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Effects of Straw Returning Methods on Soil Water, Salinity, and Organic Matter in Saline-Alkaline Soils: A Meta-Analysis of Environmental and Management Drivers

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Abstract：The improvement and utilization of saline-alkali land are crucial for safeguarding global food security and achieving sustainable agricultural development. Straw returning to the field is a commonly used ecological protection measure in the improvement of saline-alkali land. However, few studies have compared the variation characteristics of soil water, salt and nutrients after the implementation of different straw returning strategies. In this study, 976 publications on saline-alkali land improvement via straw returning in China were collected for a meta-analysis. The effects and driving mechanisms of three straw returning methods—straw mulching, straw burying, and straw-soil mixing—on soil water, salt, and nutrients were systematically evaluated, aiming to identify scientific site-specific straw returning strategies.The results showed that straw returning generally had a significant effect on saline-alkali land improvement. All different straw returning measures could significantly enhance soil water retention capacity (except straw burying), reduce soil salt content (SSC), and increase soil organic matter (SOM). In regions where the mean annual temperature (MAT) ranges from 8 to 14°C and the mean annual precipitation (MAP) is > 400 mm, the improvement effect of straw burying was not obvious. In acidic soils, the improvement effects of the three returning methods were

not significant; in strongly alkaline soils, the improvement effect of straw-soil mixing was significantly better than that of straw mulching and straw burying.Climatic conditions are important factors affecting the changes in soil water content (SWC), SSC, and SOM, and they indirectly influence the three parameters by affecting the physical and chemical properties of the soil. Different regions should determine the optimal amount of straw to be returned based on specific returning methods. The improvement effect was optimal when the combined application of nitrogen fertilizer was < 100 kg/hm². This study provides support for the scientific adoption of straw returning methods in saline-alkali regions worldwide.

Keywords: Straw mulching; Straw burying; Straw-soil mixing; Saline-alkali land improvement; Meta-analysis

1 Introduction

Soil salinization is one of the major soil degradation threats affecting soil fertility, stability, and biodiversity (Hassani et al, 2020; Peng et al, 2019). By altering soil structure and triggering soil chemical and biological reactions, it exerts severe impacts on crop yield and soil quality (Navarro-Torre et al, 2023). Under the influence of global changes and human activities, soil salinization increasingly endangers agricultural production and causes global environmental disasters (Tu et al, 2019). Currently, over 100 countries are affected by salinization (Ondrasek et al, 2021), with a total area of approximately 1.1 billion hectares and an annual growth rate of more than 2 million hectares (Pereira et al, 2020). By 2050, it is projected that more than 50% of arable land will be affected by salinization disasters (Crowin et al, 2019; Ge et al, 2022).

In China, the total area of saline-alkali land is 3.69×10^7 hm², mainly distributed in four major regions: Northwest China, North China, coastal areas, and Northeast China, with concentrated contiguous areas in provinces such as Jilin, Ningxia, Inner Mongolia, Hebei, Xinjiang, and Jiangsu (Yang Jinsong et al, 2021). This poses a serious obstacle to agricultural production activities and the sustainable utilization of resources (Sahab et al, 2021). Therefore, scientific and reasonable saline-alkali land improvement measures are crucial for sustainable agricultural development and the

safeguarding of global food security.

Straw returning to the field is a sustainable straw management method (Islam et al, 2022; Liu et al, 2023) as well as an efficient soil improvement approach (Liang et al, 2021). Appropriate amount of straw returning can increase soil organic matter content (Hao et al, 2020) and soil aggregates (Mohamed et al, 2021), providing more favorable hydrothermal conditions for crop growth (Stagnari et al, 2014). In saline-alkali land improvement experiments, straw returning methods are generally classified into straw mulching (Chen et al, 2014), straw burying (Huang et al, 2021), and straw-soil mixing (Qin et al, 2021) based on different treatment measures.

Straw mulching can effectively prevent direct exchange between soil moisture and the atmosphere, regulate soil temperature, improve soil water use efficiency, facilitate efficient infiltration and leaching of salts, and promote crop growth (Cao et al, 2012; Pang et al, 2010). Straw burying can form a capillary barrier layer in the soil, reducing the evaporation of deep soil moisture by 2%–3%, thereby minimizing the migration of salts from deep soil to the surface layer (Zhao et al, 2016; Wang Guoli et al, 2021). Straw incorporation into the soil usually involves methods such as rotary tillage and deep loosening to fully mix straw with soil, which helps reduce soil bulk density and improve soil aeration and aggregate content (Dang et al, 2023).

However, there are significant differences in the improvement effects of different straw returning methods on saline-alkali land. Some studies have shown that straw mulching can significantly reduce soil salt content, with a better effect than straw burying (Xie Xuefeng et al, 2021). Other studies have found that straw deep burying reduces soil salt content by 12.4%, which is more effective in lowering soil salt content compared to straw mulching (8.7%) and straw-soil mixing (6.9%) (E Jifang et al, 2021). Nevertheless, a unified understanding of the improvement effects of different straw returning strategies in saline-alkali regions has not yet been formed, and there is a lack of summary on the improvement mechanisms of soil water, salt, and nutrients.

Meta-analysis is an effective statistical method that enables the synthesis of previously contradictory research results (Ma et al, 2022). When the results of several

studies are inconsistent or statistically insignificant, meta-analysis can be used to obtain parameter estimates that are closer to the actual situation, thereby drawing generalizable conclusions (Lou et al, 2023; Liu et al, 2023; Jeffery et al, 2016). Therefore, this study integrated current research data and used meta-analysis to evaluate the effects of different straw returning methods on soil moisture content, soil salt content, and soil organic matter in saline-alkali land. The specific objectives are as follows: (1) Quantitatively evaluate the effects of three straw returning methods (straw mulching, straw burying, and straw incorporation) on soil water-salt characteristics and soil organic matter in saline-alkali land; (2) Determine suitable straw returning methods based on different climatic and soil conditions; (3) Clarify the improvement mechanisms of different straw returning methods on saline-alkali land.

