Long-term cattle manure application to saline-sodic soil increases maize yield by decreasing key obstacle factors in the black soil region of Northeastern China

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Abstract: Poor soil physical properties, serious salinization and low soil nutrients are the limiting factors for crop yield in saline-sodic soil. Long-term cattle manure application is an important measure that can affect the physicochemical properties and increase the maize yield of saline-sodic soil. This experiment included five treatments according to the history of cattle manure application: a control treatment with no cattle manure (CK) and treatments with cattle manure application for 14 years (14 a), 17 years (17 a), 20 years (20 a), and 25 years (25 a). The results indicated that compared with the CK treatment, long-term cattle manure application to saline-sodic soil resulted in significant increases in soil organic matter (SOM), soil total nitrogen (TN) and available nutrients at the 0-20 cm and 20-40 cm depths ($p<0.05$). The soil physical properties improved significantly, and cattle manure application significantly decreased the soil bulk density (ρ_b) and soil density (ρ_d) and increased the soil total porosity (f_t) and water-holding capacity (WHC). With the number of years of cattle manure application, the soil pH, electrical conductivity (EC), exchangeable sodium percentage (ESP) and sodium adsorption ratio ($SAR_{1:5}$) decreased significantly, and the maize yield gradually increased over time from 8690 kg/hm^2 in the CK treatment to 14 690 kg/hm^2 in the 25a treatment. There were significant differences among all treatments ($p<0.05$). The results showed that long-term cattle manure application decreased the soil ρ_b and saline-alkaline properties, which was the main factor that affected the maize yield in the saline-sodic soil, especially for soil ρ_b.

Keywords: saline-sodic soil, cattle manure, soil physicochemical properties, maize yield

DOI: 10.25165/j.ijabe.20231606.7532

Citation: Yu F, Zhao S, Zhao Y, Wang Y, Zhai C Y, Zhong R, et al. Long-term cattle manure application to saline-sodic soil increases maize yield by decreasing key obstacle factors in the black soilregion of Northeastern China. Int J Agric & Biol Eng, 2023; 16(6): 176–183.

1 Introduction

Soil salinization is serious and causes severe adverse impacts on the agricultural productivity and sustainability of many countries worldwide, especially in arid and semiarid regions[1]. The quality of saline-sodic soil is low due to poor soil structure, low soil organic matter (SOM), high alkalinity, and high salinity[2,3]. This soil is not suitable for most common economic crops[4], and 2000 hm^2 of arable land is losing productivity on a daily basis at a global scale due to salinization[5]. The Songnen Plain in China is one of the world's three major alkalization regions[6]. The region of saline-sodic soil on the Songnen Plain in Northeast China is approximately 3.42×10^6 hm^2[7] and has been characterized by excessive Na_2CO_3 and $NaHCO_3$ contents, which have severe impacts on crop growth and sustainability[8]. Furthermore, the soil physical structure and accumulation of salt[9] also indirectly affect soil nutrient use efficiency[10]. Excessive exchangeable Na^+ in saline-sodic soil results in the diffusion of clay particles[11]. Soil nutrient availability can decrease due to the poor physical and chemical properties of the soil in this area, resulting in low soil productivity, which is not conducive to the sustainable development of agriculture.

In recent decades, many research scholars have claimed to effectively restore saline-sodic soil, and various techniques, including chemical, physical, and biological methods, are utilized to improve soil fertility and crop yields[12]. However, among the restoration options, cattle manure application is one of the best yield management practices to achieve high crop yield and is an important measure for sustainable agricultural development. Qaswar et al.[13] found that fertilization can increase the content of soil available nutrients, increase the amount of soil nutrients such as total nitrogen (TN) and total phosphorus (TP), and decrease the pH value[14]. Fertilization can promote the conversion of nutrients into available forms for spike growth, which has a positive impact on crop yield[15]. Sheoran et al.[16] showed that proper fertilization can improve soil physical properties by reducing the soil bulk density (ρ_b), increasing the soil porosity, improving the water-holding capacity (WHC), and increasing soil aggregates. Organic fertilizer is beneficial for saline-sodic soil fertility improvement because it improves soil structure and aggregation, increases hydraulic conductivity, promotes nutrient levels and enhances cation exchange capacity[17]. Studies have shown that soil structure, carbon sequestration, and organic matter content can be improved through

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Received date: 2022-03-21 **Accepted date:** 2023-02-11

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long-term application of organic fertilizer, thereby enhancing the stability and sustainability of crop production[18,19]. Relevant studies have found that compared with chemical fertilizers, the use of organic fertilizers can effectively improve environmental pollution[20,21].

