Soil evaporation and its impact on salt accumulation in different landscapes under freeze–thaw conditions in an arid seasonal frozen region

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Abstract
Soil evaporation and its associated processes are vital for agricultural production and ecosystems in seasonal frozen regions. However, soil evaporation and its impact on salt accumulation in different landscapes during freeze–thaw periods have not been well elucidated. In this study, field experiments were carried out to investigate soil evaporation and salt accumulation patterns in three typical landscapes—namely, cropland, woodland, and natural land—in an arid seasonal frozen region located in the upper reaches of the Yellow River basin from November 2018 to April 2019. The results indicated the highest soil evaporation occurred on natural land with a total amount of 148.5 mm during the freeze–thaw period from 2018 to 2019, whereas woodland had the smallest soil evaporation of 56.9 mm. Over 75% of soil evaporation occurred during the thawing stage for all three landscapes. The average daily evaporation was below 1 mm d⁻¹ for the whole freeze–thaw period and was 0.1 mm d⁻¹ for the stable freezing stage. Compared with humidity and wind speed, temperature and soil water content had a greater impact on soil evaporation. At the end of the thawing stage, the salt content in the topsoil (0–10 cm) layer increased significantly with an increasing rate of 70–225%. Salt concentrations in the topsoil were significantly and linearly related to the cumulative soil evaporation during the freeze–thaw period. The current research is expected to provide implications for water management and salinity control in the upper reaches of the Yellow River basin and in other arid regions with similar conditions.

INTRODUCTION

Soil evaporation plays an important role in the study of soil water and energy balance (Or, Lehmann, Shahraeeni, & Shokri, 2013; Zhang, Li, & Lockington, 2014). The determination of soil evaporation is crucial for solving agricultural water management-related problems (e.g., farmland irrigation...
management, crop yield estimation, and soil moisture prediction; Rousseaux, Figuerola, Correa-Tedesco, & Searles, 2009; Wei, Paredes, Liu, Chi, & Pereira, 2015). This is particularly true for arid and semiarid areas (e.g., the upper reaches of the Yellow River basin [YRB] in China, irrigated areas in the arid western United States, and Fergana Valley in Central Asia; Ren et al., 2018; Xu et al., 2013). In these areas, soil evaporation is one of the major water consumption pathways. The massive non-beneficial water loss through soil evaporation may result in soil salinization and thus seriously threaten agricultural production and ecosystems (Ren et al., 2019; Yu et al., 2010). In addition, seasonal freeze–thaw processes are one of the natural phenomena that significantly affect soil evaporation in many arid and semiarid regions. During these periods, evaporation is almost the only mechanism for soil water loss because most plants are harvested, dead, and/or defoliated (Allen, Pereira, Raes, & Smith, 1998). This means that soil evaporation has a decisive influence on water consumption and soil salinization. Therefore, it is important to reveal the mechanism of soil evaporation and its impact on salt accumulation under freeze–thaw conditions.

Soil evaporation under freeze–thaw conditions has been investigated using indirect methods for quite a few years. For example, Kaneko, Kobayashi, Wang, and Cho (2006) estimated evaporation from a frozen bare soil surface in the YRB by using the aerodynamic method, and they found that 60 mm of evaporation during the soil freezing season from November to the next March cannot be ignored. Chen, Zheng, Zhang, Qin, and Sun (2015) used a water-heat model to simulate soil evaporation from lysimeters with different groundwater table depths, and they found that soil evaporation mainly occurred in unstable freezing and thawing stages. Wu, Huang, Wu, Tan, and Jansson (2016) used a mass balance method to estimate the evaporation from frost tubes with different salt contents and initial groundwater table depths. They found that lower evaporation rates persisted as the soil deeply froze and that relatively higher evaporation rates occurred at the beginning and the end of the experiments. Moreover, the cumulative evaporation increased with increasing initial salt content and declined with lowering groundwater table depths. From the data of soil water and temperature measured by soil hydrothermal sensors, Zhang et al. (2019) used a mass balance method to study soil evaporation from bare and vegetated ground at various groundwater table depths in lysimeters. Their results showed that soil evaporation was high during the thawing process and was low when the soil was freezing and that higher groundwater table depths resulted in greater cumulative evaporation levels.

Soil evaporation can also be directly monitored by using weighing lysimeters. For example, microlysimeters have been widely used to monitor soil evaporation during the non-freeze–thaw period (Boast & Robertson, 1982; Deguchi, Hat-tori, Daikoku, & Park, 2008; Facchi, Masseroni, & Min-iotti, 2016; Tesfahuney, Van Rensburg, Walker, & Allemann, 2015). It was shown that soil evaporation can be measured with reasonable accuracy using microlysimeters of appropriate heights and diameters and timely soil replacements (Daamen, Simmonds, Wallace, Laryea, & Sivakumar, 1993; Evett, Warrick, & Matthias, 1995). However, a microlysimeter cannot easily be embedded into the tested soil and taken out for weighing during freezing period. To overcome this problem, a sufficient number of microlysimeters can be inserted into the soil before freezing and they can then be gradually removed and weighed to obtain the difference of two adjacent weights from undisturbed soil samples in the microlysimeters (Chen et al., 2019, Feng et al., 2018).