2 Materials and Methods

2.1 Data Retrieval and Collection

The data for this meta-analysis were obtained from published articles in Web of Science (http://apps.webofknowledge.com) and China National Knowledge Infrastructure (CNKI). The keywords "soil salinization", "saline-alkali land", "salt", "straw returning", "straw mulching", and "straw burying" were used to search in the "title", "abstract", and "keywords" fields to acquire studies published before November 16, 2023. To avoid bias in the selection of publications, the literatures included in this meta-analysis must meet the following criteria:

（1）The experiment must be conducted on saline-alkali land in China (excluding greenhouse, plastic shed, and soil column experiments);

（2）The straw returning method must be clearly specified (straw mulching, straw burying, or straw incorporation);

（3）The experiment must include a control group (no straw returning) and treatment groups (straw mulching, straw burying, or straw incorporation);

（4）The study must contain at least one of the following parameters: soil moisture content, soil salt content, and soil organic matter;

（5）The mean value, standard deviation (or standard error) of the parameters must be obtainable from the study, and the number of repetitions must be ≥ 2.

The mean values and standard deviations of the parameters in the figures and tables were extracted using the software Get Data Graph Digitizer (http://getdata-graph-digitizer.com/). For studies that only reported the standard error, the standard deviation was calculated using Formula 1 (Liu et al. 2018):

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

In the formula, n represents the number of studies; for studies where neither the standard deviation nor the standard error was reported, the standard deviation was calculated as 10% of the mean value (He et al, 2024).

In accordance with the above criteria and strictly following the workflow outlined in Figure S1, eligible literatures were included in the meta-analysis. After screening, a total of 86 literatures containing 976 comparison reports were obtained. Literatures presenting identical data were recorded only once, while papers from the same location but different years were identified as separate observations. All experimental sites are shown in Figure 1. Among the data collected, there were 651 pairs of soil salt content data, 542 pairs of soil moisture content data, and 341 pairs of soil organic matter data.

In addition to the above data, we also extracted the following information from each published report: author, experimental location (longitude, latitude, elevation), climatic conditions (mean temperature, mean precipitation), soil conditions (soil texture, initial soil pH, soil depth), and agronomic management measures (nitrogen application rate, straw returning amount). Referring to previous studies and combining the characteristics of saline-alkali land (Wang et al, 2018), different influencing factors were classified, with specific classification criteria provided in Table 1. For literatures that did not report mean temperature or mean precipitation, the average climatic data from 1970 to 2020 were extracted from the WorldClim database (https://worldclim.org/) for supplementation; for literatures lacking soil texture or pH data, the average data from 2010 to 2018 were retrieved from the National Earth System Science Data Center (https://www.geodata.cn/) to fill in the gaps.

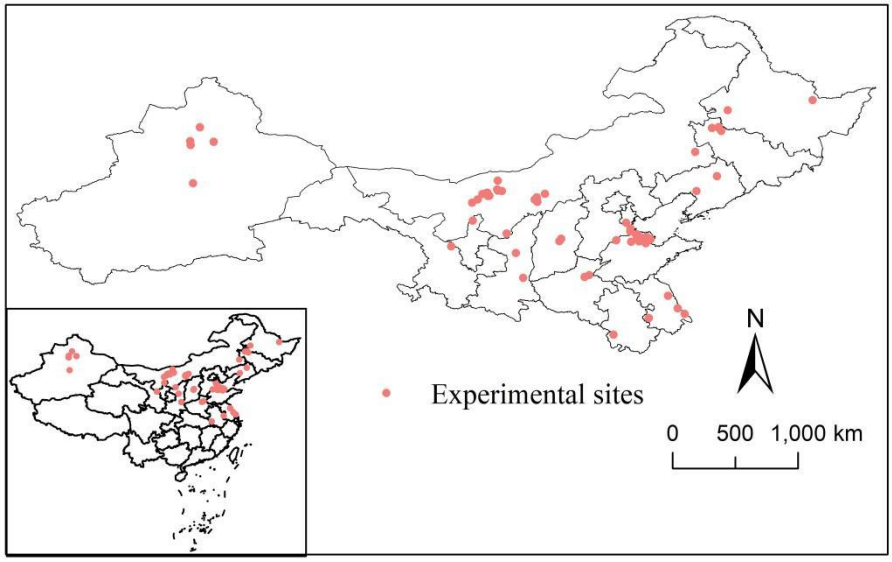


Fig.1 Schematic representation of the location of the experimental sites in the meta-analysis

Tab.1 Categorization of environmental variables included in the meta-analysis

category	**environmental variables**	Grade
Climatic Conditions	MAT (℃)	<8, 8-14, >14
	MAP (mm)	<200, 200-400, >400
Soil Conditions	Soil Texture	Sandy(Sandy loam, Sandy clay loam, Loamy sand, sand)、Loam(Silt, Loam, Silty, loam and sandy silt loam)、Clay(clay、clay loam, and silty clay)
	pH	Neutral(6.5-7.5), Alkaline(7.5-8.5),Strongly alkaline(>8.5)
	Soil Layer(cm)	0-20, 20-40, 40-60, 60-80, 80-100
Agronomic Management Practices	Nitrogen Application Rate(kg/hm^2)	<100, 100-200, >200
	Straw Return Rate (kg/hm^2)	<4000, 4000-9000, >9000

2.2 Meta-Analysis

The natural logarithm-transformed response ratio (*LnR*) was used to determine the variation characteristics of soil properties and soil structure in saline-alkali land after different straw returning methods (Hedges et al, 1999):

$$lnR = ln\left(\frac{X_t}{X_c}\right) \quad (2)$$

In the formula, X_t represents the mean value of the experimental treatment group (straw mulching or straw burying), and X_c represents the mean value of the corresponding control group (no straw returning).

