Salinity dynamics in soil profiles during long-term evaporation under different groundwater conditions

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Abstract
To study salinity dynamics in soil profiles under different groundwater conditions, a 3-year indoor experiment was carried out under conditions of open-air evaporation. Silt loam soil was treated under three groundwater table depths (0.85, 1.05, and 1.55 m) combined with three groundwater salinities: 0.40 dS m\(^{-1}\) (2 g l\(^{-1}\)), 0.80 dS m\(^{-1}\) (4 g l\(^{-1}\)), and 1.60 dS m\(^{-1}\) (8 g l\(^{-1}\)). A total of nine soil columns (0.14 m internal diameter) were used to simulate different combinations of groundwater depths and salinities. The results obtained showed that salt first accumulated at the bottom of the soil column, and only when soil salinity in this layer had remained relatively stable with time, salt began to accumulate in the adjacent upper soil layers. When all subsoil layers had reached dynamic salinity equilibrium, electrical conductivity (EC) of soils in the surface layer began to increase drastically. With increasing salt accumulation in the surface soil, EC of the subsoil began to rise tardily. The further up the soil layer, the earlier EC started to increase, although the redistribution of salts in the soil profile tended to be homogenous. Groundwater depth did not significantly change subsoil EC values at the same depth; however, it distinctly affected the time needed for the subsoil to reach dynamic salinity equilibrium. Groundwater salinity, on the other hand, did not significantly alter the time point at which soil salinity at the same depth began to increase rapidly or the time period needed to reach dynamic salinity equilibrium. This study explored salt transport processes in the soil profile through a long-term experiment, enabling us to reveal some general laws governing salt dynamics that will be very important to understand the mechanism of soil salinization. The results could be further used to set up strategies to prevent salinization or to improve salt-affected soils.

Keywords: Soil salinization, salt dynamics, evaporation, groundwater depth, groundwater salinity

Introduction
Salinization, one of the most challenging environmental problems, constitutes a major limiting factor in irrigated landscapes and waterways around the world (Van Schilfgaarde 1974; Ritzema 1994; Ghassemi et al. 1995a, 1995b; Miguel et al. 2013), threatening biodiversity and negatively influencing soil quality and plant growth (Chhabra & Kumar 2008; Geerts et al. 2008; Wang et al. 2008; Gowing et al. 2009; Li et al. 2012). Salt stress can decrease seedling vigor and root activities, thereby inhibiting seed germination, seedling, and plant growth (Jaffel et al. 2011; Rewald et al. 2011; Zhang et al. 2012).

Soil salinization above the water table is affected by capillary upflow, groundwater depth, groundwater salinity, and soil/crop characteristics (Prathapar & Meyer 1992; Prathapar et al. 1992; King et al. 1995; Huttmacher et al. 1996). Recharge from rainfall and irrigation can also affect soil salinization and alter water table position and salinity depending on the amount of salt stored in the soil profile and the quality and quantity of recharge water. Groundwater is one of the main factors influencing soil salinization, especially in those irrigation regions with shallow water tables. Soils underlain by shallow water tables have a high salinization risk as salt is much easily accumulated in the root zone by capillary transport.

In the last few decades, several studies have pointed out the importance of interactions between soil salt and water (Oussama et al. 2013; Phogat et al. 2013).
Generally, salinization problems will arise when more water is added to the local groundwater system than is being discharged under natural conditions. Shallow water tables are a common feature of many irrigation areas due to high recharge rates and, frequently, low drainage rates. Once groundwater is in close proximity to the ground surface, capillary upflow results in the movement of water and salts toward the soil surface, potentially leading to salt accumulation in the root zone. Removal of natural vegetation and infiltration or leakage from constructed reservoirs or dams can cause the water table to rise, thus carrying salts stored in subsoil to the soil surface and waterways. Salinity levels in groundwater will likely be altered as a result of natural recharge disruption. The main impact of dams and reservoirs on soil quality is salinization in relation to irrigation, mainly due to the maintenance of a high groundwater level (Cause 2001; GSA 2009). Salt accumulation in surface soil by brackish groundwater is influenced by groundwater depth. Several field data showed that the groundwater level affecting surface soil salinity is < 1.5 m below the ground surface, which confirmed that soil salinization was mainly caused by the capillary rise of brackish water and by the accumulation of salt occurring at the soil surface (Seeboonruang 2009).

