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The effects of freeze–thaw process on soil water migration in dam and slope farmland on the Loess Plateau, China

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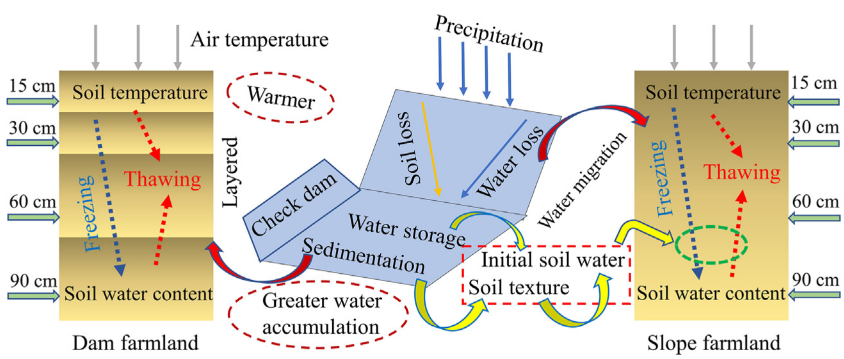
HIGHLIGHTS

- The freeze-thaw process differed between dam farmland (DF) and slope farmland (SF).
- The migration and increment of soil water content (SWC) in DF are larger than in SF.
- The freeze–thaw process was mainly affected by initial SWC in this environment.

GRAPHICAL ABSTRACT



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ABSTRACT

The seasonal freeze–thaw process affects soil water migration, which influence spring planting, especially in arid and semi-arid regions that cannot be irrigated on the Loess Plateau. This study was conducted to evaluate differences in the freeze–thaw process and water migration between dam farmland (DF) and slope farmland (SF). To accomplish this, two typical agricultural soils (DF and SF), soil water content (SWC) and soil temperature (ST) were monitored at different depths (15, 30, 60 and 90 cm), were investigated under freeze–thaw conditions from November 2015 to April 2016 in the Northwest China. The results showed that different freeze-thaw process between dam farmland (DF) and slope farmland (SF). The DF can keep soil water content resulting from longer frozen period. Thermal transmission between soil and air in SF is greater than that in DF. The SWC values in DF were higher than in SF at each depth layer under similar soil temperature. Migrated and incremental SWC in the DF is greater than that in SF during the freeze-thaw process. The initial SWC is the main impact on freeze–thaw process in this study. This research can provide useful information to guide the water management of seasonally frozen agricultural soil.

Abbreviations: DF, dam farmland; SF, slope farmland; SWC, soil water content; ST, soil temperature; AT, air temperature; CV, coefficient of variance; R^2, the determination coefficient; *p*, Pearson correlation coefficient.

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1. Introduction

Seasonal freezing and thawing of soil have an important impact on agricultural and ecological environments because of its effects on soil water distribution and heat balance (Yi et al., 2014; Ala et al., 2016). Changes in soil water potential in response to the freeze–thaw process results in variations in the soil water distribution. The freezing of soil induces a situation in which soil water migrates from the unfrozen area to the freezing front (Philip and de Vries, 1957; Nagare et al., 2012), which leads to increases in the soil water content (SWC) in the frozen soil (Gergely, 2007; Zhang and Sun, 2011). The upper soil layers first begin to thaw as the air temperature increases, while the middle soil layer begins to thaw later. Therefore, the SWC increases in the upper soil layer (Yang et al., 2008; Chen et al., 2013) because it is difficult for the melted water to infiltrate into the lower layer. Furthermore, variations in air temperature result in freeze-thaw cycles in the soil layer during the initial stage of thawing. Luo et al. (2003) reported that the freeze-thaw cycles of soil could influence the distribution of soil water content and increasing SWC was found to lead to increased water storage in the field during the freeze–thaw process (Chen et al., 2013; Yi et al., 2014). Thus, it is important that soil freeze–thaw processes are determined so that the migration of SWC can be better understood to provide guidance to hydrology management in areas subjected to freeze–thaw cycles, especially in arid and semi-arid regions.

In China, soils subjected to freeze-thaw cycles are mainly found in the Tibetan Plateau and mountains in the northwest and northeast regions (Li and Fan, 2014). In these regions, the area of seasonal freeze-thaw soil (deep freeze >0.5 m) is approximately 46.3% (Li and Cheng, 2002). Most seasonal freeze-thaw events occur in arid and semiarid regions. The loess hilly region subjected to seasonal freeze-thaw is located in northwestern China in the middle reaches of the Yellow River. In this region, soil loss is a major environmental problem threatening the sustainable development of the Loess Plateau (Feng et al., 2010; Liu et al., 2012). In recent years, many soils, and water conservation measures have been implemented in the region, including revegetation, tillage management, enclosures, terracing, and check dams (Lu et al., 2012). Among these measures, check dams built across channels to reduce stream speed and trap sediment (Zeng et al., 2009) are considered to be one of the most effective engineering approaches toward sediment retention (Li et al., 2011; Lu et al., 2012; du Plessis et al., 2015). Check dams have 50 years history on the Loess Plateau (Li et al., 2011; du Plessis et al., 2015), which has resulted in a large amount of sediment deposition behind the check dam experiencing storm events (Xu and Sun, 2006; Wei et al., 2016). Sediment deposition from many storm events promotes the formation of dam farmland (DF). In general, during storms events, flood and sediment peaks are generated synchronically, with larger flows corresponding to greater sedimentation volume (Chen et al., 1988; Wei et al., 2016; Li et al., 2016); as such, sediment layers can be correlated with individual storm events, similar to the principle of tree-ring dating (Popa and Kern, 2009; Woodhouse et al., 2013). The layered soils were discovered in DF in Wangmaogou watershed using the Cesium-137 fingerprinting technique by Li et al. (2016) and to have a corresponding relationship with soil water distribution by Zhao et al. (2010). The characteristics of the per layer of sedimentary cycle in DF lead to the soil particle gradually becoming coarser from top to bottom (Fig. 1), which leads to alteration of the soil texture in soil layers and the appearance of a water-repellent layer in each deposited layer junction (Long et al., 2008; Zhao et al., 2009). Zhao et al. (2010) also found that this kind of layered soil restricted water flow downward but limited lateral flow in layered soils of DF.

In soil that undergoes seasonal freezing, soil freeze-thaw processes play an important role in local eco-hydrological processes, such as snow-melt water infiltration, water migration and plant germination and growth (Nagare, 2011; Zhao et al., 2013). Many researchers have recently studied the mechanisms that control the movements of SWC that occur when soil is in the freeze-thaw process at different regions and environment (Yang et al., 2008; Yi et al., 2014; Ala et al., 2016). Therefore, the migration soil water and impact factor varied with location. For example, in agricultural freeze zones, the freeze-thaw process of different farmland paddies and dry lands were studied under different antecedent SWC conditions, and the results indicated that the initial SWC profiles appeared to control the amount of water migrating upward and that soils with a lower SWC were more likely to freeze at a similar temperature (Chen et al., 2013). Nagare et al. (2012) found that the SWC and soil properties affected the freezing time and ground thermal conditions. Moreover, changes in soil texture were found to have a key effect on the quantity of water that moved during the freeze-thaw (FT) process (Nagare et al., 2012; Ala et al., 2016). For instance, the accumulated soil water was greater in heavy clay than in sandy soil (Gao et al., 2000; Wang et al., 2007; Ala et al., 2016). However, the variations in soil texture and initial SWC cause changes due to the formation of DF in loess hilly region, which result in variation soil hydrological characteristics during the freeze–thaw period. Furthermore, little attention has been paid to migrate soil water and vary temperature as part of the FT process, related conditions and the spatial and temporal characteristics in this region. In this region, dam farmland is the most important crop resource for local farmers, with a yield 5–6 times that of SF, and >10 times that of some areas in the plateau (Xu and Wang, 2000). For agricultural cultivation during spring, it is necessary to understand which types of farmland a beneficial effect on soil water conservation and higher soil water has maintained after undergoing freeze-thaw. This is because the SWC in the spring will influence the germination and growth of vegetation, especially in arid and semi-arid and regions that cannot be irrigated on the Loess Plateau. Thus, it is necessary to fully understand differences in freeze-thaw and migration of SWC between areas with DF and SF to improve farmland management and to make supplementary water available to plants.