The calculation formula for the variance of lnR (V_{lnR}) in each study is as

follows (Gao et al, 2019):

$$V_{lnR} = \frac{S_t^2}{n_t X_t^2} + \frac{S_c^2}{n_c X_c^2} \quad (3)$$

In the formula, S_t and n_t represent the standard deviation and sample size of the treatment group, respectively; S_c and n_c represent the standard deviation and sample size of the control group, respectively.

The calculation formula for the weighted response ratio (*lnRR*) is as follows (Wang et al. 2021):

$$ln\,RR = \sum(\ln R_i \times w_i)/\sum w_i \quad (4)$$

$$w = 1/v \quad (5)$$

$$\boldsymbol{S} = \sqrt{\frac{1}{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}}} \quad (6)$$

$$95\%CI = R_+ \pm 1.96S \quad (7)$$

In the formula, $ln\,R_i$ and w_i represent the corresponding effect size and weight, respectively. If $ln\,R=0$, it indicates that the treatment has no effect; if $ln\,R>0$, it means that straw returning has a positive effect on the response variable; if $ln\,R<0$, the effect is negative.

The frequency distribution of effect sizes for different variables was plotted and fitted using a Gaussian distribution function to evaluate the uniformity of the observed results (Wang et al, 2017). A random-effects model was used to conduct the meta-analysis and calculate the average effect sizes of different straw returning methods in the overall and subgroup analyses. The 95% confidence interval (*CI*) was generated through 4999 iterations in MetaWin 2.1 software. If the 95% *CI* of *lnRR* for a given variable overlaps with 0, the response of that variable to straw returning indicates no significant difference between the straw treatment and the control (Luo et al, 2006).

2.3 Evaluation of Impact Factor Importance and Path Analysis

To identify the influencing factors of changes in soil moisture content, salt content, and organic matter under different straw returning methods, the "randomForest" package in R language was used for importance testing. Additionally, the R package "rfPermute" was employed to assess the significance of each factor in

the response variables.

The partial least squares path modeling (PLS-PM) was implemented using the "plspm" package in R language to establish the path relationships between RR-SWC (Relative Rate of Soil Water Content), RR-SSC (Relative Rate of Soil Salt Content), RR-SOC (Relative Rate of Soil Organic Carbon), and environmental variables. Variables with a loading value less than 0.7 were removed (Liu et al., 2023; Russolillo et al., 2012). Path coefficients represent the direction and strength of the linear relationship between variables, and the goodness-of-fit index was used to evaluate the overall performance of the model (Ai et al., 2018).

2.4 Publication Bias Test

The fail-safe number was used to test the publication bias of this study. If the fail-safe number > 5N + 10 (where N represents the total number of each independent observation result), the results of this study can be considered reliable (Li et al., 2019). In this study, the fail-safe numbers for different soil properties and soil structures were all much greater than 5N + 10 (Table S1), indicating that publication bias was negligible and the research results were reliable.

3 Results

3.1 Analysis of Differences in Plant Straw Returning Methods

The results of the meta-analysis showed that, compared with no straw returning, straw returning could significantly increase SWC (mean effect size: 0.04), reduce soil salt content (mean effect size: -0.15), and improve SOC (mean effect size: 0.19). However, there were significant differences among different straw returning methods (Figure 2).The effect of straw burial on increasing SWC was not significant. The positive effect of mixing straw with soil on SWC (mean effect size: 0.10, 95% CI: 0.09–0.12) was significantly greater than that of straw mulching (mean effect size: 0.063, 95% CI: 0.05–0.08).

In terms of increasing SOC, the effect of mixing straw with soil (mean effect size: 0.260, 95% CI: 0.22–0.30) was significantly better than that of straw mulching (mean effect size: 0.183, 95% CI: 0.15–0.21) and straw burial (mean effect size: 0.14, 95%

CI: 0.11–0.17).

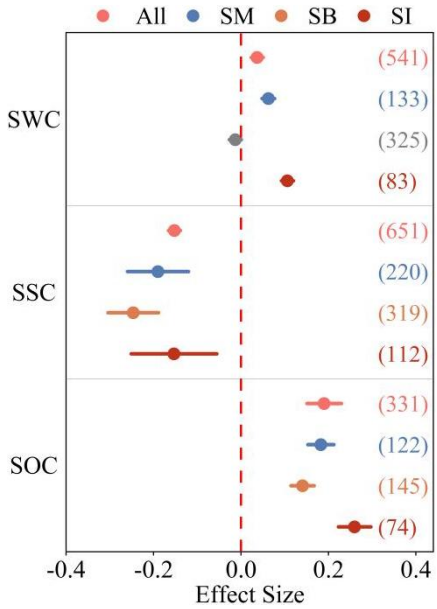


Figure 2. The effect of straw returning method on SWC, SSC, and SOM. All represents the overall impact of straw returning (without distinguishing the returning methods) on SWC, SSC, and SOM, while straw covering (SM), straw burying (SB), and straw soil mixing (SI) are different straw returning methods. If the effect of returning farmland on factors is not significant, it is displayed in gray. The red dashed line represents an average effect value of 0.

