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Soil Freeze-Thaw and Water Transport Characteristics Under Different Vegetation Types in Seasonal Freeze-Thaw Areas of the Loess Plateau

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In the arid and semi-arid regions of the Loess Plateau, seasonal freezing and thawing influence soil water movement, and water movement directly influences vegetation growth. However, currently, research with regard to freezing and thawing processes under various vegetation types and the mechanism of soil water movement is lacking. Therefore, the present study explored soil water migration characteristics of two typical vegetation types [arbor land (AL) and shrub land (SL)] on the Loess Plateau during seasonal freezing and thawing processes using bare land (BL) as a control. We used field measured data for hourly soil temperature (ST) and soil water content (SWC) at a depth of 100 cm below the soil surface from November 2017 to March 2018. Freezing and thawing process was divided into three stages based on ST change (initial freezing period, stable freezing period, and thawing period). Compared with previous studies in this area, ST is lower than expected, and SWC migration characteristics are also different. The results revealed that: 1) the maximum freezing depth of AL and SL was 60 cm, which was 30 cm less than that of BL. The freezing date of each soil layer in BL was the earliest and average ST value was the lowest. BL had the highest degree of freezing. The freezing of all soil layers in AL occurred at a later date than that of SL. ST and the minimum soil freezing temperatures were higher than those of SL, and the capacity of AL to resist freezing was higher; 2) the SWCs in AL and BL at depths of 0–10 cm and 10–30 cm decreased, whereas SWCs of AL and BL at a depth of 60 cm increased by 152 and 146%, respectively. The SWCs of SL at soil depths of 0–10 cm, 10–30 cm, and 30–60 cm increased by 46.3, 78.4 and 205%, respectively. The amount and distribution of soil moisture in SL were optimum when compared to those of AL and BL. The results of the present study could provide a scientific basis for vegetation restoration in arid and semi-arid areas of the Loess Plateau.

Keywords: soil temperature, soil water content, soil hydrothermal transport, natural freeze-thaw cycle, soil heat transfer

Abbreviations: AL, arbor land; SL, shrub land; BL, bare land; ST, soil temperature; SWC, soil water content; CV, coefficient of variance; R^2, the determination coefficient.

INTRODUCTION

Soil moisture is a key variable in the hydrological cycle that links precipitation, runoff, and groundwater (Sun et al., 2015; Wang et al., 2018b), and a key ecological factor that determines ecosystem functions and vegetation restoration (Pan et al., 2015; Wang et al., 2019c). Seasonal freezing and thawing influence the movement and distribution of soil moisture (Hu et al., 2013; Fu et al., 2018). Numerous studies have revealed that soil temperature (ST) is a primary driving force, which influences soil water movement during soil freeze-thaw cycles (Li et al., 2012; Wang et al., 2018a; Wang et al., 2019b). Variations in soil water potential caused by freezing of soil drive soil moisture from unfrozen areas to the freezing front (Li et al., 2013; Zhang et al., 2014; Yang and Wang., 2019), resulting in variations in soil moisture distribution (Wu et al., 2017; Lai et al., 2018; Lu et al., 2019). However, soil moisture distribution has had a direct impact on vegetation growth activities in recent years (Xiao et al., 2019; Frost et al., 2020), especially in the arid and semi-arid areas of the Loess Plateau, where long-term rainfall is insufficient and irrigation cannot be practiced (Yang et al., 2012; Cheng and Liu, 2014; Xiao et al., 2020). Therefore, studying soil freezing and thawing processes will enhance our understanding of soil moisture migration dynamics, and could have a guiding significance for the hydrological management of the study area.

Over the last few years, several local and international researchers have investigated the transport mechanisms of soil moisture in different regions and environments during freezing and thawing periods (Mohammed et al., 2013; Chen et al., 2016; Sun et al., 2011). The study areas were mainly distributed in Russia, Canada, the United States, and China, accounting for 50% of the global land area (Kruk et al., 2012; Wang et al., 2019a). A study by Nagare et al. (2011) revealed that freezing time and ground temperature conditions were influenced by soil water content (SWC) and soil texture. Soils with high SWCs are more likely to freeze under similar temperature conditions. During the freezing and thawing process of slope land, heat transfer efficiency between soil and air is higher than that of dam land; however, the amount of soil moisture migration and increase in dam land are greater than those of slope land (Wang et al., 2019a). Forests exhibit higher STs under freezing and thawing conditions, and their buffering capacity to variations in ST is greater than that of grasslands (Hu et al., 2013). In China, most of the current research regarding the effects of freezing and thawing is concentrated in the northeast mountainous areas, Inner Mongolia, and Qinghai-Tibetan Plateau where the freezing degree is severe (Liu et al., 2017; Guo et al., 2018; Zhang et al., 2019a). The freezing and thawing characteristics of the areas in terms of soil freezing days, number of freezing and thawing cycles, freezing temperature, and freezing depth are quite distinct from the seasonal freezing and thawing characteristics in areas of the Loess Plateau. Similarly, several researchers currently use the 24-h average ST (daily average ST) as a statistical unit, and a daily average ST below 0°C as a basis for determining the occurrence of soil freezing (Guo et al., 2011; Guo et al., 2020). However, the statistical method is not suitable for determining seasonal freezing and thawing in areas of the Loess Plateau. The statistical method does not take into account the freezing and thawing events with daily average temperatures greater than 0°C because the day and night temperature variations in the Loess Plateau area are extremely high in autumn and spring. In addition, soil freezing and thawing processes determined by the method, including freezing dates, freezing days, thawing dates, and thawing days, may be delayed or shortened.

