Variation of soil physical-chemical characteristics in salt-affected soil in the Qarhan Salt Lake, Qaidam Basin Postprint

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Abstract

Soil salinization has adverse effects on the soil physical-chemical characteristics. However, little is known about the changes in soil salt ion concentrations and other soil physical-chemical characteristics within the Qarhan Salt Lake and at different soil depths in the surrounding areas. Here, we selected five sampling sites (S1, S2, S3, S4, and S5) alongside the Qarhan Salt Lake and in the Xidatan segment of the Kunlun Mountains to investigate the relationship among soil salt ion concentrations, soil physical-chemical characteristics, and environmental variables in April 2019. The results indicated that most sites had strongly saline and very strongly saline conditions. The main salt ions present in the soil were Na+, K+, and Cl–. Soil nutrients and soil microbial biomass (SMB) were significantly affected by the salinity ($P<0.05$). Moreover, soil salt ions (Na+, K+, Ca2+, Mg2+, Cl–, CO32–, SO42–, and HCO3–) were positively correlated with electrical conductivity (EC) and soil water content (SWC), but negatively related to altitude and soil depth. Unlike soil salt ions, soil nutrients and SMB were positively correlated with altitude, but negatively related to EC and SWC. Moreover, soil nutrients and SMB were negatively correlated with soil salt ions. In conclusion, soil nutrients and SMB were mainly influenced by salinity, and were related to altitude, soil depth, and SWC in the areas from the Qarhan Salt Lake to the Xidatan segment. These results imply that the soil quality (mainly evaluated by soil physical-chemical characteristics) is mainly influenced by soil salt ions in the areas surrounding the Qarhan Salt Lake. Our results provide an accurate prediction of how the soil salt ions, soil nutrients, and SMB respond to the changes along a salt gradient. The underlying mechanisms controlling the soil salt ion distribution, soil nutrients, and SMB in an extremely arid desert climate playa should be studied in greater detail in the future.

Full Text

Preamble

Variation of Soil Physical-Chemical Characteristics in Salt-Affected Soil in the Qarhan Salt Lake, Qaidam Basin

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Abstract: Soil salinization adversely affects soil physical-chemical characteristics. However, little is known about the changes in soil salt ion concentrations and other soil physical-chemical characteristics within the Qarhan Salt Lake and at different soil depths in the surrounding areas. Here, we selected five sampling sites (S1, S2, S3, S4, and S5) alongside the Qarhan Salt Lake and in the Xidatan segment of the Kunlun Mountains to investigate the relationship among soil salt ion concentrations, soil physical-chemical characteristics, and environmental variables in April 2019. The results indicated that most sites had strongly saline and very strongly saline conditions. The main salt ions present in the soil were Na^+, K^+, and Cl^-. Soil nutrients and soil microbial biomass (SMB) were significantly affected by the salinity ($P < 0.05$).

Moreover, soil salt ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, CO_3^{2-}) were positively correlated with electrical conductivity (EC) and soil water content (SWC), but negatively related to altitude and soil depth. Unlike soil salt ions, soil nutrients and SMB were positively correlated with altitude, but negatively related to EC and SWC. Moreover, soil nutrients and SMB were negatively correlated with soil salt ions. In conclusion, soil nutrients and SMB were mainly influenced by salinity, and were related to altitude, soil depth, and SWC in the areas from the Qarhan Salt Lake to the Xidatan segment. These results imply that soil quality (mainly evaluated by soil physical-chemical characteristics) is primarily influenced by soil salt ions in the areas surrounding the Qarhan Salt Lake. Our results provide an accurate prediction of how soil salt ions, soil nutrients, and SMB respond to changes along a salt gradient. The underlying mechanisms controlling soil salt ion distribution, soil nutrients, and SMB in an extremely arid desert climate playa should be studied in greater detail in the future.