3.2 Analysis of Differences in Climatic Factors

The effects of climatic conditions on the effect values of soil water, salt and fertilizer contents vary under different straw returning methods (Figure 3).When the mean annual temperature MAT < 8°C, all three straw returning methods significantly increased SWC and reduced soil salt content; however, straw mulching had no significant effect on increasing SOC.When MAT ranged from 8°C to 14°C and the mean annual precipitation MAP > 400 mm, both straw mulching and straw-soil mixing significantly increased SWC, decreased soil salt content, and improved SOC, while the improvement effect of straw burial was not significant.When MAT > 14°C, only straw-soil mixing could significantly increase SWC (mean effect size: 0.098, 95%CI:0.06–0.14).

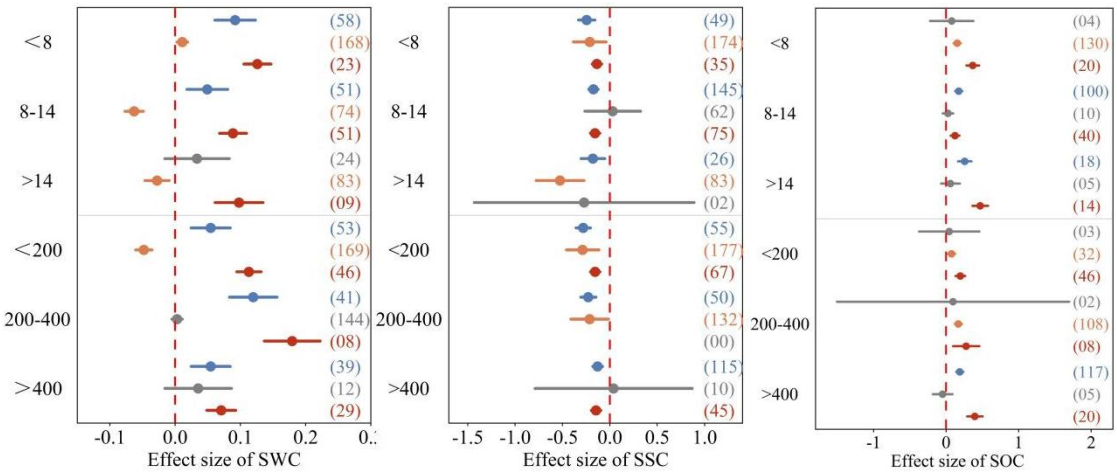


Fig.3 Effects of MAT and MAP on SWC, SSC and SOM under different straw return methods

3.3 Analysis of Differences in Soil Conditions

In sandy soil and loam soil, the ability of straw mulching and straw-soil mixing to increase SWC was significantly stronger than that of straw burial. In clay soil, the effects of straw burial on soil moisture retention, salt reduction, and fertility increase were all not significant. In acidic soil, the improvement effects of different straw returning methods were not significant. In alkaline soil, all three straw returning methods significantly increased SWC, reduced soil salt content, and increased SOC. In strongly alkaline soil, the effect of straw-soil mixing was significantly better than that of straw mulching and straw burial.

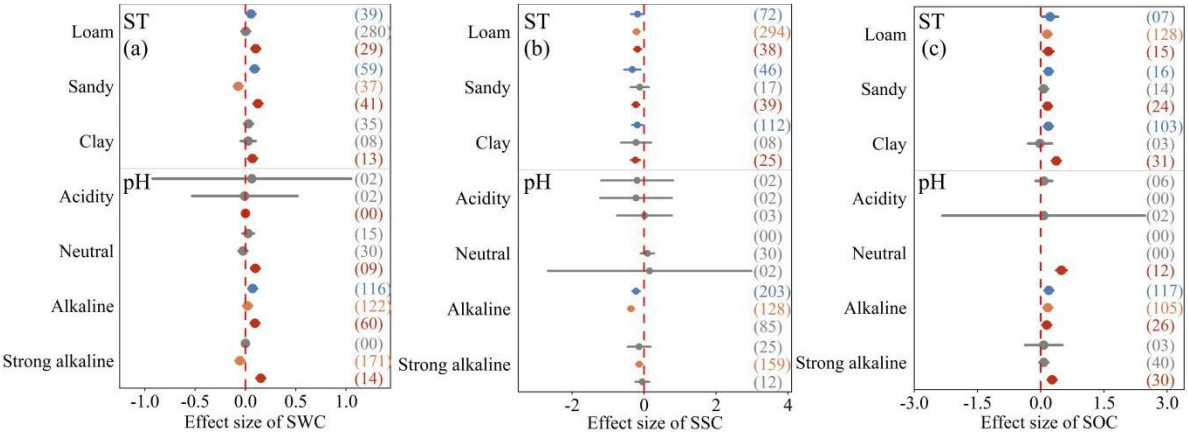


Fig. 4 Effects of ST and initial pH on SWC, SSC, and SOM under different straw return methods

3.4 Analysis of Differences in Burial Depth

Straw mulching and straw-soil mixing had a significant positive effect on SWC in the 0–20 cm and 40–60 cm soil layers, while all straw returning methods showed

no significant effect on SWC in the 20–40 cm and 80–100 cm soil layers (Figure 3a).Straw burial had no significant effect on inhibiting soil salinization in the 20–80 cm soil layer; straw-soil mixing had no significant effect in the 80–100 cm soil layer; however, straw mulching exhibited a significant salt-inhibiting effect in the 0–100 cm soil layer (Figure 3b).All three straw returning methods significantly increased SOC in the 0–60 cm soil layer. The fertility-increasing effect of straw burial showed a trend of first increasing and then decreasing across different soil layers: it significantly increased SOC in the 0–60 cm layer but significantly decreased it in the 60–80 cm layer(Fig.5).