Soil erosion is a major environmental challenge threatening the sustainable development of seasonal freeze-thaw areas on the Loess Plateau (Zhang et al., 2019b). Over the last few years, numerous soil and water conservation measures have been implemented in the Loess Plateau area, including terracing, construction of silt dams, farming management, and vegetation restoration (Li et al., 2013; Yu et al., 2020). Among the measures, vegetation restoration has been considered one of the most effective soil and water conservation measures (Guo et al., 2018). However, soil moisture is a key ecological factor that restricts vegetation restoration and sustainable development of agriculture and forestry in the area (Huang et al., 2012; Liu et al., 2012). Presently, numerous studies have been carried out with regard to the influence of vegetation restoration and returning farmland to forests on soil moisture characteristics in the Loess Plateau area. The studies have focused on the impact and response of rainy seasons, various vegetation growth periods or varying growth cycles on SWC (Zhou et al., 2015). Research regarding ST, moisture, and vegetation in winter has received relatively little attention due to the lack of rainfall in winter, low soil moisture transpiration, and limited vegetation growth in the Loess Plateau area. Soil water and heat transfer characteristics of different vegetation types under seasonal freezing and thawing conditions remain indeterminate. According to previous studies, we guess that different vegetation types have a certain buffering effect on freezing and thawing, and at the same time, they will also have different effects on the movement of soil moisture. Therefore, the present study investigated ST, SWC, and air temperature (AT) in two vegetation types and bare land (BL) to comprehensively elucidate the impacts of soil water and heat conditions under various vegetation types on the hydrological processes in frozen soil. The objectives of the present study were: 1) to investigate the freezing and thawing characteristics of BL and two vegetation types, 2) to monitor and assess the water redistribution process caused by freezing and thawing in BL and frozen soil in two vegetation types, and 3) to compare variations in soil moisture migration between two vegetation types during freezing and thawing periods.

MATERIALS AND METHODS

Overview of the Study Area

The study area is located in the Xindiangou Science and Technology Demonstration Park (E110°16′–E110°20′, N37°28′–N37°31′), a soil and water conservation scientific experimental research demonstration base in Suide County, Yulin City, Shaanxi Province, China. The research base is

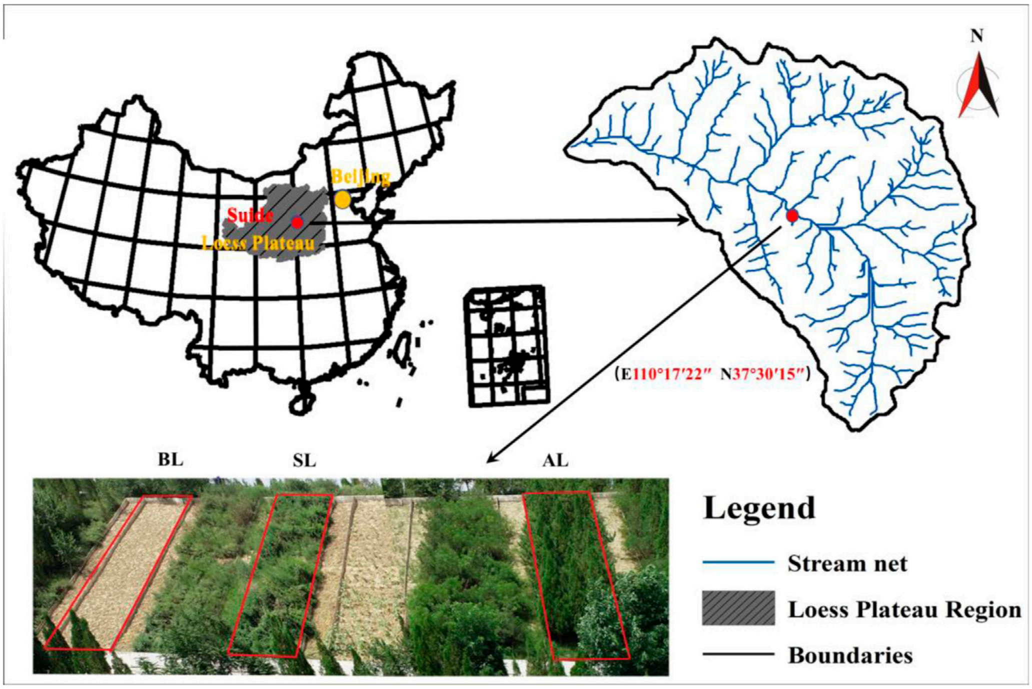

FIGURE 1 | Location map of the study area.

located in the Xindiangou Basin on the left bank of the middle reaches of the Wuding River, a tributary of the Yellow River, with an area of 1.44 km^2 and an altitude of 840–1,040 m (**Figure 1**). The climate of the area is continental temperate and semi-arid monsoon climate. The annual average temperature of the area is 9.7°C, with minimum and maximum temperatures of −27 and 39°C, respectively, and no well-defined freeze-thaw cycles. The average annual precipitation in the basin is 475.1 mm, and summer precipitation accounts for 64.4% of the total annual precipitation. The predominant soil type in the area is silty sandy loam and the vegetation type is temperate forest grassland. Artificial vegetation primarily includes poplar, white elm, dry willow, Chinese arborvitae, and Chinese pine. The shrub vegetation is dominated by yellow rose, korshinsk peashrub, sea buckthorn, and wild jujube.

Monitoring Experiment Layout

Artificial vegetation was selected as the research object. The selected tree species was *Platycladus orientalis* (family Cupressaceae) and the shrub species was *Caragana korshinskii* (family Fabaceae), which are the most commonly used species for vegetation restoration and construction in the Loess Plateau area, and *P. orientalis* is the dominant tree species in the watershed. To reduce the influence of external conditions such as topography and climate on the results of the present study, three runoff communities with similar slope length and slope direction (namely ***C.*** *korshinskii* shrub community, *P. orientalis* community, and BL community) were selected for positioning monitoring (**Figure 1**). We monitored and assessed the effects of seasonal freeze-thaw processes under various vegetation types.

