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Green Manure Mediated Improvement in Saline Soils in China: A Meta-Analysis

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Abstract: The application of green manure is a traditional and valuable practice to improve the fertility of saline soil. However, the impact of environmental factors, green manure types and returning methods on the changes in soil fertility and soil salinity remain poorly quantified at a large scale. In the present study, we conducted a meta-analysis to generate a comprehensive evaluation of the effects of green manure on soil organic carbon (SOC), soil salt content, and soil nutrients compared to bare soil in China. The results showed that compared with bare soil, green manure planting could significantly increase the SOC content of saline soil, reduce salt content, and improve the soil total nitrogen (N), soil available phosphorus (P) and soil available potassium (K) contents. On average, green manure significantly enhanced SOC by 34.82% (percentage change), soil total N by 32.23%, soil available P by 34.34% and soil available K by 17.43%, while reducing soil salt content by 47.75%, compared to bare soil. In areas with a mean annual temperature (MAT) of <10 °C or a mean annual precipitation (MAP) of 200–400 mm, green manure had the largest increase in SOC, soil total N, soil available P, and soil available K. The smallest increases were observed in areas with an MAT above 15 °C and MAP greater than 800 mm. Green manure types influenced the improvement effect of green manure on saline soil. Green manure mixtures were more conducive to increases in SOC, while the increases in soil total N resulting from mixed green manure were lower in comparison to those from both legumes and non-legumes. In addition, the initial salt content, experimental years, and returning method influenced the improvement effect of green manure on saline soil. Therefore, this meta-analysis identified green manure as a promising practice for significantly improved saline soil in China.

Keywords: green manure; saline soil; SOC; soil nutrients; meta-analysis

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1. Introduction

Soil salinity is a major problem restricting the sustainable development of agriculture in China [1]. In areas with arid climates, high groundwater levels and poor drainage, there is a high amount of evaporation near the surface and a strong vertical movement of capillary water in the soil, which carries the salt from the deep soil to the surface of the soil, resulting in soil salinization [2]. Statistics indicate that the total area of saline soil in China reaches approximately 99 million hectares, with over 9.2 million hectares classified as saline arable land, accounting for 6.62% of China's arable land area [3,4]. As the population continues to grow and the national economy develops, the pressure on food production is increasing, and saline soil is widely considered an important reserve of arable land resources [5,6]. However, the high and excessive salt content in saline soil leads to the destruction of soil structure and reductions in soil fertility and water permeability, which in turn, adversely restrict crop growth and limit soil productivity [7,8]. Therefore, it is imperative to develop a green and sustainable method for improving and developing saline soils to enhance land productivity.

The methods used to improve saline soils mainly include engineering measures, chemical measures, biological measures and comprehensive management methods [9–12]. Among the various soil improvement measures, biological measures, due to their notable environmental benefits, water-saving potential, and economic efficiency, are increasingly showing their unique advantages, and gradually occupy an important position in the management of saline soils in China, becoming an important direction of development [13–15]. Historically, China has utilized green manure to enhance soil quality and agricultural productivity. Halophytes and green manure grasses with a certain salt tolerance, such as *Sesbania cannabina*, alfalfa (*Medicago*), *Suaeda salsa*, common vetch, etc., have been successfully used to improve saline soils [16–18]. Extensive research has demonstrated that green manure plants can absorb soil salt through their roots and store it in plant tissues, thereby resulting in decreases in soil salinity [19]. The application of green manure can also produce a large number of organisms that can be returned to farmland, thus providing a large amount of soil organic matter, soil nitrogen, soil phosphorus and soil potassium, all of which contribute to enhanced agricultural productivity [20,21]. Green manure not only effectively improves soil quality and enhances soil fertility, but also aligns with the principles of ecological prioritization and sustainable development. Therefore, the application of green manure for soil improvement is receiving increasing attention.

In recent years, research on the application of green manure for saline soil improvement has gradually increased. SOC, N, P and K are essential metrics of farmland ecosystems productivity, and critical indicators for evaluating the effectiveness of saline soil amelioration [22]. However, the conclusions of the current research on the effects of green manure on soil improvement in saline soil regions have reached contradictory conclusions. For example, some studies have shown that the introduction of green manure leads to a reduction in SOC [23], which contradicts the mainstream notion that green manure can increase SOC. This was attributed to the decomposition of SOC induced by plant inputs to the soil [24], which plays an important role in changes in SOC [25]. The improvement effect of green manure varies according to climate and management measures, but the influence of climate and environmental factors cannot be reflected in a field experiment in a specific location. Furthermore, most of these isolated case studies have assessed the effect of green manure in terms of a single aspect. In order to study the relationships between multiple factors in the improvement effect of green manure, it is necessary to use the existing data of independent studies to conduct a comprehensive analysis. Meta-analysis is a comprehensive method of analyzing a series of independent studies [26]. Currently, no meta-analysis is available that quantitatively evaluates the influence of green manure on soil improvement in saline soil areas. Therefore, it is of great significance to determine the formation mechanism and influencing factors of green manure's effects, especially on saline soil improvement, in order to promote the development and utilization of low-yield fields with saline soil in China.