Organic fertilizer may improve soil quality and reduce pollution, which is meaningful to the sustainable development of agriculture[22]. Many studies have shown the effects of soil physicochemical properties on maize yield. However, the contribution of changes in soil properties to maize yield has not been studied under long-term cattle manure application. Research data obtained from long-term site experiments are reliable and can accurately reflect the amelioration effect and change trend of saline-sodic soil. Therefore, to achieve sustainable and high crop yields, it is essential to determine the effect of long-term cattle manure application on crop productivity. The main hypothesis of this study is that increases in maize yield are likely to be related to improvements in soil physical properties caused by annual cattle manure application. Therefore, the saline-sodic soil on the western Songnen Plain was used as the research material to determine the improvements in this soil resulting from the long-term cattle manure application. This study aimed to investigate the effects of long-term cattle manure application on sustainable crop production and soil physicochemical properties. Furthermore, this study investigated how long-term application of cattle manure improves crop yield by improving soil physicochemical properties. It is expected that the findings from this experiment can help to evaluate the effects of cattle manure application on saline-sodic soil restoration and will lay a theoretical foundation for land salinization management and restoration.

2 Materials and methods

2.1 Experimental site

The study was conducted at the experimental station of saline-sodic soils of Northeast Agricultural University, Zhaozhou County, Daqing city, Heilongjiang Province, China (125.06°E, 45.40°N, 149 m). The study area has a temperate continental monsoon climate, and the average annual evaporation in the study area is 1800 mm. The mean annual precipitation is 434 mm, which is 0.25 times the annual evaporation in the area. The mean annual temperature is 3.7°C, and the study site is located in the hinterland of the Songnen Plain, which is one of the world's three typical saline-sodic soil regions. The soil type is classified as solonetz based on the World Reference Base for Soil Resources. The soil has a clay texture (26% sand, 22% silt, 52% clay)[23]. Before soil reclamation, the saline-sodic areas experienced notable salinization, accounting for approximately 40% of the area. The soil physicochemical properties at a 0-20 cm depth before the test are listed in Table 1.

Table 1 Basic physical and chemical properties of soil prior to reclamation

pH value	EC/ dS·m^{-1}	ESP/ %	Organic matter/ g·kg^{-1}	Total N/g·kg^{-1}	Available N/mg·kg^{-1}	Available P/mg·kg^{-1}	Available K/mg·kg^{-1}
10.50	6.23	32.03	10.95	0.37	39.11	12.06	125.18

2.2 Experimental design

Based on the history of cattle manure application, a randomized block design consisting of five treatments and three replicates was followed. Cattle manure was applied to the saline-sodic soil in 1995, 2000, 2003, and 2006, and soil samples from all treatments were collected in 2020. Thus, saline-sodic soil samples to which manure had been applied for 25 years (25a), 20 years (20a), 17 years (17a) and 14 years (14a) were used as the experimental treatments, and a control treatment with no cattle manure (CK) at the 2020 sampling. Cattle manure was applied to the treatments at a rate of 10 000 kg/hm^2 (dry weight) in ridge planting and in combination in late April every year. Cattle manure was evenly broadcast onto the soil surface and was artificially incorporated into the ploughed soil (0-20 cm in depth) by tillage before maize was sown each year. Urea (N=46%) was applied as a top dressing application to maize in the elongation stage at a rate of 400 kg/hm^2. The properties of the cattle manure are listed in Table 2.

Table 2 Basic properties of the cattle manure

Organic matter/ g·kg^{-1}	pH	Nitrogen/ g·kg^{-1}	Phosphorus/ g·kg^{-1}	Potassium/ g·kg^{-1}	Calcium/ g·kg^{-1}	Magnesium/ g·kg^{-1}
590.69	8.42	13.28	12.02	15.35	9.77	4.58

2.3 Soil sampling

Soil samples were collected from 0-20 cm and 20-40 cm depths in mid-October 2020 after the maize harvest, and three points were randomly selected in each plot. The soil samples were air-dried and passed through a 0.25 mm and a 1.00 mm sieve for determination of the soil chemical properties respectively. The soil physical properties were determined from undisturbed soil samples collected by a ring knife of 100 cm^3 volume with 5.1 cm in diameter and 5.0 cm in height. All maize in each plot was harvested.

2.4 Laboratory methods

SOM was obtained by dichromate oxidation with heating ($K_2Cr_2O_7$-H_2SO_4). Soil TN was analysed using the Kjeldahl method. Soil available N was analysed by the alkali hydrolysis diffusion method. Soil available P was extracted with 0.5 mol/L $NaHCO_3$, and colorimetric analysis was performed at 880 nm using a spectrophotometer. Available K was analysed by the ammonium acetate extraction flame photometry method. The soil pH value and electrical conductivity (EC) values of the soil samples were measured using a pH electrode and conductivity meter at a water:soil ratio of 5:1. The sodium acetate method was used to determine the cation exchange capacity (CEC). Exchangeable Na^+ was analysed using a flame photometer after extraction with 1 mol/L NH_4OAC. The concentrations of Ca^{2+} and Mg^{2+} were measured by atomic absorption spectrophotometer, and Na^+ was analysed by flame photometry. The exchangeable sodium percentage (ESP) was calculated using the following equation:

$$\mathrm{ESP} = \frac{\mathrm{ExcNa}}{\mathrm{CEC}} \times 100\% \tag{1}$$

where, ESP is the exchangeable sodium percentage, %; ExcNa is the concentration of exchangeable Na^+, cmol/kg; CEC is the cation exchange capacity, cmol/kg.

