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Dynamics and interactions of soil moisture and temperature during degradation and restoration of alpine swamp meadow on the Qinghai-Tibet plateau

Guankui Ma[1], Yongkun Zhang[2], Hang Li[3], Yongsheng Yang[4] and Runjie Li[1,2]*

[1]School of Geographical Science, Qinghai Normal University, Xining, China, [2]State Key Laboratory of Plateau Ecology and Agriculture, Qinghai University, Xining, China, [3]State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing, China, [4]Key Laboratory of Adaptation and Evolution Plateau Biota and Key Laboratory of Restoration Ecology in Cold Region of Qinghai Province, Northwest Institute of Plateau Biology, Chinese Academy of Sciences, Xining, China

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Yixin Wang,
Hohai University, China

*CORRESPONDENCE
Runjie Li,
✉ 648001297@qq.com

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Soil temperature (ST) and soil moisture (SM) are two fundamental land surface variables that directly or indirectly affect the processes and functions of alpine ecosystems. To clarify dynamics and interactions of SM and ST during degradation and restoration of alpine swamp meadow, four successional stages of alpine swamp meadow (non-degraded, NG; Kobresia humilis-dominated degraded, DG1; bare soil/weed-type degraded, DG2; artificially restored, RE) were selected to measure SM and ST at 10, 20 and 30 cm depths with 30-minute time interval in 2021 and 2022. Results showed that: (1) With the degradation and restoration of alpine swamp meadow, SM at 10 cm depth decreased at first, and then increased significantly ($p < 0.05$), which was attributed to the role of vegetation coverage and soil organic carbon in soil evaporation and water holding capacity, respectively; (2) ST at various depths did not respond to diverse degradation and restoration stages of alpine swamp meadow ($p > 0.05$); (3) The relationships between ST and SM varied with seasons, with positive and negative linear correlation in spring and summer, and positive exponential correlation in autumn and winter ($p < 0.01$). The study of SM and ST at different degradation and restoration stages of alpine swamp meadow will provide theoretical support for the research of related ecological processes and functions of such ecosystem.

KEYWORDS

soil moisture, soil temperature, grassland degradation, plant community, Qinghai-Tibet plateau

1 Introduction

Alpine swamp meadow, which is nutrient-rich and water-logged, exerts profound impacts on water conservation and carbon sequestration of the Qinghai-Tibet Plateau (QTP). With abundant water resources, it is critical to the QTP termed as the "Asian water tower". Moreover, alpine swamp meadow, which occupies 50% of the natural wetland of the QTP (Wei et al., 2015), plays important roles in affecting the carbon sequestration of the

QTP. Therefore, exploring the changes of alpine swamp meadows under different external conditions is of great significance for better understanding and predicting water conservation and carbon sink of the QTP (Wu et al., 2010).

Soil temperature (ST) and soil moisture (SM) are two fundamental land surface variables that directly or indirectly affect the processes and functions of terrestrial ecosystems, such as water conservation, carbon sequestration, nutrient cycling and availability, seed germination and plant growth (Li et al., 2013; Kerr and Ochsner, 2020; Milbau et al., 2009; Yin et al., 2023; Qian et al., 2023a; Qian et al., 2023b). To obtain higher seedling emergence rate and biomass, studies on the variations and linkages of ST and SM are mainly focused on agricultural and forestry ecosystems (Yin et al., 2023; Seneviratne et al., 2010; Kong et al., 2020). The two factors are similarly the key drivers affecting the process and function of alpine ecosystem (Aalto et al., 2013). However, little is known on the synergistic variations of ST and SM in grasslands (Li et al., 2013; Zhang and Li, 2017; Yang et al., 2019; Zhao et al., 2021), especially in alpine grasslands (Zhang and Li, 2017; Zhao et al., 2021). Li et al. compared ST and SM of shrub and grass patches, and reported that SM of the latter responded more rapidly to rainfall, and ST was higher in summer (Li et al., 2013). Zhang and Li explored the effects of grassland types on ST and SM, and proposed that Potentilla fruticosa shrub and Kobresia meadow had higher SM and lower ST than Achnatherum splendens steppe (Zhang and Li, 2017). Yang et al. analyzed the effect of vegetation coverage on ST and SM, and found that low vegetation coverage would affect ST and shorten the freezing period (Yang et al., 2019). Zhao et al. studied the changes of ST and SM in the alpine meadow of permafrost region, and reported that ST and SM had logarithmic and exponential relationships with soil depth and monthly rainfall, respectively (Zhao et al., 2021). Alpine swamp meadow is one of the main grassland types on the QTP (Zhao et al., 2005), which is of great importance for water conservation and carbon sequestration. Studies on the dynamics and interactions of ST and SM in alpine swamp meadows were extremely rare, and the synergistic variation mechanism of ST and SM was still unclear.

Alpine swamp meadow of QTP was significantly degraded under the combined effects of climate change, overgrazing and rodent outbreaks (Wu et al., 2010; He and Richards, 2015; Yang and Sun, 2021; Chen et al., 2017; Yuan et al., 2021; Bai et al., 2019; Wu et al., 2023; Pu et al., 2020; Wu et al., 2021; Ren et al., 2013). The degradation and restoration of such ecosystem will undoubtedly change SM and ST, which will eventually affect its service function (He and Richards, 2015). Previous studies on alpine swamp meadow mainly focused on grassland management measures such as grazing intensity and fencing (Wu et al., 2010; Yang and Sun, 2021) and global change factors including climate warming and nitrogen deposition (Chen et al., 2017; Yuan et al., 2021; Bai et al., 2019). Vegetation restoration was vital to degraded ecosystems (Wen et al., 2018; Zhao, 2023; Dai et al., 2020). The researches concerning the degradation and restoration process of alpine grassland mainly focused on the alpine meadow (Dai et al., 2021b; Li et al., 2022; Guo et al., 2020; Lin et al., 2022; Li et al., 2022; Dai et al., 2021a). Studies concerning the degradation and restoration of alpine swamp meadows were relatively few, mainly involving basic soil properties, soil carbon pool, soil nutrient cycling and plant community (Wu et al., 2023; Pu et al., 2020; Wu et al., 2021; Ren et al., 2013). However, no reports had been found on dynamics and interactions of ST and SM during degradation and restoration of alpine swamp meadow.

