *SD* values in the treatment and the CK groups, respectively, and the n_t and n_c were the number of replicates in the treatment and the CK groups, respectively.

Finally, the increased or decreased percentage (E) of grain yield between the treatment and the CK groups could be calculated by Formula (6):

$$E = (exp(lnR_{++}) - 1) \times 100\% \tag{6}$$

In this study, the mean effect sizes and the 95% confidence intervals (CIs) were generated by a bootstrapping procedure with 4999 iterations [29] by using METAWIN 2.0 [38]. If the 95% CIs included a value of 0, the treatment and the control groups were considered insignificant. If 95% CIs did not contain 0 value, it was considered as a significant difference. The NSS practice increased compared with the CK (positive effect) if it was greater than 0, whilst the NSS practice decreased (negative effect) if it was less than 0 [32]. The mean effect sizes of the subgroups were compared by classification random effect analysis in this study. Sigma Plot 12.5 software was used for plotting.

3. Results and Discussions

3.1. Effects of the NSS on Grain Yields in Different Regions in China

As shown in the Figure 3, the grain yield in the treatment groups in China was increased by 3.4% compared to the CK, with a significant difference at the $p < 0.05$ level, indicating that the NSS practice could significantly improve the grain yield in China. In particular, the grain yields were improved by 3.88%, 3.89%, 3.09%, and 3.62% under the NSS practices in northeast China, northwest China, east China, and south-central China, respectively, with significant differences. In North China and southwest China, the yields were increased by 2.81% and 3.39%, respectively, but the differences between the NSS treatments and the CK were not significant due to some special features of the field experiments. For example, the result of the decreased grain yield in southwest China was primarily caused by the overly high SR of synthetic N fertilizer [32]. The negative effect of the grain yield in the northern China mainly resulted from the shortage of irrigation water, because one of the experimental factors in the research was the limited irrigation treatment [21]. Nevertheless, the effects of the NSS practice among the different study regions did not show significant differences at the $p < 0.05$ level. In general, we concluded that the application of the NSS practice in the cropping system contributed to improving the grain yield in China. Moreover, the response of the grain yield on the NSS practice was not significantly affected by the changed regions.

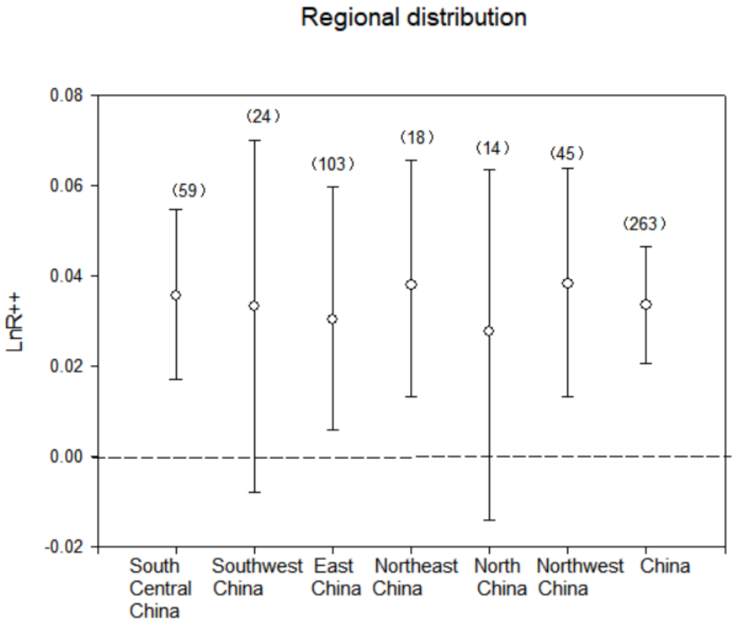

Figure 3. The weighted response of grain yield in response to different regional distributions. The values in parentheses represents the number of observations. The error bars indicates the effect sizes at the $p < 0.05$ level. The effect was statistically significant if the error bar did not bracket the dotted line (zero graduation). The notes above are applicable for the following figures as well.