The SAR of 1:5 soil-to-water extracts ($SAR_{1:5}$) was calculated by molar concentration using the following equation.

$$\mathrm{SAR}_{1:5} = \frac{\mathrm{Na}^+}{\left[\left(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}\right)/2\right]^{0.5}} \tag{2}$$

where, $SAR_{1:5}$ is the sodium adsorption ratio, mmol/L; Na^+, Ca^{2+}, and Mg^{2+} are soluble Na^+, soluble Ca^{2+}, and soluble Mg^{2+}, mmol/L, respectively.

The core method was used to determine the soil bulk density (ρ_b). The water-holding capacity (WHC) was measured by equilibrating the soil with water through capillary action immediately after soil sampling and oven drying undisturbed soil cores for 48 h at 105°C. The pycnometer method was used to determine the soil density (ρ_d). The total porosity (f_t) was calculated using the following equation.

$$f_t = \left(1 - \frac{\rho_b}{\rho_d}\right) \times 100\% \tag{3}$$

where, f_t is the total porosity, %; ρ_b is the bulk density, g/cm^3; ρ_d is the soil density, g/cm^3.

2.5 Statistical analysis

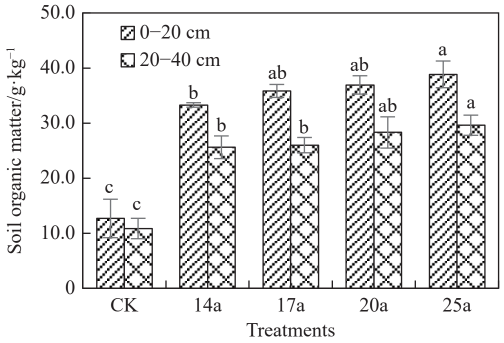
All statistical analyses were performed using SPSS 17.0. Redundancy analysis (RDA) was performed using Canoco 4.5 software, and structural equation modelling (SEM) was performed using the SPSS package of AMOS 17.0. Data were analysed with one-way analysis of variance (ANOVA) followed by the least significant difference (LSD) between treatments ($p<0.05$). RDA was performed to determine the effects of the soil physical properties on the soil saline-sodic properties and soil nutrient concentrations. RDA screening of comparatively important indicators was used to construct a structural equation model, which was used to analyse the effects of the soil physical and chemical properties on the maize yield after the application of cattle manure.

3 Results

3.1 Soil organic matter and total nitrogen

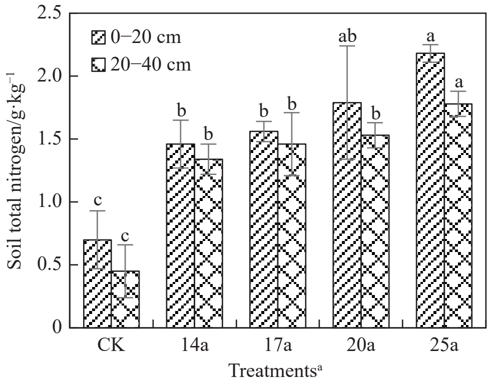
Long-term cattle manure application significantly increased the SOM and TN in different soil layers, and SOM and TN were always higher at the 0-20 cm soil depth than at the 20-40 cm soil depth. All four treatments with manure application had a significant improvement in SOM content in relation to the CK treatment.

As shown in Figure 1, the SOM content increased significantly ($p<0.05$) from 12.68 g/kg in the CK treatment to 38.85 g/kg in the 25a treatment at the 0-20 cm soil depth and from 10.85 g/kg in the CK treatment to 29.61 g/kg in the 25a treatment with cattle manure application at the 20-40 cm soil depth. Similarly, as shown in Figure 2, the TN content was the highest in the 25a treatment (2.18 g/kg), which was significantly different from the CK treatment ($p<0.05$) at the 0-20 cm soil depth. All treatments could significantly increase soil TN at the 20-40 cm soil depth, and the 25a treatment had the highest content.



Note: Values are the means±SD (n=3); different letters in same depth indicate significant differences ($p<0.05$). Control treatment with no manure (CK), cattle manure application for 14 years (14a), 17 years (17a), 20 years (20a), and 25 years (25a). The same as below.

Figure 1 Soil organic matter (SOM) under different cattle manure applications



Note: ^{a} represents treatments had been applied manure for 25 years (25a), 20 years (20a), 17 years (17a) and 14 years (14a) were used as the experimental treatments, and a control treatment with no cattle manure (CK). Same below.

Figure 2 Soil total nitrogen (TN) under different cattle manure applications

3.2 Soil available nutrients

The contents of available nutrients in response to long-term cattle manure application are listed in Table 3. Long-term cattle manure application increased the concentrations of available N, available P, and available K at different soil depths. The soil available N, available P and available K were significantly higher ($p<0.05$) in the 25a treatment than in the other treatments at the 0-20 cm soil depth, whereas there was no significant difference in available N and available P among the CK, 14a, 17a, and 20a treatments. The soil available N was significantly higher ($p<0.05$) in the 25a treatment than in the CK treatment at the 20-40 cm soil depth. The soil available P content and soil available K showed trends similar to those exhibited by available N. However, there was no significant difference in soil available N among the CK, 14a, 17a and 20a treatments. The soil available P content increased significantly ($p<0.05$) from 14.82 mg/kg in the CK treatment to 25.5 mg/kg in the 25a treatment. The soil available K content increased significantly ($p<0.05$) from 99.44 mg/kg in the CK treatment to 159.33 mg/kg in the 25a treatment at the 20-40 cm soil depth.