As an associated process of soil water movement, salt accumulation or soil salinization is closely related to soil evaporation in arid and semiarid regions, even during freeze–thaw periods (Rose, Konukcu, & Gowing, 2005; Shimojimaa, Yoshioka, & Tamagawa, 1996; Zhang et al., 2019). Zhang and Wang (2001) investigated soil salinization during freeze–thaw periods in northeast China and found that salt moved upward and accumulated in the upper soil layer with water movement due to the frozen action in the freezing stage; salt was then deposited in the topsoil and/or crystallized at the ground surface with the continuous evaporation during the thawing stage of the next spring. Similar results were also found by Bing, He, and Zhang (2015) and Wu et al. (2019). However, it is not easy to quantify the relationship between soil evaporation and salt accumulation due to the complex coupling effects between soil water and salt movement under freeze–thaw conditions and the limitations of monitoring instruments. For instance, the existence of salt depresses the soil freezing point and thus influences soil water movement and evaporation (Wu, Zhou, & Jiang, 2018).

Many studies on soil evaporation under freeze–thaw conditions mainly focused on bare cropland (Chen et al., 2015; Kaneko et al., 2006; Wu et al., 2016); little attention has been paid to evaporation of ecological landscapes (e.g., natural land and/or woodland). Evaporation from the latter two landscapes is equally important for evaluation of water consumption in the nongrowing season in arid areas with shallow groundwater tables, since these two landscapes occupy a considerable

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**Core Ideas**

- Soil evaporation from three landscapes during the freeze–thaw period was monitored and analyzed.
- Soil evaporation was affected by soil water content, groundwater table, and land surface cover.
- Salt concentrations were significantly and linearly related to the cumulative soil evaporation.
proportion (Ren et al., 2019). Meanwhile, previous studies have demonstrated that soil evaporation promotes soil salinization under freeze–thaw conditions (Bing et al., 2015; Wu et al., 2019; Zhang & Wang, 2001). However, the impacts of land use type on salt accumulation are not well elucidated, and the relationship between soil evaporation and salt accumulation in different landscapes is barely investigated under freeze–thaw conditions. Therefore, the objectives of this study are (a) to analyze and compare soil evaporation for different landscapes under freeze–thaw conditions and (b) to explore the quantitative relationships between soil evaporation and salt accumulation in different landscapes during freeze–thaw periods.

2 MATERIALS AND METHODS

2.1 Experimental site description

The experiments were carried out in the Heji area (41°92’ N, 107°39’ E; 1,045 masl; as shown in Figure 1), which is located in the upper reaches of the YRB, China, from 18 Nov. 2018, to 25 Apr. 2019. The climate in this region is a typical arid continental climate with a mean annual precipitation of 150 mm and mean annual potential evaporation in the range of 2,000–2,400 mm (Zhang, Xiong, Huang, Xu, & Huang, 2017). The precipitation shows marked seasonality with approximately 70–80% of rainfall occurring in the vegetation period from May to September. In addition, the study area experiences a long-term soil freeze–thaw periods for over 5 mo from mid-to late November to the end of April or early May of the following year, with a maximum frost depth of ∼1.2 m. The groundwater table is relatively shallow with depths varying from 0.5 to 2.5 m below the soil surface in the experimental area.

The typical land use pattern in the study area is interlaced cropland, woodland, natural land, and other landscape types. Therefore, cropland, woodland, and natural land were selected for soil water, salinity, and soil evaporation monitoring during the freeze–thaw period. The cropland is bare after maize (Zea mays L.) is harvested in early October without irrigation in autumn. The woodland was planted with poplar (Populus spp.) with an age of ∼4 yr, and the average height of the poplar is ∼18 m. The natural land is uncultivated with tamarix and sparse weeds as the main vegetation because of the high salinity. The distance between two sampling sites corresponding to different landscapes is within 1.5 km. The initial groundwater table depths for cropland, woodland, and natural land were 0.98, 1.07, and 0.70 m, respectively (see Figure 2).

The soil physical properties for the three landscapes at the study site were analyzed with samples according to the U.S. textural classification before the experiment. The soil texture for the three landscapes is mainly silt loam. The
average soil bulk density at the depth of 0–120 cm for crop-land, woodland, and natural land is 1.48, 1.46, and 1.52 g cm$^{-3}$, respectively. The average field capacity varies from 0.33 to 0.35 cm$^3$ cm$^{-3}$ for these landscapes. Detailed soil physical properties are shown in Table 1.

Meteorological data including solar radiation, air temperature, humidity, atmospheric pressure, soil surface temperature, wind speed, and direction at 2 m above the ground surface were recorded hourly by an automatic weather station (HOBO, Campbell, Scientific) that was installed in the cropland during the experimental period. Table 2 shows the monthly values of the major meteorological factors during the experiment period.