ST and soil moisture (0–100 cm depth) were selected for monitoring due to the following reasons: 1) the root systems of most plants are distributed within the top 90 cm of the soil profile (Wang et al., 2018b); 2) the maximum freezing depth of soil within the monitoring area is 90 cm.

The AT monitoring data were obtained from the weather station (RX3000, United States), and ST and SWC were monitored using ET-100 intelligent soil moisture and temperature monitor (Symorui Environmental Technology Co., Ltd., XiAn, China). Thirty probes were placed in the middle of the three runoff plots (shrubs, trees, and BL). The probes were placed at soil depths of 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 cm. The soil begins to freeze when ST is below 0°C (273.15 K) and begins to melt when ST is above 0°C. The monitoring period was from November 11, 2017 to March 25, 2018 because seasonal freezing and thawing occur between the end of November and the end of March, and there was no rainfall during the monitoring period. ST and SWC at various soil depths were recorded every 60 min.

Statistical Analyses

The classification of soil freezing and thawing processes was based on hourly STs. Soil was considered frozen when the minimum ST was lower than 0°C. Similarly, soil was considered melted when the maximum ST was higher than 0°C. Freeze-thaw cycle refers to a phenomenon in which ST is above and below 0°C simultaneously in a day. Soil was considered to have entered a stable freezing period (a characteristic of the period is that the soil no longer undergoes freezing and thawing

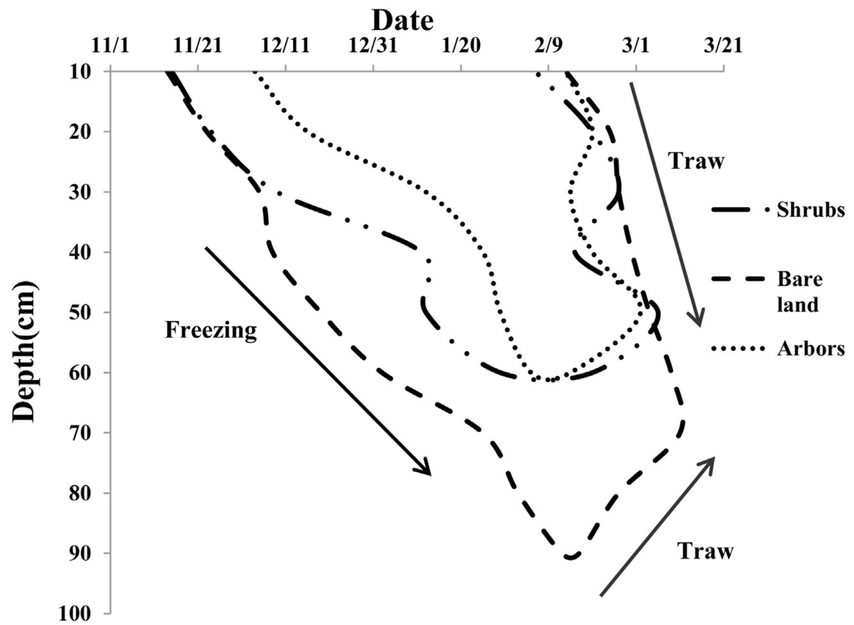

FIGURE 2 | Dynamic diagram of freezing and thawing depth.

cycles) when ST was constantly lower than 0°C. The improved statistical method could effectively reduce errors and enhance statistical accuracy.

Based on the measured ST data, soil freezing and thawing processes during the entire monitoring period was divided into three periods: initial freezing, complete freezing, and thawing periods. Initial freezing period refers to the unstable freezing period in which the soil melts during the day and freezes at night. Complete freezing period refers to the period when ST is constantly lower than 0°C in a stable freezing state for 24 h a day. Thawing period refers to the period when ST begins to be greater than 0°C to a state when ST is completely greater than 0°C.

The freezing rate is defined as the total number of days from the start of soil freezing to the time soil completely freezes at a certain depth; that is, the actual number of days in the initial period of freezing (Wang et al., 2019b).

$$v_{ifreeze} = \frac{1}{d_{iinnitial}} \tag{1}$$

where $V_{ifreeze}$ is the freezing rate of soil at a depth of *i (day)*, $d_{iinitial}$ is the total number of days in the initial freezing period at a depth of *i*.

Melting rate is defined as the number of days from the time soil at a certain depth begins to melt to the time frozen soil completely melts; that is, the actual number of days during the melting period.

$$v_{\mathrm{ithaw}} = \frac{1}{d_{imelting}} \tag{2}$$

where v_{ithaw} is the melting rate of soil at depth *i (day)*, $d_{imelting}$ is the total number of days during the melting period at a depth of *i*.

SPSS Statistics 16.0 (SPSS Inc, Chicago, IL, United States) was used to analyze the relationships among AT, ST, SWC, and soil depths in two vegetation types and BL. Levene's test was used to evaluate dynamic variations between ST and SWC during the monitoring period by measuring the coefficient of variation (CV) of soil profile. Regression analyses and plotting of graphs were performed using Origin 8.5 (OriginLab Corporation, Northampton, MA, United States).