Water table position and salinity were found to influence salt distribution in the soil profile across a number of studies (King et al. 1995; Hutmacher et al. 1996; Ayars et al. 1999; Soppe & Ayars 2003). Higher groundwater salinities (> 20 dS m$^{-1}$) resulted in an increase in salinization deeper in the profile compared to treatments with groundwater of lower salinity. Restriction of shallow groundwater use under such saline conditions limited the amount of salt accumulating in the upper part of the soil profile. However, with greater exploitation of shallow groundwater under less saline conditions, more salts were transported higher up into the profile and, when coupled with minimal leaching in the growing season, this could result in greater salt accumulation in the profile (Hutmacher et al. 1996). Groundwater consumption occurred near the bottom of the root zone, which could reduce salt accumulation in the upper part of the root zone where irrigation water was applied. However, soil water measurements showed the water increase during the fallow period after crop harvest in the root zone which tended to become salinized.

In shallow groundwater systems, variations in salinity with water table position may result in a non-uniform vertical salt distribution in the soil. Kass et al. (2005) investigated the impact of irrigation on underlying groundwater (21–24 m) quality. The salinity and composition of the top 3–5 m of the saturated zone was found to be distinctly different from the composition of irrigation water and was comprehensively controlled by irrigation water composition and processes occurring in the overlying unsaturated zone. The major chemical modifications occurring during infiltration of irrigation water suggested that a relatively complex relationship existed between the composition of irrigation water and the underlying groundwater. The researchers emphasized that the water table region could be regarded as a sensitive indicator of the extent and dynamics of groundwater quality (Ronen et al. 1988). Chloride concentrations varied down a 2-m profile in Israel, and it was determined that these variations were not related to water table fluctuations (up to 18 cm). Chloride concentrations also varied with time over the experimental period of 7 months.

A few studies were done that mainly focused on salt transport or distribution under a variety of conditions, including short-term evaporation. Some of these were carried out by analyzing samples once only or by experiments of one or more weeks, others used certain models to simulate solute transport. However, few of them analyzed the complete salt accumulation process in soil profile. Furthermore, the relationship between soil salt and groundwater conditions is still in need of further experimental investigation. Understanding the processes of salt transport in the soil profile under different groundwater conditions may help in guiding agricultural production and provide information on lowering the risk of secondary salinization.

It is not possible to isolate or sensibly experiment with a range of variables; however, as the soil texture in the Yangtze River estuary is mainly of the same type as that in Nanjing, and the weather conditions of these two regions which belong to almost the same latitude are very similar, a study was carried out in Nanjing, with the following simplified parameters and variables in a controlled environment:

- a uniform soil profile (silt loam), initially soaked from the bottom with pure water in nine soil columns;
- variable groundwater table depths (three constant depth values maintained throughout the experiment);
- variable groundwater salinity (three constant salinity values maintained for the three constant groundwater table depths);
- light/dark conditions maintained to simulate seasonal temperatures at the latitude of Nanjing;
- no rainfall or wind; and
- no irrigation.

The objectives of this work were to explore the general regulation of salt transport in the soil profile above the water table, as well as the relationship...
between electrical conductivity (EC) of the soil solution and groundwater depth and/or salinity.

**Material and methods**

An indoor experiment was carried out to study salt dynamics in the soil profile for different groundwater table depths and salinities, under conditions of open-air evaporation. Nine identical soil columns with a uniform profile of silt loam soil were established in plexi-glass tubes (with an internal diameter of 0.14 m) and numbered 1–9. Each soil column was packed layer by layer, adding 5 cm of soil sample at a time, so that the bulk density could be controlled at 1.33 g cm\(^{-3}\). After packing each 5 cm layer of soil, the surface of the previous soil layer was made scabrous to keep a soil continuum. Figure 1 shows the experimental setup of a typical column.

The silt loam soils were air-dried and ground to pass a 2-mm sieve. EC of 1:5 soil to water extractions was determined, and basic physical characteristics of the soils were measured (Table I).