The variations in soil temperature (ST) and water migration characteristics were evaluated to improve our knowledge of the characteristics of freeze-thaw processes in two typical farmland (DF and SF) on the loess hilly region. The specific objectives of this study were to: 1) survey the freeze-thaw characteristics in DF and SF; 2) identify differences in soil water migration between DF and SF during the freeze–thaw period; 3) determine the dominant impacts of soil texture and initial SWC on the freeze-thaw process.

2. Materials and methods

2.1. Study sites

Monitoring data were collected from two sites, one located in DF and the other in SF. Both sites were located in Wangmaogou (N 37°34′–37°37′, E 110°20′–110°23′) catchment in the north of Shaanxi Province, Northwest China in agricultural areas subjected to freeze-thaw (Fig. 1). In this catchment, the mean annual precipitation is approximately 513 mm/year, most of which occurs from June to September. Additionally, the mean temperature is 10.2 °C and the lowest and highest temperatures were −27 °C and 39 °C during the study period (Gao, 2013). The area of Wangmaogou catchment is 5.97 km^2, and it is at an altitude of 936–1188 m. To control soil erosion, about 23 check-dams were constructed in a gully area in Wangmaogou catchment before 2015. The Wangmaogou 2# check dam is one of two backbone dams located in the middle reaches of the Wangmaogou watershed, which was built in 1953 (Fig. 1). The Wangmaogou 2# check dam control area is 2.89 km^2 and formed the dam farmland of 3.32 hm^2. Layer structure of the sediment is shown in Fig. 1d on the dam farmland. In this region, DF and SF comprise 49.09% of the cultivation area (Xu and Wang, 2000), which are the main farmland. Therefore, DF and SF were selected experimental sites to represent the cultivated field as research subjects to study the response of soil water content and temperature to FT process. The greatest area DF was selected for this research on the control

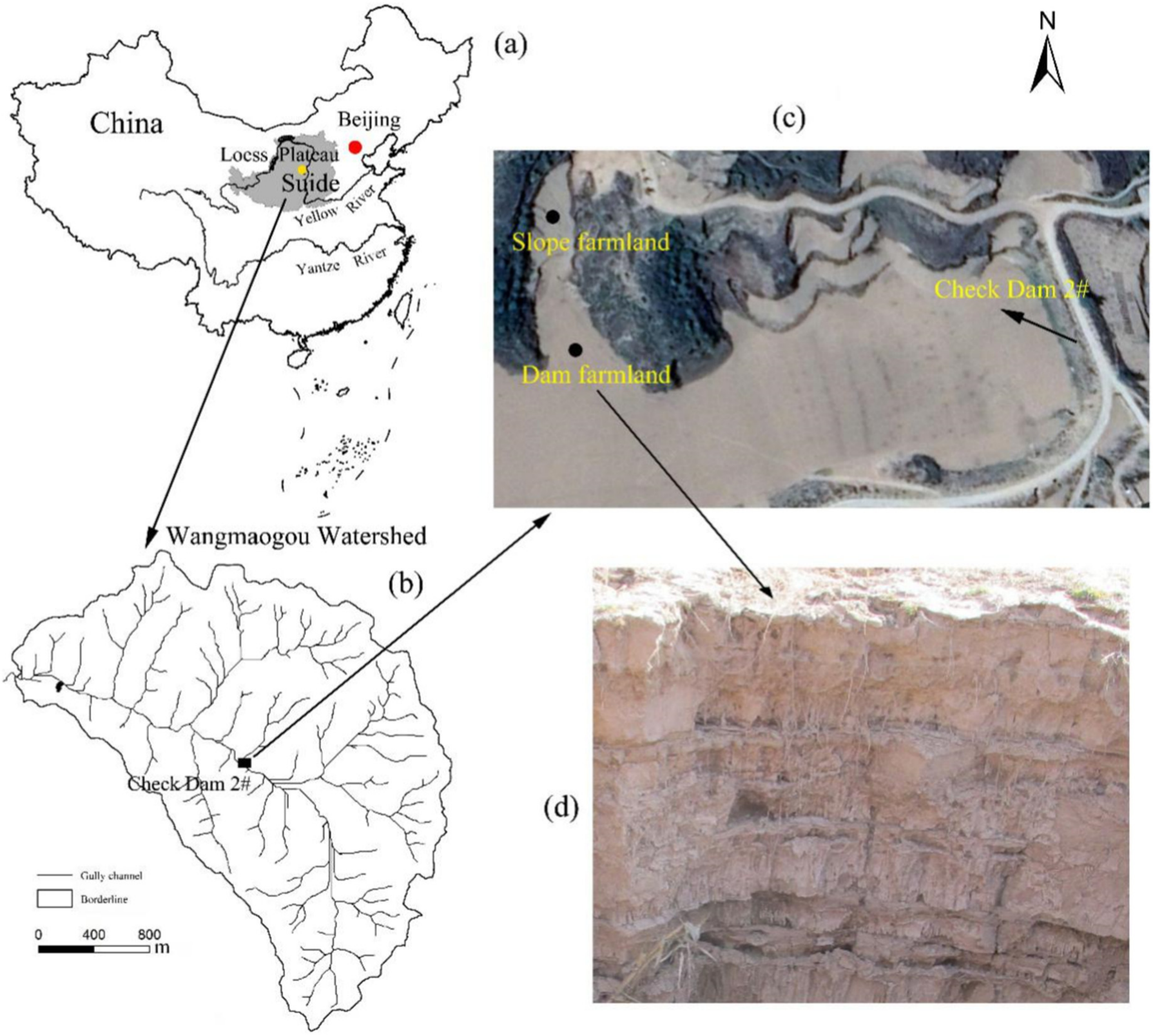

Fig. 1. The monitor sites (c) of dam farmland and slope farmland located in the Wangmaogou watershed (b) on the Loess Plateau of China (a). The layered soils of dam farmland profile (d).

watershed behind Wangmaogou 2# check dam. The monitoring sites of SF was selected 80.05 m away from the monitoring site of DF for avoiding the impact of climate factors, and the monitoring site of DF is 187.47 m away from the check dam. The altitudes of monitoring sites of DF and SF are 989.67 m and 1001.77 m, respectively, and difference of 12.10 m elevation has little effect on the air temperature variation because of air temperature rising 273.51 K with increasing 100 m elevation during winter (He, 1988). DF and SF have the same agricultural crop of corn, tillage and management measure.