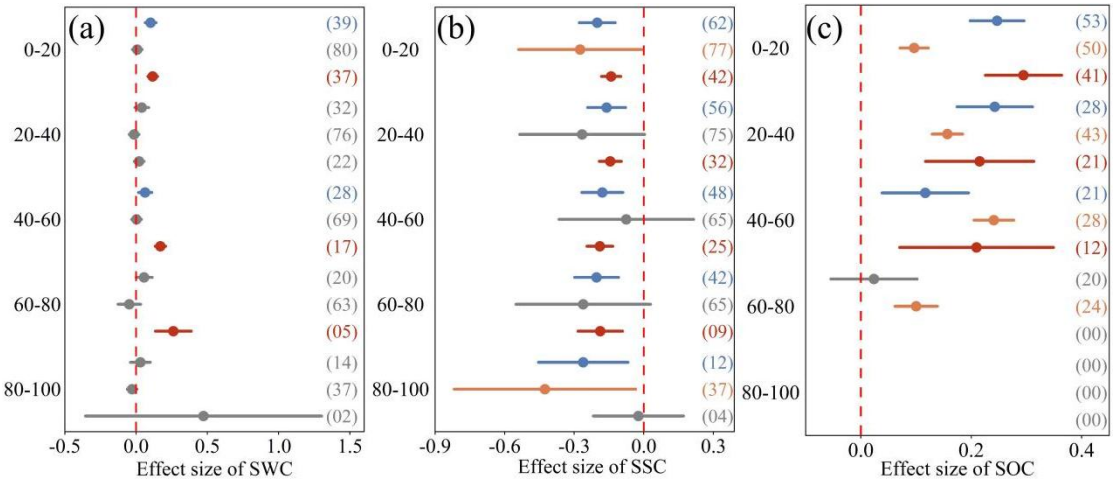


Fig. 5. Effect of different straw return methods on SWC, SSC and SOM in multiple soil layers

3.5 Analysis of Differences in Agronomic Measures

Under different field practice treatments, the effects of the three straw returning methods on crop yield, SOC and soil salt content also showed significant differences (Fig.6).When the straw returning amount SRA was < 4000 kg/hm², only straw mulching had a significant positive effect on SWC; when the SRA was > 4000 kg/hm², both straw mulching and straw burial significantly increased SWC, while straw-soil mixing had no obvious effect on SWC. Except for the scenario where the SAR was 4000–9000 kg/hm² (under which straw burial had no significant effect on reducing soil salt content), the three straw returning methods all exhibited significant effects of increasing soil fertility (i.e., increasing SOC) and reducing salt content under different straw returning amounts.Under the conditions of low NAR (NAR < 100 kg/hm²) and high NAR (NAR > 200 kg/hm²), both straw mulching and straw-soil mixing

significantly increased SWC and reduced soil salt content. All different straw returning methods significantly increased SOC under different NAR levels, except for straw burial which showed no significant effect when NAR < 100 kg/hm².

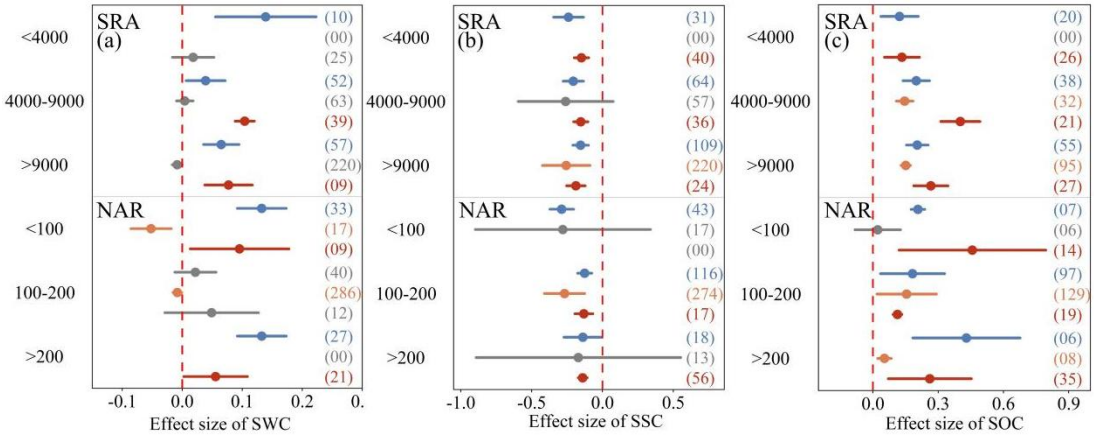


Fig.6.Effects of SRA and NAR on SWC, SSC and SOM under different straw return methods

3.6 Analysis of Comprehensive Impacts

The driving factors of changes in soil water, salt, and fertilizer under different straw returning methods (Fig.7). Among the three straw returning methods, geographical factors DEM，climatic factors (mean annual temperature, MAT; mean annual precipitation, MAP), and soil factors (silt content, Sand content, clay content, pH value, soil depth, SD) were the dominant influencing factors of SWC, with importance values ranging from 5.4% to 21.1%. Among these, SD had the greatest impact on SWC under all straw returning methods.Geographical factors (DEM) and soil factors (silt content, clay content, Sand content) had the most significant impacts on changes in soil salt content under straw mulching; under straw burial, only soil pH value had a significant impact on changes in soil salt content. Changes in SOC under straw mulching were mainly affected by soil factors and agronomic practices, while those under straw burial and straw-soil mixing were affected by the combined effects of three types of factors: climatic factors, soil factors, and agronomic practices.