Keywords: salinization; soil salt ions; soil physical-chemical characteristics; soil microbial biomass; soil nutrient; Qarhan Salt Lake

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Introduction

Soil salinization refers to the accumulation of soluble salts on the surface or near-surface, mainly including K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, and HCO_3^- (Shrestha, 2006). Salinization is one of the most important factors limiting the growth of plants and microbes, and adversely affects soil quality (Munns and Tester, 2008; Zhao et al., 2017). Soil salinization is a widespread and serious soil degradation phenomenon caused by climate change and poor management of water and soil resources (Zhang, 2010). More than 7% of the Earth's surface is affected by soil salinization (Rozema and Flowers, 2008), with approximately 4.0×10^8 hm^2 of cultivated land severely limited by soil salinization (Bot et al., 2000). In China, about 1.0×10^8 hm^2 of the land area is affected by different degrees of soil salinization (Li et al., 2014). Numerous studies have demonstrated that soil salinization has been accelerated in arid and semi-arid regions of China (Li et al., 2007).

The Qaidam Basin is the largest basin on the northern edge of the Tibetan Plateau, covering a total area of 2.75×10^5 km^2 (Jia et al., 2011), and is characterized by inland saline lake facies. It is located in a hyper-arid region of northwestern China, with low annual precipitation and high salinity (Jiao et al., 2015). The problem of soil salinization has become increasingly serious in the Qaidam Basin, now affecting about 42.5% of the agricultural land. Furthermore, soil salinization negatively impacts plant growth and worsens soil physical-chemical properties (Paul and Lade, 2014). Wang et al. (2016) reported that salt accumulation induced by long-term saline water irrigation resulted in spring maize yield loss. Wong et al. (2008) indicated that soil salinization changed soil aggregate structure, restricted the availability of soil nutrients, and reduced soil permeability. Previous studies on soil salinization effects in the Qaidam Basin have mostly focused on plant metabolism, photosynthesis, enzyme activity, nutrient absorption, and crop yields (Li et al., 2019a; Zhang et al., 2019). Li et al. (2019a) showed that soil salinization increased osmotic substances and antioxidant enzymes in Lycium ruthenicum, but photosynthesis remained suppressed, influencing crop yields. Zhang et al. (2019) also found that the photosynthetic properties of Elaeagnus angustifolia were more sensitive to salinity than those of Lycium barbarum. However, these studies mostly involved impacts on plants (i.e., main economic crops and sand-fixation plants), whereas effects on soil development, such as salt ion distribution, soil nutrients, and soil microbial biomass (SMB), have been ignored.

Soil salinization causes high levels of soluble salt ions. The dominant salt ions in most soils are K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-} (Young et al., 2015); however, Na^+ and Cl^- are the most prevalent and have been the focus of most research (Tavakkoli et al., 2010). Munns and Tester (2008) showed that excessive Na^+ and Cl^- concentrations critically affected biochemical processes and reduced plant growth. However, high levels of one or several salt ions inevitably resulted in variances in the contents of other balancing ions in the soil, and the effects of different salt ions on plants may differ (Tavakkoli et al., 2010). Genc et al. (2010) reported that changes in Ca^{2+} and K^+ concentrations may affect salinity responses. It is necessary to study salt ion distribution in soils to better understand the mechanisms controlling soil ecosystem response to salinization.

Soil salinization adversely affects soil physical-chemical characteristics. Tejada and Gonzalez (2005) showed that increased electrical conductivity (EC) negatively impacted soil structural stability, permeability, and bulk density. Mavi et al. (2012) demonstrated that soil dissolved organic matter was strongly affected by salt-affected soils. Soil salinization also affected soil microbial communities and their activities due to resulting variations in osmotic and matric potential of soil solution (Rietz and Haynes, 2003). SMB refers to the total number of soil microorganisms, such as bacteria, fungi, and protozoa, and is one of the most sensitive indicators of ecosystem stability (An et al., 2009). It is both a source and sink of available nutrients and plays a crucial role in nutrient transformation in terrestrial ecosystems (Singh et al., 1989). Studies of SMB have become a common way to explore soil functions in response to soil environmental change (Holden and Treseder, 2013). SMB variation may impact soil organic matter turnover. Lehmann et al. (2011) observed that increased SMB can influence soil nutrient cycling and soil organic carbon (SOC) mineralization. Liang et al. (2012) also reported that SMB was important in planting, fertilization, and other agricultural management activities. Therefore, studies of SMB dynamics with changes in the salt gradient will contribute to better understanding of dynamic changes in soil organic matter.