3.3 Soil pH and EC

Among the five treatments, soil pH and EC showed the same trends at different depths, and soil pH and EC decreased with the number of years of manure application. In Figures 3 and 4, the soil

Table 3 Available nutrient contents under cattle manure applications (mg/kg)

Soil depth/cm	Soil properties	Treatments^1				
		CK	14a	17a	20a	25a
0-20	Available N	56.47±27.53^{b}	68.83±23.07^{b}	70.85±30.92^{b}	77.47±13.58^{b}	129.5±14.9^{a}
	Available P	24.02±2.28^{b}	28.87±10.88^{ab}	32.66±1.82^{ab}	32.87±14.81^{ab}	47.63±11.06^{a}
	Available K	146.96±14.57^{c}	175.79±1.14^{bc}	178.45±1.1^{bc}	195.53±25^{ab}	232.39±39.64^{a}
20-40	Available N	45.73±17.96^{b}	67.67±8.44^{ab}	59.73±14.35^{ab}	63.7±13.34^{ab}	91.23±23.1^{a}
	Available P	14.82±4.23^{b}	19.95±1.4^{ab}	24.30±2.21^{a}	25.50±6.46^{a}	25.50±0.97^{a}
	Available K	99.44±10.87^{c}	117.21±14.95^{bc}	159.33±5.22^{a}	134.72±10.57^{ab}	159.33±20.8^{a}

Note: Values are the means±SD (n=3); different letters in same depth indicate significant differences ($p<0.05$). CK: Control treatment with no manure. ^{1} represents the cattle manure application for 14 years (14a), 17 years (17a), 20 years (20a), and 25 years (25a). Same below.

pH of the 14a, 17a, 20a and 25a treatments significantly (p<0.05) decreased by 1.68, 1.77, 1.92 and 2.21 units, respectively, compared with that of the CK treatment at the 0-20 cm soil depth. EC showed trends similar to those exhibited by pH. The highest EC was observed in the CK treatment, and the EC values in the treatments with cattle manure application were significantly lower (p<0.05) than that of the CK treatment. The soil EC ranged from 1.58 dS/m in the CK treatment to 0.1 dS/m in the 25a treatment at the 0-20 cm soil depth.

The highest pH value was observed in the CK treatment, and this value was significantly higher (p<0.05) than those in the treatments with manure application at the 20-40 cm soil depth. The highest EC value was measured in the CK treatment (1.75 dS/m), and there was a significant difference between the CK treatment and the other treatments with manure application (p<0.05).

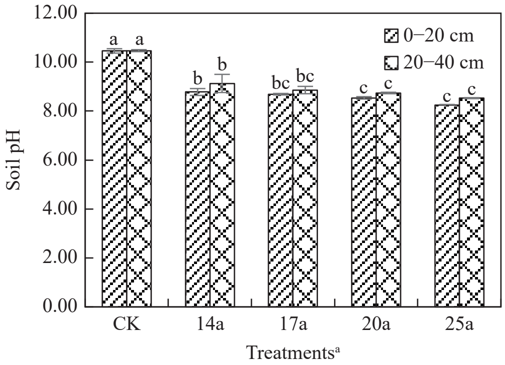


Figure 3 Soil pH under different cattle manure applications

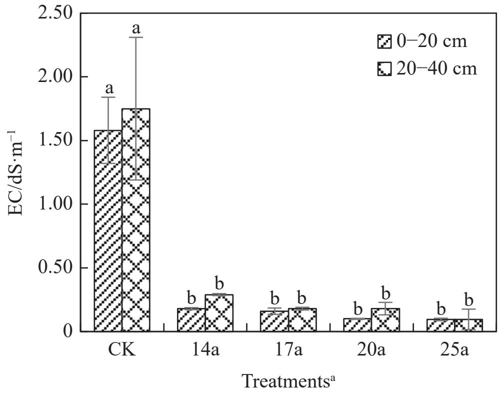


Figure 4 Soil electrical conductivity (EC) under different cattle manure applications

3.4 Soil ESP and SAR$_{1:5}$

From Figures 5 and 6, long-term cattle manure application significantly decreased ESP and SAR$_{1:5}$ in different soil layers. ESP ranged from 42.17% in the CK treatment to 0.74% in the 25a treatment at the 0-20 cm soil depth. SAR$_{1:5}$ showed trends similar to those exhibited by ESP. The SAR$_{1:5}$ of the treatments with cattle manure application were significantly (p<0.05) lower than that of the CK treatment. SAR$_{1:5}$ ranged from 17.29 mmol/L in the CK treatment to 0.38 mmol/L in the 25a treatment at the 0-20 cm soil depth. The results showed that the soil ESP and SAR$_{1:5}$ were negatively correlated with the number of years of cattle manure application.