### Table 1 Soil physical properties in a profile from 0 to 120 cm for the three landscapes

| Landscape type | Soil depth | Sand (>0.05 mm) % | Silt (0.002–0.05 mm) | Clay (<0.002 mm) | Soil texture | Bulk density g cm$^{-3}$ | Field capacity cm$^3$ cm$^{-3}$ |
|---------------|-----------|-------------------|----------------------|-----------------|--------------|------------------------|-----------------------------|
| Cropland      | 0–35      | 73.64             | 24.39                | 1.97            | Loamy sand   | 1.60                   | 0.28                        |
|               | 35–60     | 45.05             | 47.99                | 6.96            | Sandy loam   | 1.49                   | 0.33                        |
|               | 60–90     | 25.95             | 65.28                | 8.77            | Silt loam    | 1.42                   | 0.35                        |
|               | 90–120    | 37.27             | 59.05                | 3.68            | Silt loam    | 1.40                   | 0.38                        |
| Woodland      | 0–45      | 28.26             | 65.32                | 6.42            | Silt loam    | 1.49                   | 0.26                        |
|               | 45–60     | 18.74             | 75.76                | 5.50            | Silt loam    | 1.43                   | 0.41                        |
|               | 60–90     | 9.49              | 81.64                | 8.87            | Silt         | 1.45                   | 0.39                        |
|               | 90–120    | 25.88             | 69.24                | 4.88            | Silt loam    | 1.43                   | 0.40                        |
| Natural land  | 0–20      | 31.56             | 59.81                | 8.63            | Silt loam    | 1.60                   | 0.32                        |
|               | 20–70     | 20.70             | 69.51                | 9.79            | Silt loam    | 1.49                   | 0.36                        |
|               | 70–80     | 19.55             | 69.15                | 11.30           | Silt loam    | 1.45                   | 0.39                        |
|               | 80–120    | 34.66             | 62.13                | 3.21            | Silt loam    | 1.53                   | 0.35                        |

2.2 | **Sampling and measurements**

2.2.1 | **Microlysimeter preparation and measurement**

Soil evaporation was monitored using weighing microlysimeters. Each microlysimeter consisted of an inner tube and bottom cap (Figure 3). Both the inner tube and the bottom cap were made of polyvinyl chloride (PVC). The inner tube had a length of 200 mm, and the inner and outer diameters were 100 and 110 mm, respectively. The bottom cap was used to seal the bottom end of the inner tube and had an inner diameter of 110 mm and a height of 35 mm. In addition, a PVC outer tube with an inner diameter of 120 mm and height of 200 mm was used to prevent soil from entering the lysimeter. Considering the difficulty of embedding the lysimeter during soil freezing, 21 sets of inner tubes were inserted into soils with a plastic hammer at the beginning of the experiment. The distance between two adjacent tubes was ~1.0 m.

The inner tubes with the undisturbed soil cores were then removed by a special power auger to measure their weights twice a month during the freezing stage from 18 Nov. 2018 to 5 Mar. 2019, and at 3-d intervals during the thawing stage from 6 Mar. 2019 to 25 Apr. 2019. Each microlysimeter was excavated twice for measurements. At the first excavation, the outer wall of each microlysimeter was cleaned up, and its bottom was flattened and covered with a bottom cap to ensure that water loss only occurred from the upper soil surface. Then, the microlysimeter was weighed using an electronic balance with a scale of 5 kg and an accuracy of 0.1 g. Next, the microlysimeter was inserted into an outer tube and the
TABLE 2  Main monthly meteorological data during the freeze–thaw period of 2018–2019

| Meteorological data          | November, 2018 | December, 2018 | January, 2019 | February, 2019 | March, 2019 | April, 2019 |
|-----------------------------|----------------|----------------|---------------|----------------|-------------|-------------|
| Mean air temperature, °C    | −1.61          | −10.36         | −9.54         | −6.67          | 3.68        | 12.65       |
| Max. air temperature, °C    | 8.54           | 6.71           | 3.01          | 9.24           | 19.10       | 31.51       |
| Min. air temperature, °C    | −9.78          | −25.61         | −22.78        | −22.02         | −8.10       | −3.96       |
| Relative humidity, %         | 55.34          | 49.98          | 52.34         | 46.46          | 43.54       | 39.12       |
| Wind speed, m s$^{-1}$       | 2.18           | 2.31           | 2.12          | 2.34           | 2.23        | 2.40        |
| Solar radiation, W m$^{-2}$  | 109.62         | 98.20          | 102.37        | 136.49         | 192.32      | 221.28      |
| Precipitation, mm            | 0.00           | 0.00           | 0.00          | 0.00           | 0.60        | 2.60        |

Whole system was placed back into the excavated site with its top at the same level as the surrounding soil. After the scheduled time, the microlysimeter was excavated again for weight measurement. The difference in the two measured weights of the microlysimeter was considered soil evaporation during the period of the two adjacent measurements. It should be noted that three microlysimeters were used for each measurement to reduce observational errors, and each microlysimeter was only used for a single measurement interval to ensure that the soils inside the microlysimeters were in conditions as similar to the field soils as possible.

2.2.2  Soil water and salinity

Soil samples were collected at every 10-cm interval up to a depth of 100 cm by using a power auger with a diameter of 50 mm. Soil sampling was carried out twice a month from 18 Nov. 2018 to 5 Mar. 2019, and once a week from 6 Mar. 2019 to 25 Apr. 2019. The soil samples were then used to measure the total soil water content and soil salinity. Total soil water contents were measured using the thermogravimetric method. Soil salt contents (SSC, g kg$^{-1}$) were determined from the electrical conductivity of a 1:5 soil water extract (EC$_{1:5}$, dS m$^{-1}$) using the empirical formula SSC = 0.2882EC$_{1:5}$ + 0.183 (Xu et al., 2013). The liquid water in the cropland soils was monitored by a time domain reflectometer (TDR, TRIME-TDR-PICO-IPH-T3, IMKO) with an accuracy of ±2–4% under the conditions with electrical conductivity of 0–12 dS m$^{-1}$. The TDR was calibrated with data from field soil samples obtained before the experiment. A linear relationship was used to convert the raw TDR data to soil moisture data (see Figure 4).
2.2.3 Soil frost depth

Soil frost depths for each landscape were determined during the soil sampling process by identifying the upper and lower boundaries of the soil containing ice (Wu et al., 2019).