The Qarhan Salt Lake in the eastern Qaidam Basin, Qinghai-Tibet Plateau, is the largest salt lake and the largest potash and magnesium deposit production base in China (Xiang et al., 2021). The Golmud River is the major water supply to Dabsan Lake, which is the largest saline lake in the Qarhan Salt Lake system (Wang et al., 2015). In recent years, local environments and ecosystems have been exposed to high potential ecological and health risks due to industrial mining activities, agricultural development, and urbanization along the Golmud River (Xiang et al., 2021). Oasis agriculture is developing rapidly in the eastern Qaidam Basin. In this region, light and heat conditions are conducive to crop growth, with spring wheat, oilseed rape, highland barley, potato, beans, and wolfberry being the main crops (Wang et al., 2019). In the eastern Qaidam Basin, soil degradation takes the form of salinization and alkalization, occurring mainly near oasis borders and at lower elevations in non-oasis regions where effective soil moisture might have been reduced by warming-induced increases in evapotranspiration during 1990–2003 (Wang et al., 2003; Zeng and Yang, 2008).

In this study, we clarified the relationship among soil water content (SWC), soil salinity, and distance from the Qarhan Salt Lake. Specifically, we investigated dynamic changes in salt ion concentrations and other soil physical-chemical characteristics, assessed differences in SWC, salt ion concentrations, and physical-chemical properties among five sampling sites, and analyzed variation in salt ion concentrations and soil nutrients among the five sites. An evaluation of soil quality in areas surrounding the Qarhan Salt Lake based on soil physical-chemical characteristics will be valuable for adjusting local economic strategies.

2.1 Study Area

The Qarhan Salt Lake (36°37 36 –37°12 33 N, 94°42 36 –96°14 35 E) is situated in the center of the southern Qaidam Basin, northern China [Figure 1: see original paper], with an elevation of 2675 m. The lake is 168 km long from west to east and 20–40 km wide from north to south, with a gross area of 5856 km^2, making it the largest playa in the eastern Qaidam Basin (Huang and Han, 2007). The Qarhan Salt Lake has an extremely arid desert climate, where mean annual precipitation is less than 30 mm and annual potential evaporation exceeds 3000 mm (Li et al., 2015). The average wind speed is 4.3 m/s, with winds predominantly from west to northwest (Li et al., 2015).

In the Qarhan Salt Lake region, precipitation declines from the mountains to the center. Precipitation is mainly concentrated in May–September, accounting for over 80% of annual rainfall (Zhang et al., 2012). The soil type is saline sand with a mean particle size of 164.50–186.08 μm (Li et al., 2019b). Naturally dominant plants are shrub/semi-shrub desert vegetation, including Haloxylon ammodendron, Salsola spp., Ceratoides lateens, Ephedra przewalskii, Tamarix spp., Calligonum spp., Nitraria spp., and Artemisia spp. (Fan et al., 2014). Inflows to the Qarhan Salt Lake are mainly from perennial river water and spring water (Zhang et al., 1993), with perennial river water from the eastern Kunlun Mountains (Fan et al., 2015). The Xidatan segment lies on the northern side of the Kunlun Mountains at about 4350 m elevation. The climate is semi-arid, with an annual mean temperature of –3.7°C. The lowest temperature occurs in January (mean –20.0°C) and the highest in July (mean 14.0°C). Mean annual precipitation is about 400 mm, most falling from May to September (Luo et al., 2018). Dominant species are Carex moorcroftii, Stipa purpurea, and cushion plants such as Androsace tapete and Arenaria kansuensis (Yang et al., 2013).

2.2 Soil Sample Collection

This study was conducted in April 2019 in the Qaidam Basin, northwestern China. To evaluate soil salinity distribution and chemical processes, we collected soil samples and measured parameters including SWC, pH, EC, ion concentrations, SOC, total nitrogen (TN), total phosphorus (TP), total potassium (TK), microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and microbial biomass phosphorus (MBP).