To better understand roles of SM and ST in ecological processes and functions of alpine swamp meadow, SM and ST were monitored at 30 min intervals at 10, 20 and 30 cm soil depths throughout 2021 and 2022 for natural, degraded and artificial alpine swamp meadows. The objectives of this study were as follows: (1) dynamics of SM and ST at different degradation and restoration stages of alpine swamp meadow; (2) interactions between SM and ST during degradation and restoration of alpine swamp meadow. We hypothesized that: (1) there were differences in ST and SM at diverse succession stages and soil layers of alpine swamp meadow; (2) The correlation between ST and SM in the alpine swamp meadow varied with succession stages, seasons, and soil depths.

2 Materials and methods

2.1 Sites

The study area is located in Dawu Town, Maqin County, Guoluo Tibetan Autonomous Prefecture, Qinghai Province, China (34°27′48″N, 100°12′49″E, with an average altitude of 3,730 m). The average annual temperature, precipitation and evaporation is −3.9°C, 528.8 mm and 2471.6 mm (1979–2018) (He et al., 2020), which belongs to the plateau continental semi-humid climates. The primary natural vegetation types are Alpine kobresia meadow and Alpine shrub meadow. Kobresia tibetica and Kobresia humilis are the dominant species in the alpine Kobresia meadow. Elymus nutans, Poa crymophila, Festuca sinensis are the main grass species in artificial grassland established in degraded grassland. The main soil type is silty clay, which can be classified as Gelic Cambisol (Lin et al., 2015). Due to the combined effects of overgrazing, climate change, rodent outbreaks and other factors, a large number of grasslands have been degraded, and artificial grasslands have been constructed for ecological restoration (Wen et al., 2018).

The natural vegetation type in the study site was non-degraded swamp meadow (NG) with Kobresia tibetica as the dominant species. Due to overgrazing, the non-degraded swamp meadow dominated by Kobresia tibetica changed into Kobresia humilis-dominated degraded swamp meadow (DG1) with the average height in plant community varying from 21.7 cm to 3.3 cm (Table 1). Pika in alpine regions prefer to live in low plant communities, which can effectively reduce the heat loss caused by the large amount of dew in the morning in high plant communities (Zhang et al., 2018). As a result, Pika outbreaks occurred in DG1, and their burrow-digging behavior resulted in numerous bare soil degraded patches (DG2) (Song et al., 2023). For DG2, the soil was bare in winter and spring, and occupied by weeds such as Elsholtzia densa and Cirsium souliei (Song et al., 2023) in summer and autumn. On DG2, artificially restored grassland (RE) could be established. Elymus nutans, Poa crymophila and Festuca sinensis were the three grass species in the RE.

TABLE 1 Vegetation attributes at various degradation and restoration stages of alpine swamp meadows.

Succession Stage[1]	Soil depth (cm)	LAI (m^2/m^2)	Dominant species	Cover (%)	Height (cm)	Aboveground biomass (g/m^2)	Root biomass (g/m^2)
ND	0–10	3.98 ± 0.85a[2]	Kobresia tibetica	95.0 ± 2.5a	21.7 ± 1.5a	553.87 ± 29.75a	1931.5 ± 107.5a
	10–20						442.5 ± 71.5b
	20–30						143.5 ± 30.5b
DG1	0–10	1.46 ± 0.16b	Kobresia humilis	91.0 ± 1.0a	3.3 ± 0.3b	254.31 ± 20.89c	1590.0 ± 227.0a
	10–20						960.5 ± 324.3a
	20–30						243.5 ± 14.5b
DG2	0–10	1.20 ± 0.28b	Elsholtzia densa Benth, Cirsium souliei	82.0 ± 3.5b	5.4 ± 1.0b	241.77 ± 37.43c	980.5 ± 398.5b
	10–20						452.0 ± 253.0b
	20–30						113.5 ± 2.5b
RE	0–10	2.96 ± 0.78a	Elymus nutans, Poa crymophila and Festuca sinensis	94.0 ± 1.5a	21.3 ± 2.1a	395.29 ± 27.76b	1680.5 ± 107.5a
	10–20						1087.5 ± 65.5a
	20–30						541.5 ± 82.5a

Note: 1 means the succession stage of alpine swamp meadow.

TABLE 2 Comparisons of soil properties at different succession stages of alpine swamp meadows.