The present study collects field trial data on green manure cultivation for saline soil improvement in China, and based on the meta-analysis method, aims to quantify the effects of green manure on SOC, soil salinity and soil nutrients in saline soil, as well as quantitatively analyze the influences of climate, soil salt content, green manure types and returning methods on the improvement effect. This study has the following aims: (1) determine whether green manure has positive effect on saline soil improvement; (2) examine the effects of environmental conditions and biotic factors on saline soil improvement following green manure application; and (3) identify the key driving factors for saline soil improvement in China. Our report offers comprehensive scientific recommendations for the application of green manure practices in saline soil areas across China.

2. Materials and Methods

2.1. Data Collection

An extensive search of peer-reviewed literature was conducted in Web of Science, Google Scholar, Elsevier, and China National Knowledge Infrastructure (CNKI) from 1970 to 30 June 2023. As search terms, we used the following keywords and combinations: "green manure", "legume forage plant", "halo-tolerant plant", "coastal saline soil", and "alkali saline". We limited the publications to those written in English or Chinese.

The following criteria were applied to select relevant publications: (1) The experiments using green manure were conducted in China, and the basic information such as the start and end year and location of the experiment is clear. (2) The experiments were conducted in field conditions only and for at least one year. (3) The field experiment included one treatment group with a green manure application compared with no green manure (fallow) as a control group. (4) The experimental results included at least one of the following indicators: SOC, soil organic matter, soil total N, available P, available K, and soil salt content. (5) The observations of experiments included at least the top 20 cm of soil depth. (6) The experimental results included the sample size, mean, and standard deviation (SD), and the sample size was not less than 3 replicates. Eventually, 30 peer-reviewed publications and 455 observations were compiled into the dataset. Most data were either obtained from tables and the main text or extracted from figures using GetData Graph Digitizer v2.25. In addition, the number of replicates, SDs and other relevant information were extracted (i.e., climatic conditions, green manure types, number of experimental years, etc.). Detailed information on the location and green manure type in each study can be found in Supplementary Materials.

2.2. Data Calculation

SOC content (g kg^{-1}) was transformed from soil organic matter (g kg^{-1}) content with a conversion coefficient of 0.58 [27], in cases where the soil organic matter (SOM) value was reported but the SOC value was missing. The formula was as follows:

$$SOC = SOM \times 0.58 \tag{1}$$

where SOM means soil organic matter (g kg^{-1}).

2.3. Data Categorization

The effects of green manure on soil improvement in saline soil were further defined according to sub-groups for mean annual temperature (MAT), mean annual precipitation (MAP), initial soil salt content (ISSC), green manure types, experimental years, and returning methods. Specifically, MAT was divided into three categories: <10 °C, 10–15 °C, and >15 °C. MAP was categorized as four groups: <200 mm, 200–400 mm, 400–800 mm, and >800 mm. The ISSC was divided into four categories: 1–3 g kg^{-1}, 3–5 g kg^{-1}, 5–10 g kg^{-1}, and >10 g kg^{-1}. The green manure types were grouped into three categories of legume, non-legume and mixtures. The returning methods of green manure were divided into incorporation and non-incorporation. The number of experimental period was categorized according to actual conditions.

2.4. Meta-Analysis

The natural log of the response ratio (RR) as the effect size was used to test the green manure effect on the measured parameters and was calculated as follows [28]:

$$lnR = ln(\frac{Y_e}{Y_c}) = ln(Y_e) - ln(Y_c) \tag{2}$$

where Y_e and Y_c represent the mean values for green manure treatments and bare fallow controls, respectively. Use of the natural log ratio ensures that equal proportionate changes occurred in the numerator and the denominator.

The error variance (V) was calculated as [29]:

$$V = \frac{S_e^2}{N_e Y_e^2} + \frac{S_c^2}{N_c Y_c^2} \tag{3}$$

where Y_e and Y_c represent the mean values for green manure treatments and bare fallow controls, respectively; S_e and S_c are standard deviations, and N_e and N_c are the number of replications for green manure treatments and bare fallow controls, respectively.

The weight (W) for each RR was calculated as follows:

$$W = 1/V \tag{4}$$

The overall mean RR (RR_{E++}) was calculated as follows [30]:

$$RR_{E++} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{m} W_{ij}RR_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{m} W_{ij}} \tag{5}$$

where n and m are the numbers of green manure treatments and bare fallow controls in each category.

The standard error of RR_{E++} was calculated as follows [30]:

$$SE = \sqrt{\frac{1}{\sum_{i}^{n}\sum_{j}^{m} W_{ij}}} \tag{6}$$

The 95% confidence interval (95% CI) was calculated as follows [26]:

$$95\%CI = RR_{E++} \pm 1.96SE \tag{7}$$

If the 95% confidence interval is >0, the green manure application has a significant positive effect on saline soil improvement; if it is <0, green manure application has a negative effect on saline soil improvement; if it overlaps 0, green manure application has no significant effect on saline soil improvement.