Nine combinations of three different groundwater table depths and salinities were simulated. The three groundwater depths of the columns were 0.85 m (Nos 1–3), 1.05 m (Nos 4–6), and 1.55 m (Nos 7–9), and the three groundwater salinity of the columns were 0.40 dS m\(^{-1}\) (Nos 1, 4, and 7), 0.80 dS m\(^{-1}\) (Nos 2, 5, and 8), and 1.60 dS m\(^{-1}\) (Nos 3, 6, and 9).

The columns were maintained at steady saline water table depth, natural soil water capillary action, and free air evaporation. In order to keep a steady groundwater table and measure water evaporation directly, Mailiot equipment was used to regularly measure and replace water that had evaporated (Figure 1).

Temperatures were controlled to simulate seasonal variation, and above each soil column, an infrared lamp was placed to simulate a 9-h daylight period (from 8:30 to 17:30 h). An Automatic Temperature Control system was used to control the temperature of surface soils (at about 3 cm depth) in different seasons. The experiment lasted 3 years, from mid-December 2009 (early Northern hemisphere winter) to mid-December 2012. Temperature of surface soils was set at 30°C in spring and autumn, 35°C in summer, and 20°C in winter. These temperatures reflect soil surface conditions in the Yangtze estuary. The subsoil below 3 cm depth was kept at room temperature in the laboratory that varied seasonally.

![Figure 1. Schematic diagram of the experimental device.](image-url)
In each soil column, salinity and soil tension were measured regularly using 54 salinity sensors and 54 tensiometers, by which EC, water tension, and their variations could be observed directly. Salinity sensors and tensiometers were placed at different measuring depths. The salinity sensors and tensiometers were made by the Institute of Soil Science, Chinese Academy of Sciences. Readings of such salinity sensors are adjusted automatically to 25°C.

After the columns were filled up, distilled water was supplied from the bottom of each column by the Mailot equipment. Initially, soils were wetted by capillary action to the full soil column height, after which the salinity sensors and tensiometers were placed.

Table II showed the measuring depths of the salinity sensors for the three groundwater table depths simulated. The measuring depths were identical within each set of three columns simulating one groundwater table depth.

After the instruments had been installed, saline groundwater was added to the bottom of the soil column by the Mailot equipment, keeping the groundwater table at the same level throughout the experiment. All groundwater was artificial with a soluble salt composition corresponding to that of natural groundwater of the Yangtze River estuary.

From the start of the experiment (i.e., the day on which saline groundwater was added for the first time, 17 December 2009) to the end of the second month, observations of EC of soil were made at each measuring depth every 2 days. During the next 3 months, observations were made every 3 days, while, for the rest of the experiment, observations were conducted every 5 days.

Results

The results of the 3-year experiment are presented in Figures 2–4. The time scale is nonlinear due to the differences in time period between measurements as the experiment proceeded.

Salt dynamics in soil profile

Figure 2 shows the salt dynamics in soil column No. 2 (water table depth of 0.85 m and water salinity of 4 g L⁻¹ or EC of 0.8 dS m⁻¹) as an example reflecting
The process of salt transport in the soil profile. The curve of EC at 0.05 m depth is a smoothed trend line. It can be seen from Figure 2 that about 15 days after the experiment started, the EC of soils at the lowest measuring point (i.e., at the very top of the water table, 0.85 m below soil surface) began to rapidly increase to a relatively stable EC value of 8.0 dS m\(^{-1}\) with little fluctuation. Then progressively over the next 135 days, the EC of the adjacent higher layer soils began to increase up to the 8.0- dS m\(^{-1}\) value. It took approximately 150 days from the start of the experiment for subsoil at all depths to reach the dynamic salinity equilibrium (except 5 cm-depth surface soils on top of the soil column), after which the EC of the surface soils started to increase very rapidly. The EC of surface soils increased to 75.0 dS m\(^{-1}\) over the total 3-year experiment time.