Succession stage[1]	Depth (cm)	Soil particle content			BD[2] (g/cm^3)	TC[3] (g/kg)	SOC[4] (g/kg)	TN[5] (g/kg)
		Clay (%)	Silt (%)	Sand (%)				
ND	0–10	22.4 ± 2.3a[6]	68.6 ± 1.7a	9.0 ± 0.6a	0.7 ± 0.1c	79.5 ± 3.2a	73.9 ± 2.5a	6.8 ± 0.1a
	10–20	21.9 ± 2.3a	67.8 ± 2.3a	10.2 ± 0.5a	1.1 ± 0.1ab	35.9 ± 2.3cde	33.2 ± 2.2de	3.3 ± 0.2bc
	20–30	24.7 ± 1.8a	65.3 ± 1.2a	10.0 ± 0.6a	1.2 ± 0.1a	29.9 ± 4.8cde	24.9 ± 6.5de	2.6 ± 0.7bc
DG1	0–10	22.9 ± 0.2a	67.2 ± 0.3a	9.8 ± 0.5a	0.9 ± 0.1bc	40.19 ± 9.1c	35.9 ± 9.0cd	3.3 ± 0.7bcd
	10–20	21.2 ± 2.6a	65.9 ± 1.7a	12.8 ± 3.0a	1.1 ± 0.1ab	26.2 ± 10.7cde	23.6 ± 11.9de	2.1 ± 0.8c
	20–30	21.0 ± 1.9a	66.7 ± 3.3a	12.5 ± 3.1a	1.3 ± 0.1a	24.5 ± 7.0cd	22.5 ± 6.9de	2.0 ± 0.6bc
DG2	0–10	17.6 ± 1.3a	72.1 ± 1.0a	10.2 ± 0.8a	0.9 ± 0.1bc	55.7 ± 9.3b	51.8 ± 7.9bc	4.9 ± 0.6ab
	10–20	21.3 ± 1.7a	64.7 ± 0.3a	13.8 ± 1.5a	1.2 ± 0.1a	21.5 ± 0.8e	17.7 ± 3.1e	1.9 ± 0.3c
	20–30	20.6 ± 6.5a	67.5 ± 4.8a	11.7 ± 2.5a	1.2 ± 0.1a	23.5 ± 4.6e	19.0 ± 3.8de	1.9 ± 0.2c
RE	0–10	23.1 ± 2.9a	69.3 ± 2.6a	7.6 ± 0.2a	1.0 ± 0.1ab	62.0 ± 1.4b	57.2 ± 4.0b	5.2 ± 0.1ab
	10–20	34.6 ± 9.2a	59.2 ± 7.9a	6.1 ± 1.3a	1.1 ± 0.1ab	39.1 ± 7.5cb	32.9 ± 8.3de	3.3 ± 0.7bcd
	20–30	27.8 ± 7.2a	64.6 ± 7.7b	7.5 ± 2.8a	1.1 ± 0.1ab	29.4 ± 0.5cde	23.2 ± 1.0de	2.6 ± 0.1bc

Note: 1, 2, 3, 4 and 5 represent the succession stage of alpine swamp meadow, bulk density, soil total carbon, soil organic carbon and soil total nitrogen, respectively.

2.2 Experimental design and samplings

Four sites for automatic ST and SM monitoring were set up in the centers of the NG, DG1, DG2 and RE swamp meadows. Centered on each ST and SM monitoring site, three 20 m × 20 m plots were randomly established, and three 1 m × 1 m quadrats were randomly selected from each plot. In each quadrat, plant samples were collected to measure aboveground biomass, 0–10, 10–20 and 20–30 cm root biomass, coverage and height; soil samples were collected from 0–10, 10–20 and 20–30 cm soil layers to measure soil bulk density, soil particle composition, soil organic carbon, and soil total nitrogen.

2.3 Monitoring of soil moisture, soil temperature, precipitation and air temperature

ST and SM were monitored in the NG, DG1, DG2 and RE swamp meadows during 2021 and 2022. Monitoring equipment was ZL6