2.2.4 Groundwater table depth

To monitor groundwater level, an observation well was installed to a depth of 4 m in each landscape. The groundwater table depths were observed every 7–15 d with a measuring tape.

2.3 Determination of soil evaporation

Soil evaporation was determined according to the change of the two measured weights of the microlysimeter during a measurement interval. The density of water was considered a constant, and the soil evaporation was calculated as follows:

\[ E_i = \frac{4(M_b - M_c)}{\pi d^2 \rho_w} \times 10 \]  

(1)

where \( E_i \) is the total evaporation within the \( i \)th interval (mm); \( M_b \) is the initial weight of the microlysimeter in a monitoring interval (g); \( M_c \) is the final weight of the microlysimeter in a monitoring interval (g); \( d \) is the inner diameter of the microlysimeter (cm); \( \rho_w \) is the density of water, which is assumed to be a constant value of 1 g cm\(^{-3} \); and the constant 10 is used to convert centimeters to millimeters.

The cumulative soil evaporation is calculated as follows:

\[ E_{\text{cum}} = \sum E_i \]  

(2)

where \( E_{\text{cum}} \) is the cumulative soil evaporation from the first to the \( i \)th monitoring intervals (mm).

The average daily soil evaporation for any given period is calculated using the following equation:

\[ E_{av} = \frac{\sum E_i}{\sum T_i} \]  

(3)

where \( E_{av} \) is the average daily soil evaporation during the calculation period (mm d\(^{-1} \)), and \( T_i \) is the total number of days in the \( i \)th monitoring interval corresponding to \( E_i \) (d).

2.4 Statistical analysis

The data were statistically analyzed by one-way ANOVA using SPSS 21.0 software (SPSS). Statistical differences among different landscapes were determined by Duncan’s multiple range test at \( P \leq .05 \). In addition, principal component analysis (PCA) was used to reduce the dimension of meteorological factors with the criteria that the cumulative contribution was \( \geq 85\% \) and the eigenvalue was \( >1 \). If these criteria were satisfied, then the principal components (PCs) were selected to represent all meteorological information (Feng et al., 2018; Sun, Chen, Jiang, & Zhang, 2018). The multiple linear regression (MLR) method was then used to describe the impacts of the PCs and soil water contents on the evaporation properties of the different landscapes.

3 RESULTS

3.1 Air temperature and soil water content

The maximum, minimum, and mean daily air temperatures during the experiment are shown in Figure 5. The daily air temperature decreased noticeably at first; for example, the mean daily air temperature was 1.58 °C on 26 Nov. 2018 and decreased to −17.57 °C on 7 Dec. 2018. Then, the daily air temperature remained in a relatively stable stage from 7 Dec. 2018, to 15 Feb. 2019. During this stage, the mean daily air temperature fluctuated and its lowest value of −19.77 °C occurred on 27 Dec. 2018, whereas the highest value of −3.12 °C occurred on 17 Dec. 2018. Next, the daily air temperature gradually increased. During the freeze–thaw period, rainfall was very rare with a total amount of 3.2 mm and no snow events occurred.

As shown in Figure 5c, the liquid soil water content in the 0-to-20-cm soil layer of cropland exhibited a similar variation trend as the air temperature. It decreased from 0.30 cm\(^3 \) cm\(^{-3} \) on 18 Nov. 2018 to 0.10 cm\(^3 \) cm\(^{-3} \) on 7 Dec. 2018, due to soil freezing and then remained stable until 15 Feb. 2019. Next, it increased gradually to 0.28 cm\(^3 \) cm\(^{-3} \) on 18 Mar. 2019 and then declined due to increased evaporation. The total soil water content in the 0-to-20-cm topsoil layer increased from 0.30 cm\(^3 \) cm\(^{-3} \) on 18 Nov. 2018, to 0.34 cm\(^3 \) cm\(^{-3} \) on 7 Dec. 2018, with an increase rate of 13.3%, and then remained relatively stable; it finally decreased at a rate of 41.2% at the end of the freeze–thaw period (see Figure 5c). As shown in Figure 5d, the increasing and decreasing trends for the total soil water content in woodland and cropland were not as significant as those for natural land.

According to the change patterns of air temperature and soil water content, soil evaporation was divided into three stages (i.e., the unstable freezing stage [USFS] from 18 Nov. to 7 Dec. 2018, the stable freezing stage [SFS] from 7 Dec. 2018 to 15 Feb. 2019, and the thawing stage [TS] from 15 Feb. to 25 Apr. 2019). In USFS, the air temperature gradually dropped below zero at night, and the highest temperature during the day was above zero. The surface soil layer might undergo a
frequent change of air temperature, accompanying the processes of freezing at night and thawing during the day. Meanwhile, the liquid water content in topsoil (0–20 cm) for cropland gradually decreased as well. In SFS, the air temperature was below zero for both day and night. The frost depth of soil increased gradually, and the liquid water content in topsoil (0–20 cm) remained around 0.1 cm$^3$ cm$^-3$ with a slight fluctuation. In TS, the air temperature gradually rose above zero and soil began to thaw; then, the liquid water content in topsoil (0–20 cm) increased rapidly.