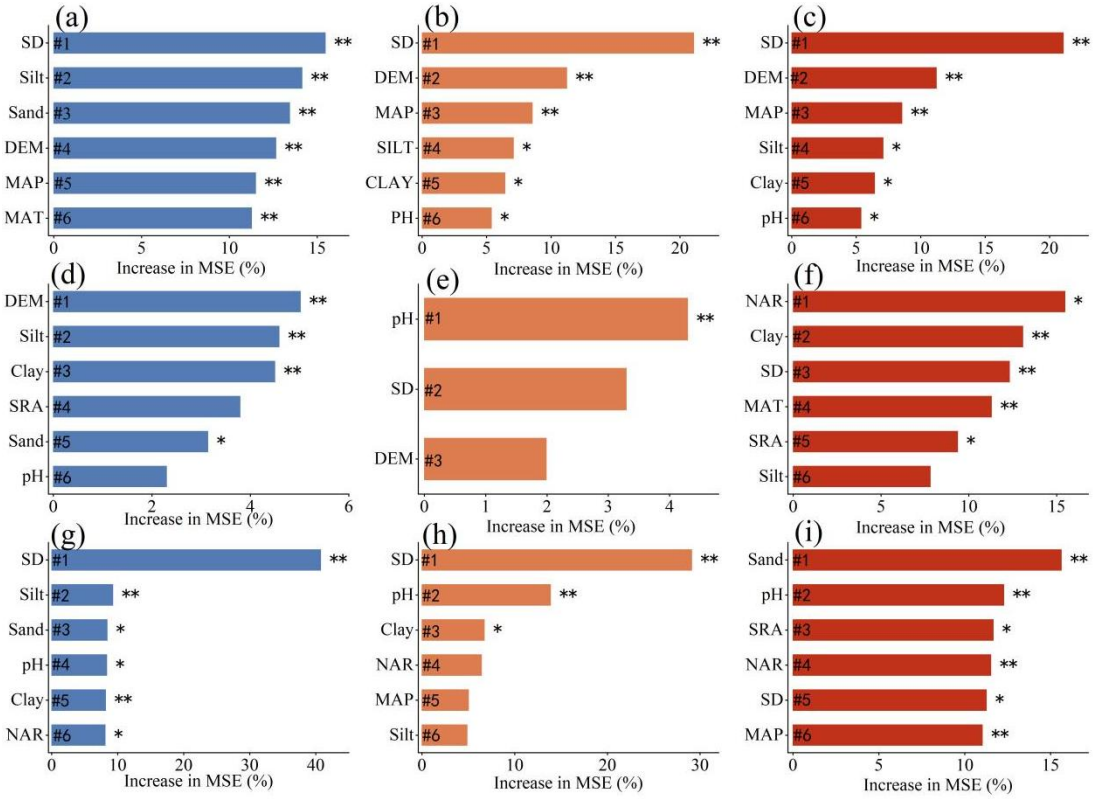


Fig. 7.Analysis of factors affecting changes in soil water content, salinity and organic matter under different straw return methods. (a), (b) and (c) are SWC drivers under different straw return methods. (d), (e), and (f) are SSC drivers under different straw return methods. (g), (h), and (i) are SOM drivers under different straw-returning methods. Different colors represent the different methods of straw return, blue for straw mulching, orange for straw burying, and red for straw mixing with soil.

A partial least squares path model (PLS-PM) was constructed to clarify the action paths of environmental conditions and agronomic practices on soil water content, soil salt content, and soil organic matter in saline-alkali soil under three straw returning methods (Fig.8). The model showed that straw treatment methods significantly regulated soil water retention capacity, salt migration processes, and changes in organic matter. Among them, changes in soil physical properties, as a mediating factor, played a key role between climatic conditions and management measures.Under the three straw returning methods, the increase in soil water content had a positive impact on soil organic matter, while the increase in soil salt content showed an inhibitory effect on soil organic matter, and the increase in soil water content also had a significant inhibitory effect on soil salt content. Under different straw returning methods, environmental factors and agronomic practices affected

changes in soil water content, soil salt content, and soil organic matter by influencing soil physical and chemical properties (pH, soil texture), but there were partial differences in the action paths.Straw returning amount had a significant positive impact on soil texture under straw mulching (total effect = 0.22), while it had negative impacts under straw burial and straw-soil mixing, with total effects of -0.49 and -0.07, respectively.