We selected five sampling sites (S1, S2, S3, S4, and S5) alongside the Qarhan Salt Lake and the Xidatan segment of the Kunlun Mountains [Figure 1: see original paper]. Their distances from the Qarhan Salt Lake followed the order S1, S2, S3, S4, and S5. General characteristics of each sampling site based on field investigation are summarized in . At each site, we established three quadrats (10 m × 10 m) and collected five soil samples using a soil auger along each quadrat's diagonal at depths of 0–5, 5–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm. Five replicate soil samples from the same depth were evenly mixed into a composite sample for each quadrat, yielding 105 soil composite samples across five sites. All composite samples were randomly divided into three parts: one for SWC determination; another air-dried, ground, and passed through a 2 mm-mesh sieve for salt ion concentration measurement (including Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, CO_3^{2-}, SO_4^{2-}, and HCO_3^-) and other physical-chemical properties (pH, EC, SOC, TN, TP, TK); and the third stored in liquid nitrogen for MBC, MBN, and MBP analysis. Additionally, we dug a hole about 0.50 m deep and 0.25 m square in each 10 m × 10 m quadrat to measure salt crust thickness directly using a steel tape.

2.3 Sample Analysis

SWC was determined by the gravimetric method, in which soil samples were oven-dried for 48 h at 105°C to constant weight (Nanjing Institute of Soil Research, CAS, 1980). pH and EC were measured using a pH meter and portable conductivity meter, respectively (Chen et al., 2017). SOC was estimated using wet oxidation with $K_2Cr_2O_7$ and titration with ferrous ammonium sulfate following Li et al. (2010). TN was determined by the Kjeldahl method, TP by spectrophotometry after perchloric acid-sulfuric acid digestion, and TK by flame photometry (Gammon, 1951; Olsen and Sommers, 1982).

Salt ion concentrations were determined using the soil diluted extract method. K^+ and Na^+ concentrations were measured by flame photometry, Ca^{2+} and Mg^{2+} by EDTA titration, Cl^- by silver nitrate titration, SO_4^{2-} by EDTA complexometric titration, and CO_3^{2-} and HCO_3^- by acid-alkali neutralization titrimetric method (pH $\sim$ 4.8) (Yang et al., 2014; Chen et al., 2019).

Each fresh soil sample was divided into six equal subsamples for MBC, MBN, and MBP estimation using the fumigation extraction method (Brookes et al., 1982, 1985). Carbon and nitrogen were extracted from fumigated (with ethanol-free $CHCl_3$) and non-fumigated samples with 50 mL 0.5 mol/L K_2SO_4, shaken for 30 min at 200 r/min, and filtered (Dijkstra et al., 2015). MBC and MBN were calculated as the difference between carbon and nitrogen extracted from fumigated and non-fumigated samples, using extraction efficiencies of 0.38 (Jiang et al., 2006) and 0.54 (Brookes et al., 1985), respectively. MBP was analyzed calorimetrically with a spectrophotometer (Xue et al., 2014). Fumigated soil samples were extracted by 0.5 mol/L $NaHCO_3$ in an oscillator, then Mo-Sb spectrochrometry solution was added for color development, with simultaneous extraction of non-fumigated samples. After 30 min, color intensity was analyzed at 700 nm wavelength. The difference between phosphorus extracted from fumigated and non-fumigated samples was converted to MBP using an extraction efficiency of 0.4 (Brookes et al., 1985).

2.4 Statistical Analysis

All data are expressed as mean ± standard deviation (SD) with three biological replications. One-way analysis of variance followed by Duncan's test evaluated differences in SWC, salt ion concentrations, and physical-chemical properties among sites. Data were log-transformed to normalize distributions, with significance defined at $P < 0.05$. Statistical analyses were conducted using SPSS 16.0 software (SPSS Inc., Chicago, IL, USA). Redundancy analysis (RDA) explored how salt ion concentrations and soil nutrients varied with environmental variables (altitude, SWC, EC, soil depth). Data were initially analyzed by detrended correspondence analysis (DCA) to assess gradient length, confirming that a linear model RDA was appropriate (SD<3) (Rubino and McCarthy, 2003). DCA and RDA were conducted in R 3.5.1 software using the vegan package.