In fact, the combined application of organic materials and synthetic fertilizer has been viewed as an effective approach for increasing grain yields in different regions in the world for hundreds of years [39–42]. The addition of organic materials in farmlands could improve the quality of the soil. The organic materials could not only effectively promote the reduction of soil compactness in farmlands, but also increase the buffer capacity and fertilizer retention performance in the soil [43]. Compared to the single application of synthetic N fertilizer, the decomposition and transformation rate of N in organic materials was relatively slow, which was conducive to the accumulation of N pools in the soil [44]. Meanwhile, the addition of organic materials in the farmland increased the diversity and the richness of soil microorganisms. The input of active organic carbon brought by organic materials provided a rich carbon source for the growth of soil microorganisms, thereby increasing the soil microbial activity and the N use efficiency in the farmland [44]. Moreover, more synthetic N would be fixed in the microbial body when the organic materials were applied into the soil, thus lowering the N volatilization and loss from the soil. When the N requirement of the crops increased in the middle and late growth period, the energy material in the soil to maintain the life activities of microorganisms would be inhibited. As a result, a large number of microorganisms died off, releasing part of the immobilized N that could be absorbed by the crops [45]. Moreover, the NSS practice improved the metabolism of the soil microorganisms and the crops, thereby improving the soil fertility and crop yield [26,46,47].

3.2. Influence from Grain Types

This study mainly considered the staple grain crops in China, including wheat, maize, and rice. As shown in Figure 4, the NSS practice increased the yield of rice and maize by 4.16% and 3.07%, with significant differences at the $p < 0.05$ level. The grain yield in the treatment groups for wheat production was also increased by 1.11% compared to the CK, but the difference was not significant. For example, the growing period of wheat encountered dry weather, resulting in extreme water shortage and the lower yield [48]. The soil carbon content and nutrients in the experimental treatments were much lower than in the CK group of the experiment area [49]. The soil texture is saline-alkali soil, and the organic materials released mineral elements slowly under conditions of low rainfall, thereby resulting in a significant reduction of the wheat yield [48]. Besides, one reason was possibly that the maize and the rice were mainly cultivated in the warm conditions in China while the wheat was generally cultivated in cool weather conditions. The lower temperature in the wheat planting regions limited the N mineralization and the supply from the organic materials [50]. The transfer rate of the N to the grains was reduced because the wheat was sensitive to the high N input in the late growth period [51]. Although the yield increase effect of the wheat was not significant, the combined application of the organic and the synthetic fertilizers could improve the quality of the wheat grains, including the increase of crude protein and crude fat content in the grains [49]. Moreover, the difference among the wheat, maize, and rice yields under the NSS practice were not significant.

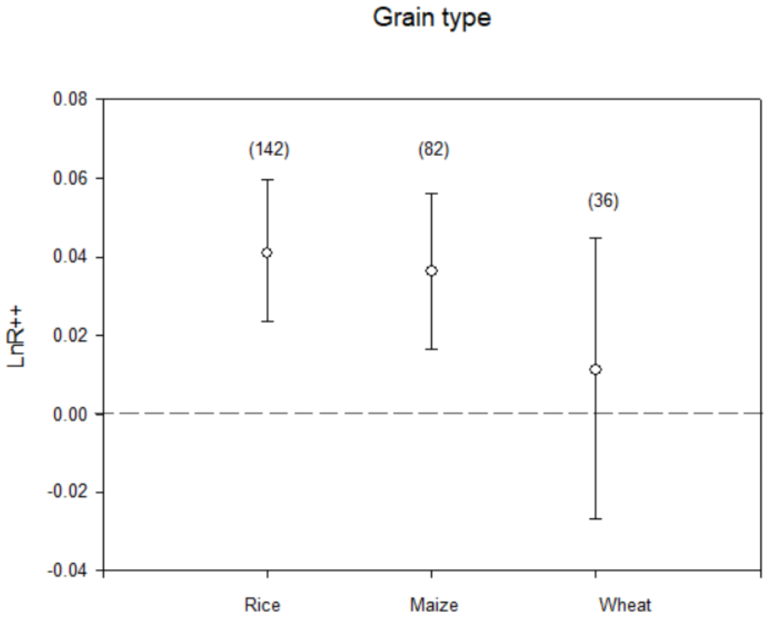

Figure 4. The weighted response of grain yield in response to different grains types.