At the beginning of the experiment, profiled soil samples were collected from each depositional layer using a hand auger with a diameter of 6.9 cm. A total of 12 samples were taken in each site from three soil sample for each layer and combined to obtain a composite sample in the DF and SF on 15 Nov. 2015. A portion of the soil samples was used to calibrate the SWC sensor, while the remainder was brought back to the laboratory to measure the soil texture using a Mastersizer2000 particle size analyzer. Soil particle-size distribution was described in terms of percentages of clay (<0.002 mm), silt (0.002–0.05 mm) and sand

Table 1
Soil particle size-distributions and initial SWC at different depth on dam and slope farmland.

Land use	Soil depth (cm)	Soil texture (%)			Initial SWC ($cm^3 \cdot cm^{-3}$)
		Clay (<0.002 mm)	Silt (0.05–0.002 mm)	Sand (0.05–2 mm)	
DF	0–15	0.24	60.56	39.21	0.108 ± 0.0004bA
	15–30	0.24	64.41	35.35	0.312 ± 0.002aA
	30–60	0.34	83.27	16.39	0.098 ± 0.005bA
	60–90	0.13	57.16	42.72	0.04 ± 0.0001cA
SF	0–15	0.25	67.13	32.62	0.085 ± 0.001aB
	15–30	0.28	69.56	30.16	0.086 ± 0.0001aB
	30–60	0.19	66.18	33.63	0.085 ± 0.001aB
	60–90	0.19	67.31	32.50	0.026 ± 0.001bB

Note: the different capital letters at the same layer in different land use showed significant difference of $p < 0.05$; the different lower letters in one profile showed significant difference of $p < 0.05$.

(>0.05–2 mm) (Table 1). The textural classification of soils in dam and SF was silty sandy loam.

2.2. Measurements

This study was designed to provide guidance regarding agricultural management through monitoring of the soil freeze–thaw process in DF and SF. Thus, the 0–90 cm soil profile was surveyed because the longest crop root depth is about 90 cm (Hao et al., 2012).

The air temperature (AT) was monitored at a weather station (RX3000, USA), while the ST (K) was monitored using a HA1002 (Handan Dingrui Technology, Hebei of China) through eight ST probes (Pt-1000) placed at soil depths of 15, 30, 60 and 90 cm in DF and SF, defined as D15, D30, D60 and D90 for DF and S15, S30, S60 and S90 for SF. Soil starts to freeze when the ST is sustained at <273.15 K, while it starts to thaw when the ST is sustained at higher than 273.15 K. A soil water monitoring automatic station (Watchdog 2008, TDR type, Spectrum, USA) was used to measure the SWC ($cm^3 \cdot cm^{-3}$) through eight sensors that were placed at the same depths as for soil temperature measurements in the DF and SF. The initial SWC at different layer are showed in Table 1. Two replicates of the SWC and ST measurement location were set up at distance of 0.5 m to minimize the errors because of soil heterogeneity (Chen et al., 2013). The ST and SWC were recorded every 60 min at different depths from 16 Nov. 2015 to 13 April 2016 resulting from the frozen season occurs between the end of November and the middle of April of the following year (Xiao et al., 2019).

2.3. Data analysis

2.3.1. Calculations

The freezing and thawing rate in the freeze-thaw process was estimated with the following equation:

$$R_i = \frac{H_{i+1} - H_i}{D_{i+1} - D_i} \tag{1}$$

where, R_i ($cm \cdot d^{-1}$) is the freezing and thawing rate at the depth of i, H_{i+1} (cm) is the soil thickness at the depth of $i+1$, H_i (cm) is the soil thickness at the depth of i, D_{i+1} is the date of freezing or thawing at the depth of $i+1$; D_i is the date of freezing or thawing at the depth of i.

The ST and SWC were standardized by the following formula:

$$a = \frac{X - \overline{X}}{\overline{X}} \tag{2}$$

where, a was the standardized value of ST or SWC, X was the value of ST (K) or SWC ($cm \cdot cm^{-3}$) at moment I, and $\overline{X}$ was the average value of ST (K) or SWC ($cm \cdot cm^{-3}$) at a certain time period.

2.3.2. Statistical analysis

The AT, ST, and SWC were analyzed as the 24 h mean. The SPSS16.0 (IBM Corp., Armonk, NY, USA) software was employed to analyze versus and correlation of ST and SWC. The coefficient of variance (CV) of the SWC and ST was examined to evaluate the dynamics during the monitoring period. Regression analysis was applied to compare the effects of the AT on the ST during the monitoring period in DF and SF. The Kriging method starts from the research variable itself and models the autocorrelation based on the spatial positional relationship between the existing and measured sample points, and then the measured points can be linearly unbiased, and estimated variance could be obtained at the same time, which is a better description of the geographical phenomenon studied than the IDW and Natural neighbor methods (Zhang, 2018). Therefore, Kriging interpolation is considered as the method to illustrate the insight of spatial and temporal of soil temperature during the FT process (Yi et al., 2014) using Surfer 8.0 software.

3. Results

3.1. Freeze–thaw process in soil profile

The spatial and temporal changes in soil freezing and thawing of ST at different depths were illustrated by the Kriging interpolation (Fig. 2). Similar trends existed in the soil freezing and thawing process on the DF and SF. Based on the daily variation of ST, the freeze-thaw process was divided into three phases: freezing process (from the initial monitoring point to the freezing point), the frozen process (from the freezing point to the thawing point), and the thawing process (the thawing point to the end of the monitoring point) at each layer (Fig. 3).

3.1.1. Variations in ST during the freeze-thaw process

The contour map clearly indicated that the date of soil freezing from the surface soil down to the deep soil in the DF was later than that in the SF at the corresponding soil depth (Fig. 2 and Table 2). The upper soil depth of 15 cm for the DF and SF started to freeze on 4 Dec. 2015 and on 3 Dec. 2015, respectively (Fig. 3 and Table 2). The DF soil started to freeze 1, 6 and 8 days later than that on SF at depths of 15, 30 and 60 cm, respectively. The soil freezing time was gradually delayed with increased depth. The frozen depth reached 90 cm after 47 days of freezing for DF and 48 days for SF. The STs of freezing at depths of 15 cm, 30 cm, 60 cm and 90 cm in DF and SF were 273.13 K, 273.05 K, 273.12 K, 273.05 K and 272.99 K, 273.00 K, 273.05 K, and 273.07 K,