RESULTS

Freezing Process of Soil Profile

The freezing date of arbor land [AL] soil from the surface layer to the deep layer occurred later than that of the corresponding soil layers in shrub land [SL] and [BL] (**Figures 2,3**; **Table 1**). The surface soil layers (0–10 cm) of BL, SL, and AL began to freeze on November 14, November 15, and December 4, 2017, respectively. The freezing dates of SL and AL delayed by one and 21 days, respectively when compared with that of BL (**Figure 2**; **Table 1**). The freezing rates of the three types of land were not significantly different at soil depths below 30 cm and the soil was completely frozen in only 1–2 days. The overall freezing rate of soil in SL was the lowest, followed by BL, while the freezing rate of soil in AL was the highest within the 10–30 cm soil layer. The maximum number of days of soil freezing was observed in the 20–30 cm soil layer, and followed the order of 85 days for BL > 77 days for SL > 63 days for AL. The minimum freezing STs were observed in the 0–10 cm soil layer and were as follows: −13.5°C in SL, −13.45°C in BL, and −8.3°C in AL. During the entire freeze-thaw process, ST in AL at a similar soil depth was the highest, and the soil freezing date was delayed (**Table 2**). The freezing depth of soil in BL was

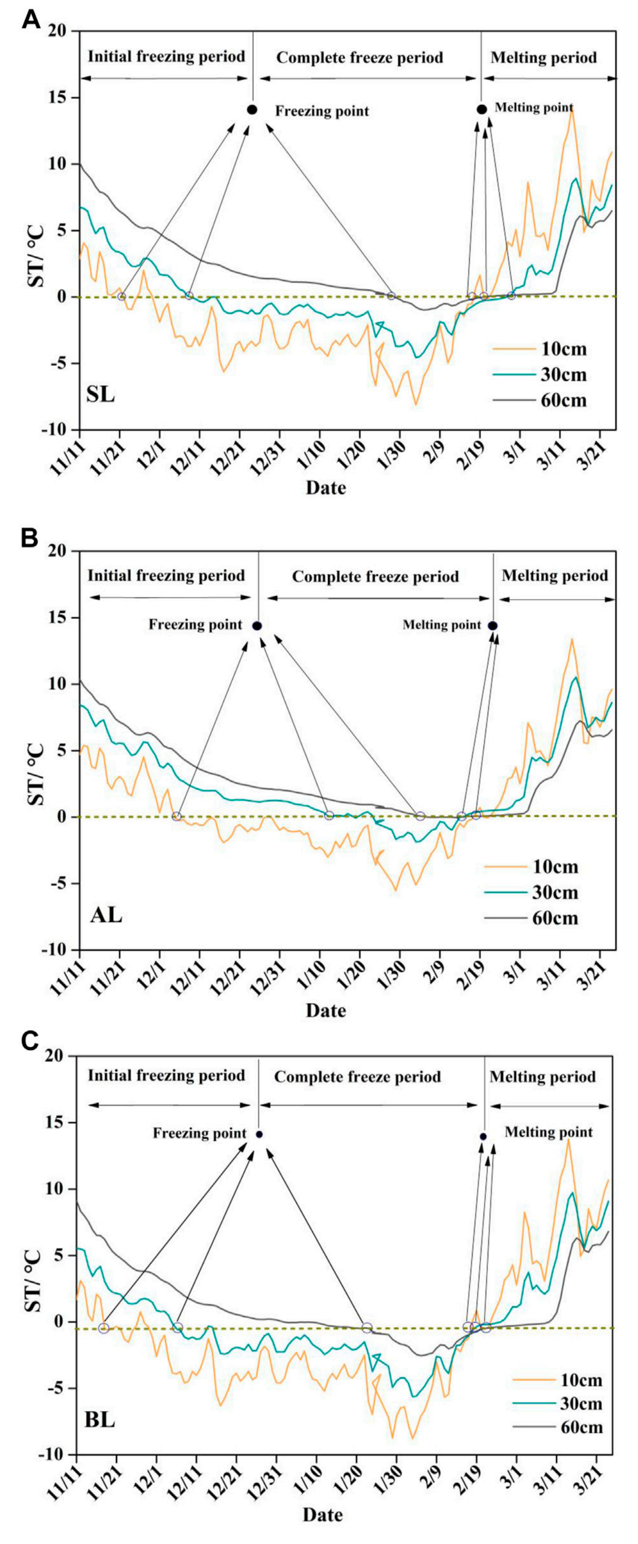

FIGURE 3 | ST dynamics of different land types **(A,B,C)**.

90 cm and that in AL and SL was 60 cm. The freezing depth of soil in BL was 30 cm greater than that of AL and SL (**Figure 2**).

CV was used to describe the degree of ST change. The CV value of ST in AL at the same soil depth was the lowest. Temperature variations in AL soil layers were similar. CV value decreased with increase in depth of the soil layers, and the fluctuating trend gradually plateaued (**Table 2**; **Figure 3**). The enclosed area formed by the intersection of the ST curve and the 0°C line was used as an evaluation criterion for the degree of soil freezing. The degree of soil freezing in BL was the highest, followed by SL, and the lowest degree of freezing was observed in AL (**Figure 3**).

Melting Process of Soil Profile

The soil freezing front moved downwards from the surface layer, in turn, resulting in a unidirectional soil freezing phenomenon. However, thawing of soil was two-way; that is, the top and deepest soil layers began to thaw first and they thawed in turn to the middle soil layers (**Figure 2**; **Table 1**). The thawing rate was similar to the freezing rate, and the thawing time of soil layers below 30 cm was 1–2 days. SL exhibited the lowest melting rate in soil layers with a surface depth of 10–20 cm, followed by BL, and AL, which exhibited the highest melting rate.

The maximum number of freeze-thaw days and the maximum number of freeze-thaw cycles were observed at a depth of 10 cm below the soil surface. The total number of freeze-thaw days observed in SL, BL, and AL were 105, 105, and 84 days, respectively, while the total number of freeze–thaw cycles observed in SL, BL, and AL were 51, 32, and 24 cycles, respectively.

Soil Water Redistribution During Freezing and Thawing

Statistical analyses were performed using SWC data for two vegetation types and BL throughout the monitoring period. The analyses results revealed that the average SWCs of the initial freeze-thaw period, the complete freezing period, and the thawing period in AL were significantly higher than those observed in SL and BL. The CV values of ST in AL were the lowest at various freeze-thaw stages and soil depths (**Table 2**; **Figure 4**). To comprehensively understand the variations in soil moisture migration at different stages during the monitoring period, SWCs at depths of 0–10 cm, 10–30 cm, and 30–60 cm were divided into initial water content (pre-freezing period), freezing period water content (freezing period), melting period water content (melting period), and final water content (average SWC seven days after the melting period). We observed that soil moisture content varied considerably at various soil depths and stages of the freezing period (**Figure 5**).