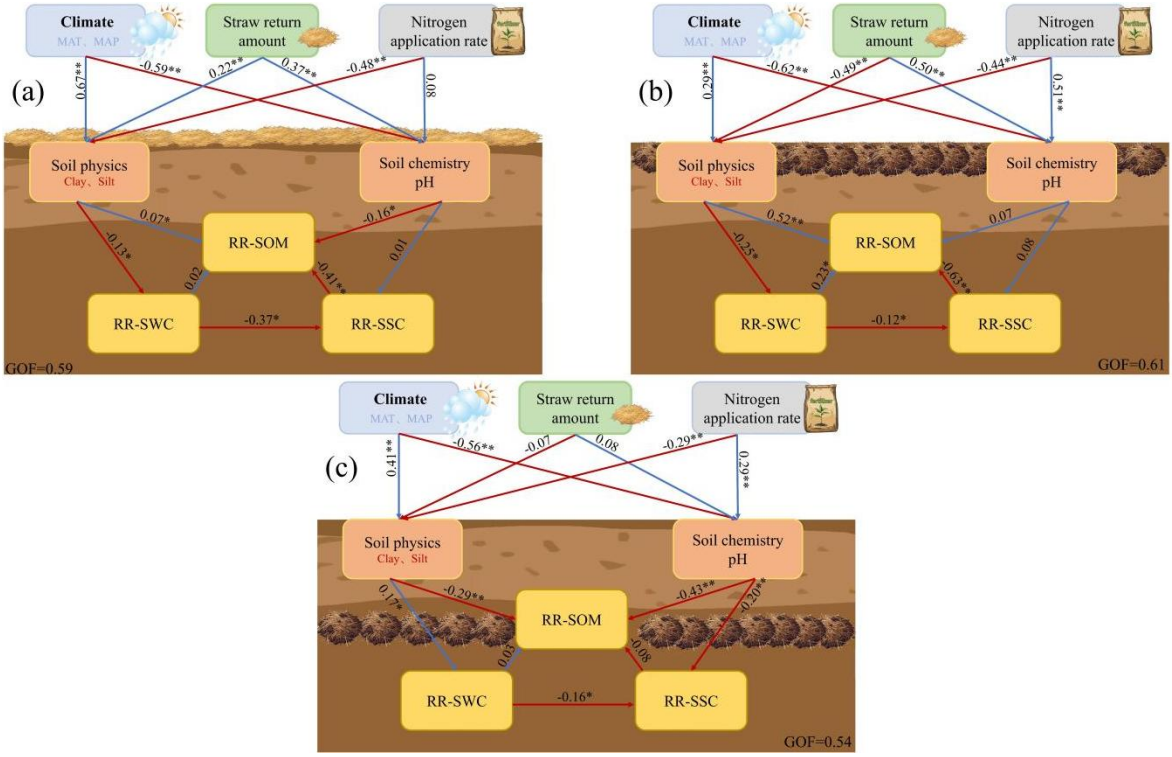


Fig. 8. PLS-PM model depicting the main pathways of key climate, agronomic practices, and soil physicochemical property factors in the effects of straw mulching (a), straw-soil mixing (b), and straw burial (c) on soil water content, soil salinity, and soil organic matter weighted effect values (RR). Blue and red lines represent positive and negative pathways, respectively. "*" indicates P<0.05 and "**" indicates P<0.01. MAP is mean annual rainfall and MAT is mean annual temperature.

4 Discussion

4.1 The Mechanism of Climatic Factors on Soil Improvement

Climatic factors directly determine the soil temperature and moisture conditions in the field (Nouri & Homaee, 2021) and also significantly affect the rate of straw decomposition (Wahdan et al., 2023). The results of this study showed that there were significant differences in the effects of different straw returning methods on SWC,

SSC, and SOM within the subgroups of MAT and MAP. In regions where MAT < 8°C, all straw returning methods significantly increased SWC and decreased SSC. This is mainly due to the reduced soil evaporation under low-temperature conditions, which is conducive to water retention and the leaching of salts (Figure 6). However, low-temperature and arid environments restrict microbial activity and reduce the decomposition rate of organic matter, thereby limiting the effect of SOM improvement (Wu et al., 2023; Liu et al., 2023).In regions where MAT > 14°C and MAP > 400 mm, the strategies of straw mulching and straw-soil mixing were significantly superior to straw burial in maintaining soil moisture, reducing soil salt, and increasing SOM. This can be attributed to the fact that under high-temperature and rainy conditions, straw mulching inhibits the accumulation of salt in the soil surface layer, promotes deep infiltration of water, accelerates the salt leaching process, and effectively reduces the overall soil salt content (Tian et al., 2017; Zhu et al., 2022). In contrast, straw-soil mixing optimizes the soil structure and provides sufficient organic carbon sources for soil microorganisms, thereby accelerating the decomposition and transformation of SOM (Zhang et al., 2020; Qin et al., 2017). By comparison, although straw burial increases the amount of soil organic materials, it is relatively less effective in reducing water evaporation, controlling salt accumulation, and accelerating the transformation of organic matter.

4.2 Influence Mechanism of Soil Conditions on Soil Improvement

Soil physical and chemical properties are also important factors influencing the improvement effects of different straw returning methods (Figures 5 and 6). Studies have shown (Zhang et al., 2007; Noah et al., 2021) that soil texture usually determines soil aeration, thereby affecting the capacity of soil water infiltration and salt migration. This study found that in clay soil, the use of the straw burial method had no significant effects on water retention, salt reduction, and fertility increase of saline soil, while the straw mulching and straw-soil mixing methods exhibited better improvement effects. This may be due to the high water retention capacity of clay soil (Zhang et al., 2024); the additional water retention effect achieved by further straw

burial may be insignificant, and even the excessive water retention may lead to poor soil aeration, which is unfavorable for root respiration (Wang et al., 2023). In addition, due to the low permeability of clay soil, even though straw burial can promote salt leaching to a certain extent, its effect is relatively limited, and it is difficult for water and salt to migrate in the vertical direction (Chen et al., 2022).

Soil pH affects soil microorganisms and soil enzyme activity, thereby influencing straw decomposition and soil nutrient transformation (Hao et al., 2019). The improvement effect of straw returning in alkaline soil is significantly stronger than that in acidic soil. This is because a lower pH affects the composition and activity of microbial communities, especially those microorganisms involved in organic matter decomposition and nutrient cycling. Acidic conditions limit the diversity and quantity of microorganisms, slow down the decomposition rate of straw, and thus reduce the transformation efficiency of organic matter and the release of nutrients (Qiu et al., 2021; Alburquerque et al., 2013). Therefore, the improvement effects of different straw returning methods in acidic soil may be insignificant due to the limitation of microbial activity and the reduction of organic matter decomposition rate.Compared with acidic soil, alkaline soil provides more suitable environmental conditions, which is conducive to maintaining higher microbial diversity and activity, and promoting the rapid decomposition of organic matter and the effective cycling of nutrients (Xu et al., 2021). In addition, in alkaline soil, straw returning increases the content of soil organic matter, and the organic acids produced by microbial action can partially neutralize soil alkalinity, improve the soil pH environment, and enhance soil fertility (Liu et al., 2019; Zhang et al., 2022).