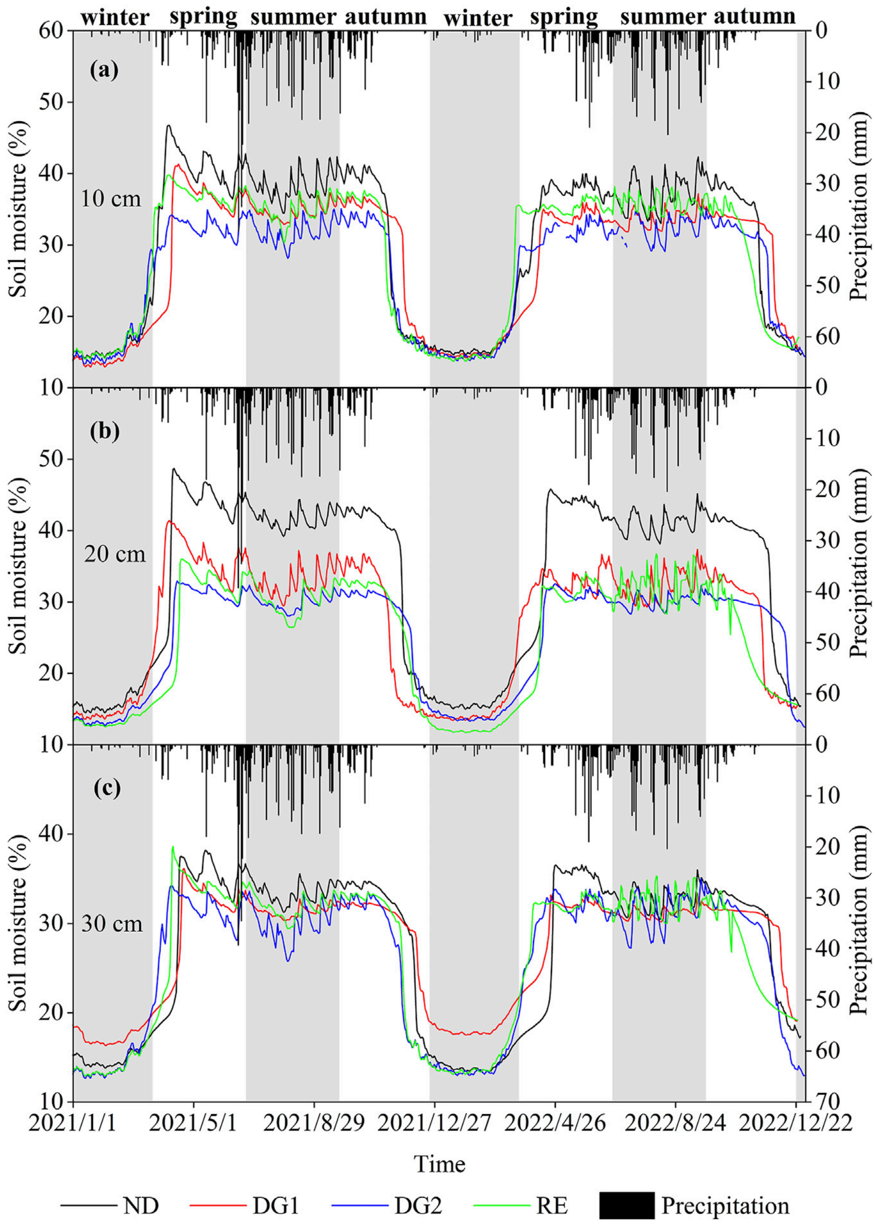

FIGURE 1
Soil moisture dynamics at different soil depths and succession stages of alpine swamp meadow. Notes. NG, DG1, DG2 and RE represented non-degraded swamp meadow, Kobresia humilis-type and bare soil/weed-type degraded alpine swamp meadow, artificially restored swamp meadow, respectively. **(A–C)** represent soil moisture at depths of 10, 20 and 30 cm, respectively.

(Decagon Devices, Inc., Washington, USA); measuring depths were 10, 20 and 30 cm; time interval was 30 min. Air temperature and precipitation were obtained from the National Meteorological Station of Maqin County, which was 500 m away from the studied plot.

2.4 Determination of soil properties and vegetation characteristics

The soil particle composition included clay (<2 μm), silt (20–2 μm) and sand (2000–20 μm), which were gauged and analyzed by laser diffractometer Mastersizer 3,000. Soil bulk density was measured by the gravimetric method. Soil organic carbon and total carbon were measured by elemental analyzer. All plants in the quadrats were harvested and stored in strong paper bags for measuring aboveground biomass. The vegetation height and coverage of the quadrat were measured *in situ*. The root biomass was obtained with a root drill, then washed and oven-dried. After scanning the mature and complete leaves randomly selected by the scanner, the leaf area (LAI) was calculated using ImageJ software.

2.5 Statistical analysis

One-way ANOVAs were carried out to investigate the differences of SM, ST, soil properties and vegetation attributes at

TABLE 3 Descriptive statistics of seasonal variations of soil moisture at different succession stages of alpine swamp meadow.

Soil depth (cm)	Succession stage	Season			
		Spring	Summer	Autumn	Winter
0–10	ND	38.1 ± 4.6a^2	37.9 ± 2.2b	29.3 ± 10.3ab	16.0 ± 2.1abc
	DG1	32.7 ± 6.2cd	34.2 ± 1.3cd	29.6 ± 7.5ab	15.1 ± 1.6bcd
	DG2	31.8 ± 1.6cd	31.9 ± 2.1efg	26.9 ± 7.5ab	15.9 ± 3.3abc
	RE	36.1 ± 1.5ab	35.5 ± 1.5c	26.5 ± 9.0ab	16.5 ± 4.2ab
10–20	ND	39.6 ± 8.6a	41.4 ± 1.5a	34.6 ± 10.1a	16.3 ± 1.7ab
	DG1	34.1 ± 3.4bc	32.7 ± 2.0e	26.2 ± 8.5ab	15.1 ± 2.2bcd
	DG2	28.5 ± 5.0e	30.0 ± 1.0h	27.9 ± 4.9ab	14.1 ± 1.1cd
	RE	28.6 ± 6.6e	31.2 ± 2.3fgh	25.4 ± 6.9b	13.0 ± 1.0d
20–30	ND	30.4 ± 7.6de	33.2 ± 1.3de	29.7 ± 5.9ab	14.7 ± 1.1bcd
	DG1	29.6 ± 4.6de	31.3 ± 0.7fgh	29.6 ± 3.8ab	18.0 ± 1.1a
	DG2	30.8 ± 3.0de	30.7 ± 2.1gh	27.1 ± 6.7ab	14.3 ± 1.7bcd
	RE	31.4 ± 4.3cde	32.2 ± 1.4ef	26.7 ± 6.4ab	14.4 ± 1.7bcd

diverse depths among various degradation and restoration stages of alpine swamp meadow. Tukey's HSD for multiple comparisons was used to evaluate differences for the above properties at a significance level of $\alpha = 0.05$. Pearson correlation was used to examine the relationships of SM, ST and other properties. All the above-mentioned statistics were conducted with SPSS 20.0 (IBM SPSS). All the figures were plotted by Origin 2021.

3 Results

3.1 Soil properties

Comparisons of soil properties at different succession stages of alpine swamp meadows were summarized in Table 2. Soil bulk density (Bd) did not respond to soil depth ($p > 0.05$) from 10–20 cm (1.1 g/cm^3) to 20–30 cm soil layer (1.2 g/cm^3) in non-degraded swamp meadow; the average Bd in 0–10 cm layer (0.7 g/cm^3) was significantly lower than that in 10–30 cm sub-surface layer ($p < 0.05$). For the 10–20 cm and 20–30 cm soil layers, no significant difference existed in Bd between the NG and the DG1, DG2 ($p > 0.05$); the average Bd in the 0–10 cm layer significantly increased ($p < 0.05$) from 0.7 g/cm^3 in NG to 1.1 g/cm^3 in DG1 and 1.2 g/cm^3 in DG2.