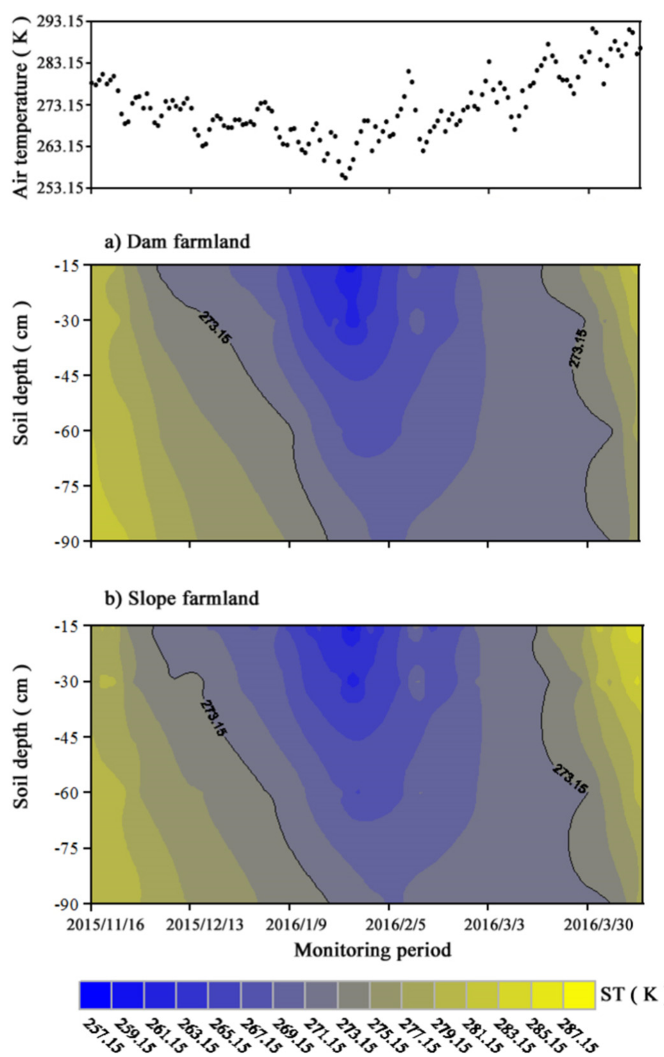

Fig. 2. Evolutions of frost depths and ST in the DF (a) and SF (b) from 16 Nov. 2015 to 13 Apr. 2016.

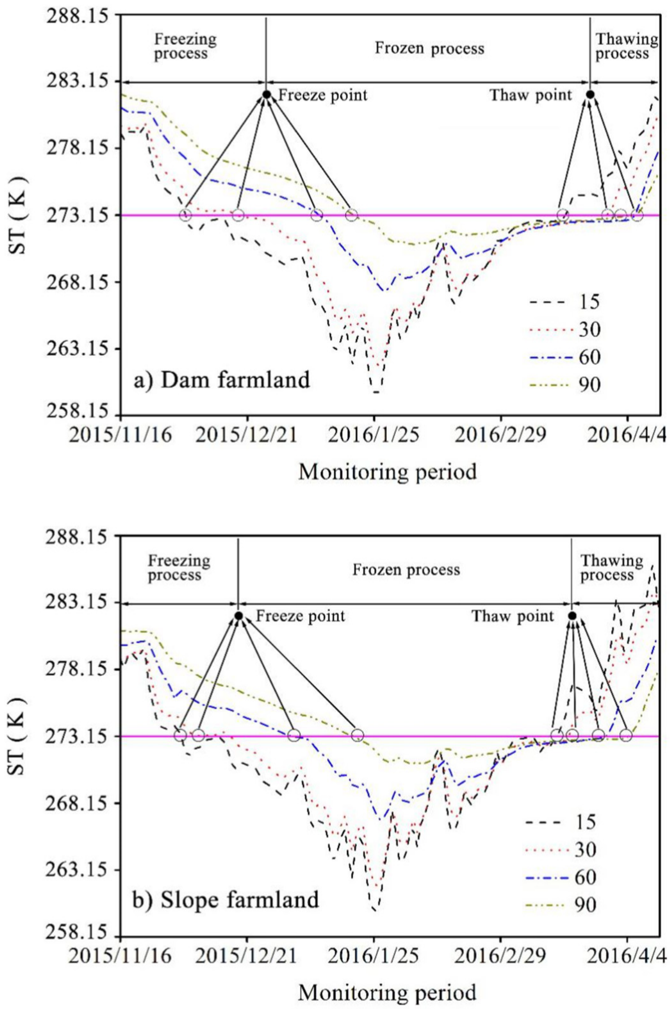

Fig. 3. Freezing process, frozen process and thawing process at depths of 15, 30, 60 and 90 cm over the monitoring period in the DF and the SF.

respectively (Fig. 3 and Table 2). The mean ST in the DF was greater than that in SF at each corresponding soil depth during the freezing period (Table 2). At a depth of 15 cm to 30 cm, the rate of soil freezing was 0.75 $cm \cdot d^{-1}$ for the DF, but 1.07 $cm \cdot d^{-1}$ for the SF. At a depth of 30 cm to 60 cm, the rate of soil freezing for DF was 1.30 $cm \cdot d^{-1}$ and 1.43 $cm \cdot d^{-1}$, respectively, in the SF. However, at a depth of 60 cm to 90 cm, the rate of soil freezing in DF was 1.89 times greater than that in SF, and the rate of soil freezing of DF and SF were 3.33 $cm \cdot d^{-1}$ and 1.76 $cm \cdot d^{-1}$, respectively.

The date of soil thawing from the surface soil to the deep soil in the DF was later than at corresponding soil depths in the SF (Fig. 2). The DF and SF soil started to thaw on 20 Mar. 2016 and 17 Mar. 2016 (Fig. 3 and Table 2). Furthermore, the DF soil started to thaw 3, 10 and 8 days later than soils of SF at depths of 15, 30 and 60 cm, respectively. As soil depth increased, the soil thawing time was gradually delayed, except for D90 in the DF. The thaw depth reached 90 cm after thawing for 18 days for DF and after 19 days for SF. The mean ST in DF was lower than that in SF at each corresponding soil depth during the thawing period (Table 2). At 15 cm to 30 cm, the rate of soil thawing was 1.5 $cm \cdot d^{-1}$ for the DF, but the corresponding value was 5 $cm \cdot d^{-1}$ for the SF. However, at soil depths of 30 cm to 90 cm, the rate of soil thawing for DF was two times greater than that for SF, and the rate of soil thawing of DF and SF was 3.75 $cm \cdot d^{-1}$ and 1.88 $cm \cdot d^{-1}$, respectively.

The lowest ST was 259.79 K in the DF and 260.07 K in the SF at a depth of 15 cm during the freeze-thaw process. The frozen days from the depth of 15 cm to 90 cm in DF and SF were 107, 97, 87, and 77 days and 105, 93, 87, and 76 days, respectively (Table 2). The mean ST in DF was greater than that in SF at each corresponding soil depth during the frozen period (Table 2).

Fig. 5 shows a box plot using the freezing temperature (273.15 K) as a reference. The closer to 273.15 K the median value of ST is, the fewer days the soil is frozen. In DF and SF, the median value of ST becomes closer to 273.15 K with increasing soil depths, which indicates that the frozen days decreased with increasing soil depths during the freeze–thaw process (Table 3 and Fig. 5). At the same soil depth, the median value of ST was closer to 273.15 K in SF than in DF, except at 90 cm, indicating that the soil experienced more frozen days in DF than in SF. Actually, the frozen days in DF was the same as for SF at 60 cm and there was only one more frozen day in DF compared to SF. As shown in Fig. 5 and Table 3, the mean values of ST at D60 and D90 are lower than at S60 and S90.

3.1.2. The relationship between ST and AT

During the freeze-thaw process, there were 6, 3, 4 and 2 freeze-thaw cycles at the depth of 15 cm, 30 cm, 60 cm and 90 cm in DF and SF, which showed that the ST of the upper layer was fluctuating. As shown in Fig. 3, the STs fluctuated significantly at D15 for the DF and SF at the onset of the freezing process. Evaluation of the range, coefficient of variation (CV) (Table 3) and degree of dispersion (Fig. 5), and the CV value decreased with increasing soil depths at the same landscape (DF or SF), and the values of CV in SF were greater than in DF at the same soil depth.