4.3 Influence Mechanism of Agronomic Measures on Soil Improvement

Different straw returning strategies have positive effects on improving the physical and chemical properties of soil and enhancing soil nutrients. However, to achieve the optimal improvement efficiency, the SRA should be precisely regulated based on specific returning methods. For example, when straw mulching or straw-soil mixing is adopted, the effect is optimal when the SRA ranges from 4000 to 9000

kg/hm²; if straw burial is used, an SRA of > 9000 kg/hm² is required to achieve a significant salt-inhibiting effect (Figure 4).In addition, the rational application of nitrogen fertilizer is crucial for balancing the nitrogen demand during straw decomposition, reducing nitrogen competition, and promoting crop growth and soil fertility improvement (Liu et al., 2023; Chen et al., 2023). However, under the condition of insufficient irrigation, excessive application of nitrogen fertilizer will lead to nitrogen loss, soil acidification, and accumulation of soluble salts, thereby posing potential risks to the ecological environment (Vermoesen et al., 2023).Consistent with the national-scale analysis results by Huang et al. (2021), this study also shows that an excessively high NAR does not significantly increase soil nutrients. Furthermore, this study further points out that in saline-alkali soil: when the NAR is < 100 kg/hm², straw mulching and straw-soil mixing can significantly increase SWC and SOM, while reducing soil salt content; when the NAR ranges from 100 to 200 kg/hm², all three straw returning methods can significantly reduce soil salt content and increase SOM, but have no obvious effect on SWC. Therefore, when improving saline-alkali soil through different straw returning methods, the improvement effect is optimal when the combined application of nitrogen fertilizer is < 100 kg/hm².

4.4 Analysis of the Influence Mechanism of Comprehensive Factors

Among different straw returning methods, climatic conditions, NAR, and SRA exert indirect effects on soil physical and chemical properties, which in turn regulate changes in SWC, salt content, and organic matter content. Soil texture has varying impacts on changes in SWC and SOM under different straw returning conditions. Under straw mulching and straw-soil mixing, soil texture shows a positive effect on SOM changes and a negative effect on SWC changes; however, the opposite trend is observed under straw burial (Figure 6). The reason for this difference may be that, under the strategies of straw mulching and straw-soil mixing, these two methods enhance the input of organic matter in the soil surface layer and microbial activity. As a result, the water retention capacity and nutrient retention capacity of fine-textured

soil are improved (Soinne et al., 2020), thereby positively promoting the accumulation of SOM (Buttler et al., 2019). Nevertheless, the high water retention capacity of fine-textured soil may limit the deep infiltration of water. Particularly under straw mulching, this easily leads to the accumulation of water in the soil surface layer, which instead exerts a negative impact on SWC (Wang et al., 2020). In contrast, straw burial places straw in the deeper soil layer, reducing organic matter and microbial activity in the surface soil. This may result in a decrease in SOM accumulation in coarse-textured soil. However, the poor water retention capacity of coarse-textured soil is improved under the influence of straw burial, which may thus exhibit a positive effect on SWC. In addition, regardless of the straw returning method, a decrease in SWC can lead to a reduction in soil salt content, and the reduction in soil salt content can further promote the accumulation of SOM. The increase in SWC has a positive but non-significant effect on SOM accumulation. This indicates that the rational selection of straw returning strategies can not only optimize soil water retention and SOM management but also effectively reduce soil salt content. This is a key measure to achieve sustainable soil health and enhance the agricultural sustainability of saline-alkali soil.

5 Conclusions

All straw returning measures could significantly enhance soil water retention capacity (except for straw burial), reduce soil salt content, and increase soil organic matter. In regions where the MAT ranged from 8 to 14°C and the MAP was > 400 mm, the improvement effect of straw burial was not significant. In sandy soil and loam soil, the ability of straw mulching and straw-soil mixing to increase SWC was significantly stronger than that of straw burial. In strongly alkaline soil, the improvement effect of straw-soil mixing was significantly better than that of straw mulching and straw burial. Different regions should determine the optimal SRA based on specific straw returning methods; the improvement effect was optimal when the combined application of nitrogen fertilizer was < 100 kg/hm². In conclusion, the results of this study can provide a scientific basis for selecting scientific and reasonable straw returning

methods to improve saline-alkali soil in different salt-affected regions worldwide, considering influencing factors such as climate and soil.

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Conflict-interest

The authors declare that they have no competing interests.

Ethics approval and consent to participate

This article is a meta-analysis based exclusively on previously published literature. It contains no studies involving human participants or animals performed by any of the authors; therefore, ethics approval and informed consent are not applicable.

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analysed during this study are included in this published article and its supplementary information files. The literature search strategy, screening process, and the full list of studies included in the meta-analysis are provided in the Methods section and Supplementary Table S1.

Authors' contributions

Yinghui Zhou: Conceptualization, Methodology, Formal analysis, Writing—original draft, Supervision, Funding acquisition.

Jiangqin Chao: Investigation, Data curation.

Yingyun Li: Software, Visualization.

Huan Deng: Investigation, Validation.

Zhihua Li: Investigation, Data curation.

Zheyan Mao: Data curation, Formal analysis.

All authors read and approved the final manuscript.

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