SWC in SL at soil depths of 0–10 cm, 10–30 cm, and 30–60 cm decreased by 46.5, 43.4, and 25.6%, respectively. SWC in AL at soil depths of 0–10 cm, 10–30 cm, and 30–60 cm decreased by 39, 49, and 5.3% respectively, and SWC in BL decreased by 56.7, 48.6, and 28.8%, respectively. Overall, BL exhibited the highest

TABLE 1 | Freeze-thaw characteristics of different land types.

	Depth (cm)	Initial freezing period	Number of days	Complete freezing period	Number of days	Thawing period	Number of days	The lowest temperature (°C)	The total number of days	FTC (cycles)
Shrubs	10	17/11/15–17/12/14	30	17/12/14–18/2/5	54	18/2/6–18/2/26	21	−13.05	106	51
	20	17/11/24–17/12/5	12	17/12/5–18/2/15	16	18/2/19–18/2/26	8	−9.813	95	20
	30	17/12/9–17/12/10	2	17/12/10–18/2/24	77	18/2/25–18/2/26	2	−6.125	80	4
	40	18/1/11–18/1/12	2	18/1/13–18/2/14	31	18/2/15–18/2/16	2	−3.06	25	4
	50	18/1/12–18/1/13	2	18/1/13–18/3/5	52	18/3/6–18/3/7	2	−2.5	55	4
	60	18/1/29–18/1/30	2	18/1/30–18/2/18	20	18/2/19–18/2/20	2	−1.063	23	4
Arbors	10	17/12/4–17/1215	12	17/12/16–18/2/12	59	18/2/13–18/2/25	13	−−8.3	84	24
	20	17/12/16–17/12/17	2	17/12/18–18/2/18	63	18/2/19–18/2/23	5	−5.75	70	4
	30	18/1/12–18/1/23	12	18/1/24–18/2/13	21	18/2/14–18/2/15	2	−2.63	33	10
	40	18/1/25–18/1/25	1	18/1/26–18/2/18	24	18/2/19–18/2/20	2	−1.625	25	2
	50	18/1/29–18/1/29	1	18/1/29–18/3/1	32	18/3/2–18/3/2	2	−0.625	34	2
	60	18/2/5–18/2/5	1	18/2/6–18/2/13	8	18/2/14–18/2/15	2	−0.063	9	2
Bare land	10	17/11/14–17/12/1	18	17/12/1–18/2/13	75	18/2/13–18/2/26	14	−13.375	105	32
	20	17/11/23–17/12/1	9	17/12/1–18/2/23	85	18/2/23–18/2/26	4	−10.56	95	13
	30	17/12/5–17/12/6	2	17/12/6–18/2/25	82	18/2/25–18/2/25	13	−7.33	83	3
	40	17/12/8–17/12/10	3	17/12/10–18//2/28	81	18/2/28–18/3/2	1	−5.188	85	6
	50	17/12/19–17/12/20	2	17/12/20–18/3/4	75	18/3/4–18/3/4	1	−3.56	76	3
	60	18/1/2–18/1/2	1	18/1/2–18/3/9	67	18/3/9–18/3/9	1	−2.637	67	2
	70	18/1/25–18/1/26	2	18/1/26–18/3/11	45	18/3/11–18/3/11	1	−1.57	46	3
	80	18/2/2–18/2/3	2	18/2/3–18/2/25	23	18/2/25–18/2/26	2	−0.19	25	4
	90	18/2/12–18/2/12	1	18/2/12–18/2/16	5	18/2/16–18/2/16	1	−0.063	5	2

decrease rates in SWC in each soil layer, followed by SL and AL, which exhibited the lowest decrease (**Figure 6**; **Table 2**). In addition, SWC from complete freezing to the end of thawing periods in SL exhibited the highest increase, followed by BL, and AL, which had the lowest SWC (**Figure 6**; **Table 2**).

The difference between the initial water content and the final water content was regarded as the amount of soil water migration at each soil depth during the freezing period. The SWCs in SL at a depth of 0–10 cm increased from 0.082 to 0.12 $cm^3\ cm^{-3}$ (an increase of 46.3%), increased from 0.125 to 0.223 $cm^3\ cm^{-3}$ (an increase of 78.4%) at a depth of 10–30 cm, and increased from 0.092 to 0.348 $cm^3\ cm^{-3}$ (an increase of 205%) at a depth of 30–60 cm. The SWCs in AL in the 0–10 cm soil layer increased from 0.123 to 0.126 $cm^3\ cm^{-3}$ (an increase of 2.4%), decreased from 0.136 to 0.119 $cm^3\ cm^{-3}$ (a decrease of 12.5%) at a depth of 10–30 cm, and increased from 0.142 to 0.358 $cm^3\ cm^{-3}$ (an increase of 152%) at a depth of 30–60 cm. The SWCs in BL in the 0–10 cm soil layer decreased from 0.118 to 0.074 $cm^3\ cm^{-3}$ (a decrease of 37%), decreased from 0.117 to 0.095 $cm^3\ cm^{-3}$ (a decrease of 19%) at a depth of 10–30 cm, and increased from 0.132 to 0.325 $cm^3\ cm^{-3}$ (an increase of 146%) at a depth of 30–60 cm. The maximum SWCs in AL and BL were observed at a depth of 30–60 cm, while SWC in SL increased at depths of 0–10 cm, 10–30 cm, and 30–60 cm (**Figure 6**).

