Seasonal Performance and Spatial Heterogeneity of Soil Salt Ions in a Semiarid Orchard of Northwest China

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Abstract. The relationship between spatial and temporal dynamics of major salt ions and their toxicology is still unclear, particularly in perennial orchard fields. A seasonal soil sampling was conducted from Apr. to Oct. 2011 in a salinized orchard soil in semiarid northwest China. Soil moisture content and concentrations of total soluble salt and eight salt ions were measured every 2 weeks in the soil at 0 to 2, 2 to 5, 5 to 10, 10 to 15, 15 to 20, 20 to 25, 25 to 40, 40 to 60, 60 to 80, and 80 to 120 cm during the growing period of apple trees. Soil moisture content decreased early in the growth season (Period 1) but with increasing rainfall in the middle of growing season (Period 2 and Period 3) and reached a maximum at late season (Period 4) at all depths. Soil salt concentration increased along with soil profile, particularly in the 60- to 120-cm soil layer at all periods. The highest soil salt level was observed in Period 4. The contents of HCO_3^- , Ca^{2+} , and Mg^{2+} were almost uniform in all soil layers, but the contents of Cl^- , SO_4^{2-} , and Na^+ increased with soil layer. The content of K^+ decreased from the upper to the deeper layers of soil profile. The distribution of CO_3^{2-} had a high temporal and spatial heterogeneity with soil depths and season. Analysis of the charge balance on positive and negative salt ions indicated that the horizontal movement of ions and the transfer of soil water were likely the driving factors affecting soil salinization. The movement of Na^+ and Mg^{2+} ions in the top soil may be responsible for rhizospheric ions composition and toxin effect to restrain apple tree growth in the early growth period.

Soil salinization is a critical environmental issue in the arid and semiarid regions of the world (Sheng et al., 2010; Wang et al.,

2008). In dry areas, annual evaporation greatly exceeds precipitation and the salts dissolved in the groundwater are accumulated in soils. The excessive amounts of salt adversely affect the soil physical and chemical properties as well the microbiological processes (Lakhdar et al., 2009). The western region of northeast China is one of the main agricultural regions of the country, but soil salinization has become a critical environmental issue (Liu et al., 2002), restricting agricultural development and threatening the survival of human kind in this region (Pan et al., 2003). Although most of this salinity is natural, the extension of salinity in soils is increasing in a substantial proportion in cultivated agricultural land because of land

clearing or irrigation (Munns, 2005). Nearly 50% of the irrigated land in arid and semiarid regions has some degree of soil salinization (O'Hara, 1997). The mitigation and control of soil salinity is one of the main challenges in the agriculture of the 21st Century (Amezket, 2006).

Qin'an County in the Gansu province of China is an arid region and saline water with salt levels from 2.4 to 2.8 g·L⁻¹ applied to irrigate field-grown fruit trees. This practice has accelerated soil secondary salinity in the orchards causing the wilting and dying of apple trees leaves since 1997. Soil salinization is a gradual process and the impact of salt intrusion is noticeable after several years of development (Guganesharajah et al., 2007). Because the relative proportions of Ca^{2+} , Na^+ , Mg^{2+} , and K^+ in the soil are critical for plant development under salinity (Grattan and Grieve, 1992; Reimann and Breckle, 1993, 1995; Wang and Redmann, 1996), the quantification of the ratios between the concentration of these ions and the variability through the year is very important (Alvarez-Rogel et al., 2001). Previous studies on the soil–plant–atmosphere continuum (SPAC) have focused on cereal crops and rarely on fruit trees. Cereal crops are annual plants and the soil where they grow is often disturbed by farming activities, which tend to homogenize secondary substances accumulated. Fruit trees are perennials and there is no disturbance in the growing soil. The distribution characteristics of their root system are different from that of cereals crops. In studying the temporal and spatial dynamics of salt ions down, the soil profile in an orchard is a prerequisite to determine the mechanism of mass transfer in the SPAC in dry areas.