Among the four soil monitoring depths, the CV of the ST at 15 cm was largest in both DF and SF (Table 3), which indicated that the STs fluctuated significantly in the near-surface profile. Pearson's correlation was implemented to test the relationship between the AT and ST under each soil depth in DF and SF.

The ST and AT values were positively correlated in the soil layers, except at 90 m (Table 4). Therefore, regression analysis was conducted to investigate the relationship between AT and ST at every soil depth in DF and SF, respectively. The determination coefficient of R^2 was 0.63, 0.41, 0.09 and 0.003 in D15, D30, D60 and D90, respectively. The determination coefficients of R^2 were 0.75, 0.65, 0.25 and 0.017 in S15, S30, S60 and S90, respectively (Table 4). Therefore, the regression equations

Table 2
Statistical characteristics of time point and soil temperature in dam and slope farmland during different stages.

Depth (cm)	Freezing point	Mean freezing temperature (K)	Freezing temperature (K)	Mean frozen temperature (K)	Thawing point	Mean thawing temperature (K)	Frozen duration (day)
D15	2015/12/4	277.14 ± 0.52	273.13	268.82 ± 0.35	2016/3/20	276.93 ± 0.49	107
D30	2015/12/24	276.03 ± 0.46	273.05	269.56 ± 0.31	2016/3/30	276.69 ± 0.59	97
D60	2016/1/11	276.65 ± 0.34	273.12	270.96 ± 0.17	2016/4/7	276.13 ± 0.60	87
D90	2016/1/20	277.55 ± 0.32	273.05	272.42 ± 0.07	2016/4/6	274.50 ± 0.42	77
S15	2015/12/3	276.58 ± 0.61	272.99	268.59 ± 0.34	2016/3/17	279.22 ± 0.68	105
S30	2015/12/17	275.53 ± 0.45	273.00	269.18 ± 0.30	2016/3/19	278.19 ± 0.66	93
S60	2016/1/3	276.24 ± 0.33	273.05	270.89 ± 0.19	2016/3/30	276.89 ± 0.56	87
S90	2016/1/20	276.94 ± 0.30	273.07	272.39 ± 0.25	2016/4/5	275.62 ± 0.59	76

Table 3
Statistical characteristics of soil temperature in dam and slope farmland during the monitoring period.

Soil depths	Mean (K)	Median (K)	Range (K)	CV (%)
D15	271.28	271.46	22.29	1.843
D30	271.67	272.29	18.42	1.586
D60	273.28	272.65	13.74	1.250
D90	274.62	273.07	11.24	1.156
S15	271.76	271.86	25.92	2.032
S30	272.05	272.32	21.95	1.751
S60	273.20	272.84	13.77	1.418
S90	274.47	273.07	9.94	1.229

were built between the AT and ST values of D15, D30, S15 and S30 (Fig. 5).

As shown in Fig. 5, the correlation between ST and AT was consistent with the linear relationship ($y = ax + b$). The equation parameter a is defined as the thermal transfer efficiency between the air and soil, and equation parameter b is defined as the base of ST. As shown in Table 4, the equation parameter a in DF is smaller than that in SF at the same soil depth. As shown in Fig. 4, the ST variation was slower in DF than in SF for the same AT at the depths of 15 and 30 cm, which confirmed that the DF was freezing and thawing later than that in SF. Equation parameter a varied with the soil characteristics, with a larger a indicating faster thermal transmission between ST and AT.

3.2. The SWC redistribution during the freeze–thaw process

3.2.1. Variations of SWC in DF and SF during the freeze–thaw process

The SWC values in DF were higher than in SF at each depth layer at similar ST (Fig. 6). For example, the ST at the depth of 15 cm in both the DF and SF was 270.75 K on 27 Nov. and 25 Nov., while the corresponding SWC was 0.102 and 0.080 $cm^3\ cm^{-3}$, respectively. The changes in SWC differed between the two lands at different depths in the freeze–thaw process (differences existed in changes of SWC between the two lands during the freeze–thaw process). The initial and final SWC values were obtained based on the mean SWC for five consecutive days. The initial SWC at D15 and D60 did not differ significantly, but these values were significantly different compared with the D30 and D90 SWC (Table 5). The highest and lowest initial SWC were observed at D30 and D90 in the DF, respectively. Additionally, the highest SWC at D30 existed between the similar SWC values observed for D15 and D60, indicating that the layered soil restricted downward water flow.

The mean SWC per soil per depth differed significantly in DF during the freezing process (Table 5). The mean SWC values of S15 and S30 did not differ significantly but were significantly different from those of S60 and S90 during the freezing process (Table 5). The mean SWC in the upper soil depth was greater than that in the deeper soil layer in DF and SF. Furthermore, the mean SWC per depth in the DF was higher than the corresponding soil depth in SF, and this difference was significant for SWCs at depths of 15 cm and 30 cm (Table 5). The SWC at D15, D30, D60, and D90 was 0.108 to 0.039 $cm^3{\cdot}cm^{-3}$, 0.312 to 0.153 $cm^3{\cdot}cm^{-3}$, 0.098 to 0.043, and 0.040 $cm^3{\cdot}cm^{-3}$ to 0.014 $cm^3{\cdot}cm^{-3}$, while the SWC decreased by 63.89%, 50.96%, 56.12% and 65.0% in freezing period, respectively. In addition, during the freezing process, the SWC at S15, S30, S60, and S90 ranged from 0.085 to 0.048 $cm^3{\cdot}cm^{-3}$, 0.086 to 0.052 $cm^3{\cdot}cm^{-3}$, 0.085 to 0.046, and 0.026 to 0.014 $cm^3{\cdot}cm^{-3}$, while the SWC decreased by 43.53%, 39.53%, 45.89% and 46.15%, respectively. Therefore, the SWC showed a rapidly decreasing trend in the freezing process (Fig. 7).

The mean SWC of D15 did not differ significantly from that of D60, which did differ significantly from the mean SWC of D30 and D60 during the frozen process (Table 5). The mean SWC per soil depth was significantly different in SF during the frozen process (Table 5). Specifically, the highest mean of SWC occurred at D30 and S30. Additionally, the mean SWC at D30 was significantly greater than at S30, while the mean of SWC at D60 was significantly lower than that at S60. The mean of SWC at D15 and D90 did not differ significantly at the same soil depth in SF (S15 and S90).

During the thawing process, the mean SWC per soil depth was significantly different in DF (Table 5). The mean SWC of per soil depth was significantly different in SF during the thawing process (Table 5). The mean SWC per soil depth in DF was significantly higher than that at the corresponding soil depth in SF, except at 90 cm. The highest

Table 4
The decision coefficient (R^2) and Pearson correlation between the AT and STs at per soil depth.