For ease of interpretation, the overall mean RR_{E++} was transformed back to the percentage change using the formula below [31]:

$$RR(\%) = (exp(RR_{E++}) - 1) \times 100\% \tag{8}$$

In the present study, a random effects model was used for the data analysis. Rosenthal's fail-safe number was used to test the biasness of the publication. A fail-safe number > (5n + 10), where n is the number of observations, indicates no publication bias. As shown in the table, the heterogeneity test reached a significant level ($p < 0.05$), and the safety factors were all above the threshold (5n + 10), indicating no publication bias (Supplementary Tables S1 and S2).

2.5. Statistical Analysis

Statistical analyses were performed using MetaWin 2.1 [32] (Sinauer Associates Inc., Sunderland, MA, USA). All plots were prepared using GraphPad Prism 10.0 (GraphPad Software Inc., SanDiego, CA, USA).

3. Results

3.1. Impacts of Green Manure on SOC

Compared with bare soil treatments, green manure applications had a significant positive effect on SOC in saline soil areas (Figure 1). Excluding humid areas, green manure had significant SOC-increasing effects in all climatic regions compared with bare soil, and the maximum SOC increase of 78.36% was observed at MAP 200–400 mm (Figure 1a). Temperature also influenced the SOC-increasing effect of green manure in saline soils. When MAT was in the range of 10–15 °C or ≤10 °C, green manure increased SOC significantly by 21.94% and 46.71%, respectively; while the SOC increase was not significant under a MAT of ≥15 °C (Figure 1b). Moreover, green manure increased SOC by 26.13%, 11.88%, 25.75%, and 36.15% when the ISSC was in the ranges 0–3, 3–5, 5–10, and ≥10 g kg^{-1}, respectively (Figure 1c).

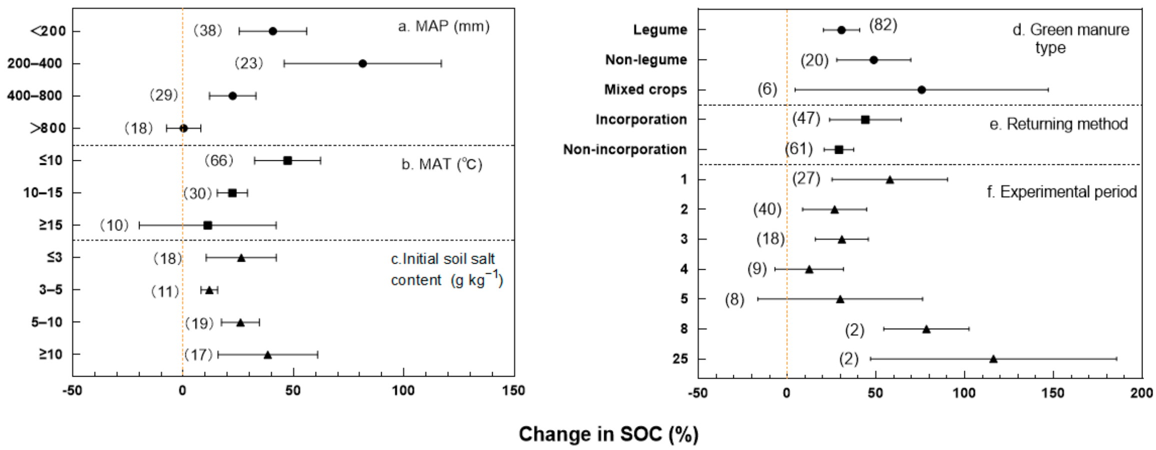

Figure 1. The effect of green manure on soil organic carbon (SOC). The number beside each bar indicates the number of observations. Error bars indicate the effect sizes at $p < 0.05$ level. The effect is statistically significant if the error bar does not overlap the zero graduation.

Compared with bare soil, the highest increase (66.09%) in SOC was observed under mixtures of legume and non-legume green manure, followed by non-legume green manure at 47.04%, and the legume green manure had the smallest increase at 30.23% (Figure 1d). Green manure under both returning methods has a positive effect on SOC, which increased by 42.5% under green manure with incorporation and by 29% under green manure without incorporation (Figure 1e). Compared with bare soil, green manure significantly increased the SOC of saline soil by 55.88% (1 year), 25.84% (2 years), and 28.92% (3 years). However, the SOC increase was not significant when the experimental period was 4 and 5 years. However, when the experimental period exceeded 5 years, the SOC significantly increased by 77.24% (8 years) and 108.78% (25 years) (Figure 1f).

3.2. Impacts of Green Manure on Soil Salt Content

Compared with bare soil, green manure significantly reduced the salt content of saline soil overall, with a decrease of 47.75% (Figure 2). Rainfall influenced the decreasing effects of green manure on soil salt content. In areas with MAP < 200 mm and MAP > 800 mm, green manure significantly reduced soil salt content by 48.56% and 45.18% compared to bare soil. Under the conditions of MAT > 15 °C, 10–15 °C, and <10 °C, green manure significantly reduced soil salinity by 52.68%, 47.37%, and 46.84%, respectively, compared to bare soil. The above results show that the higher the annual temperature, the higher the rate of soil salt content decrease. In addition, the decreasing effect of green manure on soil salinity varies among different types of saline soils. Compared to bare soil, green manure decreased soil salt content significantly, by 53.28%, 42.74%, 24.23% and 60.83%, when the ISSC was <3, 3–5, 5–10, and ≥10 g kg^{-1}, respectively.