So far, the mechanism of the movement of salt ions that regulates the formation of soil salinization in semiarid environments has not been fully understood. Most studies have been concerned with the spatial dynamics (Doescher et al., 1984; Macdonald et al., 1999; Sheng et al., 2009) or temporal dynamics alone (Sarah, 2001) of salt in soil. Little is known about the temporal and spatial distribution of the movement of salinity in the soil and plant system. The few existing studies have been conducted under simulation conditions of the laboratory rather than in the field. There are a variety of factors affecting the salt movement such as land topographic heterogeneity, parent rock, soil physical and chemical trait (Baver et al., 1972; Charley and West, 1975), seasonal rainfall and atmospheric temperature (Sarah, 2001), vegetation cover (Zwickel et al., 2007), and overland flow (Macdonald et al., 1999; Schlesinger et al., 1990; Zaady et al., 2001). Regardless of the factors (topographic, parent rocks, climate, biology, and others factors) that strongly affect the salinity distribution, the result cannot entirely elucidate salt transport and distribution on farmland soil and a vegetation system. The aim of this study was to determine the temporal and spatial dynamics of salt and ions in the soil profile of apple trees in a semiarid region of China

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during the growth period. It also aimed to determine the regulation of the movement of salt and ions between the soil and the fruit tree.

Material and Methods

Study site. The study was conducted in Qin'an County (lat. 34°44' to 35°11'N, long. 105°21' to 106°02'E) situated along the Hulu River, which is a tributary to the Wei River. It is located in the southeast region of Gansu province with an area of 1601.6 km² and an orchard area of 16640 ha. Its elevation is between 1120 and 2230 m above sea level. Its climate is semiarid to arid with an annual precipitation of ≈400 mm, and the rain falls mainly during July to September. The average annual temperature is 10.4 °C, and the annual potential evaporation far exceeds the annual rainfall with a mean annual amount of ≈1500 mm. The soils of the area are mostly classified as calcareous soil; the soil pHs are more than 8.0. Classification of soil particles is according to their size, the names follow the U.S. Department of Agriculture system, and the soil texture is a clay, which has 5.2% sand, 33.9% silt, and 60.9% clay. In the top 0- to 20-cm soil layer, the soil organic matter is 10.15 ± 1.15 g·kg⁻¹, and the average soil salinity and pH of 1:5 and 1:1 soil:water extracts is 0.063 ± 0.011% and 8.29 ± 0.11, respectively. The groundwater table at this site varied from 5.0 to 6.0 m with a salt content ranging from 2.42 to 2.8 g salt/L.

Soil sampling and climate data. The incidence of the wilting and dying of apple trees leaves in the orchards was over 50% as replication, and the areas of the orchards are 1/15 to 2/15 ha, row spacing is ≈4 to 5 m, a replication is per disease plant, and three replications were set up per orchards, which were ranged by means of random blocking. Soil samples from six orchards under salinity stress were measured at 0 to 2, 2 to 5, 5 to 10, 10 to 15, 15 to 20, 20 to 25, 25 to 40, 40 to 60, 60 to 80, and 80 to 120 cm. At each soil level, electrical conductivity (EC), soil moisture, and concentrations of several ions were determined. Soil samples at each site were taken from the down crown of apple trees, two times a month, at the beginning and ending of the middle 10 d of a month. The sampling began in Apr. 2011 and ended in Oct. 2011. Monthly potential evaporation and rainfall were on-site manually measured using an evaporator (AM3, Φ200 mm + 0.6 mm) and rain gauges (HJ03-JQR-1, Φ200 mm) during the study; respectively, the observed potential evaporation began at 2000 HR everyday, the effective precipitation observed after each rainfall.

Sample analysis. The collected soil samples were air-dried and thoroughly mixed ground to pass through a 1.0-mm sieve. Soil pH was measured in a 1:1 soil-to-water solution using a glass electrode (PHS-3C; Shanghai Shengci Instrument Limited Company, Shanghai, China). Total soluble salt concentration in the filtrate was determined by measuring the mass of the residue after

evaporating the solution at 100 °C using electric-heated thermostatic water bath. EC was measured in a 1:5 soil-to-water solution using a conductance instrument (DDS-11A; Shanghai Shengci Instrument Limited Company) and the concentration of Na⁺ and K⁺ and Ca²⁺, Mg²⁺, and SO₄²⁻ were measured by flame photometry and by the titrimetric method, respectively (Jackson, 1958). HCO₃⁻ and CO₃²⁻ were measured by double indicator titration (Lu, 2000), whereas Cl⁻ was measured by titration with silver nitrate. Gravimetric soil water content was determined by the oven-drying method at 105 °C ≈8 to 12 h.