Soil depth (cm)	Decision coefficient (R^2)	Pearson correlation
D15	0.63	0.793**
D30	0.41	0.645**
D60	0.09	0.316**
D90	0.003	0.058
S15	0.75	0.868**
S30	0.62	0.790**
S60	0.25	0.504**
S90	0.017	0.129

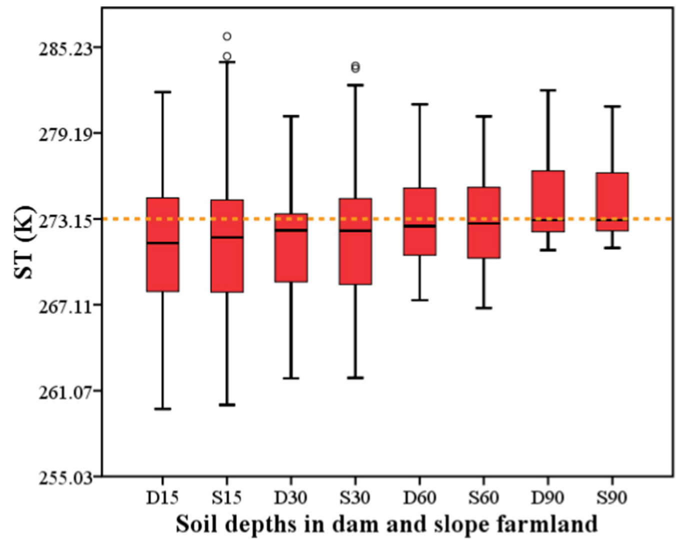

Fig. 4. The box plot of the soil temperature at different soil depths in dam and slope farmland.

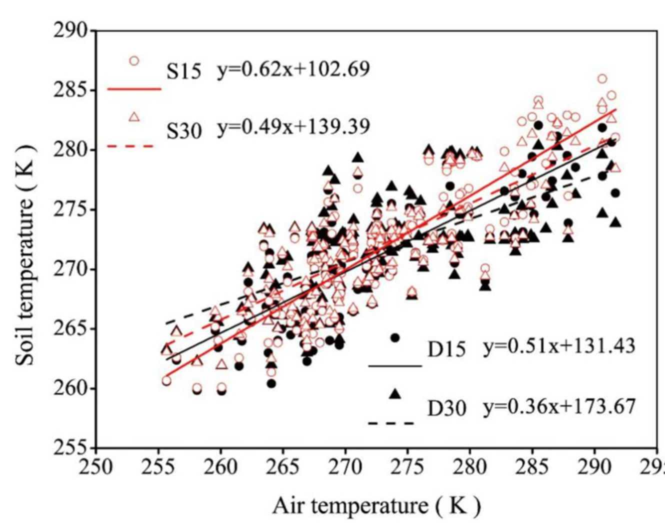

Fig. 5. The correlation of the ST and AT in the D15 in the dam and SF.

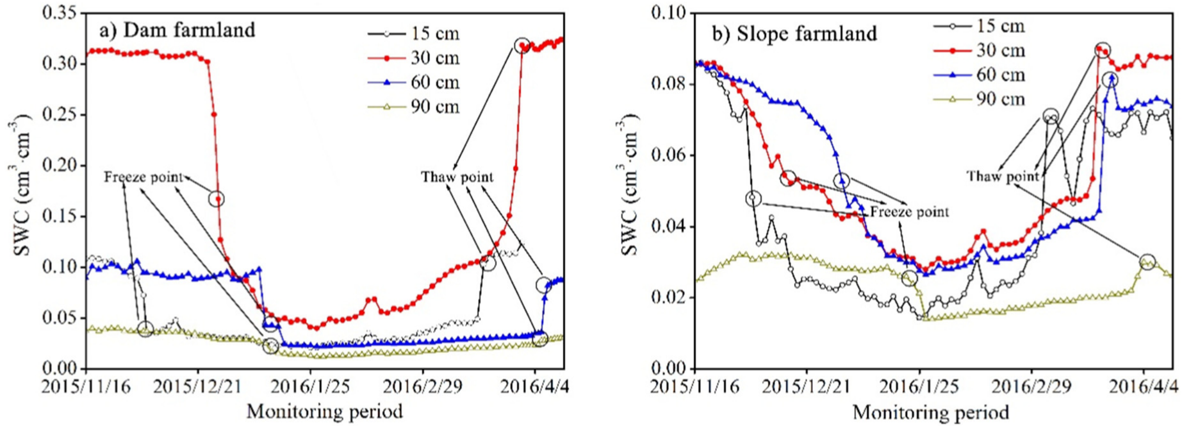

Fig. 6. The dynamic variations of the SWC at depths of 15, 30, 60 and 90 cm over the monitoring period in the dam and the SF.

mean SWC occurred at D30 and S30 during the thawing process. During the thawing process, the variation of SWC at D15, D30, D60, and D90 was 0.078 to 0.122 $cm^3 \cdot cm^{-3}$, 0.309 to 0.323 $cm^3 \cdot cm^{-3}$, 0.069 to 0.087 $cm^3 \cdot cm^{-3}$, and 0.028 to 0.031 $cm^3 \cdot cm^{-3}$, and the SWC increased by 56.41%, 4.53%, 26.09% and 10.71%, respectively. The variation of the SWC at S15, S30, S60, and S90 was 0.059 to 0.068 $cm^3 \cdot cm^{-3}$, 0.054 to 0.088 $cm^3 \cdot cm^{-3}$, 0.055 to 0.075 $cm^3 \cdot cm^{-3}$, and 0.021 to 0.027 $cm^3 \cdot cm^{-3}$, and the SWC increased by 15.25%, 62.96%, 36.36% and 28.51%, respectively.

3.2.2. Effect of freezing on the redistribution of SWC

A line and scatter plot of the water transport characteristics of the soil depth and the SWC at the initial and final times was generated based on the combination of soil freezing characteristics with the initial and final SWC in the DF and SF (Fig. 7). It can be presumed that the water moved upwards (to above 30 cm depth) toward the downward-propagating freezing front in the DF and SF. However, the final SWCs were lower than the initial SWCs except at 30 cm in SF. The initial SWC per depth in the DF was higher than in the SF ($p < 0.05$). The final total water contents in D15, D30 and S30 (Fig. 7) also differed significantly with respect to water movement and the location of the maximum water accumulation at the two sites ($p < 0.05$). At the same soil depth, the initial and final SWC differed significantly in DF and SF, except at S90 (Fig. 7). Moreover, the initial SWC was significantly greater than the final SWC at D15, D30 and S30 (Fig. 7).

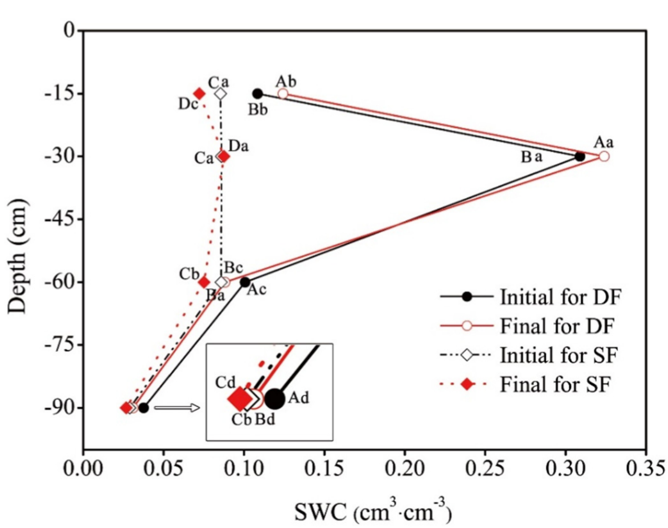

Fig. 7. The initial and final SWCs in the dam farmland (DF) and slope farmland (SF). Note: the different capital letters in one layer showed significant difference of $p < 0.05$; the different lower letters in one profile showed significant difference of $p < 0.05$.