It is worth noting that green manure types also had a significant impact on the salt content of saline soil, with the reduction effect of legume green manure (49.74%) being higher than that of non-legume green manure (42.15%). Compared with bare soil, green manure with non-incorporation reduced soil salt content by 49.27%, while the reduction effect of green manure with incorporation was 25.26%, which was also significant but lower than the former. Finally, with the increase in experimental years, the decrease in soil salinity showed an increasing trend. From 1 year to 25 years, the decrease in soil salt content was 39.93%, 33.64%, 56.01%, 52.20%, 69.33%, and 76.59%, respectively.

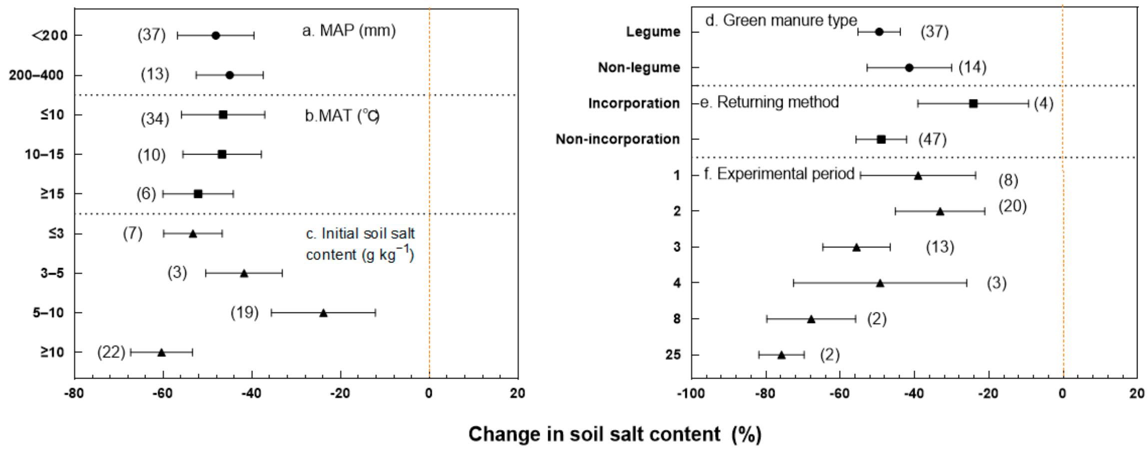

Figure 2. The effect of green manure on soil salt content. The number beside each bar indicates the number of observations. Error bars indicate the effect sizes at $p < 0.05$ level. The effect is statistically significant if the error bar does not overlap the zero graduation.

3.3. Impacts of Green Manure on Soil Nutrients

3.3.1. Impacts of Green Manure on Soil Total N

Compared with bare soil, green manure significantly increased the soil total N in saline soil (with an average effect size of 32.23%). Compared with bare soil, green manure increased soil total N significantly, by 32.79% in MAP < 200 mm, by 41.65% in 200–400 mm, by 38.32% in 400–800 mm and by 9.76% in MAP > 800 mm (Figure 3a). In areas with a MAT of 10–15 °C and ≤10 °C, the increases in soil total N were similar, at 35.27% and 35.57%, respectively. However, soil total N showed no significant change as a result of the introduction of green manure in areas with a MAT of ≥15 °C (Figure 3b). In saline soils with different ISSC, the highest soil total N increase of 66.98% was observed at 3–5 g kg^{-1} of ISSC, and the lowest soil total N increase (36.95%) was observed at 5–10 g kg^{-1} of ISSC. Moreover, the soil total N increase was 44.64% under ISSC ≤ 3 g kg^{-1}, and 41.86% under ISSC ≥ 10 g kg^{-1} (Figure 3c).