Statistical analysis. Analysis of the temporal and spatial dynamics of salt as well as the concentration of several ions with each value being the mean of six measurements was conducted using Surfer 8.0 software (Golden Software Company, Inc.). In analyzing the temporal performance of eight ion movements, the whole growth season of apple trees was divided into four periods, including Period 1 (from 15 Apr. to 5 May), Period 2 (from 5 May to 14 June), Period 3 (from 14 June to 24 July), and Period 4 (from 24 July to 6 Oct.). The different layers or different time are the blocks; analysis of variance was conducted as a randomized complete block design. The Student-Neuman-Keuls test was applied to evaluate the significance of differences between the individual treatments.

Results

Meteorological conditions and initial distribution of ions

During the growth season, evaporation decreased with time and rainfall increased gradually but decreased toward the end of the season (Fig. 1). Na⁺ was the main cation measured in the soil and HCO₃⁻ was the anion. Whereas the soil content of HCO₃⁻, K⁺, Ca²⁺, and Mg²⁺ decreased down the soil profile, the soil content of Na⁺ and CO₃²⁻ increased (Fig. 2). There was a little variation in the content of Cl⁻ with soil depth. SO₄²⁻

was higher in the top and bottom layers of the soil profile than in the middle layers (Fig. 2).

Temporal and spatial dynamics of soil moisture

Soil moisture content changed with season and with soil depth (Fig. 3). The change with season was more marked than the change with soil depth and the change in the top soil layer was more marked than in the bottom layer. In the 0- to 20-cm layer of the soil profile, the change in soil moisture content was higher on 6 Oct. and lower on 5 May (Fig. 3). In the 20- to 120-cm layer of the soil profile, soil moisture content was higher on 4 July and lower on 19 June. In conclusion, soil moisture varied with soil depth and sampling time, which ranged from 40 g·kg⁻¹ to 225 g·kg⁻¹ and was closely related with the seasonal rainfall patterns.

Temporal and spatial dynamics of total dissolved salts

There were four periods of variation in the soil total dissolved salt (TDS) from the time the apple trees started flowering until harvest of the fruits. The first one was a period of "stabilization of salt" from 15 Apr. to 5 May. This period was characterized by no change in the content of TDS in the soil profile except in the 0- to 5-cm soil layer, where there was a small accumulation of salt (Fig. 4). The second one was a period of "abrupt accumulation of salt" from 5 May to 14 June. This period was characterized by a rapid accumulation of TDS in the whole soil profile, particularly at the 20-cm soil layer. The content of TDS increased gradually from 0.05% to 0.12% and 0.125% to 0.155% at 60-cm and 120-cm soil depths, respectively. The third one was a period of "desalinization in the top and accumulating of salt in the bottom" from 14 June to 19 July. The soil salt was then moved downward to depths of 0 to 60 cm. Desalinization was marked at 20 cm of the soil profile and the content of TDS decreased gradually from 0.08% to 0.055%.

At a depth of 60 cm in the soil profile, TDS content decreased gradually from

Fig. 1. Monthly potential evaporation (○) and rainfall (●) during the experimental seasons.

Fig. 2. Initial distribution of ion composition in the 0- to 120-cm soil layer of the soil profile in Apr. 2011. The X axis stands for the content of several salt ions (CO_3^{2-} , HCO_3^- , Cl^- , SO_4^{2-} , Ca^{2+} , Mg^{2+} , K^+ , and Na^+); the Y axis stands for the depth of soil profile.

Fig. 3. Changes in soil moisture content in the 0- to 120-cm soil layer of the soil profile during the growth of apple trees.

0.12% to 0.09%, but at depth of 90 cm, it increased from 0.12% to 0.14% and then decreased from 0.14% to 0.12%. The content of TDS at the depth of 120 cm in the soil profile increased from 0.15% to 0.17%. Therefore, salt accumulation lag in the bottom than in the top. The fourth one was

a period of “moderate salt accumulation” from 19 July to 6 Oct. In this period, there were no changes in the content of TDS at depths of 0 to 40 cm. At depths of 40 to 90 cm, salt accumulated in small quantities but at a depth of 90 to 120 cm, the accumulation of salt was marked (Fig. 4).

Temporal and spatial dynamics of the concentration of ions

Temporal and spatial dynamics of anions.