For the 10–20 cm and 20–30 cm soil layers, the NG had the highest soil organic carbon (SOC) and total carbon (TC) contents ($p < 0.05$); the NG in 0–10 cm soil layer had the more SOC and TC contents than RE (Table 2, $p < 0.05$). The SOC and TC content in the 10–20 and 20–30 cm layers decreased slightly, but did not vary with grassland degradation in the swamp meadow (Table 2, $p > 0.05$); SOC and TC in the 0–10 cm surface layer of NG were significantly higher than those in the DG1 and DG2 (Table 2, $p < 0.05$). The average total nitrogen (TN) content in the 0–10 cm layer of NG, RE, DG1, DG2 were measured to be 6.8, 5.2, 3.3, and 4.9 g/kg, respectively. Compared with the NG, artificial restoration of degraded swamp meadows did not enhance TN contents of 0–10 cm soil layers ($p > 0.05$); significant difference in TN contents of 0–10 cm surface soil were observed between the NG and the DG1, DG2 ($p < 0.05$).

3.2 Soil moisture dynamics

Time series of soil moisture (SM) dynamics at diverse soil depths (10, 20 and 30 cm) and succession stages (NG, DG1, DG2 and RE) of alpine swamp meadow were presented in Figure 1. The SM fluctuations at various depths for the four succession stages of the alpine swamp meadow were similar, and responded to precipitation rapidly (Figure 1). Especially, SM at depth of 10 cm was more sensitive and intense to rainfall pulses than that at depth of 30 cm (Figures 1A, C).

Taking SM dynamics in 2021 as an instance, in winter from January 1 to March 15, soil liquid water content (LSWC) was almost stable between 14% and 18%; in spring from March 16 to April 10, LSWC rose quickly, with an increment of 20%–25%; during the growing season from April 11 to October 22, LSWC fluctuated between 30%–40%; in autumn, from 23 October to 22 December, LSWC decreased dramatically, with a reduction by 15%–25% (Figure 1). In the growing season from April to October, the averaged SM values of NG was significantly higher than DG1 and DG2 at 10, 20 cm depths (Table 3; Figure 1, $p < 0.05$). The averaged SM values of RE at 10 cm depth was significantly higher than that of DG1 and DG2 in spring and summer (Table 3; Figure 1A, $p < 0.01$). At a depth of 20 cm, the SM values of NG was significantly higher than that of the other swamp meadow types in the growing season from April to October (Figure 1B; Table 3, $p < 0.01$). SM of DG1 was as highest as 19.5% at 30 cm depth in winter than that of other swamp meadow types (Figure 1C; Table 3, $p < 0.01$).

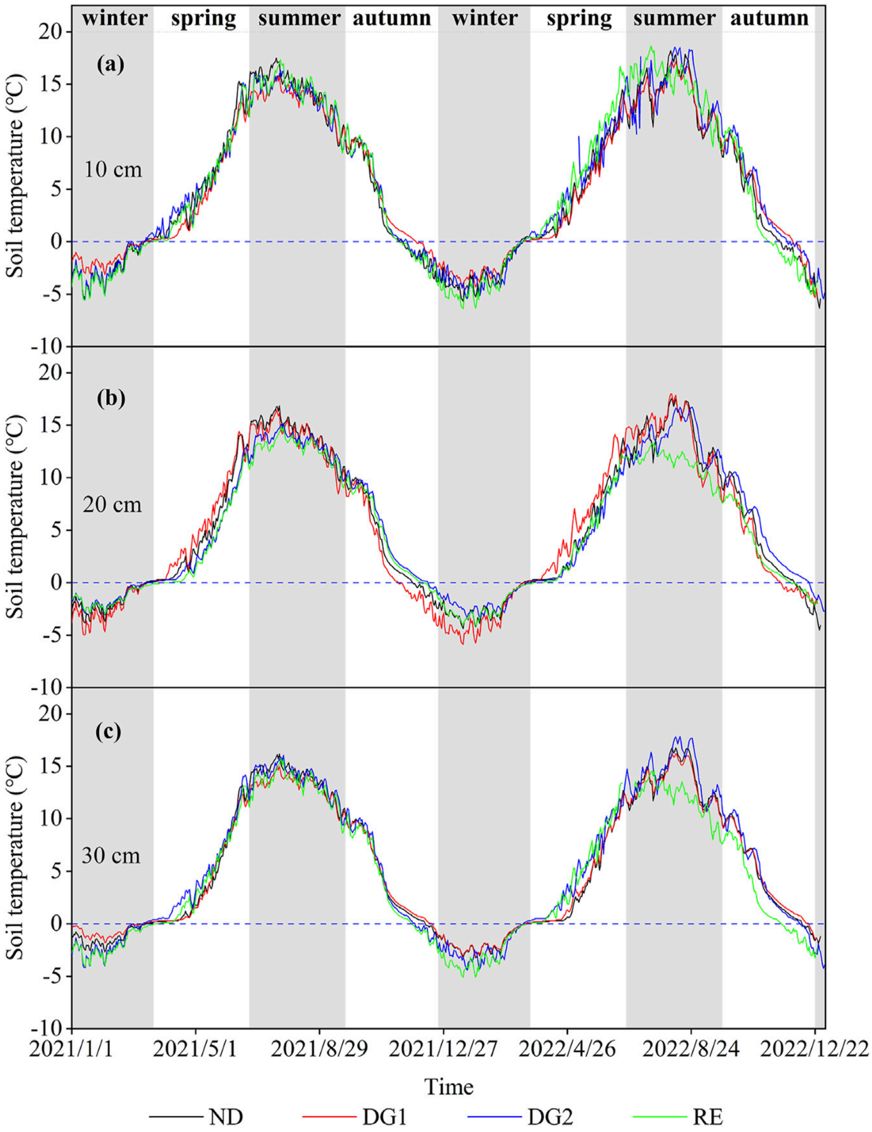

FIGURE 2
Soil temperature dynamics at various soil depths and succession stages of alpine swamp meadow. Notes. NG, DG1, DG2 and RE represented non-degraded swamp meadow, Kobresia humilis-type and bare soil/weed-type degraded alpine swamp meadow, artificially restored swamp meadow, respectively. **(A–C)** represent soil temperature at depths of 10, 20 and 30 cm, respectively.