With a groundwater table of 0.85 m, independent of groundwater salinity, the time for subsoil to reach the dynamic salinity equilibrium was about 150 days from the start of the experiment; with the 1.05-m depth groundwater table, it was about 280 days; and with the 1.55-m depth groundwater table, it was about 630 days. Therefore, it could be concluded that for similar groundwater table depths, the time for subsoil to reach the dynamic salinity equilibrium appeared to be independent of groundwater salinity, and that groundwater depth was the dominant factor in determining the time for salts in the soil profile to reach dynamic salinity equilibrium.

Figure 2 furthermore shows that during the 1.5 years of the experiment, the EC of the subsoil did not increase much; subsequently, the EC of the shallowest subsoil layer (at 20 cm depth) started to increase very tardily, while the EC value of all the other subsoil layers kept relatively stable throughout the whole experiment. This phenomenon was observed only in columns with 0.85 m groundwater depth, while the EC of subsoil in other columns in dynamic salinity equilibrium kept stable throughout the whole experiment.

Table III shows EC of the subsoil when the profiles had reached dynamic salinity equilibrium. Groundwater salinity was crucial to the EC of soils whether the soil profiles had reached dynamic salinity equilibrium or not. From Table III, it can be concluded that in soil profiles at dynamic salinity equilibrium, the groundwater salinity showed a
positive correlation with subsoil salinity at the same groundwater depth, while the impact of groundwater depth on subsoil salinity was not marked under conditions of equal groundwater salinity.

**Effects of groundwater depth on salt dynamics**

Figure 3 shows the salt dynamics of soils at 0.35 m depth with 1.60 dS m\(^{-1}\) (8.0 g kg\(^{-1}\)) groundwater salinity and different groundwater table levels. At dynamic salinity equilibrium, the soils had all reached a similar EC, varying from 14.0 to 16.0 dS m\(^{-1}\). With increasing groundwater depth from 0.85 to 1.05 m and then to 1.55 m, the time at which the EC of soils at 0.35 m depth began to increase was 40, 60, and 210 days, respectively, after saline groundwater was first supplied. EC values became relatively stable again at 90, 160, and 730 days after the experiment started, respectively. Thus, with an increase in groundwater depth, the soil EC at the same depth layer began to increase later (a nonlinear effect with time); furthermore, it took much longer for the EC of soils at the same depth to become relatively stable again, although the values at dynamic salinity equilibrium were almost the same.

**Effects of groundwater salinity on salt dynamics**

As soil salt mainly came from groundwater in this experiment, groundwater salinity should be considered a very important factor affecting salt dynamics. In this section, salt dynamics in the soil profile under conditions of the same groundwater depth but with different groundwater salinities were analyzed over a 3-year period. Figure 4 shows the salt dynamics of soils at 0.35 m depth with different groundwater salinities (numbers in the figure legend represent column numbers). Under conditions of different groundwater salinities of 0.40 (column 4), 0.80 (column 5), and 1.60 dS m\(^{-1}\) (column 6), it took about 60 days for the EC of soils at 0.35 m depth to begin to increase after saline groundwater was supplied, and about 160 days for soil salinity at 0.35 m depth to reach the stable state.

The stable-state EC values of soil at 0.35 cm depth were 5.0, 11.0, and 15.0 dS m\(^{-1}\), respectively, for groundwater salinities of 0.40, 0.80, and 1.60 dS m\(^{-1}\). Table III shows the ratios of subsoil EC value to groundwater salinity value at dynamic salinity equilibrium. The ratios varied from 13.0 for groundwater with the lowest salinity (0.4 dS m\(^{-1}\)) to 9.3 for groundwater with the highest salinity (1.60 dS m\(^{-1}\)). Under conditions of equal groundwater depth, the ratio showed a negative correlation with groundwater salinity.

In conclusion, increasing groundwater salinity resulted in higher equilibrium EC values of soil at 0.35 cm depth; however, the dynamics of this increase, i.e., the time period over which this change occurred (60–160 days), was very similar.

**Combined effects of groundwater salinity and depth on salt dynamics**

The relationship among the EC of subsoil at dynamic salinity equilibrium, and groundwater depth and salinity, is given as follows (\(r = 0.98^{**}, n = 9\)):

\[
Y = 3.326 - 0.603X_1 + 7.440X_2,
\]

where \(Y\) is the EC of the subsoil (dS m\(^{-1}\)), \(X_1\) is the groundwater depth (m), and \(X_2\) is the groundwater salinity (dS m\(^{-1}\)).