The content of Cl^- markedly decreased at depths of 40 to 80 cm from 15 May to 5 June (Fig. 5A). Because of the arid climate and the summer conditions, the Cl^- salts crystallized within the rock pores as well as on the surface of the stones. When rainfall exceeded 10 mm, it leached below 80 cm of the soil profile from 15 May to 5 June. The content of Cl^- markedly increased from 5 June to 20 June. The mean Cl^- content in the soil profile on 20 June was $\approx 0.004\%$ at 10 cm, 0.006% at 20 cm, 0.008% at 50 cm, and 0.01% at 100 cm. After 20 June, the variation in Cl^- followed a similar pattern to that of the TDS with the accumulation of Cl^- being 0.004% at 40 cm and 0.006% at 60 cm, but the content of Cl^- at 80 cm increased from 0.008% to 0.01% .

The SO_4^{2-} was mainly distributed in the soil profile of below 80 cm; however, the changes in SO_4^{2-} contents were more marked in the 0- to 80-cm soil layer (Fig. 5B). Furthermore, the temporal pattern of SO_4^{2-} content change in shallow soil (0 to 20 cm) was different from that of deeper soil layers (20 to 80 cm), i.e., the changes of SO_4^{2-} content in shallow and deeper soil layers were not synchronized. The rapid increases of SO_4^{2-} content in the shallow layer were focused on the early stage of growth period, yet those of the deeper layer were observed

Fig. 4. The temporal and spatial dynamic of total dissolved salt (TDS) contents in the 0 to 120-cm soil profiles. The TDS content was interpolated by ordinary kriging techniques.

from the early to mid-late stages, a significantly longer period. Specifically, the rapid accumulation of SO_4^{2-} contents was found on 20 May at the depth of 5 to 10 cm and 1 June at the depth of 10 to 20 cm, respectively. In the 20- to 80-cm soil layers, there were three rapid accumulation periods for soil SO_4^{2-} contents, including 5 May, 14 June, and 1 Aug. at depths of 40 cm, 60 cm, and 40 cm, respectively. In general, the concentrations of the SO_4^{2-} were increased down the whole soil profile, from 0.016% to 0.036% or higher.

There were three periods of variation in the CO_3^{2-} in the soil profile from flowering to fruiting (Fig. 5C). In the first period, the CO_3^{2-} moved upward before 3 June and the water-soluble CO_3^{2-} in the soil profile was more variable in the bottom than in the top layers. In the second period the CO_3^{2-} accumulated from 3 June to 20 Aug. and the concentration of CO_3^{2-} ions increased gradually from 0.0018% to 0.0038% as soil depth increased from 0 to 120 cm. In the third period, CO_3^{2-} leached after 20 Aug. and the CO_3^{2-} ions were equally distributed in different soil layers of the soil profile.

There were two periods of seasonal variation in the HCO_3^- in the soil profile from flowering to fruiting (Fig. 5D). In the first period, before 10 July, the concentration of HCO_3^- in the whole soil profile decreased from 0.042% to 0.026% with time. In the second period after 10 July, the concentration of HCO_3^- in the whole soil profile increased from 0.026% to 0.054% with time. This may be a consequence of the increasing rainfall later in the growth season (Fig. 1). As mentioned previously, the soil pH was 8.4, but because the pH of rainfall was less than 7, the CO_3^{2-} in the soil combined with the H^+ of the rainfall and while infiltrating into soil, it would have transformed into the HCO_3^- . In this case, the concentration of the CO_3^{2-} decreased, whereas the concentration of the HCO_3^- increased in the whole soil profile. This variation occurred almost simultaneously in the upper and deeper soil layers. The HCO_3^-

was almost evenly distributed in various soil layers (Fig. 5D).

Temporal and spatial dynamics of cations. There were two periods of seasonal variation in the Na^+ in the soil profile from flowering to fruiting (Fig. 5E). In the first period before 5 May, Na^+ ions moved rapidly upward. The concentration of the Na^+ in the whole soil profile increased rapidly from 0.05% to 0.40% as soil depth increased from 0 to 120 cm. In the second period after 5 May, the variation of the Na^+ ions was relatively moderate. At the spatial scale (i.e., in varying soil depths), there was a difference on the concentration of the Na^+ in the soil layers. It was $\approx 0.1\%$ at 30 cm, 0.2% at 60 cm, 0.3% at 80 cm, and 0.4% at 100 cm, respectively.

