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Salt characteristics and soluble cations redistribution in an impermeable calcareous saline-sodic soil reclaimed with an improved drip irrigation

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ABSTRACT

Saline-sodic and sodic soils are characterized by the occurrence of excessive Na^+ that adversely affect soil properties. Takyric solonetz, a saline-sodic soil with a poor structure, a low permeability (saturated hydraulic conductivity <0.1 mm d^{-1}) and a considerable $CaCO_3$, widely distributes in arid regions, Northwest China. A 3-year field experiment was conducted to reclaim this impermeable saline-sodic wasteland with an improved drip irrigation, where a sand-filled niche beneath drip emitter was adopted for ridge cultivation of *Lycium barbarum* L. Through the extensive sampling in soil transects, the salt characteristics and redistributions of soluble cations were evaluated. Results indicated that the soil properties that hindered takyric solonetz from being reclaimed orderly were, soil salinity, structure, alkalinity, and the concentrations of other ions (e.g. K^+). Salt leaching through the water regulation had the highest priority in reclaiming takyric solonetz, and followed by improving soil structure through changing ions composition and reducing soil sodicity. After reclamation, soil Na^+ concentrations decreased in root zone, but increased in top layers of ridge slope and furrow, while the increases of K^+ were only found beneath drip line, behaving little mobility with water flow. Considerable increases of divalent cations (Ca^{2+} and Mg^{2+}) occurred beneath drip line, but no obvious changes occurred in other regions of soil transect. It was concluded that irrigation water and dissolution of intrinsic $CaCO_3$ provided sufficient Ca^{2+} to replace the excessive Na^+, and the replaced Na^+ was leached out of root zone, resulting in a decrease of soil sodicity and improvement of soil structure. The reclamation measures were expected to have good sustainability, which was supported theoretically by the priorities of actions derived from salt characteristics. Thus, this improved drip irrigation provided a potential substitute for the costly amendments to ameliorate impermeable saline-sodic soils, especially with considerable amount of $CaCO_3$.

1. Introduction

Reclamation of salt-affected soils is a global issue, especially for the arid and semiarid regions (Mahmoodabadi et al., 2013). Among the categories of salt-affected soils, the saline-sodic and sodic soils are characterized by presence of excessive Na^+ in soil solution and in the exchange phase up to the levels, which can adversely affect the soil properties (Qadir et al., 2001; Tejada et al., 2006). It is widely considered more difficult for the saline-sodic and sodic soils to be ameliorated, than the saline soils (Oster and Shainberg, 2001; Qadir et al., 2001), because various obstacles should be coped with when reclaiming a saline-sodic or sodic soil, e.g., high alkalinity, poor soil structure, low permeability, as well as the high salinity, among which only the last probably occurred in saline soils.

Takyric solonetz (IUSS Working Group WRB, 2007) is a saline-sodic soil widely spread in arid regions, Northwest China. Generally, it does not have very high salinity except for the surface layer, but is always characterized by the high alkalinity (pH > 9.5), high sodicity (exchangeable sodium percentage (ESP) >60), extremely poor soil structure, and compacted soil layers (bulk density > 1.6 g cm^{-3}) with the crusting-prone surface. All these soil properties result in a low soil hydraulic conductivity of takyric solonetz, saturated hydraulic conductivity (K_s) is usually less than 0.1 mm d^{-1} (Wang et al., 1993; Chi et al., 2012; Zhang et al., 2013). Considerable

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CaCO3 generally exists in the form of calcite in the native profile. No vegetation was supported in this soil, except some blue-green algae, such as microcoleus, growing in patches during the monsoon season (Comprehensive Exploration Team, 1963; Yin, 1985; Wang et al., 1993). Therefore, the successful reclamation of this highly saline-sodic wasteland is of great importance both for environmental improvement and for agricultural productivity. In the recent decades, many methods have been reported to be effective to reclaim saline-sodic soils (Mace et al., 1999; Oster et al., 1999; Qadir et al., 2001; Clark et al., 2007; Yazdanpanah et al., 2013). However, many conventional methods (e.g. deep ploughing, application of organic fertilizer, phytoremediation) were not effective for takyric solonetz primarily due to the extremely low K_s (Yin, 1985; Wang et al., 1993). And application of the chemical amendments (gypsum) was too costly and provided only marginal economic interest for the local farmer (Wang et al., 2016).

Since 2009, a field study had been conducted to test the possibility of reclaiming takyric solonetz with drip irrigation but without chemical amendments. The vegetation planted was wolfberry (*Lycium barbarum* L.), a renowned medicinal fruit crop in Northwest China (Zhang et al., 2013; Zhang et al., 2017). The results showed that a considerable reclamation of this impermeable saline-sodic wasteland could be achieved in three years (Zhang et al., 2013). The drip irrigation used in this study was improved through adoption of the sand-filled niches beneath drip emitters, which facilitated the soil infiltration, and finally made the reclamation possible. Then, the changes of soil water and salt distribution (Zhang et al., 2013), nutrients status (Zhang et al., 2017) and soil enzymes activities (Zhang et al., 2014) were studied. An integrated agronomic measure was proposed for reclamation of takyric solonetz, mainly including ridge cultivation, sand-filled niches beneath drip emitters, mulched drip irrigation triggered by soil matric potential. However, some further studies are still needed for the amelioration mechanism and sustainability evaluation of the agronomic measure.