3.3 Soil temperature dynamics

The changes of soil temperature (ST) in alpine swamp meadow throughout the year is a unimodal curve with normal distribution (Figure 2). The annual maximum ST occurred on 15 July 2021 (17.3°C) and 12 July 2022 (18.1°C). The annual minimum ST values were −5.5°C and −6.25°C on 21 January 2021 and 6 February 2022. In spring from March 21 to 22 June 2021, no significant differences in ST were observed between different swamp meadow types at depths of 10 cm and 30 cm; DG1 at 20 cm depth had the highest ST value than other swamp meadow types. In summer from June 23 to 21 September 2021, ST at the three soil depths did not vary with the four types of swamp meadows. In the first half of autumn (from September 23 to October 22), there was no significant difference in ST among different types of swamp meadows; During the second half of the autumn (from October 23 to December 22), DG1 at 10 cm and 30 cm depths had the highest ST, DG1 at 20 cm depth had the lowest ST, and DG2 had the highest ST. In winter from 23 December 2021 to 21 March 2022, DG1 at 10, 30 cm depths had the highest ST; DG1 at 20 cm depth had the lowest ST, while DG2 had the highest ST.

Compared with the deep soil layer, ST of surface layer (0–10 cm) had the highest correlation with air temperature, which was observed for swamp meadow types except DG2 (Figure 3). For NG, correlation coefficients between ST and air temperature decreased with the increasing depth, being 0.87, 0.83 and 0.79, respectively (Figure 3).

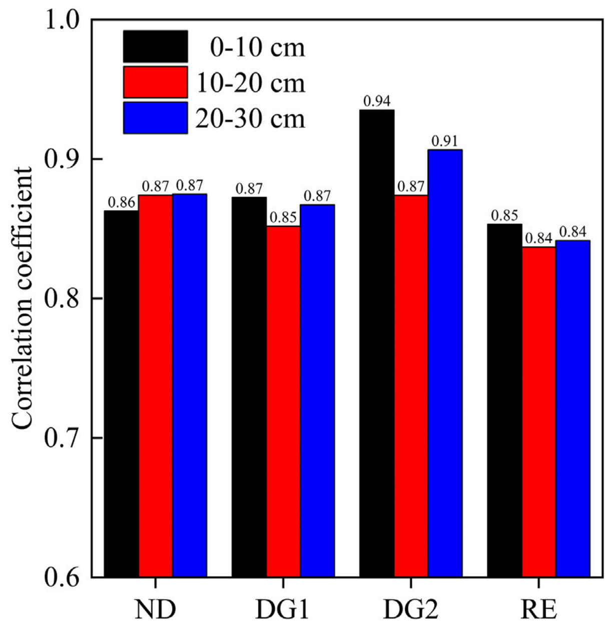

FIGURE 3
The correlation between soil temperature and air temperature varied with the degradation and restoration stages of alpine swamp meadow. Notes. NG, DG1, DG2 and RE represented non-degraded swamp meadow, Kobresia humilis-type and bare soil/weed-type degraded alpine swamp meadow, artificially restored swamp meadow, respectively.

3.4 Interactions between soil moisture and temperature

In spring, summer, autumn and winter, determination coefficients of the fitting curves between SM and ST in alpine swamp meadow varied from 0.005–0.306, 0.039–0.287, 0.741–0.907 and 0.897–0.99, respectively (Figure 4). In 0–10 cm soil layer, the average determination coefficients of the fitting curve between SM and ST in spring, summer, autumn and winter were 0.10, 0.12, 0.78 and 0.6, respectively. In 10–20 cm soil layer, the corresponding determination coefficients significantly increased to 0.20, 0.18, 0.84 and 0.97, respectively. In winter, the correlation between SM and ST was extremely high, and the lowest correlation was observed in the 0–10 cm soil layer of the DG2 stage (Figure 4A).

As ST was 0°C in spring, soil thawing continued to occur, resulting in an increase of soil liquid water (LSWC) to 30%–40% for each depth (Figure 4). As ST rised from 0°C to near 16°C, SM remained almost stable at 30%–40% due to the dynamic balance between rainfall and evapotranspiration (Figure 4). SM reduced with the increases of ST in summer (Figure 4, $p < 0.01$). In autumn, with the decreasing ST from 12°C to 0°C, LSWC in 0–10 cm and 10–20 cm soil layers of non-degraded swamp meadow was maintained at about 40%. In other types of swamp meadows, LSWC at different depths was typically stable between 30%–35%. When ST dropped to 0°C in autumn, soil freezing occurred and LSWC was continuously reduced, eventually decreasing to a LSWC of 15%–20% (Figure 4). With ST decreasing from 0°C to −2°C in winter, LSWC decreased slowly, with a reduction of 2%–5%. When ST in winter was below −2°C, LSWC did not decrease with the reduced ST, and basically maintained between 14%–15%.

4 Discussion

4.1 Soil properties, moisture and temperature

Soil Bd significantly increased, while SOC, TC and TN significantly decreased with soil depth (p < 0.05) (Table 2). This result indicated that soil bulk density, soil organic carbon, total carbon, and total nitrogen were all depth-dependent. It could be attributed to that the external input of soil carbon and nitrogen (roots and aboveground biomass) decreased with soil depth (Table 1), which in turn reduced soil porosity and enlarged soil Bd. Compared with the NG, SOC, TC and TN of DG1 and DG2 significantly decreased (p < 0.05) (Table 2). Such decrease was due to the significant reduction of aboveground and belowground biomass with swamp meadow degradation (p < 0.05) (Table 1).