The soil ESP and SAR$_{1:5}$ in the cattle manure treatments decreased significantly compared with those in the CK treatment at the 20-40 cm soil depth. However, among the cattle manure treatments, there was no significant difference in ESP and SAR$_{1:5}$ between the 14a treatment and the 17a, 20a, and 25a treatments (p<0.05) at the 20-40 cm soil depth.

3.5 Soil physical properties

As shown in Figure 7, the WHC in the 14a, 17a, 20a and 25a treatments was 0.23%, 6.37%, 28.75%, and 45.73% higher, respectively, than that in the CK treatment. The WHC was the highest in the 25a treatment (37.51%). There was a significant difference (p<0.05) in WHC among the CK, 20a and 25a treatments at the 0-20 cm soil depth. The WHC was the highest in the 25a treatment at the 20-40 cm soil depth. Compared to the CK treatment, there was a significant difference (p<0.05) in the WHC among the CK, 20a and 25a treatments at the 20-40 cm soil depth.

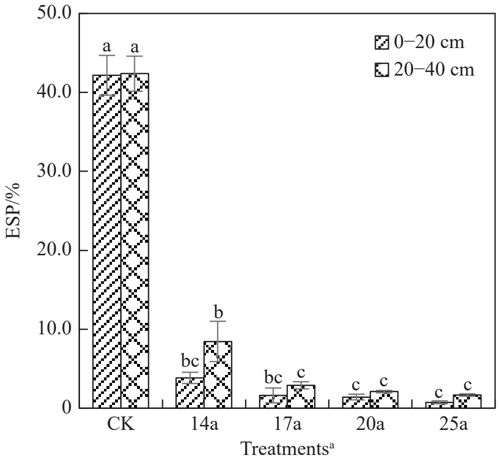


Figure 5 Soil exchangeable sodium percentage (ESP) under different cattle manure applications

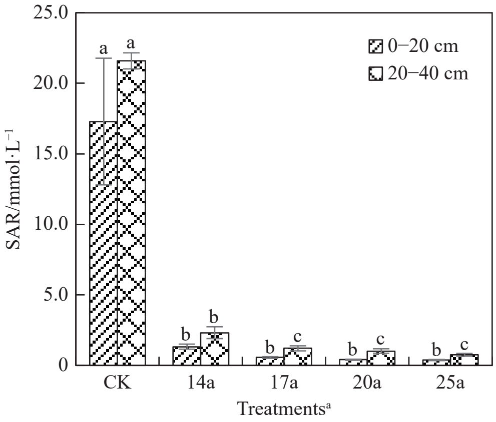


Figure 6 Sodium adsorption ration (SAR$_{1:5}$) under different cattle manure applications

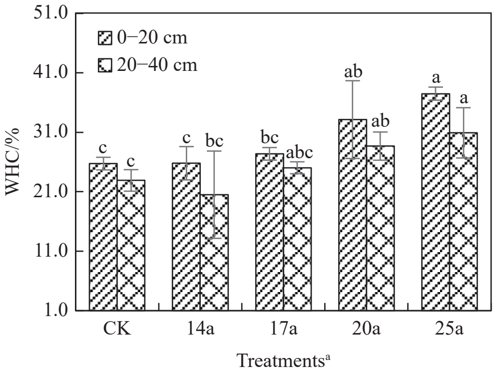


Figure 7 Water-holding capacity (WHC) under different cattle manure applications

Compared to the CK treatment, ρ_b was reduced by 13.13%, 5.63%, 11.88%, and 15.00%, respectively. There was a significant difference between the CK treatment and 25a treatment (p<0.05). The ρ_d showed trends similar to those exhibited by ρ_b. The ρ_b and ρ_d were significantly improved in the 25a treatment (p<0.05). In the 25a treatment, the ρ_d values decreased by 8.20%, compared to the CK treatment. Compared to the CK treatment, f_t increased by 20.23%, 3.12%, 9.04% and 42.64%, respectively. There was a significant difference between the CK treatment and the 25a treatment (p<0.05). As shown in Table 4, all treatments significantly reduced ρ_b at the 20-40 cm soil depth compared to the CK treatment. The ρ_d increased from 34.69% in the CK treatment to 41% in the 25a treatment at the 20-40 cm soil depth. The ρ_d in the 25a treatment was the lowest, and there was a significant difference between all treatments and the CK treatment (p<0.05). The 25a treatment had the highest f_t, and there was no significant difference among all the treatments (p>0.05) at the 20-40 cm soil depth.