3.1 Soil Water Content (SWC), pH, and Electrical Conductivity (EC)

SWC, pH, and EC displayed diverse tendencies across sampling sites and soil depths . Within 0–100 cm depth, SWC first increased then decreased with distance from the Qarhan Salt Lake, reaching a maximum at S3, especially in the upper 0–10 cm. Soil pH showed no obvious trend from S1 to S5, ranging between 8.03 and 8.88. Average EC significantly decreased with distance from the Qarhan Salt Lake. At S1 (closest to the lake), EC within 0–5 cm reached 25.2 dS/m, but was only 6.6 dS/m at S5 (farthest) . Soil depth also affected SWC, pH, and EC. Except at S5, SWC rapidly increased with depth from the surface to 40 cm, then remained constant at 40–100 cm, while pH gradually decreased with depth. Similarly, EC decreased with depth at all five sites. Mean EC values at 80–100 cm were 6.9, 7.0, 7.7, 3.7, and 4.2 dS/m at S1, S2, S3, S4, and S5, respectively—reductions of 72.62%, 71.19%, 63.85%, 43.08%, and 36.36% compared with 0–5 cm . These results indicated that distance from the Qarhan Salt Lake had little effect on soil pH but influenced SWC and EC. Additionally, soil depth affected SWC, pH, and EC at all sites except S5.

3.2 Soil Nutrient Contents

Soil nutrient contents were affected by distance from the Qarhan Salt Lake and soil depth. SOC significantly increased from S1 to S5, with the amplitude becoming larger with increasing distance. For S2 to S5, SOC increased substantially by 0.3%, 15.4%, 43.2%, and 61.5% at 0–5 cm depth, and by 5.7%, 18.7%, 48.5%, and 70.2% at 20–40 cm depth, compared with S1 . However, soil nutrient concentrations decreased gradually with depth at S1–S5, reaching minimum values at 80–100 cm. Increased depth caused SOC reductions of 3.5%, 13.2%, 30.8%, 39.3%, 38.6%, and 40.6% at 5–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm, respectively, compared with 0–5 cm at S3 . Similar trends occurred for TN, TP, and TK. SOC, TN, TP, and TK increased with distance from the Qarhan Salt Lake but decreased with soil depth.

3.3 Soil Salt Ion Concentrations

Soil salt ion concentrations differed across sampling sites and depths, displaying decreasing trends with distance from the Qarhan Salt Lake and being remarkably lower at S5 than S1. At 10–20 cm depth, Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, CO_3^{2-}, SO_4^{2-}, and HCO_3^- concentrations at S3 significantly decreased by 57.7%, 0.0%, 2.8%, 9.3%, 67.8%, 19.2%, 42.0%, and 15.5%, respectively, compared with S1 [Figure 2: see original paper].

At the same site, different salt ions displayed various trends with increasing depth. Within 0–20 cm, average Na^+, K^+, Cl^-, SO_4^{2-}, and HCO_3^- concentrations gradually decreased with depth, while Ca^{2+}, Mg^{2+}, and CO_3^{2-} reached maximum values at 5–10 cm. At S5, average Na^+, K^+, Cl^-, SO_4^{2-}, and HCO_3^- concentrations decreased with depth by 7.1%, 40.0%, 7.3%, 33.7%, and 9.3% at 5–10 cm, respectively. Na^+, K^+, Cl^-, SO_4^{2-}, and HCO_3^- concentrations reached a minimum at 10–20 cm, decreasing by 57.1%, 60.0%, 36.6%, 70.9%, and 11.3% compared with 0–5 cm. Average Ca^{2+}, Mg^{2+}, and CO_3^{2-} concentrations increased by 9.6%, 18.1%, and 65.8% at 5–10 cm compared with 0–5 cm [Figure 2: see original paper]. These results showed that distance from the Qarhan Salt Lake strongly influenced soil salt ion concentrations, with greater accumulation closer to the lake.

3.4 Soil Microbial Biomass

SMB varied across sampling sites and depths. MBC, MBN, and MBP concentrations increased with distance from the Qarhan Salt Lake, reaching maxima at S5. At S5, MBC, MBN, and MBP significantly increased by 66.3%, 72.4%, and 36.4% at 0–5 cm; by 72.6%, 62.7%, and 30.8% at 5–10 cm; and by 61.8%, 72.0%, and 65.1% at 10–20 cm, compared with S1 [Figure 3: see original paper]. Variations in MBC, MBN, and MBP across depths at the same site were complex. MBC tended to decrease with depth, reaching a minimum at 10–20 cm [Figure 3a: see original paper]. Similarly, MBN fell to minimum values of 9.53, 9.66, 9.96, 11.11, and 16.05 mg/kg at 10–20 cm at S1–S5, respectively, decreasing by 20.8%, 21.0%, 45.5%, 42.3%, and 29.2% compared with 0–5 cm [Figure 3b: see original paper]. MBP was highest at 5–10 cm, followed by 10–20 cm, and lowest at 0–5 cm [Figure 3c: see original paper]. These results indicated that distance from the Qarhan Salt Lake significantly influenced SMB, with variability among depths.