In the initial stage of spring, soil liquid water content (LSWC) increased rapidly (Figure 1). The phenomenon of huge rise in LSWC was similarly exhibited in results of (Li et al., 2013; Yang et al., 2019). The reason for the increasing LSWC was that the sum of LSWC generated by permafrost thawing and SWC from rainfall infiltration in early spring was much higher than water consumption for plant growth. In contrast, SWC decreased quickly in Mid-Autumn (Figure 1). This was mainly ascribed to the superimposed effect of vegetation water consumption and the reduction of LSWC from freezing during this period.

SWC in each soil layer was significantly higher for non-degraded swamp meadow (NG) than degraded swamp meadow (including DG1 and DG2) (Figure 1; Table 3, p < 0.05). This result was consistent with the conclusion of Yang et al. (2019). The lower SWC in degraded swamp meadows was because grassland degradation led to coarse soil, low Bd (Table 2) (Tian et al., 2017), and reduced vegetation coverage (Yang et al., 2019; Tian et al., 2017), which in turn increased soil evaporation and reduced SWC.

In summer, SWC at 20 cm depth was significantly higher in the non-degraded swamp meadow than in the other swamp meadow types (Figure 1B; Table 3, p < 0.05). The results were consistent with a prior study made by Zhang and Li in the alpine ecosystems including Achnatherum splendens steppe and Potentilla fruticosa shrub (Zhang and Li, 2017). The higher SWC in this layer in summer might be due to a sharp reduction in root biomass of this soil layer compared with the surface (Table 1), resulting in a decrease in root water uptake and an increase in SWC. SWC in the DG1 at a depth of 30 cm was significantly higher than that in other swamp meadow types in winter (Figure 1C; Table 3, p < 0.05). This was because soil temperatures were highest at a depth of 30 cm in the DG1 in winter (Figure 2C), bringing with it more liquid water content.

Soil temperature (ST)in the surface layer (0–10 cm) had the highest correlation with air temperature compared to the deep soil layer (Figure 3), which was reflected in all swamp meadow types except DG2. This indicated that the effect of air temperature on soil temperature was depth-dependent.

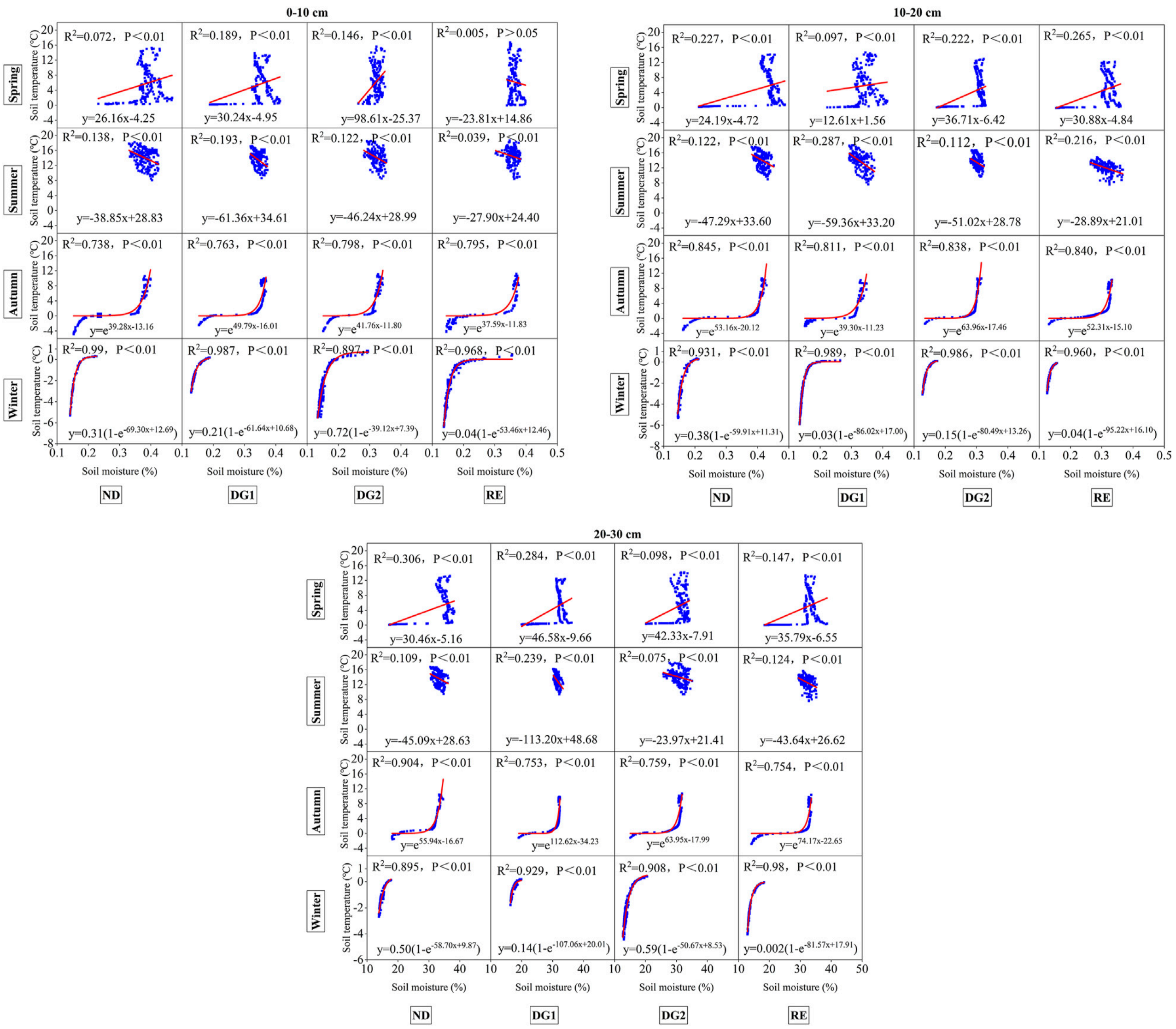

FIGURE 4
The correlation between soil temperature and soil moisture varied with the degradation and restoration stages of alpine swamp meadow. Notes. NG, DG1, DG2 and RE represented non-degraded swamp meadow, Kobresia humilis-type and bare soil/weed-type degraded alpine swamp meadow, artificially restored swamp meadow, respectively.