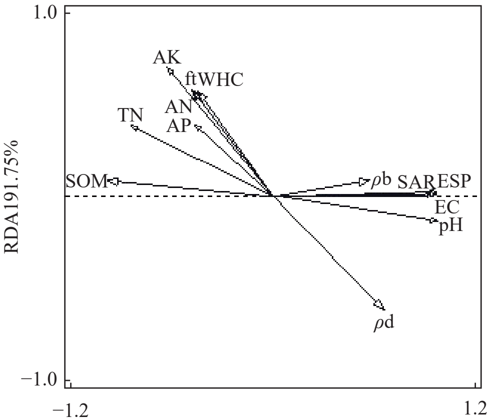
Table 4 Soil physicochemical properties under different cattle manure applications

Soil depth/ cm	Soil properties	Treatments^1				
		CK	14a	17a	20a	25a
0-20	ρ_b/(g·cm^{-3})	1.60±0.03^a	1.39±0.13^{ab}	1.51±0.01^{ab}	1.41±0.08^{ab}	1.36±0.21^b
	ρ_d/(g·cm^{-3})	2.44±0.03^a	2.40±0.01^b	2.36±0.01^c	2.28±0.01^d	2.24±0.02^e
	f_t(%)	34.94±1.52^c	42.01±5.61^b	36.03±0.2^c	38.10±3.84^{bc}	49.84±1.08^a
20-40	ρ_b/(g·cm^{-3})	1.60±0.02^a	1.42±0.01^c	1.53±0.02^b	1.45±0.03^c	1.43±0^c
	ρ_d/(g·cm^{-3})	2.45±0.01^a	2.41±0.02^b	2.37±0.01^c	2.36±0.02^c	2.27±0.03^d
	f_t/%	34.69±1.87^a	40.82±0.30^a	35.46±0.19^a	40.16±1.98^a	41.00±8.10^a

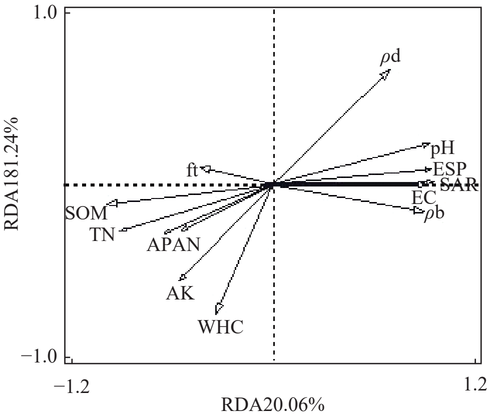
Note: Values are the means±SD (n=3); different letters in same depth indicate significant differences (p<0.05). Control treatment with no manure (CK), cattle manure application for 14 years (14a), 17 years (17a), 20 years (20a), and 25 years (25a). ρ_b is the bulk density; ρ_d is the soil density; f_t is the total porosity.

3.6 Relationship among soil properties

In the present study, the application of cattle manure significantly increased the SOM content in the saline-sodic soil, which had a negative relationship with ρ_b. There was a significantly positive relationship between soil ρ_b and ρ_d and pH, EC, ESP and SAR$_{1:5}$ at the 0-20 cm depth. There was the same pattern at the 20-40 cm soil depth, where there was a significantly positive relationship between soil ρ_b, ρ_d and saline-alkaline properties. In addition, ρ_b and ρ_d had the greatest negative impacts on TN, available N, available P and available K. In this study, the results showed that long-term application of cattle manure significantly increased SOM, which had a significantly positive relationship with soil TN and available nutrients. There was a negative relationship between WHC and f_t. Figures 8a and 8b show similar results. The results suggested that the application of cattle manure improved soil physicochemical properties at different soil depths.



a. 0-20 cm



b. 20-40 cm

Note: ρ_b, bulk density; ρ_d, soil density; f_t, total porosity; WHC, water-holding capacity; SOM, soil organic matter; AN, available nitrogen; AP, available phosphorus; AK, available potassium; EC, electrical conductivity; ESP, exchangeable sodium percentage; SAR, sodium adsorption ration.

Figure 8 Biplot for redundancy analysis (RDA1 & RDA2) for the relationship among soil properties of saline-sodic soil in different depth

3.7 Maize yield

The long-term application of cattle manure resulted in a significant increase (p<0.05) in maize yield compared to the CK treatment. Figure 9 shows that the annual average maize yield in the 14a, 17a, 20a and 25a treatments increased by 43.11%, 48.06%, 53.36%, and 69.04%, respectively, compared to the CK treatment. The results showed that the maize yield increased significantly with the increase of application years.