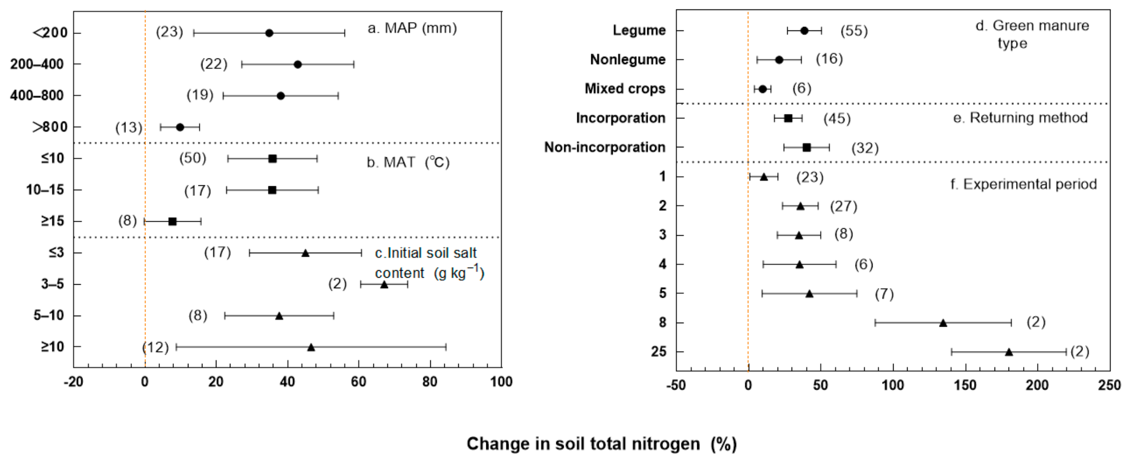

Figure 3. The effect of green manure on soil total nitrogen (N). The number beside each bar indicates the number of observations. Error bars indicate the effect sizes at $p < 0.05$ level. The effect is statistically significant if the error bar does not overlap the zero graduation.

Compared to bare soil, the legume green manure had the greatest soil total N increase rate of 38.48%, while the non-legume and mixed green manure had soil total N increases of 20.87% and 9.65%, respectively (Figure 3d). Green manure with incorporation reduced soil salt content by 27.41%, while the reduction effect of green manure with non-incorporation was 39.32%, which was higher than the former (Figure 3e). Compared to bare soil, soil total

N was significantly increased by 10.35% (1 year); over 1 year, the increase in soil total N became larger (by an average value of 34.87%) for 2–5-year experimental periods; after applying green manure for 8 and 25 years, the soil total N significantly increased, reaching 131.45% and 178.18%, respectively (Figure 3f).

3.3.2. Impacts of Green Manure on Soil Available P

Compared with bare soil, green manure significantly increased soil available P by 64.32% and 38.05% in areas with MAP < 200 mm and >800 mm, while its effect on soil available P was not significant for areas with MAP of 200–400 mm and 400–800 mm (Figure 4a). The P-increasing effect of green manure was in the following order: 10–15 °C (39.05%) > above 15 °C (34.06%) > below 10 °C (30.13%) (Figure 4b). Under ≤3, 3–5, 5–10 and ≥10 g kg^{-1} ISSC, the soil available P increases were 35.98%, 43.4%, 46.00%, and 50.04%, respectively. The overall trend showed an increase with the increase in salinity (Figure 4c).

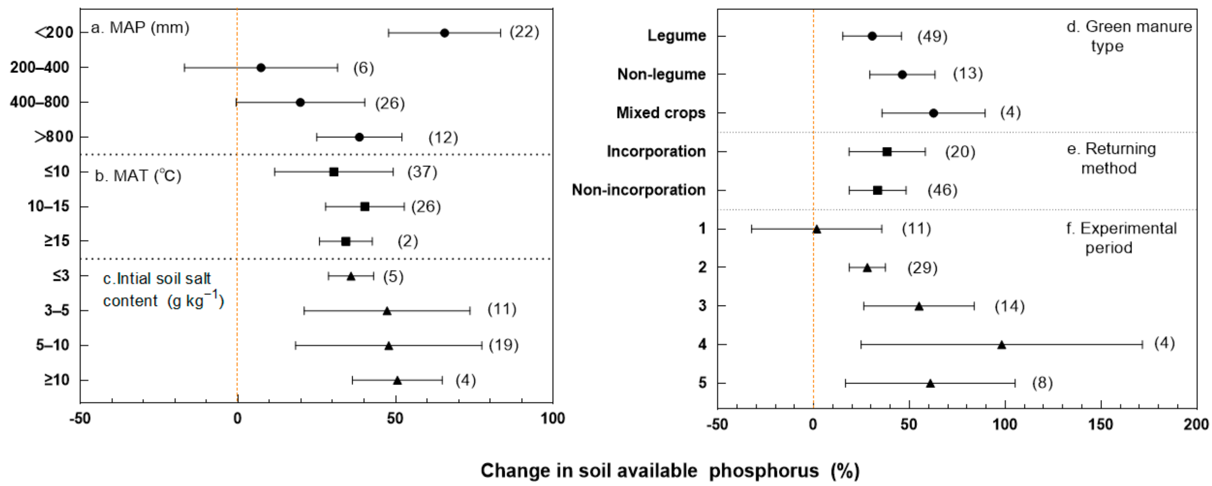

Figure 4. The effect of green manure on soil available phosphorus (P). The number beside each bar indicates the number of observations. Error bars indicate the effect sizes at $p < 0.05$ level. The effect is statistically significant if the error bar does not overlap the zero graduation.

Green manure types also influenced the increase rate of soil available P, with legume green manure and non-legume green manure significantly increasing soil available P by 30.21% and 44.15%, respectively; under green manure mixture conditions, soil available P increase reached the greatest value of 57.53% (Figure 4d). Both green manure with or without incorporation had a positive effect on soil available P, which significantly increased by 36.94% under incorporation and by 33.23% under non-incorporation (Figure 4e). In terms of experimental years, the application of green manure for one year did not show a significant P-increasing effect compared to bare soil; over two years, the increase in soil available P became larger with multiple experimental years until it reached its maximum value of 85.45% for a four-year experimental period, but over four years, the increase dropped to 55.73% (Figure 4f).