Regression analyses results of ST and soil moisture in SL, AL, and BL revealed that the relationship between ST and soil moisture was linear. Based on soil depths of 0–10 cm, 10–30 cm, and 30–60 cm, SL R^2 values were 0.65, 0.68, and 0.60, respectively; AL R^2 values were 0.40, 0.44, and 0.45, respectively, and BL R^2 values were 0.66, 0.70, and 0.69, respectively (**Table 3**). BL exhibited the highest R^2 values at each soil depth, followed by SL and AL, which exhibited the lowest R^2 values.

The parameter "a" in the linear relationship equation, $Y = aX + b$ was defined as the transfer efficiency between ST and SWC. Based on the equation, parameter "a" of BL was the highest and the value of "a" in AL was the lowest (**Table 3**).

TABLE 2 | Changes in ST and SWC at each stage of the monitoring period.

Land type	Stage	Depth	ST (K)	CV	SWC	CV
Shrub land (SL)	Initial freezing period	10	272.29	0.0095	0.082	0.412
		30	273.04	0.008	0.125	0.055
		60	273.02	0.0004	0.092	0.089
	Complete freezing period	10	269.19	0.0097	0.044	0.145
		30	271.66	0.0043	0.071	0.2113
		60	272.6	0.001	0.068	0.075
	Thawing period	10	272.17	0.014	0.073	0.408
		30	273.13	0.0004	0.098	0.126
		60	275.07	0.0002	0.074	0.0136
Arbor land (AL)	Initial freezing period	10	272.88	0.0025	0.123	0.189
		30	273.23	0.001	0.136	0.087
		60	273.17	0.001	0.142	0.01
	Complete freezing period	10	271.06	0.0064	0.075	0.208
		30	272.16	0.002	0.068	0.056
		60	273.14	0.0001	0.134	0.011
	Thawing period	10	273.3073	0.0042	0.127	0.29
		30	273.173	0.0002	0.074	0.012
		60	273.1526	0.0001	0.135	0.009
Bare land (BL)	Initial freezing period	10	272.834	0.006	0.118	0.289
		30	272.83	0.0016	0.1165	0.166
		60	273.13	0.0001	0.132	0.012
	Complete freezing period	10	268.81	0.0095	0.051	0.147
		30	271.06	0.0052	0.0598	0.1495
		60	272.36	0.0028	0.0937	0.263
	Thawing period	10	272.923	0.0094	0.099	0.349
		30	273.1422	0.0002	0.083	0.042
		60	273.115	0.0002	0.176	0.025

DISCUSSION

The Influence of Vegetation on Soil Freezing and Thawing Processes

Seasonal soil freezing and thawing is not only influenced by climate, topography, soil texture and hydrology but also ground vegetation. Significant differences were observed in soil freezing and thawing processes and hydrothermal characteristics with regard to initial freezing time, freezing depth, ST and soil moisture content, and soil moisture migration due to the influence of vegetation types.

The freezing depth of BL soil was 30% greater those of SL and AL, while BL had the lowest ST. The degree of soil freezing in BL was significantly higher than those of AL and SL, which suggested that vegetation exerted a positive effect on soil resistance to freezing and thawing in winter. The ST of AL was greater than that of BL, and the freezing and thawing days were 22 days less than that of SL; the freezing time was delayed by 20 days when compared to BL and the maximum number of freeze-thaw cycles was 27-fold less than that of BL. In addition, the CV value of ST in AL was lower than that of SL during the entire monitoring period. Therefore, the degree of soil freezing in AL was significantly lower than that of SL, which suggested that AL exhibited superior freezing resistance capacity to SL, and the observation is consistent with the findings of Dulamsuren and Hauck. (2010). During seasonal freezing and thawing processes, AL soil maintains a higher temperature under similar conditions. The observation could be explained by the low shrub canopy, which considerably intercepts radiation from the Sun on the ground, in turn, decreasing ST. In addition, arbor forests can promote the growth of bryophytes, reduce wind speeds, and accumulate thick humus layers (Giraldo et al., 2009), which can enhance the maintenance of high STs in AL during winter. Numerous studies have revealed that the influence of vegetation on the thermal state of frozen soils is manifested in several ways. First, through shading in which the vegetation canopy reflects and absorbs most of the downward solar radiation, in turn, reducing its impact on the soil surface (Shur and Jorgenson, 2007; Chasmer et al., 2011). Second, the canopy structure and its physiological functions alter the meteorological conditions of the vegetation, which, in turn, influences heat and moisture exchange between the atmosphere and the soil. Finally, the vegetation canopy can also influence ST by intercepting snow and reducing wind speeds (Chang et al., 2014). Therefore, freezing and thawing processes can vary due to different vegetation types when other factors remain constant. Similarly, SWC was also a factor that should be taken into consideration. Studies have revealed that SWC has a significant impact on freezing and thawing processes (Cheng et al., 2018). The SWC in AL was significantly higher than that in SL and BL. The higher the SWC, the greater the specific heat capacity of the soil. When temperature increases or decreases, the amount of heat that is required to be absorbed and released is greater than that of soil with low water content (Wang et al., 2012), which also explains why the CV value of ST in AL during the entire monitoring period was relatively low.