3.2 Soil freeze–thaw processes and the variations of groundwater table

The soil freeze–thaw processes in the three different landscapes are presented in Figure 6. The patterns of the soil freezing and thawing processes were similar for all three landscapes. The soil freezing process was a unidirectional process. With decreases in air temperature, soils began to freeze starting from the surface and then the frost depth gradually increased downward. However, the soil thawing process was a bidirectional process. Soils began to thaw at both the surface and bottom of the frozen layer with increased air temperatures. In addition, the soil thawing rate was much higher than for soil freezing, and the thawing rate in the topsoil was higher than in the subsoil for all three landscapes.

The timing of soil freeze beginning and thaw ending showed differences among the three different landscapes. The soil freeze beginning date for cropland and natural land was 18 Nov. 2018, which was earlier than that for woodland. The soil thaw end date was 25 Apr. 2019 for cropland and 19 Apr. 2019 for natural land, which were much later than the date of 27 Mar. 2019 for woodland. Differences in soil frost depths were also found among the three different landscapes. The maximum frost depths for cropland and natural land were approximately the same with a value of $\sim$100 cm, which was two times greater than that for woodland.
The variations of groundwater table depth for the three different landscapes were affected by freeze–thaw processes with an increasing trend in freezing stage and a decreasing trend during thawing stage (see Figure 2). The minimum and maximum groundwater table depths were 0.97 and 2.25 m for cropland, 1.07 and 2.21 m for woodland, and 0.70 and 1.89 m for natural land, respectively. Natural land always maintained a shallowest groundwater table depth among the three landscapes during the experiment.

### 3.3 Soil salt accumulation

The salinities in the 0-to-10-cm soil layer in the freezing and thawing stages for the three different landscapes are presented in Figure 7. The salinities in the 0-to-10-cm soil layer increased slightly during the freezing stage, whereas they increased significantly during the thawing stage. For example, for natural land, the salinities in the 0-to-10-cm soil layer were 3.40 g kg\(^{-1}\) at the end of the freezing stage and 9.38 g kg\(^{-1}\) at the end of the thawing stage, which were 18 and 225% higher, respectively, than the value of 2.89 g kg\(^{-1}\) at the beginning of the freeze–thaw period.

Salt accumulations in the 0-to-10-cm soil layer were different for different landscapes. The largest salt accumulation occurred in natural land, whereas the smallest salt accumulation occurred in woodland. During the freeze–thaw period, the salinities in the 0-to-10-cm soil layer increased from 3.19 to 6.41 g kg\(^{-1}\) with an increase rate of 101% for cropland and from 2.43 to 4.14 g kg\(^{-1}\) with an increase rate of 70% for woodland, which was much lower than that for natural land.
Soil evaporation levels of the three different landscapes at different freezing and thawing stages are presented in Figure 8 and Table 3. As shown in Figure 8a, the cumulative soil evaporation increased with increased time, but different freezing and thawing stages had different increasing rates of soil evaporation with the largest and smallest values occurring in the TS and SFS, respectively. As shown in Figure 8b, soil evaporation mainly occurred in the thawing stage, whereas soil evaporation in the freezing stage only accounted for a small part of total soil evaporation. For cropland, soil evaporation was 68.89 mm in TS, 9.39 mm in USFZ, and 7.56 mm in SFS, which accounted for 80, 11, and 9% of the total evaporation during the freeze–thaw period, respectively. In addition, the average daily soil evaporation levels in different freezing and thawing stages were significantly different from each other (see Table 3). For cropland, the average daily soil evaporation in TS was 1.35 mm d\(^{-1}\), which was over twice the value of 0.55 mm d\(^{-1}\) in USFS. The average daily soil evaporation in USFS was approximately seven times as great as the value of 0.08 mm d\(^{-1}\) in SFS.

During the freeze–thaw period, total soil evaporation was largest in natural land with a value of 148.5 mm, which was significantly larger than that of woodland (56.9 mm) and cropland (85.8 mm). During the thawing stage, the cumulative soil evaporation values for cropland and woodland were 68.9 and 44.3 mm, respectively, which were approximately one-half and one-third of the value of 134.0 mm for natural land. The cumulative soil evaporation levels for the three landscapes was <10 mm with significant differences in USFS and were close to 8 mm without significant differences in SFS.

### TABLE 3 Average daily soil evaporation, and proportion of soil evaporation at different freezing and thawing stages to total soil evaporation for cropland, woodland, and natural land

| Landscape   | Avg. daily soil evaporation | Proportion of soil evaporation |
|-------------|----------------------------|--------------------------------|
|             | USFS           | SFS      | TS      | Freeze–thaw period | USFS | SFS | TS     |
| Cropland    | 0.55 ± 0.01a   | 0.08 ± 0.01a | 1.35 ± 0.11a | 0.55 ± 0.04a | 10.94 | 8.81 | 80.26 |
| Woodland    | 0.25 ± 0.01b   | 0.09 ± 0.01a | 0.87 ± 0.09b | 0.36 ± 0.03b | 7.62  | 14.53| 77.85 |
| Natural land| 0.38 ± 0.05c   | 0.09 ± 0.01a | 2.63 ± 0.11c | 0.93 ± 0.05c | 4.37  | 5.37 | 90.25 |