These measurements indicate 2.02 mm and 1.73 mm changes in storage in the upper 0–15 cm and 15–30 cm layers for the DF and a 0.33 mm change in the storage in the 15–30 cm layer for the SF (Fig. 8). Thus, it is possible that the water in the dam farmland from the deeper zones with initially higher water content, in contrast to that in the slope farmland, moved upward toward the freezing front during the winter season giving the results that are shown in the final profiles. The difference in soil construction and slope gradient also resulted in differences in soil water movement.

4. Discussion

4.1. Effects of soil texture and initial SWC on the freeze–thaw process

The characteristics of soil freezing, and thawing may be attributed to differences in land use, soil texture and initial SWC (Iwata et al., 2008; Chen et al., 2013; Ala et al., 2016). The result of comparing with beginning time of freezing and thawing in this study are different from those of Ala et al. (2016) who found that sand dunes frozen and thawed earlier than interdune areas during the freeze–thaw process above depths of 100 cm. This situation was owing to the greater sand content and low SWC in sand dunes by Ala et al. (2016). The sand content differences between DF and SF range from 5.19% to 17.27% (Table 1). However, beginning time of freezing and thawing in DF were later than that in SF. Although the sand content of DF was greater than the SF, a higher SWC was observed for DF in this study (Table 1). Therefore, the

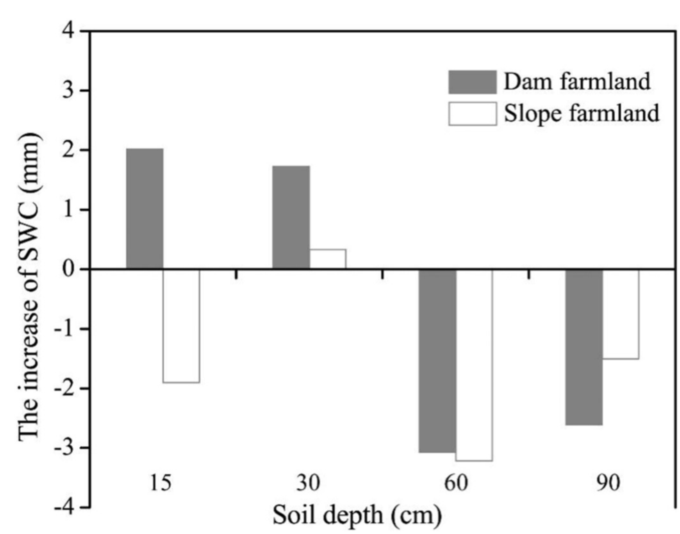

Fig. 8. Comparison of the SWC increase at each soil depth during the experimental period.

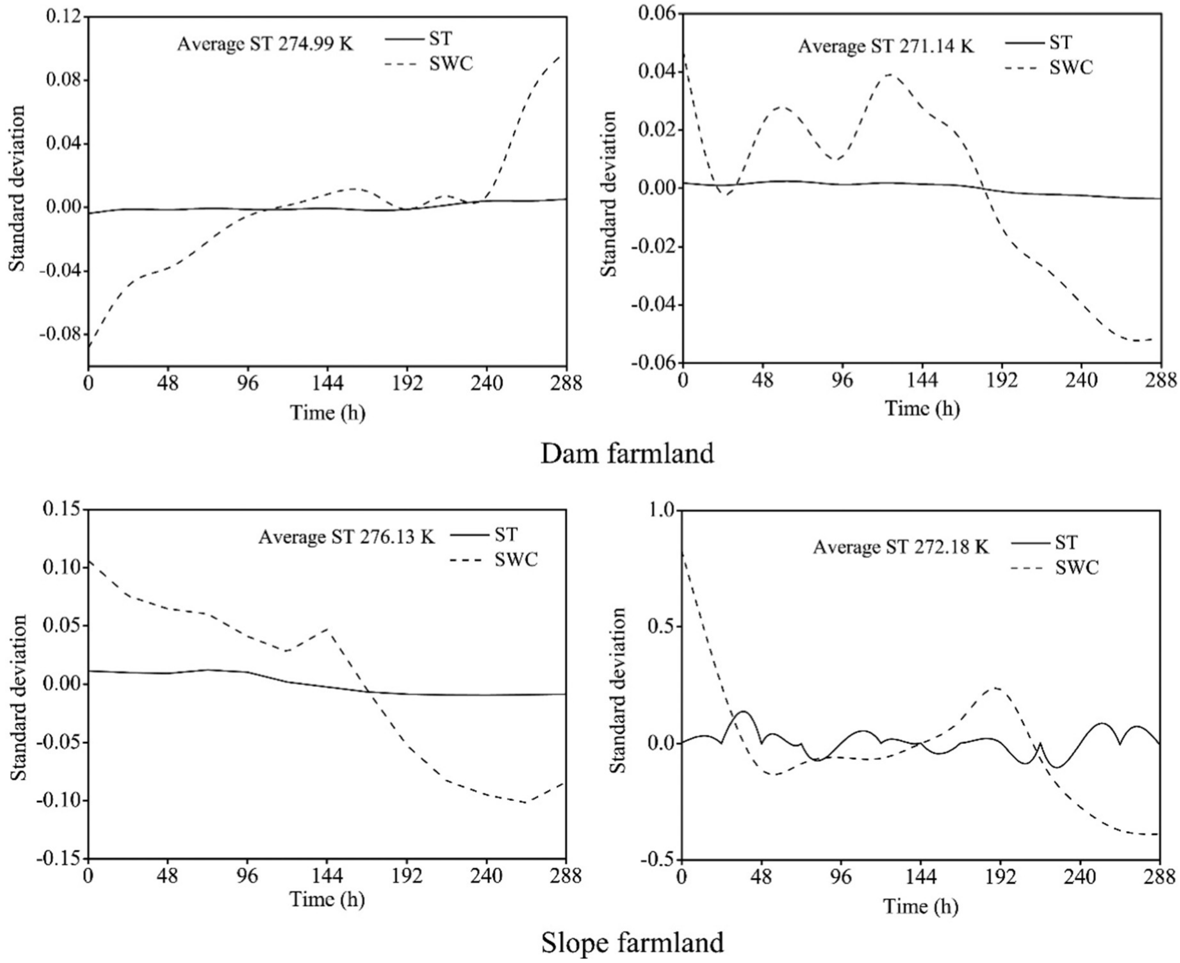

Fig. 9. The temperature-water content variation contrast in different average temperatures at D15 and S15.

SWC has greater affect than soil texture on the freeze–thaw process in this study.

The difference in SWC at each depth between DF and SF may have been due to runoff gathering area in which surface runoff is collected from a sloped surface, resulting in a higher SWC under DF. In addition, the soil particles gradually became coarser from top to bottom at each layer of the sedimentary cycle, with the bottom layer being composed of coarser soil particles and the top layer being clay, resulting in a water-repellent layer (Wei et al., 2016). It is difficult to transport water between sediment layers during the sedimentary cycle because of the water-repellent layer in DF (e.g., the initial SWC of 3.18 times at D30 comparing with at D15 and D60). Zhao et al. (2010) also reported that the layered soil hindered the downward water flow and water was accumulated above the interface between the two soils in DF. Therefore, the DF has a higher SWC than SF. Variation in water phase was strongly associated with the soil heat transported during the freeze-thaw processes. The soil thermal conductivity increased when soil froze and decreased during the thawing period because the thermal conductivity of ice is about four times that of liquid water (Campbell, 1985), which is confirmed that the rate of thawing was greater than the rate of freezing in this research. It also has been reported that different soil thermal conductivity in different land use mainly attributed to different SWC and higher SWC had lower soil thermal conductivity (Yi et al., 2014). Therefore, a larger quantity of heat was transported downward or upward during freezing and thawing in SF. Furthermore, thermal transfer efficiency parameter *a* could agree with above discussion

Table 5
The soil water content in per stage during the freeze-thaw process.