3.5 The Relationship Between Environmental Variables and Soil Physical-Chemical Properties

As shown in [Figure 4: see original paper], 58.18% of cumulative variation in soil physical-chemical properties was explained by the first axis and 23.72% by the second axis. According to permutation tests, the first ($F = 239.93$, $P < 0.001$), second ($F = 97.82$, $P < 0.001$), and third ($F = 34.37$, $P < 0.01$) canonical axes were highly significant for soil physical-chemical properties . Soil salt ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}) were positively correlated with EC and SWC but negatively correlated with altitude and soil depth [Figure 4a: see original paper]. Unlike soil salt ions, soil nutrients and SMB concentrations (BMC, BMN, BMP) were positively correlated with altitude but negatively correlated with EC and SWC. The first axis explained 77.60% of cumulative variation in soil nutrients and SMB, while only 2.34% was explained by the second axis [Figure 4b: see original paper]. According to permutation tests, the first canonical axis was highly significant for soil nutrients and SMB ($F = 149.06$, $P < 0.001$;). Soil nutrients and SMB concentrations were negatively correlated with soil salt ions, with Cl^-, Na^+, K^+, and SO_4^{2-} having more influence than Ca^{2+}, Mg^{2+}, CO_3^{2-}, and HCO_3^- [Figure 4b: see original paper].

4 Discussion

EC can compare different soils and is classified by salinity hazard and effects on crop yields (Rengasamy, 2010). Our results indicated most sites were strongly saline (EC=8–16 dS/m) or very strongly saline (EC>16 dS/m), with salinity decreasing with distance from the Qarhan Salt Lake and soil depth. This decrease may relate to environmental factors (rainfall, temperature, altitude, evaporation). The soil depth influence may be due to salt accumulation, which tended to occur in topsoil (0–20 cm), with some leaching to deeper layers (80–100 cm) (Yu et al., 2007; Zlotopolski, 2017). As in previous studies, our pH results indicated saline-alkaline soil (pH>8.5) (van Beek and Tóth, 2012).

Distance from the Qarhan Salt Lake strongly influenced soil salt ion concentrations, with greater accumulation near the lake. This may relate to water inflows containing high salt levels. Near the lake (S1–S3), lower altitude results in more perennial river and spring water inflows, causing more salt accumulation (Fan et al., 2015). Differences in climatic conditions (S1–S3: extremely arid desert; S4–S5: semi-arid) (Li et al., 2015; Luo et al., 2018) may also influence concentrations. Low annual mean temperature and high precipitation likely restricted salt ion concentrations at high-altitude sites (S4 and S5). Hu et al. (2018) indicated cation exchange and mineral dissolution/precipitation were key factors in brine dynamics, with evaporation and enrichment being main mechanisms of underground brine evolution. Salt-bearing rocks and eolian salt migration occurred in moisture-deficit locations, but precipitation redistributed salts in automorphic salt-affected soil profiles (Pankova and Konyushkova, 2013). Increased precipitation usually accompanied decreased weathering intensity and initial salt accumulation, with salts entering low-altitude regions via runoff. Our study showed Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, and HCO_3^- were main soil salts, derived from rock salt (NaCl), sodium carnallite, gypsum ($CaSO_4 \cdot 2H_2O$), calcite ($CaCO_3$), feldspar ($KAlSi_3O_8$–$NaAlSi_3O_8$–$CaAl_2Si_2O_8$), sylvine (KCl), and dolomite ($CaMg(CO_3)_2$) in the Qaidam Basin halide layer (Ye et al., 2015). Soil salt ion formation patterns may have been affected by paleoclimatic conditions, where dry and relatively humid climate alternation with wet events over the last millennium significantly influenced soil salinity (Chen et al., 2009). Soils differed in percentage salt content and salinization chemistry. Salt distribution was mainly determined by salt-bearing rock presence and eolian salt migration (Hu et al., 2018).