3.3.3. Impacts of Green Manure on Soil Available K

Compared with bare soil, green manure significantly increased soil available K by 27.81% and 34.18% in areas with MAP of <200 mm and 200–400 mm, while its effect on soil available K was not significant in areas with MAP of 400–800 mm and >800 mm (Figure 5a). The K-increasing effect of green manure was in the following order: 10 °C (23.84%) > above 15 °C (15.09%) > 10–15 °C (7.96%) (Figure 5b). Under ≤3, 3–5, 5–10 and ≥10 g kg^{-1} ISSC, the soil available K increases were 16.05%, 6.88%, 15.57%, and 40.20%, respectively. The overall trend showed a decrease followed by an increase (Figure 5c).

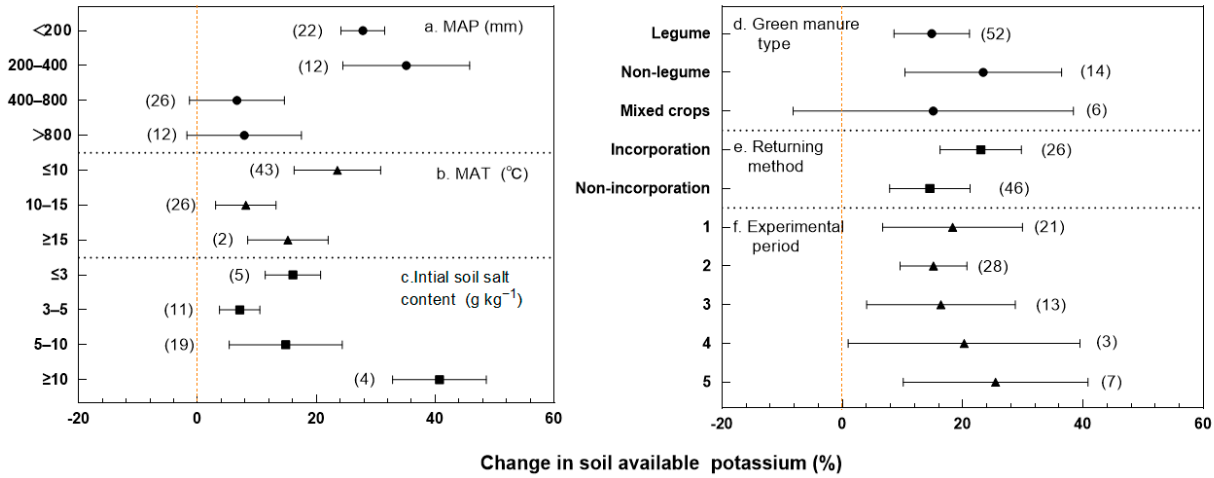

Figure 5. The effect of green manure on soil available potassium (K). The number beside each bar indicates the number of observations. Error bars indicate the effect sizes at $p < 0.05$ level. The effect is statistically significant if the error bar does not overlap the zero graduation.

Legume green manure and non-legume green manure significantly increased soil available K by 15.6% and 25.24%, while the green manure mixture did not have a significant positive effect on soil available K (Figure 5d). Both green manure with or without incorporation had a positive effect on soil available K, which significantly increased by 22.52% under incorporation and by 14.47% under non-incorporation (Figure 5e). With increased experimental years, the overall trend was an increase in soil available K. The maximum soil available K increase of 22.86% was observed when the number of experimental years was 5 (Figure 5f).

3.3.4. Factors Affecting the Response of SOC, Soil Salt Content, Soil Total N, Soil Available P, and Soil Available K to Green Manure in Saline Soils

MAP and MAT were predominant predictors influencing SOC and available K under green manure application. Overall, 39.54% and 23.67% of the variation in SOC could be explained by the MAP and MAT factors, respectively. Experimental years was the most dominant factor driving variation in soil salt content (RI = 62.71%), in soil total N (RI = 71.31%), and soil available P (RI = 37.38%).