3.3. Influence from the Type of Organic Materials

As shown in Figure 5, when the pig manure, chicken manure, and straw were used as a N source, the grain yields were increased by 4.79%, 7.68%, and 3.28%, respectively, with significant differences at the $p < 0.05$ level. The grain yields in the cow manure and the biochar treatments were also increased by 0.97% and 1.4%, respectively, but the differences were not significant at the $p < 0.05$ level. Specifically, the chicken manure showed the greatest increase effect on the grain yield, possibly due to the high nutrient content. The effect of improving the yield by the chicken manure NSS practice presented significant differences when compared to the cow dung and the biogas residue treatments. The N supply capacity of the pig manure, the cow manure, the crop straw, and the biochar were generally less than that of the chicken manure. When the proportion of the synthetic fertilizer was at a low level, the chicken manure could supply timely nutrients for the grain compared to the other organic materials [52]. However, the grain yield in the biogas-residue-based NSS treatment was decreased by 2.95%, although the difference was not significant at the $p < 0.05$ level. The possible reason was that the content of the organic carbon in the biogas residue was less than the other types of organic materials, which affected the soil fertility. Moreover, because the collected data on the biogas-residue-based NSS treatment were limited, the effect of the biogas residue on the grain yield should be further analyzed by using more and longer experimental results. Generally, we believed that the application of different types of NSS practice in the cropping system, except for the biogas residue, contributed to improving the grain yield in China. The NSS practices involving the chicken manure, the pig manure, and the straw were the best options for improving the grain yield in China according to the current published results.

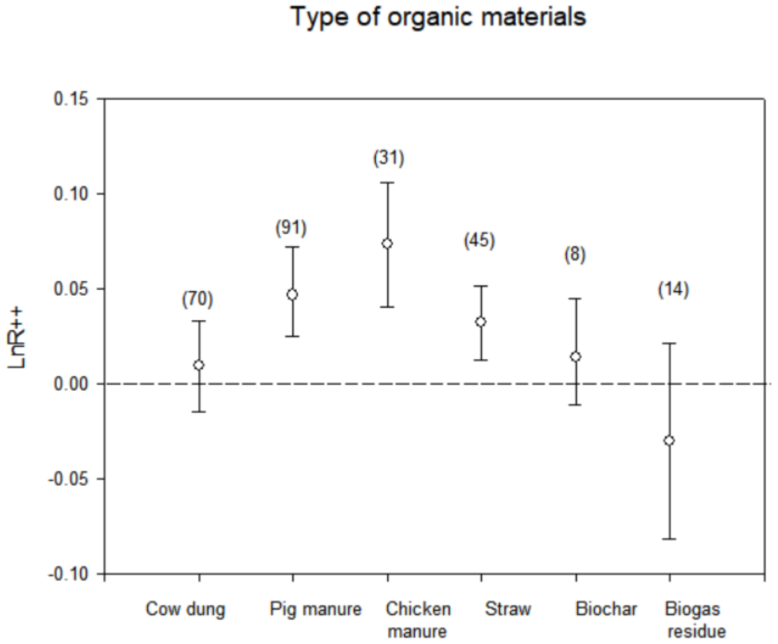

Figure 5. The weighted response of grain yield in response to different types of organic materials.

3.4. Influence from Substitution Ratio

According to Figure 6, when the SRs were less than 60%, the grain yields were increased by 3.01–4.08% compared to the CK, respectively, with significant differences at the $p < 0.05$ level. The grain yield was increased by 3.16% as well when the SR was more than 60%, but the difference was not significant because some of the published results showed a negative effect on the grain yield. Meanwhile, the effects among the different SRs also did not present significant differences. Clearly, the overly high SR in the NSS practice could potentially have caused the reduction of the grain yields. The primary reason was that the slow release of the organic materials limited the N supply to the early stage of crop growth. The original soil fertility was the most important factor related to the SR of the NSS practice. The soil with poor fertility should adopt a lower SR to meet the immediate demand of crops for nutrients. For the soils with higher fertility, the higher SR in the farmland contributed to improving the soil microbial activity, activating the soil nutrients, and hence simultaneously increasing the grain yield [25,53]. In fact, the yield of the cropping system that only applied the organic materials was even higher than the combined application of the organic and the synthetic fertilizers in some studies when the soil fertility was high enough [26]. In addition, different types of the organic materials had different mineral rates and humification coefficients [54]. The results implied that the appropriate SR must be scientifically decided based on the actual conditions of the research regions, although the higher SR meant the lower input of synthetic N fertilizer and the more consumption of organic wastes in the farmland, which was possibly helpful for decreasing environmental pollution.