Soil depth	SWC ($cm^3 \cdot cm^{-3}$)						
	Initial	Freezing process (Mean)	Freezing point	Frozen process	Thawing point	Thawing process (Mean)	Final
D15	0.108 ± 0.0004bA	0.101 ± 0.008 bA	0.039	0.032 ± 0.007 bA	0.078	0.111 ± 0.011 bA	0.122 ± 0.002bA
D30	0.312 ± 0.002aA	0.311 ± 0.002 aA	0.153	0.077 ± 0.067 aA	0.309	0.318 ± 0.004 aA	0.323 ± 0.001aA
D60	0.098 ± 0.005bA	0.094 ± 0.005 cA	0.043	0.028 ± 0.005 bB	0.069	0.083 ± 0.007 cA	0.087 ± 0.001cA
D90	0.04 ± 0.0001cA	0.032 ± 0.007 dA	0.014	0.017 ± 0.004 cA	0.028	0.029 ± 0.001 dA	0.031 ± 0.0001dA
S15	0.085 ± 0.001aB	0.079 ± 0.006 aB	0.048	0.029 ± 0.014 cA	0.059	0.069 ± 0.003 cB	0.068 ± 0.004cB
S30	0.086 ± 0.0001aB	0.080 ± 0.012 aB	0.052	0.039 ± 0.007 aB	0.054	0.087 ± 0.002 aB	0.088 ± 0.0001aB
S60	0.085 ± 0.001aB	0.075 ± 0.009 bB	0.046	0.035 ± 0.006 bA	0.055	0.075 ± 0.001 bB	0.075 ± 0.001bB
S90	0.026 ± 0.001bB	0.029 ± 0.002 cB	0.014	0.018 ± 0.003 dA	0.021	0.028 ± 0.001 dA	0.027 ± 0.001 dB

Note: the different capital letters at the same layer in different land use showed significant difference of $p < 0.05$; the different lower letters in one profile showed significant difference of $p < 0.05$.

well. Consequently, the wetter conditions in the DF would delay the freezing and thawing processes, as indicated by other studies (Yang et al., 2003; Chen et al., 2013; Yi et al., 2014). These findings also indicate that the DF showed greater heat preservation than the SF. More importantly, the mean STs of DF at each soil depth were greater than at the corresponding soil depth in SF during the freezing and frozen stages (Table 2). However, the mean STs of SF at each soil depth were greater than at the corresponding soil depths in DF at the thawing stages because of the early melting of SF with greater soil thermal conductivity.

4.2. Soil water migration during the freeze-thaw process

At the beginning of the freezing process, the ST gradients were the main factor driving soil water migration, resulting in an upward flux of water from the deeper regions into the upper layer (Zhang et al., 2005; Yao et al., 2009; Chen et al., 2013). Subsequently, the water in the frozen soil profile is most likely redistributed toward the freezing front before the ST falls below the freezing point (Dirksen and Miller, 1966). Reduction in SWC of 0.02 and 0.037 $cm^3 \cdot cm^{-3}$ in DF and SF at 15 cm were agreement with a previous study in which 0.02 $cm^3 \cdot cm^{-3}$ reduction was observed at 15 cm (Chen et al., 2013). This reduction indicates that water potential gradients are required to cause such magnitudes of water flow toward the freezing front. Furthermore, water movement was accelerated upward in the soil profile because of freezing in the upper soil layer, which should be expected given the change in gradient because of changes in water potential.

Moreover, the soil freeze–thaw cycle may affect soil physical properties, which can subsequently impact the soil hydrology (Viklander, 1998; Yamazaki et al., 2006). A large pore pressure could be created by unfrozen water between warmer and colder regions, resulting in transport of water from large-pore spaces to smaller-pore spaces in soil (Dash et al., 1995; Chen et al., 2013). A reduction in the SWC was observed at different depths in both the DF and SF during the freezing process. The SWC was significantly correlated with ST ($p < 0.05$). The variation trend of SWC and ST was drawn at D15 and S15 depending on the standardized value of ST and SWC through the formula 2, when the average temperature was above the 273.15 K and below the 273.15 K, respectively. Changes in ST and SWC with time indicated that changes in ST always lagged behind those in SWC (Fig. 9). In addition, dramatic changes in ambient temperature affected the freezing process so that the SWC redistributed prior to be observed at the upper soil (Yao et al., 1996; Zhou et al., 2008; Chen et al., 2013).

Studies also have verified that the movement of soil water during the freeze–thaw process depended on the time series of initial and final water content at different depths (Nagare et al., 2012). During the freeze–thaw process, the deeper soil has little evaporation or water uptake from crop; therefore, the factor driving water migration have been the freezing effect. The SWC in the final profiles indicated that the SWC in deeper layers may migrate upward toward the freezing front during the freeze–thaw process. A 2.02 mm and 1.73 mm increase in SWC occurred in the upper 0–15 cm and 15–30 cm layer of the DF, respectively. However, an increase of only 0.33 mm in SWC occurred in S30 (Fig. 8). Melting water infiltrated from the surface to the deeper soil and water migrated from the deeper to upper soil depths, which resulted in increased SWC in the upper soil in the DF. In the SF, a portion of the melted surface water flow toward the bottom along the slope, a portion of melted surface water infiltrate along the soil profile and the water evaporated from the top soil in early spring, which lead to the SWC decreasing relative to the initial value at S15. As shown in Fig. 8, the increase in water in DF was higher than that of SF in the upper layer during the monitoring period, and this difference was due to infiltration and slope gradient. Moreover, the DF soil started to thaw later than SF soil at corresponding depths, which reduced the consumption of SWC by evaporation. Furthermore, the change in accumulative water was lower than the 3.93 mm change recorded in paddy fields (Chen et al., 2013) during winter. This large difference may have been caused by the heavy clay soil, which was significantly correlated with the soil water storage (Zhao et al., 2010; Xu et al., 2016). Moreover, previous researchers confirmed that more soil water accumulated in heavy clay than loess soil (Ala et al., 2016).

5. Conclusions

Field monitoring was conducted to evaluate the effect of freeze–thaw process on SWC and ST in two typical agricultural soils (DF and SF). The SWC in DF were greater than at the corresponding depth in the SF during freeze-thaw process. The DF starts to freeze and thaw later than the SF. Thermal transmission between soil and air in SF is greater than that in DF. During the freeze–thaw process, increasement 2.02 mm and 1.73 mm changes in storage in the upper 0–15 cm and 15–30 cm layers for the DF and a 0.33 mm change in the storage in the 15–30 cm layer for the SF. The initial SWC has greater impact on the freeze-thaw process than soil texture in this study. Moreover, the results presented herein will be useful to management of areas with seasonally frozen agricultural soil, especially in arid and semi-arid and regions that cannot be irrigated on the Loess Plateau.

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