The K^+ ions were mainly distributed in the soil profile above 100 cm (Fig. 5F). At the temporal scale, the concentration of the K^+ in the 0- to 20-cm soil layer decreased from 0.04% to 0.02% with time. At the spatial scale, the K^+ ions leached downward under rainfall. It was in the 60-cm soil layer that the K^+ ions congregated.

There were two periods of seasonal variations in the Ca^{2+} in the soil profile from flowering to fruiting (Fig. 5G). In the first period before 24 July, there were two accumulation periods and one overlapping spot for the soluble Ca^{2+} movement along with the soil profile. The first accumulation period was ≈ 5 May and the accumulation spot was at the depth of 0 to 10 cm. The second accumulation period was ≈ 20 May and the accumulation spot was at the depth of 100 to 120 cm. There was a congregation at the bottom. In the second period after 24 July, the content of the Ca^{2+} in the whole soil profile increased from 0.014% to 0.022% with time. Because the pH value of natural rainfall was less than 7, calcium carbonate in soil was dissolved into soluble calcium by the high rainfall in July and then released into the soil. This directly led to the rapid increase in calcium ion content of soil at the later period (since 24 July).

There were two periods of seasonal variations in the Mg^{2+} in the soil profile from flowering to fruiting of the apple trees (Fig. 5H). In the first period, the concentration of soluble Mg^{2+} was largely reduced in deeper soil layers (from 60 to 120 cm), which could have resulted from a rapid absorption by the root system of apple trees. However, the time-soluble Mg^{2+} started to accumulate in Period 2 and early Period 3 (from 25 May to 14 June), particularly in the 10- to 20-cm soil layer. In the late Period 3, after 24 July, the concentration of soluble Mg^{2+} in the whole soil profile increased from 0.007% to 0.012%. Overall the dynamics of the variation of soluble Mg^{2+} were similar to that of soluble Ca^{2+} .

Temporal and spatial dynamics of ionic charge

The seasonal variation in the charge balance of positive (Na^+ , K^+ , Ca^{2+} , Mg^{2+}) and negative ions (CO_3^{2-} , HCO_3^- , SO_4^{2-} , and Cl^-) can be seen in Figure 6. The sum charge of four negative ions was relatively stable in various layers of the soil profile, ranging from 0.85 ± 0.32 to 2.17 ± 0.32 meq/100 g (Fig. 6). However, the sum charge of four positive ions increased with soil depth and with the progress of the season with a continuous increase from 2.74 ± 1.06 meq/100 g in the 0- to 20-cm soil layer in Period 1 to 22.32 ± 4.40 meq/100 g in the 80- to 120-cm soil layer in Period 4 (Fig. 6). The absolute values of the sum of positive charge were greater than those of the sum of negative charge (Fig. 6). The plus values of positive and negative charge in each soil layer of the soil profile followed a similar trend to the sum of positive charge (Fig. 6). This suggests that the loss of charge balance in a saline soil may be one of the factors affecting the differences in the accumulation of salt components when soil salinization occurs.

Discussion

Seasonal and spatial dynamics of total salt content in the soil profile. TDS was an important parameter affecting the growth of apple trees. It was widely recognized as a core factor for constructing a quantitative model of water and salt transport. More understanding on the temporal and spatial dynamic of soil TDS would be helpful to reveal the mechanism of salinity hazard occurrence. Temporal variation in rainfall and temperature could determine the pattern of salt movement in the soil (Sarah, 2001) and soil texture played a critical role in the availability and movement of soil salt components (Bayer et al., 1972; Charley and West, 1975). Spatial changes in soil salinity in the soil profile are also affected by soil moisture (Bush, 2006). In this study, the temporal and spatial variation of eight main salt ions determined the extent and distribution of soil salinization. The selected use of ions by the root system of apple trees was another critical factor that affected the temporal and spatial distribution of salt ions such as

Fig. 5. (A–H) The temporal and spatial dynamic of salt ion contents in the 0- to 120-cm soil profiles. The content of salt ions was interpolated by ordinary kriging techniques.

Fig. 6. Seasonal dynamics of several salt ionic charges in soil profiles. NC, PC, and PC+NC stand for negative charge, positive charge, and positive charge+negative charge, respectively; horizontal bars represent the mean of six replications $\pm$ sd. P1, P2, P3, and P4 stand for Period 1, Period 2, Period 3, and Period 4, respectively.