4. Discussion

4.1. SOC Changes Due to Green Manure

The results from this meta-analysis indicated that green manure significantly increased the SOC content of saline soil compared to bare soil treatment (Figure 1). On the one hand, the organic matter such as roots and litter from green manure is returned back into the soil, where it undergoes decomposition and mineralization, thereby releasing essential nutrients and contributing to an increase in soil carbon storage [33,34]. On the other hand, the application of green manure enhances the soil carbon sequestration capacity through several mechanisms. The root secretions and humus from green manure bind soil particles into larger aggregate structures, which encapsulate organic carbon [35]. This physical protective effect mitigates the decomposition and utilization of organic carbon, thereby improving its sequestration in the soil [36]. Additionally, green manure increases surface vegetation coverage, reduces soil erosion [22], and consequently diminishes the loss of SOC. The initial soil salt content has a great influence on the effects of green manure on SOC. The results show that the organic carbon increase in saline soils with a ISSC of 1–3 g kg^{-1} was higher than that for soils at 3–5 g kg^{-1} and at 5–10 g kg^{-1}, while the organic carbon increase at >10 g kg^{-1} was significantly higher than the former three (Figure 1c). This result indicates that there was not a simple linear relationship between salt content and SOC increase. This might be due to the fact that green manure crops used in saline soil areas usually have a certain salt tolerance. Low salt concentration can promote their growth and contributes to increasing SOC input, while high salt stress shows inhibition of green manure growth. Furthermore, the salt content affects organic carbon mineralization by influencing soil microorganisms and soil carbon and nitrogen fixation ability [37], which ultimately leads to more SOC accumulation in saline soils with a salt content of 1–3 g kg^{-1}. It should be noted that the highest observed increase in SOC may be related to the initially low native organic carbon content of these soils. The relative increase in SOC following green manure planting was much greater in saline soils at a salt content >10 g kg^{-1}, compared to the other three types of saline soils with different salt concentrations (≤3 g kg^{-1}, 3–5 g kg^{-1}, 5–10 g kg^{-1}).

Precipitation and temperature are key climatic factors influencing the effects of green manure on SOC in saline soil areas (Figure 6). The SOC-increasing effect of green manure was not significant in areas with MAT > 15 °C or MAP > 800 mm (Figure 1a,b), indicating that a humid and warm climate was not conducive to the accumulation of organic carbon in saline soils. Previous research reports that runoff and erosion are closely related to soil SOC change. Green manure cultivation can reduce the runoff and erosion effects through the presence of vegetative cover, which in turn promotes the accumulation of SOC [38]; however, in warm and humid environments, there is more surface and underground runoff, as well as intensified hydraulic erosion and microbial activity compared to other climates. Studies have shown that as temperature and humidity increase, soil respiration and soil microbial biomass carbon are relatively high, leading to higher SOC losses than in other climates [39]. Mo et al. [25] observed that the microbial priming effect, namely the organic carbon decomposition induced by exogenous plant organic matter input, is an important driving factor for SOC changes, leading to stronger priming effects and greater SOC losses in areas with humid and hot climates. Based on the above reasons, the SOC losses caused by a humid climate cannot be balanced by the SOC-increasing effect of green manure, resulting in insignificant SOC increases under this climate condition.

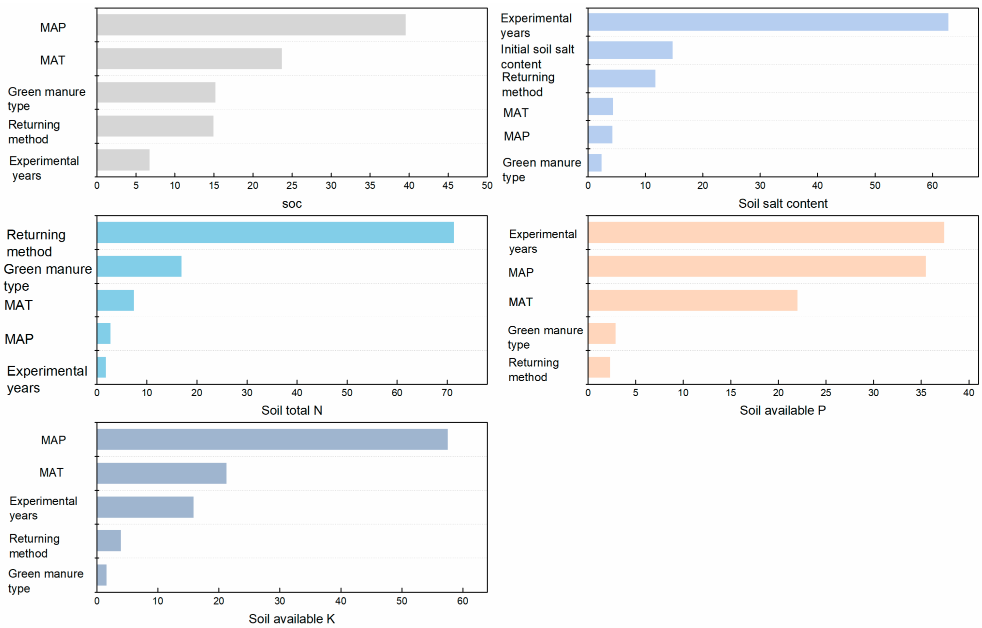

Figure 6. The relative influence (RI: %) of MAP, MAT, initial soil salt content, green manure types, returning method, and experimental years on SOC, soil salt content, soil total N, soil available P, and soil available K.