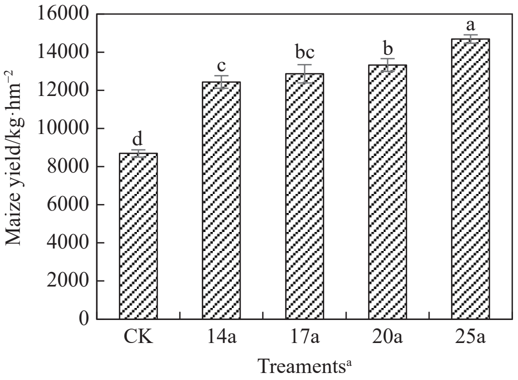


Figure 9 Maize yield under different cattle manure applications

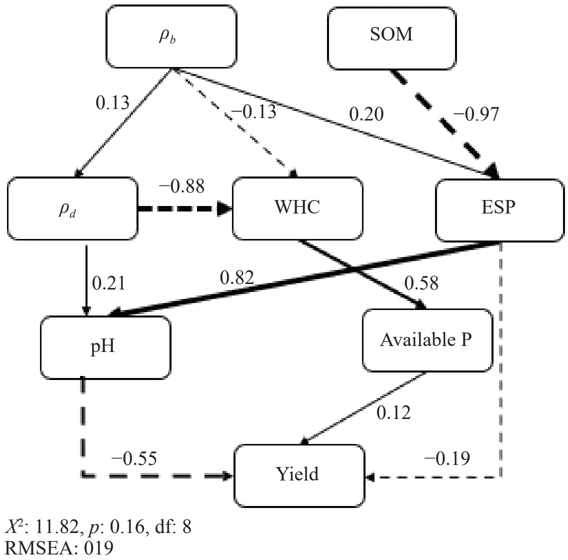
3.8 Relationship between soil properties and maize yield

As shown in Figure 10, the structural equation model (SEM) results indicated that the model fit well with the data, the p value of the model was 0.16, and the effect of soil properties on maize yield was analysed. The SEM indicated that the path coefficient of the effect of SOM on ESP was –0.97, with a negative correlation. The effect of ρ_b on ESP was 0.20, with a positive correlation. The ρ_b also indirectly affected the pH value and available P by influencing WHC and ESP. The path coefficient of the effect of pH value on maize yield was –0.55, and the correlation was negative. This result indicated that cattle manure could increase maize yield by decreasing ρ_b and increasing SOM, and then WHC, ρ_d and ESP indirectly affected the pH value and available P in the saline-sodic soil.

4 Discussion

4.1 Effects of cattle manure application on SOM and soil nutrients

SOM significantly increased after the long-term application of cattle manure, especially in the 25a treatment (Figure 1). This mainly results from manure having a high content of organic carbon[24], and the application of manure increases the ability to fix and maintain organic carbon[25], thus effectively increasing SOM in saline-sodic soil. This result is consistent with the observations of Zhao et al.[26], who reported that improved sequestration and accumulation of organic carbon due to long-term application of manure appropriately replenishes the carbon sources in the organic carbon pool[27]. In addition, the release of virgin undecomposed organic matter in the soil results from the application of manure[28]. This contributes to the release of organic carbon into the soil through mineralization processes[29].



Notes: The value above the SEM line represents the standardized path coefficients. A solid-line path indicates that the effect is positive; dashed-lines path indicate that the effect is negative. ρ_b, bulk density; SOM, soil organic matter; ρ_d, soil density; WHC, water-holding capacity; ESP, exchangeable sodium percentage. X^2 means Chi-square; df means degrees of freedom; p means probability level; RMSEA is root mean square error of approximation.

Figure 10 Structural equation model (SEM) for the mechanisms of yield in response to long-term cattle manure application

Furthermore, manure is rich in important resources that replenish soil nutrients, such as nitrogen, phosphorus, potassium, and organic matter, in different amounts[30,31]. The long-term application of manure can make full use of both available and total nutrients, and the soil nutrient content increases significantly, which is conducive to improving soil physical and chemical properties[13,32]. In this study, the application of cattle manure increased the soil available nutrients and total nutrients at the 0-20 cm and 20-40 cm depths (Table 3). This result is consistent with that of Huang et al.[33], who observed that long-term manure application accelerated soil nutrient activation, improved the soil nutrient content, maintained the balance of available nutrients, and improved soil fertility. Cattle manure can also increase the activity of microorganisms and enzymes with regard to nutrient transformation, thus increasing soil available nutrients. The RDA results showed that SOM had a positive effect on soil nutrients (Figure 8). A higher SOM content and higher content of available nutrients were observed[34]. The increase in soil nutrients with cattle manure application might be due to the higher SOM content, which could provide a large pool of macronutrients in the saline-sodic soil. However, the research data showed that the increased soil available N at the 20-40 cm depth was not ideal, which may be associated with excessive loss of N under the high pH in the soil environment[35].

4.2 Effect of long-term application of cattle manure on improvements in soil physical properties

In this study, long-term cattle manure application caused a decrease in ρ_b at the 0-20 cm and 20-40 cm depths. Previous research showed a similar trend[32], which demonstrated that ρ_b rapidly decreased after long-term (6 years) fertilizer application in saline-sodic soil. Cattle manure has a low bulk density and high porosity, so mixing with the denser mineral fractions of soil after cattle manure application causes a decrease in ρ_b[36,37]. However, the soil ρ_b in the 17a treatment was higher than those in the other treatments, and there was no significant difference between the CK and 17a treatments (Table 4). This finding may be related to the high clay content. This is consistent with the research results of Wei et al.[38], who reported that the increased soil ρ_b due to the clay content did not change significantly after long-term tillage disturbance. Previous studies have shown that an increase in SOM can also improve the soil structure and promote the formation of aggregates. SOM can not only provide nutrients needed for plant growth but can also effectively improve the soil structure, resulting in loose soil, promoting the formation of water-stable aggregates, and increasing the soil water retention and fertilizer retention capacity[39].