**Discussion**

About one-third of the 260-million hectares of irrigated land around the world, producing 40% of the global food supply, are suffering from salinization (FAO 2003). Salinity affects physical and chemical characteristics of the soil in the root zone, leading to deteriorated soil structure, reduced infiltration properties and nitrogen fixation, and increased pH, and thus to a reduction in plant yield and quality.

| Soil column no. | Groundwater depth (m) | Groundwater EC (dS m\(^{-1}\)) | Groundwater salinity (g l\(^{-1}\)) | EC of subsoil (dS m\(^{-1}\)) | Soil EC relative to No. 1 | Ratio of EC soil to EC groundwater |
|-----------------|-----------------------|-------------------------------|-----------------------------------|-----------------------------|--------------------------|----------------------------------|
| 1               | 0.85                  | 0.40                          | 2.0                               | 5.0                         | 1.0                      | 12.5                             |
| 2               | 0.85                  | 0.80                          | 4.0                               | 9.5                         | 1.9                      | 11.9                             |
| 3               | 0.85                  | 1.60                          | 8.0                               | 14.0                        | 2.8                      | 8.8                              |
| 4               | 1.05                  | 0.40                          | 2.0                               | 5.2                         | 1.0                      | 13.0                             |
| 5               | 1.05                  | 0.80                          | 4.0                               | 10.0                        | 2.0                      | 12.5                             |
| 6               | 1.05                  | 1.60                          | 8.0                               | 14.8                        | 3.0                      | 9.3                              |
| 7               | 1.55                  | 0.40                          | 2.0                               | 5.0                         | 1.0                      | 12.5                             |
| 8               | 1.55                  | 0.80                          | 4.0                               | 8.7                         | 1.7                      | 10.9                             |
| 9               | 1.55                  | 1.60                          | 8.0                               | 14.0                        | 2.8                      | 8.8                              |
was similar. When groundwater salinity was
at a certain value in the dynamic salinity equilibrium,
salt accumulation only occurred at a much higher rate. When salinity of subsoil was kept at a certain value in the dynamic salinity equilibrium, soluble salts from the groundwater accumulated only in surface soils.

When subsoil reached the dynamic salinity equilibrium, groundwater salinity was positively correlated to subsoil salinity, while the impact of groundwater depth on subsoil salinity was not remarkable under conditions of the same groundwater salinity. With the increase of groundwater depth, it took progressively longer before the EC of the subsoil (of the same groundwater salinity) at the same depth layer started to increase; the rate of salt accumulation also decreased though the EC value of these soils at dynamic salinity equilibrium was similar. When groundwater salinity was $<1.60$ dS$m^{-1}$ $(8.0$ g$l^{-1})$, the difference in groundwater salinity did not change the time point at which soil salinity at the same depth layer started to increase
or the time period needed to reach dynamic salinity equilibrium.

Groundwater salinization in coastal wetland is usually caused by the effects of climate change, sea-level rise, and anthropogenic interferences (Pauw et al. 2012), while in arid and semi-arid areas evaporation is one of the main factors controlling either groundwater or soil salinity (Huang & Pang 2012; Ohrtman et al. 2012). Our experimental setup simulated the typical groundwater conditions in the Yangtze River estuary under the influence of the Three Gorges Project, and thus the results obtained not only illuminate the processes of salt transport in the soil profile, but also provide some reliable theoretical references to build up a countermeasure system against the negative effects of the project.

Long-term salt dynamics and distribution under condition of evaporation with different groundwater characteristics were revealed by the presented research. The results obtained have an important theoretical value for exploring the laws of soil salt accumulation and the construction of sustainable plant biosystems. However, some valuable parameters, such as wind, rainfall, and irrigation, were not considered in this study. Further studies on soil salt dynamics, which consider more parameters to simulate the natural environment, are needed to give a more detailed and comprehensive theoretical basis for keeping a balanced ecosystem.

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