Note. USFS, SFS, and TS represent the unstable freezing stage, stable freezing stage, and thawing stage, respectively. Evaporation values in the same column with different lowercase letters are significantly different at the 5% probability level.
Kurylyk & Watanabe, 2013; Zhang & Sun, 2011). This movement then results in increased total soil water content in the topsoil. However, for SFS, with the further increase of frost depth, ice in the soil pores significantly decreases hydraulic conductivity, which reduces the water supply from the deeper unfrozen layers to the topsoil (Peng et al., 2016). In addition, evaporation from the frozen topsoil is relatively low in SFS (Wu et al., 2016). Therefore, the total soil water contents in topsoil become relatively stable. In TS, water from melted ice in the upper layer is obstructed by the middle unthawed layer, causing increased liquid soil water content in the upper layer (Zhang et al., 2019). However, the melted water evaporates from the soil surface and thus results in decreased total soil water content in the topsoil.

Soil freezing and thawing processes are mainly dependent on variations in air and ground temperatures (Xu, Wang, & Zhang, 2001; Zhang & Wang, 2001). During the freezing period, negative air temperatures are the sole reason for soil freezing because the ground temperature below the frozen layer always remains positive and results in a unidirectional freezing phenomenon (i.e., soil freezes from the surface downward to deeper layers). During the thawing period, both the air and soil below the unthawed layer are at positive temperatures, which causes a bidirectional thawing phenomenon (i.e., soil thaws both from the top and bottom of the unthawed layer). However, air temperatures increase rapidly (see Figure 5b), whereas soil temperatures below the unthawed layer remain relatively stable and lead to a higher temperature gradient in the topsoil than that in the subsoil. As a result, the thawing rate in the topsoil is higher than that in the subsoil for all three landscapes. It should be noted that during the bidirectional thawing period, the unthawed layer prevents downward infiltration of the thawed water in the topsoil, which contributes to soil evaporation (Bing et al., 2015; Xu et al., 2001).

Soil water variations and freeze–thaw processes are also influenced by land uses and groundwater table depths (Hermansson & Guthrie, 2005; Watanabe, Kito, Wake, & Sakai, 2011; Yi et al., 2014). Different land uses usually correspond to different land cover and vegetation root conditions. For woodland, the fallen leaves covered in the soil surface are similar to straw mulch, which can prevent heat transfer from soil to atmosphere in winter (Lu et al., 2019; Yi et al., 2014), and thus weaken and delay the soil freeze–thaw processes. In addition, Zhang et al. (2019) pointed out that the roots of Salix psammophila could increase soil temperatures during freeze–thaw periods. The mechanism is that the accumulation of water in the roots releases a substantive amount of heat when water experiences freezing process and thus slows down the penetrating of freezing front. Based on the above analysis, the smallest frost depths and earliest thawing end times observed in our woodland experiment should mainly result from the effects of fallen leaves and poplar roots. Shallower groundwater table depths generally lead to higher soil water contents and greater water accumulations in the upper soil when the soil is experiencing freezing because of the stronger water supply capacity in the lower soil layers (Chen et al., 2015; Hermansson & Guthrie, 2005). Therefore, the largest increase in total soil water content in natural land in our experiment should be mainly caused by its shallowest groundwater table depth (Figure 2). However, shallower groundwater table depth or higher soil water content can lead to lower frost depth. The main reason is that higher soil water content releases higher latent heat and resists the penetrating of freezing front, as explicitly expressed by the Stefan equation (Kurylyk & Hayashi, 2016). Moreover, shallower groundwater table depths can lead to greater water accumulations in the upper soil when the soil is experiencing freezing. The upward water carries heat from lower soil layers, thus causes the redistribution of soil temperature and hinders the downward transfer of surface low temperature (Wu, Huang, Tan, & Wu, 2014). Cropland had slightly greater frost depths than natural land in our experiment. This should be due to shallower groundwater table depths in natural land. Finally, the decrease in total topsoil water content for three landscapes during the thawing stage is caused by the combined effects of soil evaporation and downward infiltration (Wu et al., 2019).

4.2 Impacts of meteorological conditions, land use, and groundwater table depths on soil evaporation

The atmospheric evaporation capacity and soil water supply are the two critical factors for controlling soil evaporation (Allen et al., 1998; Aluwihare & Watanabe, 2003; Or et al., 2013). The atmospheric evaporation capacity depends mainly on solar radiation, air temperature, relative humidity, and wind speeds (Allen et al., 1998). The soil water supply is mainly determined by the liquid water content in the topsoil. At the beginning of the freezing stage, although both the atmospheric evaporation capacity and liquid soil water content in topsoil decrease with the decreased air temperature, energy provided by solar radiation could still maintain a certain level of evaporation (Feng et al., 2018). Then, both the atmospheric evaporation capacity and liquid soil water content in topsoil reach a very low level with further decreases in air temperatures and cause weak evaporation during the stable freezing stage. In our experiment, the daily evaporation for all three landscapes was close to 0.1 mm d⁻¹. This result is consistent with that of Wu et al. (2016), who reported that daily evaporation during the stable freezing stage was smallest with a value of 0.1 mm d⁻¹ for all treatments. However, in the thawing stage, a rapid increase in soil evaporation occurred due to increased atmospheric evaporation capacity and liquid soil water content in the topsoil. In our experiment, soil evaporation for the three landscapes during the thawing stage accounted for >75% of total evaporation during the freeze–thaw period. A similar result was found by Zhang et al. (2019),
The ratios of soil evaporation to the reference evapotranspiration ($ET_o$) at different freezing and thawing stages for the different landscapes

| Landscape     | USFS  | SFS  | TS   | Freeze–thaw period |
|---------------|-------|------|------|--------------------|
| Cropland      | 0.59  | 0.16 | 0.39 | 0.36               |
| Woodland      | 0.27  | 0.17 | 0.25 | 0.24               |
| Natural land  | 0.41  | 0.17 | 0.75 | 0.61               |