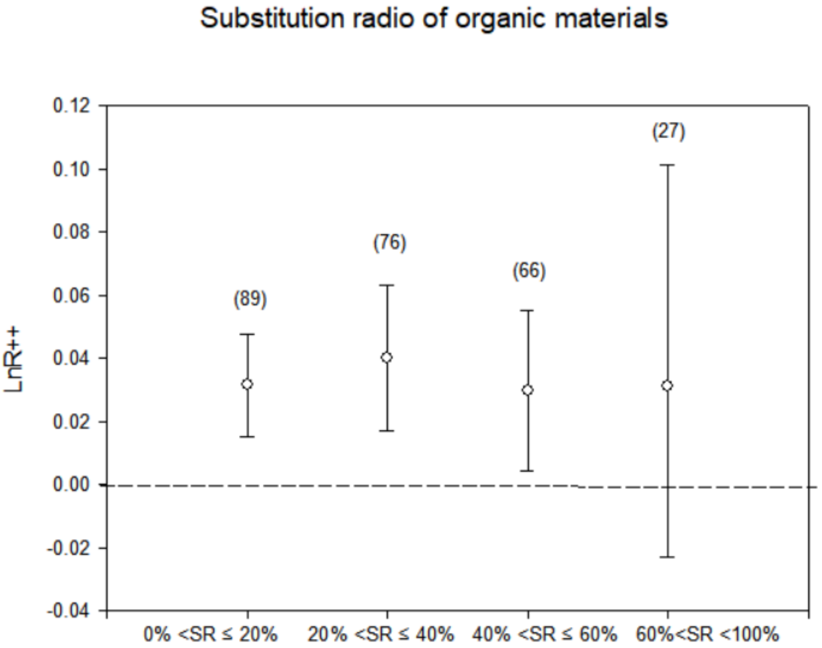

Figure 6. The weighted response of grain yield in response to different substitution ratios of organic materials.

4. Conclusions

The effects of the NSS practice on grain yields, the primary objective of agricultural activity, were still uncertain in China. This study conducted a meta-analysis to quantitatively assess the impacts of the NSS practices with different types of organic materials on grain yields in China. The results showed that the application of the NSS practice in cropping systems contributed to the improvement of rice and maize yields in China. Moreover, the response of the grain yields on the NSS practice would not be significantly affected by the changed regions. According to the current published results, chicken manure, pig manure, and straw were the best options to replace synthetic N fertilizer for improving grain yields in China. Moreover, in the case of poor soil texture, the NSS practice has a negative effect on the grain yield. Therefore, it is recommended to use SRs less than 60%. However, 60% SRs could also be considered when the soil original fertility is superb.

We also noted two limitations in this study. First, this study did not analyze the responses of the soil properties, the crop varieties, and the characteristics of the organic materials to the NSS practice in China due to the lack of detailed data. Second, because one of the important standards of collecting a raw dataset was the same amount of N input between the CK and the treatment groups, the relative published results in some regions were limiting. They lowered the reliability of the conclusions derived from the meta-analysis, especially for those in the North China Plain and in southwest China.

Overall, the application of the NSS practice in the cropping system has generally showed the positive effect on increasing the present grain yield in China. Considering the long-term effects of the applied organic materials, the improvement of the grain yield by the NSS practice should be expected in the long-term period of application. Under the background of the development of a sustainable agricultural system in China, the NSS practice showed a good potential to spread to more regions. The key points of effectively applying the NSS practice were to scientifically decide on the type of organic materials and the appropriate SR based on the actual conditions of the soil and the crops during agricultural production.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11122429/s1, Table S1: Key word list; Table S2: Information on long-term field experiments in the published references.

Author Contributions: X.F.: Writing Original draft preparation, Data curation. Z.C.: Investigation. Z.N.: Investigation. R.Z.: Data curation. J.O.: Data curation. X.L.: Methodology. X.W.: Writing-Reviewing and Editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

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