Fig. 7. Seasonal dynamics of total soil salt content in soil profiles, the mean ($\pm$ sd) values for total dissolved salt (TDS) at depths 0 to 120 cm in six orchards during P1, P2, P3, and P4, respectively.

soluble Mg^{2+} . This is likely to be related to the modification of the patterns of water and solute ion uptake by the roots in the rooting zone.

Spring, from 15 Apr. to 5 May, was mainly a period for salt stabilization because during this time, average air temperature was low while the plants germinate and the size of

the tree canopy was small. This contrasts with other studies in which spring is the salinization period as a result of high evaporation and low rainfall and summer the desalination period resulting from high rainfall (Li et al., 2008). Soil evaporation increased gradually, but the rate of increase was slow. Therefore, TDS content in the different layers of the soil profile was stable.

During the period of accumulation of salt (5 May to 14 June), the rate of accumulation of salt in the soil profile increased mainly because air temperature and soil evaporation increased. This period overlapped with the period when apple leaf margin started to wither, indicating that a regulation of salt accumulation occurred before the appearance of apple leaf margin blight. Considering the variation in salt contents in the soil profile, it may be concluded that a high salt content in the depth of 10 to 30 cm of the soil profile was the major driving factor to restrain growth of apple root and leaf.

During the moderate period of accumulation of salt (19 July to 6 Oct.), the TDS content at depths of 0 to 40 cm did not change, mainly because the orchard ground was shaded by foliage, reducing soil evaporation and distributing the soil water uniformly. At depths of 40 to 90 cm, the accumulation of

Fig. 8. Seasonal dynamics of several salt ions content in soil profiles. P1, P2, P3, and P4 stand for Period 1, Period 2, Period 3, and Period 4, respectively.

salt was low and at depths of 90 to 120 cm, the accumulation of salt was high. This is not in agreement with the study of Tripathia et al. (2007), in which salt accumulation was low during the monsoon season. To determine the distribution of salt in the soil profile in each of the four periods, TDS contents in the same soil layer at every period were calculated (Fig. 7). In Period 2, the TDS content significantly increased in the whole soil profile. In Period 3, the TDS content decreased at depths of 0 to 60 cm and increased at depths of 60 to 120 cm. In Period 4, the TDS contents in all soil layers increased in comparison with those of the former three periods.

Seasonal and spatial dynamics of several salt ions content in soil profiles. The movement of several salt ions in the soil profile had different synchronizations. This might be attributed to differences in the solubility and mobility of the salts, different microtopographical positions of the profiles, and the effect of the vegetation (Boettinger and Richardson, 2001). Mmolawa and Or (2000) showed that the analysis and measurement of solute movement and distribution is complex as a result of the uncertainty resulting from root distribution and functionality. Salts largely fall into two categories, those that are easily taken up by plant roots and those that are excluded by plant roots. Both types of salts can either be highly mobile or relatively immobile in the soil (Mmolawa and Or, 2000).

In this study, the variation of Cl^- was similar to that of SO_4^{2-} . The Cl^- and SO_4^{2-} moved upward or downward under evaporation and rainfall, but the Cl^- was more sensitive to various environments than the SO_4^{2-} . For instance, the solubility of Cl^- was higher and its ability of migration was strong, but the solubility of SO_4^{2-} was low and it is likely that temperature affected its solubility. Consequently, its rate of mobility was slower (Chen and Yu, 1995). The variation of CO_3^{2-} is different from that of HCO_3^- . This may be a consequence of soil pH being more than 8.4 in this region and the mutual transformation of CO_3^{2-} and HCO_3^- by the H^+ from rainfall (pH is less than 7). The K^+ was uniformly distributed in the top layer of the soil profile from April to October. The Na^+ and Mg^{2+} ions congregated in the top layers of soil profile, whereas the Ca^{2+} ions congregated in the bottom layers during spring, and in the depth of 0 to 20 cm of the soil profile, the content of Na^+ was increased evidently from 0.003% to 0.068%, its content was increased by 22.7 times ($P < 0.05$), the content of Mg^{2+} was increased from 0.0036% to 0.0156%, its content was increased by 4.3 times ($P < 0.05$), but in the depth of 80 to 120 cm of the soil profile, the content of Ca^{2+} was increased from 0.014% to 0.094% and its content was increased by 6.7 times ($P < 0.05$).