Note. USFS, SFS, and TS represent the unstable freezing stage, stable freezing stage, and thawing stage, respectively.

who reported that soil evaporation was high during the thawing stage and low during the freezing stage.

During the freeze and thaw periods, the reference evapotranspiration ($ET_o$) can also be considered as the indicator of atmospheric evaporation capacity (Yu, Jiang, & Shang, 2016).

As shown in Table 4, the ratio of soil evaporation to $ET_o$ was highest in TS and smallest in SFS; this is because topsoil had the highest liquid water content in TS and the lowest liquid water content in SFS, which caused more water supply for evaporating in TS and less water supply for evaporating in SFS. During the freeze and thaw periods, natural land had the highest ratio of soil evaporation to $ET_o$, whereas woodland had the smallest ratio. This is attributed to natural land having the shallowest groundwater table depth, which presented fewer constraints on evaporation, whereas woodland had deeper groundwater table depth in addition to the cover provided by fallen leaves, which presented more significant constraints on evaporation.

Different meteorological factors have different impacts on soil evaporation. The impact of meteorological indicators on soil evaporation was explored by the PCA method. The results are summarized in Table 5. Nine meteorological indicators including mean air temperature, maximum air temperature, minimum air temperature, mean relative humidity, mean wind speed, mean solar radiation, precipitation, mean atmospheric pressure, and mean soil surface temperature were synthesized into three PCs, which were significant and explained 90.62% of the total variability. Of these components, PC1 can be classified as the temperature factor (e.g., mean air temperature, maximum air temperature, minimum air temperature, and mean soil surface temperature) with coefficients > .95; PC1 explained 66.43% of the total variability. PC2 can be classified as the wind speed factor with the largest coefficient of .84; PC2 explained 13.91% of the total variability. PC3 can be classified as the humidity factor (e.g., precipitation and mean relative humidity) with the largest coefficients of .742 for precipitation and .457 for mean relative humidity; PC3 explained 10.28% of the total variability. Multiple linear regression analysis was carried out between soil evaporation and PCs in combination with the total soil water content in topsoil (0–20 cm, (see Table 6). The coefficient of determination ($R^2$) and $P$ values of cropland and natural land were >.5 and <.05, respectively, which indicated that significant linear correlations exist between soil evaporation, PCs, and total soil water content in topsoil for cropland and natural land. However, the $R^2$ (.452) and $P$ value (.062) of woodland were <.5 and >.05, respectively. This might be due to the cover provided by fallen leaves.
FIGURE 9 The relationship between the cumulative soil evaporation and salinity in the 0-to-10-cm soil layer of (a) cropland, (b) woodland, and (c) natural land

and the root effects of poplar. For cropland, the standard coefficient of the total soil water content in the topsoil was largest, which indicated that the total soil water content in topsoil had the greatest impact on soil evaporation. However, the standard coefficient for natural land occurred with PC1. The reason for this difference might be that the soil water contents in the topsoil of natural land were always higher than those of cropland and caused fewer constraints on evaporation of the soil water supply in natural land. In addition, the standard coefficients of PC1 for cropland and natural land were positive values, which indicated that increased air temperatures would promote evaporation.

The differences in soil evaporation among the three different landscapes during different freezing and thawing stages may be due to different reasons. As shown in Figure 8, in USFS, the soil evaporation levels among the three different landscapes were significantly different from each other; the largest value occurred in cropland and the smallest value occurred in woodland. This might be because the highest initial salt content occurred in the cropland topsoil and the lowest initial salt content occurred in woodland topsoil. Higher soil salinities result in lower freezing points and higher liquid soil water contents (Lu et al., 2019), causing greater soil evaporation. During SFS, soil was in a stable frost condition with very low liquid soil water contents for all landscapes; therefore, no significant differences in soil evaporation were found among the three landscapes. In TS, soil evaporation levels among the three different landscapes were significantly different from each other, with the largest value occurring in natural land and the smallest value occurring in woodland. This may be because the natural land had the shallowest groundwater table depth, which caused the greatest water accumulation in the upper soil during the freezing stage (see Figure 5d). In contrast, the lowest soil water content in topsoil, in addition to the influence from fallen leaves, resulted in the lowest evaporation in woodland compared with the other two landscapes.