According to Figure 2, in the warming stage of spring, compared with other swamp meadow types, ST of degraded swamp meadow termed as DG1 increased rapidly at 20 cm; in contrast, in the cooling stage of autumn, ST of DG1 decreased significantly. The reason may be that the surface of the degraded swamp meadow is relatively exposed, and the soil responded rapidly to air warming and cooling (Wu et al., 2011). In addition, the rapid increase of ST in the spring could accelerate the decomposition of SOC by soil microbes, thus reducing SOC (Qi et al., 2016).

4.2 Interactions between soil moisture and temperature

Compared with autumn and winter, correlations between soil temperature (ST) and soil moisture (SM) in spring and summer was relatively lower (Figure 4). This could be a result of the combined effect of rainfall, freeze-thaw, plant growth and other factors in this study period, which reduced correlation between SM and ST. Correlation between SM and ST in the 10–20 cm soil layer in spring, summer, and autumn was significantly higher than that in the 0–10 cm surface layer. The main reason was that the relationship between ST and SM in the 0–10 cm surface soil layer was more easily broken by rainfall and plant growth during this study period. The weakest correlation between ST and SM in winter occurred in the 0–10 cm soil layer of the DG2 stage (Figure 4A). The reason may be that the DG2 swamp meadow was bare soil in winter, and the topsoil was easily affected by snowmelt, which reduced the correlation between ST and SM.

In spring, SM was significantly positively correlated with ST, and correlation coefficients almost varied between 0.306–0.553 (Figure 4, $p < 0.01$). Pablos et al. reached a similar conclusion, but with a correlation coefficient of about 0.27 (Pablos et al., 2016). In summer, ST and SM were significantly negatively correlated (Figure 4, $p < 0.01$). This result was also consistent with the conclusion of (Pablos et al., 2016). The negative correlation was due to the increasing ST, which enhanced soil evaporation and promoted water uptake by roots for plant growth, ultimately leading to a reduction in SM. In autumn and winter, SM was significantly positively correlated with ST ($p < 0.05$). This was because less rainfall, slow plant growth, and freezing under temperature declining process in alpine swamp meadows in autumn and winter would lead to a reduction in SM.

In autumn, as ST decreased from 12°C to 0°C, LSWC of each soil layer in different types of swamp meadows varied little, maintaining between 30%–40% (Figure 4). The reason for the stability was that both rainfall and plant water consumption decreased with the reduced temperature in autumn, and the two remained relatively balanced. Specifically, with the decreasing ST in autumn, LSWC in 0–10 and 10–20 cm soil layers could be maintained at about 40% in the NG. LSWC of other types of swamp meadows at different depths remained stable between 30%–35%. The higher SWC in the 0–10 and 10–20 cm soil layers of the NG may be due to its higher organic carbon content (Table 2) and stronger soil water holding capacity. As ST was maintained at 0°C in autumn, LSWC decreased continuously over time, and eventually was reduced to 15%–20% of LSWC, with a reduction of 15%–20% (Figrue 4). During the cooling process of ST from 0°C to −4°C in autumn, LSWC decreased by 3%–5%. In conclusion, the main process of LSWC reduction during freezing occurred in autumn and mainly at 0°C.

As ST was below −2°C in winter, LSWC did not decrease with the decreasing ST and was basically maintained between 14%–15%. Hu et al. also found this phenomenon in alpine swamp meadow at higher altitudes, but their stable SWC was between 2%–4% (Hu et al., 2023). The difference in stable SWC values may be due to the higher altitude (4,808 m) and deeper soil depth (50 cm) studied by hu et al. (Hu et al., 2023). During the warming process of ST from −2°C to 0°C in winter, soil solid water melted and LSWC slowly increased, with an rise of 2%–5%. (Figure 4). This result was confirmed by Hu et al. (2023). The above results indicated that −2°C was also a critical temperature for soil freezing. The relationships between ST and SM varied with the seasons, with positive and nega-tive linear correlation in spring and summer, and positive exponential correlation in autumn and winter (Figure 4, $p < 0.01$). The positive exponential correlation was similarly demonstrated in the study of Hu et al. (2023).

5 Conclusion

Through analysis of soil temperature, soil moisture and related properties during degradation and restoration of alpine swamp meadow, the following conclusions were drawn:

(1) With the degradation and restoration of alpine swamp meadow, plant biomass, plant height, plant leaf area index, soil organic carbon, soil total carbon and soil total nitrogen decreased significantly at first, and then increased significantly ($p < 0.01$);
(2) As alpine swamp meadow degraded, soil moisture in 0–20 cm soil layer decreased significantly ($p < 0.05$), the establishment of artificial grassland on degraded swamp meadow can significantly increase the soil moisture of 0–10 cm soil layer ($p < 0.05$); Soil temperature fluctuated between 18.1°C and −6.25°C, and did not vary significantly with the degradation and restoration of alpine swamp meadow ($p > 0.05$);
(3) The relationships between ST and SM varied with seasons, with positive and negative linear correlation in spring and summer, and positive exponential correlation in autumn and winter ($p < 0.01$); the negative correlation between soil moisture and soil temperature in summer was due to the increase of soil evaporation accompanied by soil temperature, which led to the decrease of soil moisture; the positive correlations in other seasons was triggered by the effect of freeze-thaw on soil liquid water content.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

GM: Writing–original draft. YZ: Writing–review and editing. HL: Data curation, Writing–review and editing. YY: Writing–review and editing. RL: Investigation, Writing–review and editing.

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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.

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