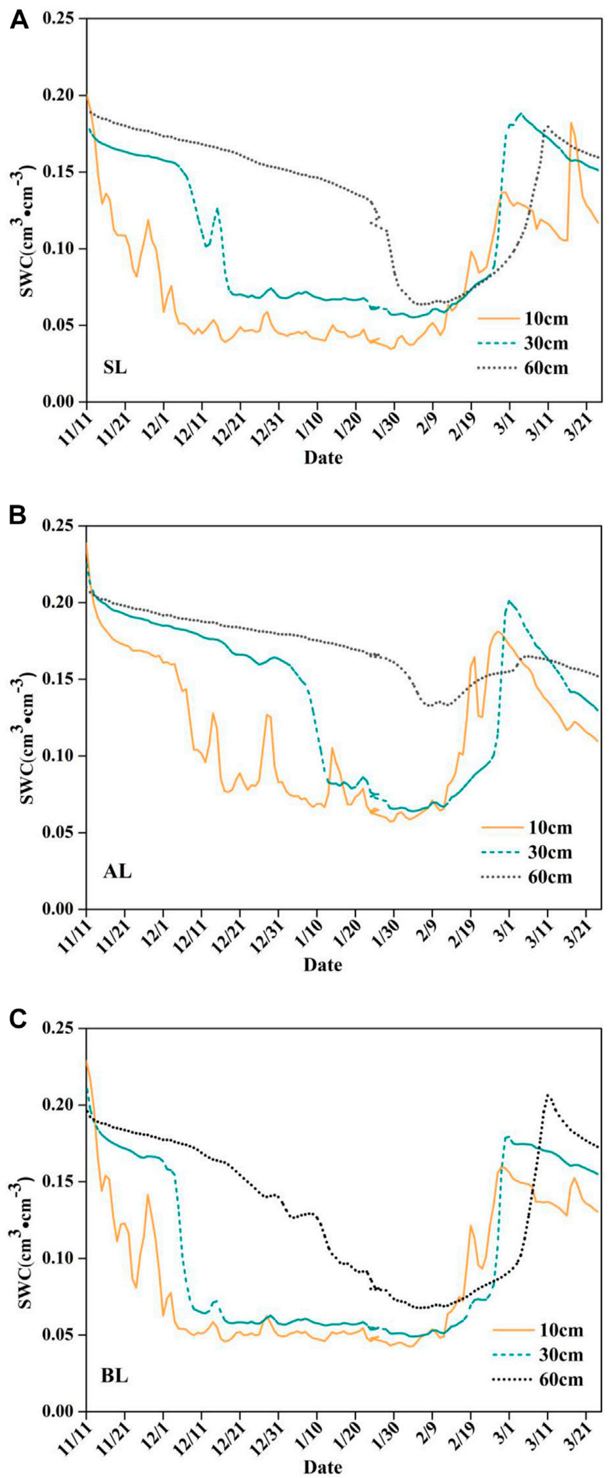

FIGURE 4 | SWC dynamics of different land types **(A,B,C)**.

Although the degree of soil freezing in BL was greater than that in SL, the numbers of freeze-thaw cycles in SL and BL soils were 51 and 32 cycles, respectively. The number of freeze-thaw cycles observed in SL was significantly greater than that in BL, which could be attributed to the variations in snow cover thickness. Several researchers have investigated the influence of snow cover on ST variations and established that snow as an insulator exerts a certain thermal insulation effect on the surface soils (Fu et al., 2018; Wang et al., 2020). The increase in snow cover thickness can reduce the freezing degree of the top soil (Hu et al., 2013). The shrub canopy partially intercepted snow; therefore, the thick bottom layer of snow on the SL surface was less than that on BL surface. The minimum frozen ST in the 0–10 cm soil layer of SL was lower than that in the 0–10 cm soil layer of BL (**Table 1**). The results indirectly demonstrate that increasing the depth of snow cover can reduce the freezing degree of surface soil.

Influence of Freezing and Thawing Processes on Water Movement

Variations in soil water potential caused by soil freezing drive soil moisture from unfrozen areas to the freezing front (Li et al., 2012). ST is a key driving factor in the movement of soil water, causing water to move upwards from deep soil layers (Chen et al., 2013). We conducted regression analyses to determine the relationship between ST and soil moisture in SL, AL, and BL, and established that the relationship between ST and soil moisture was linear. R^2 values at various soil depths varied in different soil types, and the values were influenced by the degree of soil freezing at corresponding depths. The degree of soil freezing at each depth in BL was the highest, with the highest R^2 value, followed by SL. The degree of soil freezing in each soil layer in AL was the lowest and the R^2 value was the lowest. Conversely, poor frost resistance or lack of vegetation cover results in an increase in the CV value of ST, which, in turn, increases the driving force of soil water transport and explains why the variations in ST and soil moisture in AL during the entire freezing period were the lowest.

We defined the equation parameter "a" in the linear relationship equation of ST and SWC ($Y = aX + b$) as the transfer efficiency between moisture and temperature. The value of the equation parameter "a" within the same soil layer in AL was the lowest, while "a" value within the same soil layer in BL was the highest (**Table 3**), which could be attributed to the variations in thermal conductivity of water at different phases. As a solid, thermal conductivity of ice is greater than that of liquid water. Therefore, the more the water freezes in frozen soil, the greater the thermal conductivity "a". The finding confirmed that the degree of soil freezing in AL was the lowest during the entire monitoring period, and the amount of soil water transport was the least. The difference between the final and the initial soil moisture contents can be used to estimate the amount of soil water transport. **Figure 5** illustrates the SWC variations in different soil layers in the two vegetation types and BL at various stages of the monitoring period. The amount of soil water transport in the 0–10 cm, 10–30 cm, and 30–60 cm soil layers in AL increased by 2.4%, decreased by 12.5%, and increased by 152%, respectively. The amount of soil water transport in the 0–10 cm, 10–30 cm, and 30–60 cm soil layers in BL decreased by 37%, decreased by 19%, and increased by 146%, respectively, while in SL, the amount of soil water transport increased by 46.3,