Conclusion

Scenarios of the movement of several ions were grouped into four periods following the regulation of salt movement to determine the

relationship between seasonal dynamics of soil salt and the movement of ions (Fig. 8). Different spatial and temporal distribution characteristics were observed in relation to sampling time and depth of the soil profile. In all soil layers, the HCO_3^- , Na^+ , and K^+ showed a clear periodic change, whereas the changes in the contents of Cl^- , CO_3^{2-} , and Mg^{2+} were limited to a certain stage, and the changes of Ca^{2+} and SO_4^{2-} contents were not detected. The content of HCO_3^- was the highest in the fourth period in the whole soil profile and the order was: $\text{P}_4 > \text{P}_1 > \text{P}_2 > \text{P}_3$ (Fig. 8). Na^+ contents and its changes in the 0- to 40-cm layer of the soil profile were different from those between 40- and 120-cm soil layers and followed the order $\text{P}_2 > \text{P}_3 > \text{P}_4 > \text{P}_1$ in the 0- to 40-cm soil layers, whereas in the 40- to 120-cm soil layers, the order was $\text{P}_4 > \text{P}_3 > \text{P}_2 > \text{P}_1$, suggesting that the Na^+ tended to continuously accumulate with the time being in the soil layer of 40 to 120 cm. Interestingly, the seasonal variation of K^+ contents was similar to that of the Na^+ content in the 0- to 40-cm soil layers, but there was no clear trend in other soil layers for the K^+ contents.

Overall Cl^- , SO_4^{2-} , and Na^+ in the soil profile increased in the soil layers from the upper to the bottom. This agrees with the results of Marion et al. (2008) despite simulation modeling showing that the sulfate element tended to accumulate in the deeper layers of the soil profile. Conversely, the distribution of K^+ clearly showed a gradient pattern of "being higher in the upper layers and being lower in the lower layers." HCO_3^- , Ca^{2+} , and Mg^{2+} had a uniform distribution down the soil profile, but the distribution of CO_3^{2-} was largely related to the periodic and spatial developments. In the first period, the content of CO_3^{2-} was almost zero and in the second and third periods, it tended to accumulate in the middle layers of the soil profile but was very low in the bottom layers. Only in the fourth period did its contents gradually present a uniform distribution in soil layers.