In the present study, the RDA results showed that ρ_b was negatively correlated with f_t and WHC and f_t had a positive effect on WHC (Figure 8), suggesting that the soil tightness and permeability improved, and the soil WHC increased with decreasing ρ_b. This result is consistent with that of Rehman et al.[40], who observed that long-term application of manure to soil effectively improved the WHC. The pore structure of manure itself and the aggregate structure formed with soil can hold water, which will inhibit the upward movement of water, reduce the soil evaporation rate, and reduce soil water dispersion[41]. Mukherjee et al.[42] claimed that a significant increase in soil moisture is related to the formation of soil pores. It can be concluded that the improvement in physical properties had an important effect on the improvement of saline-sodic soil.

4.3 Response of soil saline-alkaline properties to cattle manure application

The long-term application of cattle manure to the soil effectively reduced the pH of the saline-sodic soil at the 0-20 cm and 20-40 cm depths, and the soil pH value decreased with increasing years of cattle manure application. This is consistent with the research results of Chaganti et al.[43]. Organic acids derived from the decomposition of cattle manure could increase the acidic functional groups, which could neutralize CO_3^{2-} and HCO_3^- and thus reduce the soil pH. Decreased EC was observed after cattle manure addition because of the reduction in soluble salts, especially Na^+[44]. The reduction in Na^+ was attributed to the cattle manure-induced improvements in soil porosity and hydraulic conductivity that accelerated salt leaching[45]. The RDA results showed that WHC had a negative effect on EC (Figure 8). Because a high soil water content could help promote a decrease in EC and dissolve more salts, salts in solution will generally drain into relatively deeper soils due to gravity[46,47].

Organic acids promote the dissolution of calcium carbonate in soil[48] and thus increase the Ca^{2+} amount in soil solution. This phenomenon leads to large increases in Ca^{2+}, which facilitate the removal of Na^+ from cation exchange sites and subsequently lead to a corresponding decrease in Na^+ and contribute to a reduction in the ESP[49]. Cattle manure can increase aggregate stability and hydraulic conductivity and may enhance salt leaching, thereby reducing ESP. A significantly higher efficiency in decreasing soil $SAR_{1:5}$ occurred due to cattle manure increasing Ca^{2+} in the soil solution and promoting the displacement of adsorbed Na^+, followed by subsequent leaching[50].

In the present study, the RDA results also indicated significant ($p<0.01$) positive correlations among the pH, EC, ESP, and $SAR_{1:5}$, at each soil depth (Figure 8). With an increasing number of years of cattle manure application, the saline-alkaline properties decreased significantly compared with the CK treatment.

4.4 Relationship between soil physicochemical properties and maize yield

The SEM results showed that the maize yield increased significantly, which can be attributed to the improvement in soil ρ_b due to cattle manure application. This improvement occurred because the application of cattle manure significantly decreased soil ρ_b and increased the soil porosity, resulting in higher soil permeability and water retention and improved soil structure. The improvement of physical properties increases the leaching of Na^+ and soluble salts from saline-sodic soil with rainfall, thus leading to significant decreases in soil sodicity, salinity and pH[50]. The increase in SOM also improved soil saline-alkaline properties. This result is consistent with that of Meng et al.[51], who observed that the decrease in soil pH with cattle manure application can be attributed to the organic acid produced during the decomposition of the organic fraction of the manure; moreover, there was a negative correlation among SOM, soil sodicity, salinity and pH.

As a result of these improved soil physical and chemical properties, marked increases in maize yield were observed in the cattle manure-treated soils. Liu et al.[52] and Chen et al.[53] found that the application of manure effectively improved soil physical and chemical properties, decreased soil salt accumulation and increased salt removal in certain layers, thus enhancing plant growth and crop productivity. In this study, the soil physical properties changed significantly after the long-term application of cattle manure, and the soil saline-alkaline properties and soil nutrients improved. The SEM results shed light on the importance of soil ρ_b as a determinant factor affecting maize yield in the long term. Based on the long-term research trend, long-term cattle manure application may be a sustainable approach to ensure yield stability.

5 Conclusions

After long-term application of cattle manure, soil physical properties were obviously improved, soil saline-alkaline properties significantly decreased, and soil nutrients significantly increased. With the increase in the number of years of cattle manure application, the maize yield increased gradually, and the 25a treatment was more effective in increasing yield than the other treatments. It was concluded that long-term cattle manure application decreased the soil ρ_b and decreased the saline-alkaline properties, which, in descending order, were the main factors affecting maize yield in the saline-sodic soil. The decreased soil ρ_b resulted in the improvement of soil structure, which in turn increased soil f_t, improved water retention, and facilitated the leaching of Na^+ and soluble salts from the saline-sodic soil.

Acknowledgements

The authors appreciate the staff of the laboratory of Soil Degradation Control and Remediation, School of Resources and Environment, and Northeast Agricultural University. This work was financially supported by the National Natural Science Foundation of China (Grant No. 42177320).

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