Quantitative study of soil salt characteristics is the basis for salt-affected soil management. However, the specific salt characteristics, dominative and restrictive factors of reclamation, and priorities of various actions in reclamation process, are still unknown for takyric solonetz. Meanwhile, the complexity and large spatial variability of soil salt compositions increased the difficulty of such quantitative study. This problem might be partly solved by extensive sampling and appropriate factor analysis. Additionally, a widely used amelioration method for sodicity-induced degraded soil is addition of chemical amendment (gypsum) to promote the replacement of exchangeable Na^+ by Ca^{2+}, and the replaced Na^+ is removed either below root zone or out of soil profile with leaching water (Oster et al., 1999; Qadir et al., 2001; Mahmoodabadi et al., 2013). However, in our study, takyric solonetz was reclaimed through exclusive drip irrigation without any chemical amendments containing Ca^{2+}. In this case, some questions may be raised: what were the Ca^{2+} resources and whether they were sufficient, and how about the leaching efficiency of excessive Na^+ out of the root zone, and even what were the migration and redistribution of soluble cations concurrent with the complex ions exchange adsorption and desorption. The answers to these questions would help us to understand the amelioration mechanism and to evaluate the sustainability of agronomic measures.

In this study, it was hypothesized that the theoretical possibility of our reclamation measures could be proved by the salt characteristics and restrictive factors emerged in takyric solonetz, and that the solution of native calcite ($CaCO_3$) under cropped conditions can supply sufficient Ca^{2+} to reclaim this saline-sodic soil. The objectives of this study were: (1) to analyze salt characteristics and dominative factors of takyric solonetz to prioritize the relevant actions during the reclamation; and (2) to evaluate the migrations and redistributions of soluble cations in soil transects in three continuous planting years. The results will not only provide an alternative soil amelioration technique for impermeable saline-sodic soils, but also help complete the methodology of salt-affected soil amelioration.

2. Materials and methods

2.1. Experimental site

The experimental site is located in Xidatan area (38°47′–38°57′N, 106°20′–106°30′E, 1095 m), in Pingluo County, Ningxia Hui Autonomous Region, Northwest China. The station has a typical arid continental climate, with a mean annual temperature of 9.4 °C, and a mean annual precipitation of 178 mm. The mean annual potential evaporation is >2000 mm. The studied soil is classified as takyric solonetz (IUSS Working Group WRB, 2007). Xidatan, where is the low-lying area (a natural collecting area) of piedmont alluvial plain of Helan Mountain, is the typical distribution area of takyric solonetz in China (Wang et al., 1993). Without any vegetation, local soil environment is extremely infertile. The local water table is about 2.5 m and the mineral concentration of groundwater is generally <3 g L^{-1}. Little inter-annual variation existed in water table and salinity of ground water, indicating that groundwater did not participate in modern soil formation, probably due to the impermeability of takyric solonetz (Wang et al., 1993).

The typical arid climate and geographical conditions result in the high salinity and sodicity in the surface of takyric solonetz. For the 0–30 cm soil layer, the average electrical conductivity of saturated paste extract (EC_e), pH of saturated paste (pH_s) and sodium adsorption ratio of saturated paste extract (SAR) were 12.3 dS m^{-1}, 9.4 and 44.1 ($mmol_c$ L^{-1})$^{0.5}$, respectively (Table 1). Besides the high pH and

Table 1
Main physicochemical properties in uncultivated soil and irrigation water.

Soil depth (cm)	Soil texture components (%)			Soil texture [a]	Bulk density (g cm^{-3})	$CaCO_3$ (%)	EC_e (dS m^{-1})	pH_s	SAR ($mmol_c$ L^{-1})$^{0.5}$	Cation concentration ($mmol_c$ L^{-1}) [b]			
	<2 μm	2–50 μm	>50 μm							Na^+	K^+	Ca^{2+}	Mg^{2+}
0–10	1.35	90.59	8.07	Silt	1.44	10.62	18.54	8.90	35.7	123.5	0.39	5.5	6.5
10–20	0.99	95.93	3.08	Silt	1.53	14.53	11.66	9.58	54.0	108.0	0.34	2.0	2.0
20–30	0.85	95.75	3.40	Silt	1.59	12.40	6.69	9.52	38.6	77.2	0.2	2.0	2.0
30–40	1.02	92.32	6.66	Silt	1.64	18.61	4.16	9.51	23.2	46.4	0.2	2.0	2.0
40–80	0.65	82.38	16.97	Silt loam	1.62	11.14	2.17	9.47	11.6	23.2	0.27	2.0	2.0
80–120	0.48	77.45	22.07	Silt loam	1.58	6.19	1.59	9.21	6.9	15.4	0.65	2.5	2.5
Irrigation water [c]							2.14	8.87	6.0	11.9	0.34	1.32	6.46

[a] According to American soil classification standards.
[b] Cation concentration in saturated paste extract.
[c] The salinity values of irrigation water were the three-year averages measured once every year during the experiment. EC_e, electrical conductivity of saturated paste extract; pH_s, pH of saturated paste; SAR, sodium adsorption ratio of saturated paste extract.