Literature Cited

- Álvarez-Rogel, J., R. Ortiz, and F. Alcaraz. 2001. Edaphic characterization and soil ionic composition influencing plant zonation in a semi-arid Mediterranean salt marsh. *Geoderma* 99: 81–98.
- Amezquita, E. 2006. An integrated methodology for assessing soil salinization, a precondition for land desertification. *J. Arid Environ.* 67:594–606.
- Baver, L.D., W.H. Gardner, and W.R. Gardner. 1972. *Soil physics*. 4th Ed. John Wiley and Sons, New York, NY.
- Boettinger, J.L. and J.L. Richardson. 2001. Saline and wet soils of wetlands in dry climates, p. 383–390. In: Vepraskas, M.J., C.B. Craft, and J.L. Richardson (eds.). *Wetlands soils: Genesis, hydrology, landscapes, and classification*. Lewis Publishers, Boca Raton, FL.
- Bush, J.K. 2006. The role of soil moisture, salinity, and oxygen on the growth of *Helianthus paradoxus* (Asteraceae) in an inland salt marsh of west Texas. *J. Arid Environ.* 64:22–36.
- Charley, J.L. and N.E. West. 1975. Plant induced soil chemical patterns in some shrub-dominated semi-desert ecosystems of Utah. *J. Ecol.* 63: 945–964.
- Chen, D.M. and R.P. Yu. 1995. Distributing character on salt movement in soil-plant system. *Chinese Journal of Soil Science* 26:3–5.
- Doescher, P.S., R.F. Miller, and A.H. Winward. 1984. Soil chemical patterns under plant communities dominated by big Sagebrush (*Artemisia tridentata*) in eastern Oregon. *Soil Sci. Soc. Amer. J.* 48:659–663.
- Grattan, S.R. and C.M. Grieve. 1992. Mineral element acquisition and growth response of plants grown in saline environments. *Agr. Ecosyst. Environ.* 38:275–300.
- Guganesharajah, K., J.F. Pavey, J. van Wonderen, G.M. Khasankhanova, D.J. Lyons, and B.J. Lloyd. 2007. Simulation of processes involved in soil salinization to guide soil remediation. *Journal of Irrigation and Drainage Engineering-ASCE* 133:131–139.
- Jackson, M.L. 1958. *Soil chemical analysis*. Prentice Hall, Englewood Cliffs, NJ.
- Lakhdar, A., M. Rabhi, T. Ghnaya, F. Montemurro, N. Jedidi, and C. Abdely. 2009. Effectiveness of compost use in salt-affected soil. *J. Hazard. Mater.* 171:29–37.
- Li, Z.G., X.J. Liu, X.M. Zhang, and W.Q. Li. 2008. Infiltration of melting saline ice water in soil columns: Consequences on soil moisture and salt content. *Agr. Water Mgt.* 95:498–502.
- Liu, X.T., Y. He, W. Deng, Z. Song, and Z. Wu. 2002. Research on comprehensive development of regional agriculture in Northeast China. Science Press, Beijing, China [in Chinese].
- Lu, R.K. 2000. Analysis method in soil agricultural chemistry. China Agricultural Science Technology Press, Beijing, China. p. 87–98 [in Chinese].
- Macdonald, B.C.T., M.D. Melville, and I. White. 1999. The distribution of soluble cations within chenopod-patterned ground, arid western New South Wales, Australia. *Catena* 37:89–105.
- Marion, G.M., P.S. Verburg, E.V. McDonald, and J.A. Arnore. 2008. Modeling salt movement through a Mojave Desert soil. *J. Arid Environ.* 72:1012–1033.
- Mmolawa, K. and D. Or. 2000. Root zone solute dynamics under drip irrigation: A review. *Plant Soil* 222:163–190.
- Munns, R. 2005. Genes and salt tolerance: Bringing them together. *New Phytol.* 167:645–663.
- O'Hara, S.L. 1997. Irrigation and land degradation: Implications for agriculture in Turkmenistan, central Asia. *J. Arid Environ.* 37:165–179.
- Pan, X., W. Deng, D. Zhang, F. Li, and Y. Wang. 2003. Sustainable agriculture in the semi-arid agro-pastoral interweaving belt of northern China, a case study of west Jilin Province. *Outlook Agr.* 32:165–172.
- Reimann, C. and S.W. Breckle. 1993. Sodium relations in Chenopodiaceae: A comparative approach. *Plant Cell Environ.* 16:323–328.
- Reimann, C. and S.W. Breckle. 1995. Salt tolerance and ion relations of *Salsola kali* L.: Differences between spp. *ragus* (L.) Nyman and spp. *ruthenica* (Iljin) Soó. *New Phytol.* 130:37–45.
- Sarah, P. 2001. Soluble salts dynamics in the soil under different climatic regions. *Catena* 43:307–321.
- Schlesinger, W.H., J.F. Reynolds, G.L. Cunningham, L.F. Huenneke, W.M. Jarrell, R.A. Virginia, and W.G. Whitford. 1990. Biological feedbacks in global desertification. *Science* 247:1043–1048.
- Sheng, J.D., L.C. Ma, B.A. Jiang, B.G. Li, F. Huang, and H.Q. Wu. 2010. Digital soil mapping to enable classification of the salt-affected

- soils in desert agro-ecological zones. *Agr. Water Mgt.* 97:1944–1951.
- Tripathia, S., A. Chakraborty, K. Chakrabarti, and B.K. Bandyopadhyay. 2007. Enzyme activities and microbial biomass in coastal soils of India. *Soil Biol. Biochem.* 39:2840–2848.
- Wang, X.Y. and R.E. Redmann. 1996. Adaptation to salinity in *Hordeum jubatum* L. populations studied using reciprocal transplants. *Vegetation* 123:65–71.
- Wang, Y.G., D.N. Xiao, Y. Li, and X.Y. Li. 2008. Soil salinity evolution and its relationship with dynamics of groundwater in the oasis of inland river basins: Case study from the Fubei region of Xinjiang Province, China. *Environ. Monit. Assess.* 140:291–302.
- Zaady, E., Z.Y. Offer, and M. Shachak. 2001. The content and contribution of the accumulated aeolian organic matter in a dry ecosystem. *Atmos. Environ.* 35:769–776.
- Zwicker, S., H. Lavee, and P. Sarah. 2007. Temporal evolution of salts in Mediterranean soils transect under different climatic conditions. *Catena* 70:282–295.