Salinization causes soil degradation with numerous negative effects on ecological and non-ecological soil functions (Daliakopoulos et al., 2016), especially soil nutrient content. Our results showed SOC, TN, TP, and TK concentrations increased with distance from the Qarhan Salt Lake while decreasing with soil depth. Several reasons explain why soil nutrient content decreased with increasing salt content. First, salinity degree (salt content, composition, crust thickness) was higher in low-altitude regions due to lower precipitation, higher evaporation, and more potential saline ion sources via runoff or river water from high-altitude regions (Li et al., 2015; Song et al., 2017; Luo et al., 2018). Generally, higher saline ion concentrations adversely impacted soil quality improvement. Second, nutrient cycling was inhibited by salinity's adverse effects on plants. As one of the most brutal environmental factors, salinity limited plant productivity, with most plants sensitive to high soil salt concentrations and salt-affected land area increasing daily (Shrivastava and Kumar, 2015). Saline growth media affect almost all aspects of plant development (Ashraf, 2004), limiting nutrient fixation, conversion, and storage, thereby degrading soil quality. Third, soil salinity affected vegetation distribution patterns in the Qaidam Basin, where harsh climatic conditions and unique geographical location already stressed vegetation growth (Wang et al., 2018a). Vegetation distribution was somewhat influenced by soil nutrient status. Salinity's adverse impacts on soil nutrients could also occur through decreased soil biodiversity and microorganism activity (Singh, 2015). Soils were sensitive to salinity, with carbon losses reported after short- and long-term exposure (Servais et al., 2019). Depending on form and development stage, salinization seriously degraded soil fertility, ultimately eliminating all vegetation (JRC et al., 2012; Trnka et al., 2013). SOC loss due to salinization created negative feedback on soil fertility, microbial activity, and enzyme activities, increasing clay particle dispersion and wind/water erosion rates, thereby directly or indirectly influencing soil nutrients (De la Paix et al., 2013; Singh, 2015).

Salinity regulates nitrogen cycling by shaping nitrifier and denitrifier community structure (Wang et al., 2018b). Our results showed SMB was significantly affected by salinity, with microbial biomass decreasing under high-salt conditions, reflecting microorganism sensitivity to salinity. Rath et al. (2016) indicated microbial processes were strongly inhibited by salinity, though fungal growth was less influenced than bacterial growth. With increasing salinity, redox potential, electron acceptor availability, osmotic stress, and organic substrate quantity/quality change, affecting microbe-mediated biogeochemical processes (Chambers et al., 2014; Servais et al., 2019). These variations may ultimately influence soil nutrients (Flower et al., 2017) and microbial community composition (Ikenaga et al., 2011). Moreover, soil salinization was closely related to soil physicochemical properties, with soil nutrients considered key factors influencing salinization differences (Xie et al., 2019). Our results indicated salinization negatively affected available nutrient content. One explanation is decreased soil organic matter under saline conditions, where plant inputs decreased due to sparse vegetation cover, while enhanced carbon-degrading extracellular enzyme activity and microbial decomposition rates negatively affected available nutrients (Morrissey, 2014). Saline soils likely had low organic matter content due to decreased plant input rather than increased decomposition (Setia et al., 2013).

5 Conclusions

Our results indicated most sites from the Qarhan Salt Lake to the Xidatan segment were strongly or very strongly saline. The main soil salt ions were Na^+, K^+, and Cl^-. Comparative data along salt gradients suggested salinity decreased with increasing altitude and soil depth. SOC, TN, TP, and TK concentrations increased with altitude. SMB was influenced by salinity, decreasing under high-salt conditions and being significantly affected by salinity. Future research should determine how microorganism diversity and composition vary across salinity gradients within the extremely arid desert climate playa (Qarhan Salt Lake) in the southern Qaidam Basin center. Specifically, understanding how salt ions, soil nutrients, and SMB interact is needed to clarify their relationships.

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Note: Figure translations are in progress. See original paper for figures.