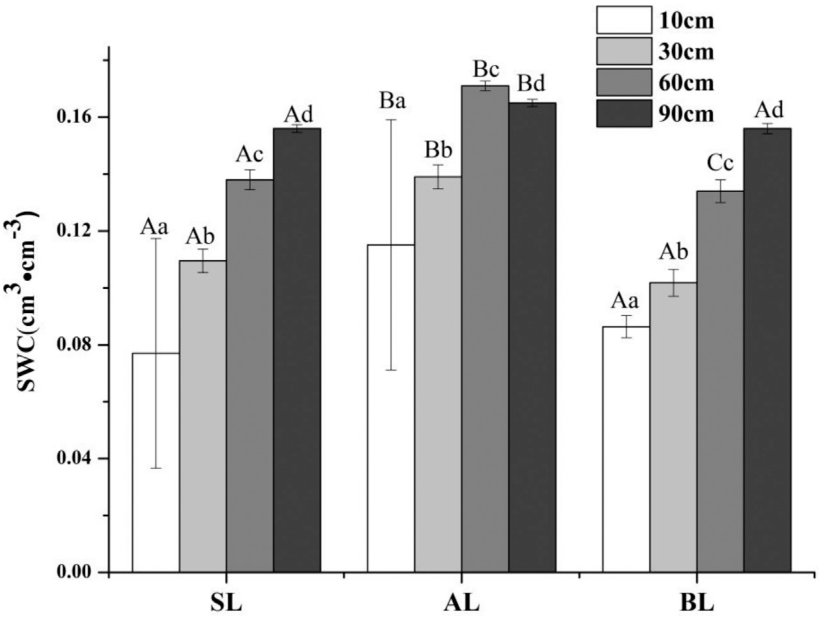

FIGURE 5 | Average soil water content of different vegetation types and depths during the monitoring period.

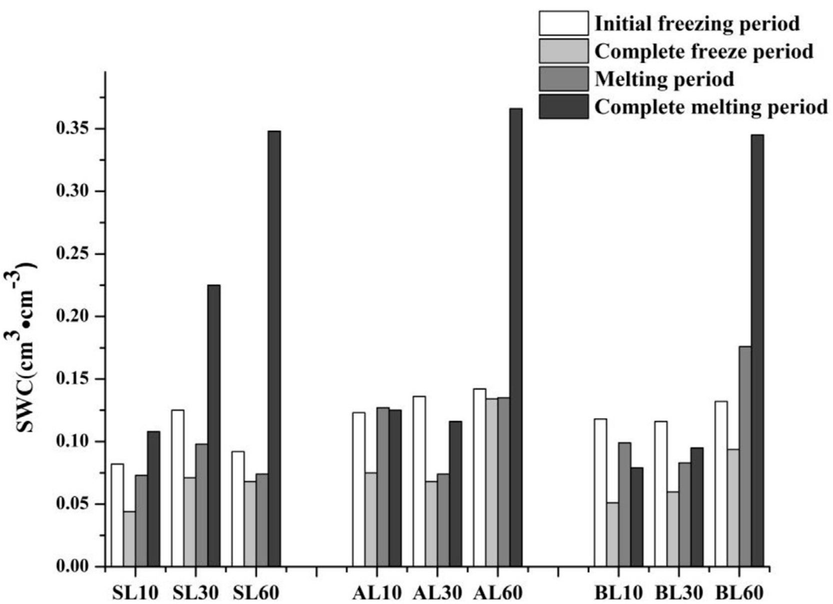

FIGURE 6 | SWC changes in different freezing stage.

78.4, and 205%, respectively. Generally, the maximum SWCs in AL and BL were observed at a depth of 60 cm, while SWC in SL increased in the 0–10 cm, 10–30 cm, and 30–60 cm soil layers. The observations could be explained by the following factors. First, the moisture in the soil profile to migrate to the 50–70 cm, since the soil layer of AL and BL thawed at a relatively later date. Second, the capacity of SL to resist freezing was relatively poor and the degree of freezing was more severe than that of AL. The CV value of SL ST was relatively higher, which makes SL to exhibit a greater driving force. Although the degree of soil freezing in BL was more severe, SL had a high number of root channels within the 30–60 cm soil layer when compared with BL, which had no vegetation. Studies have revealed that root systems can form water transport channels between various soil layers, and the rate of water movement through such channels is much faster than the flow velocity of liquid or gaseous phases of soil water (Wang et al., 2020). Therefore, SL exhibits optimum conditions for soil moisture migration.

TABLE 3 | Linear regression of soil moisture and temperature.

Depth (cm)/Land type	Shrub land (SL)		Arbor land (AL)		Bare land (BL)	
	Linear regression equation of SWC and ST	R^2	Linear regression equation of SWC and ST	R^2	Linear regression equation of SWC and ST	R^2
10	Y = 0.0069X + 0.0797	0.65	Y = 0.0072X + 0.108	0.40	Y = 0.0075X + 0.094	0.66
30	Y = 0.0125X + 0.1011	0.68	Y = 0.0104X + 0.113	0.44	Y = 0.0132X + 0.0999	0.70
60	Y = 0.0115X + 0.1121	0.60	Y = 0.0047X + 0.157	0.45	Y = 0.0135X + 0.01164	0.69

CONCLUSION

During freezing and thawing, BL soil froze to a depth of 90 cm, which was 30% greater than those of AL and SL. The maximum number of freeze-thaw cycles was observed at a depth of 10 cm in AL, SL, and BL, and the order of the number of freeze-thaw cycles was as follows: SL 51 cycles > BL 32 cycles > AL 24 cycles. The number of freeze-thaw days observed in AL was 84, which was 26% less than those of SL and BL. Average ST was greater in AL than in SL and BL. Overall, AL exhibited superior “insulation” and “buffering” effects. SWC in AL and BL was mainly concentrated near the 60 cm depth, and increased by 152 and 146%, respectively. SWC in SL increased by 46.3, 78.4, and 205% at depths of 0–10 cm, 10–30 cm, and 30–60 cm, respectively. Therefore, SL exhibited superior water transport characteristics. The results of the present study could provide a scientific basis for vegetation restoration in arid and semi-arid areas of the Loess Plateau.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

LB and LX conceived the main idea of this manuscript. ZL, GX, BM, and PL designed and performed the experiment. LB wrote the manuscript and all authors contributed to improving the manuscript.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.