Green manure types influenced the impact on SOC content. In the present study, legume green manure was associated with lower increases in SOC compared to non-legume green manure (Figure 1d). The reasons might be as follows: (1) Most of the non-legume green manure samples in this study belonged to the Poaceae family. The biomass of Poaceae green manure is greater than that of legume green manure [40], which means there is a greater input of organic matter into the soil. Studies have shown that there is a strong positive correlation between the amount of organic matter input and SOC content [41], and the increased biomass of Poaceae plants is more conducive to enhanced SOC accumulation. (2) The carbon-to-nitrogen (C/N) ratio of green manure significantly influences its decomposition and the conversion of organic carbon in the soil. Organic materials with lower C/N ratios are more readily assimilated by microorganisms, resulting in a substantial portion of the carbon being incorporated into the microorganisms themselves, which can reduce the growth rate of SOC. Pan et al. [42] reported that when green manure with low C/N ratios is incorporated, the growth rate of SOC was only 2.6% to 8.9% of the carbon released from its decomposition. In contrast, approximately 50% of the carbon released from straw with high C/N ratios can be converted into SOC [43]. Considering the methods of returning green manure into the field, when green manure is left on the surface without being incorporated into the soil, its residues remain exposed and are not easily decomposed by microorganisms. In contrast, when green manure is incorporated into the soil, the plant residues are mixed with the mineral soil, which provides a protective effect on the organic matter. Therefore, this incorporation results in a more significant increase in SOC compared to simply spreading the green manure on the surface. Additionally, the duration of green manure planting influences SOC accumulation. As the number of planting years increases, the biomass yield of green manure rises, leading to a significant enhancement in the growth rate of SOC [44].

4.2. Soil Salt Content Changes Due to Green Manure

The results of this study indicate that green manure significantly reduces the soil salt content of saline soils (Figure 2). This reduction may be attributed to several reasons: (1) The root system of the green manure penetrates the soil, which reduces soil bulk density and improves soil structure, thereby facilitating the downward leaching of salts [45,46]. (2) Green manure could enhance surface coverage, which decreases the ineffective evaporation of soil moisture, and then inhibits the return of soil salts [47]. (3) The humus resulting from the decomposition of green manure possesses buffering and absorption capacities [48], which contribute to a reduction in soil salinity. The organic matter in green manure increases the solubility of cations and anions in the soil, further promoting soil desalination. (4) Green manure itself can also absorb soil salts [49], thereby further decreasing soil salt content.

In the present study, the results show that climate type has a relatively minor effect on soil salinity. The reduction in soil salinity was similar in MAP < 200 mm and 400–800 mm regions (Figure 2a). However, the reduction was slightly greater in areas with MAT above 15 °C compared to those with MAT at 10–15 °C (Figure 2b). This difference is attributed to the more favorable climate in warmer regions, which supports a larger green manure biomass and greater surface vegetation coverage, both of which could effectively reduce soil salt content. The relative importance analysis revealed that annual precipitation and annual temperature contribute only 2.68% and 7.37%, respectively, to the impact of green manure planting on soil salinity. The number of experimental years has the most significant effect on the salt content of saline soil (Figure 6). As the number of planting years increases, soil salt content decreases progressively, demonstrating that long-term green manure planting can substantially reduce soil salinity, thereby promoting soil desalination.

4.3. Soil N, P and K Changes Due to Green Manure

The research results demonstrate that green manure significantly enhances the content of soil total N, available P, and available K. Considering legume green manure, they can fix atmospheric nitrogen through rhizobia, thereby increasing soil total N [50]. Although non-legume green manure does not possess biological N fixation capacity, its roots can absorb nitrogen from deeper soil layers and accumulate it in the plant body, which in turn, releases N compounds at the soil surface after it is returned to the field [51]. Green manure also positively affects soil P and K in saline soil areas. Green manure plants absorb P and K from the soil in forms that are not easily absorbed and utilized by other crops. After the green manure is returned to the field and decomposed, the phosphorus and potassium return to the soil in more accessible forms, increasing soil available P and available K contents significantly. Furthermore, the rhizosphere effect of green manure accelerates the conversion of non-available nutrients to available forms, thereby enhancing soil nutrient availability [52].

5. Conclusions

In China, green manure application can significantly reduce soil salt content, improve SOC, total N, available P and available K contents in saline soil. The impact of green manure on SOC and nutrient content varies depending on the method of returning green manure to the field. Compared with green manure with non-incorporation, the increase in SOC, soil available P and K, and the decrease in salt content are greater under the condition of green manure with incorporation. The SOC-increasing effect of green manure varies according to green manure types. Mixed planting of legumes and non-legumes is more conducive to increases in SOC in saline soil. Taken together, our findings suggest that, in China, mixtures of legume and non-legume green manure with incorporation into the field should be considered to improve saline soil. We also found that climate and planting years are two key factors affecting the effectiveness of green manure. Among them, SOC is more susceptible to the influence of climate factors. Especially in warm and humid areas, the increase in various improvement indicators is relatively low. This discovery provides important theories for us to gain a deeper understanding of the improvement effect of green manure. Therefore, in practical applications, we need to adjust and optimize the green manure planting strategy according to climate conditions to achieve the best improvement effect on saline soil.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14092068/s1. Table S1: The change rate and publication bias test results of SOC, soil salt content, soil total N, soil available P, and soil available K; Table S2: Results of random effects model inter-group heterogeneity testing.

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