In addition, sublimation may be a pathway of water loss from microlysimeter as long as ice exists in topsoil. However, it is quite difficult to distinguish the evaporation of liquid soil water and the sublimation of iced soil water. Meanwhile, liquid water always exists in soils even at very low temperatures (Kurylyk & Watanabe, 2013). The evaporation of liquid water consumes less energy than the sublimation of ices. Therefore, evaporation may still be the main pathway of water loss from soil in winter. In many previous studies, only the sublimation of snow cover was considered as part of the land-surface hydrological processes (Lauenroth, Schlaepfer, & Bradford, 2014; Miralles, De Jeu, Gash, Holmes, & Dolman, 2011; Obrist, Yakir, & Arnone, 2004). In our experiment, sublimation of snow cover was not considered due to no snow events occurring.
Microlysimeters may underestimate soil evaporation due to the sealed bottoms. However, in our experiment, the underestimation was very limited and mainly occurred in USFS. In SFS, soil water contents in topsoil were relative stable and evaporation was relatively small. Thus, the accuracy of monitoring could be guaranteed with an interval of about half a month. For TS, to avoid overestimation or underestimation of soil evaporation, the monitoring interval was adjusted to 3–4 d. The soil conditions in microlysimeters were approximately the same as those in field. Thus, the microlysimeter is still a promising tool to measure soil evaporation in freeze–thaw periods. However, the effects of microlysimeter diameter, length, bottom cap, and so on, on soil evaporation measurement under freeze–thaw conditions deserve further research.

The measured data in the 1-m soil profile combined with the mathematical models can be used for evaluating soil evaporation. These models can be either the water balance conceptual models or the dynamic models. After calibration with measured data in 1-m soil profile, the models can be used to estimate soil evaporation. Further studies are required for improving the estimation of soil evaporation using the mathematical model with the microlysimeter measurement.

4.3 Impacts of land use, soil evaporation, and groundwater table depth on soil salt accumulations

Significant salt accumulations in topsoil were observed in the three landscapes. This is consistent with the results of Lu et al. (2019) and Wu et al. (2019), who reported that soil freezing and thawing processes clearly increased the risk of soil salinization. The mechanism of soil salinization caused by freezing and thawing can be explained as follows: during the freezing stage, the dissolved salt is brought to the topsoil from the subsoil by upward water flux due to the soil water potential difference and results in increased salinity in the topsoil. During the thawing stage, the thawed water above the unthawed layer is prevented from infiltrating into the deeper soil and continuously provides a source for evaporation; then, the dissolved salt remains and accumulates in the topsoil when the water evaporates in spring (Bing et al., 2015; Zhang & Wang, 2001), which leads to continuous and significant salt accumulation in the topsoil.

Different land uses exhibit different salt accumulations in the topsoil. This result may mainly be attributed to the differences in evaporation and salt movement for different landscapes. Upward movement of dissolved salt is a process associated with soil water movement (Lu et al., 2019; Wu et al., 2019). Therefore, the differences in these two critical processes among the three landscapes cause different salt accumulations in topsoils (Bing et al., 2015; Li, Shi, Flerchinger, Zou, & Li, 2013; Zhang & Wang, 2001). In general, higher initial soil water contents and shallower groundwater table depths lead to greater soil evaporation and cause greater salt accumulations during freeze–thaw periods (Bing et al., 2015). Our experiments indicated that both the greatest soil evaporation and salt accumulation occurred in natural land due to its highest initial soil water content and shallowest groundwater table depth among the three landscapes. In contrast, woodland showed the smallest soil evaporation and salt accumulation due to its lowest initial soil water content, deepest groundwater table depth, and fallen leaf cover. As shown in Figure 9, the relationship between cumulative soil evaporation and salt accumulation in the 0- to 10-cm soil layer for all three landscapes can be quantified by linear functions, and their determination coefficients were .84 for cropland, .72 for woodland, and .94 for natural land. This implies that soil evaporation is one of the decisive factors for salt accumulations in topsoil during freeze–thaw periods.

5 CONCLUSIONS

In this paper, field experiments spanning 5 mo were conducted to investigate soil evaporation and its impact on salt accumulations in different landscapes under freeze–thaw conditions. The soil evaporation amounts in all three landscapes were noteworthy, with most evaporation occurring during the soil thawing stage and a small proportion of the evaporation occurred during the soil freezing stage. As an associated process of evaporation, salt accumulation in topsoil was found to significantly and linearly increase with soil evaporation for all three landscapes. The differences in soil evaporation and salt accumulation among the three landscapes were caused primarily by landscape-dependent initial soil water contents, groundwater table depths, and land surface cover. Natural land exhibited the greatest soil evaporation and salt accumulation due to its highest initial soil water content and shallowest groundwater table depth, whereas the least soil evaporation and salt accumulation occurred for woodland because of the combined effects of the lowest initial soil water content, deepest groundwater table depths, and fallen leaf cover. Additionally, soil freezing caused water to accumulate in the upper frozen layer, which can benefit soil water conservation and further promote vegetation restoration and crop sowing after freeze–thaw periods. However, strong soil evaporation occurred during the thawing stage and resulted in massive nonbeneficial water loss as well as severe salt accumulation, both of which are harmful to agricultural production and ecological vegetation growth. Further research is required to reduce soil evaporation during the thawing stage in the upper reaches of the YRB, as well as in other arid regions with similar conditions.
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AUTHOR CONTRIBUTIONS
Sheng Liu: Formal analysis; Investigation; Writing-original draft. Quanzhong Huang: Supervision; Writing-review & editing. Dongyang Ren: Methodology. Xu Xu: Resources. Yunwu Xiong: Conceptualization. Guanhua Huang: Supervision; Writing-review & editing.

CONFLICT OF INTEREST
The authors declare no conflict of interest.

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