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Response Relationship between the Seasonal Freezing-Thawing Process of Soil and Spatial Factor Changes in the Dayekou Basin of the Qilian Mountains

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Abstract

Objective: In this study, the influence and response relationship between the seasonal freezing-thawing process of soil and the spatial factor changes in the management and utilization of water resource processes were explored. **Methods:** The monitoring equipment in this study was arranged at different altitudes, gradients, and slope directions, such as the typical forest sample area in the Dayekou Basin of the Qilian Mountains. The spatial variation characteristics of the seasonal freezing-thawing process of the soil were analyzed, and a regression model was established. **Results:** 1) The results of this study determined that the rate of the soil's freezing increased with the altitude in a trend of volatility. However, the rate of the thawing of the frozen soil was found to have an opposite trend. The variation degree of the freezing-thawing process increased with the altitude in a trend of volatility. The end time of the approximate soil freezing with altitude increased in a volatility trend ahead of schedule. However, the opposite was observed in the thawing rate of the frozen soil; 2) The rate of the soil's freezing under the mosses of the spruce forest at an altitude of 3028 m was found to be the lowest. However, in the sub-alpine scrub forest at an altitude of 3300 m, a maximum in the spatial ordering was observed, with an average of 1.9 cm·d^{-1}. The thawing rate of the frozen soil in scrub-spruce forest at an altitude of 3300 m was found to be minimal. However, in the sunny slope grassland at an altitude of 2946 m, a maximum in the spatial ordering was observed, with an average of 1.5 cm·d^{-1}. In the spatial ordering of the variation degree of the process of freezing-thawing with an average of 1.2, the scrub-grassland at an altitude of 2518

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m was found to be the lowest, and the scrub-spruce forest at an altitude of 3195 m was also low; 3) The soil freezing began on approximately October 20th, and the rate of soil freezing gradually became reduced. The arrival time of the frozen soil of up to 150 cm in depth in sub-alpine scrub forest was first observed at an altitude of 3028 m. However, the scrub-spruce forest at an altitude of 3100 m did not become frozen until approximately January 12th on average. Then, the thawing rate of the frozen soil increased gradually. The end time of the thawing was earliest observed in the sunny slope grassland at an altitude of 2946 m. However, the scrub-spruce forest at an altitude of 3100 m was found to be the last to thaw, and averaged approximately July 27th. The average durations of the freezing and thawing of the soil were 77 and 121 days, respectively, and the average duration of the entire process of freezing-thawing was 199 days; 4) This study's established regression models of the duration time of frozen soil's thaw, and the rate of frozen soil's thaw, all passed the R test of goodness of fit, F test of variance, and t test. **Conclusions:** The characteristics of the seasonal freezing-thawing process of the soil with the spatial changes were seasonal. However, the characteristics under the different spatial factor influences were not the same.

Keywords

Freezing-Thawing, Spatial Factor, Seasonal Frozen Soil, Dayekou Basin of the Qilian Mountains

1. Introduction

The frozen earth changes are the main research content of a cryosphere, and the freezing-thawing process of soil directly affects basin runoff. It is known that, within a basin, the freezing-thawing process of soil tends to be sensitive to spatial changes. Therefore, in order to explore the basin runoff process, the spatial variation attributes of the freezing-thawing process of soil should be considered [1] [2]. One of the most important and difficult problems in frozen earth research is the determination of the spatial changes of the frozen earth, especially those on a basin scale [3]. The previous research regarding the spatial changes of frozen earth has mainly concentrated on three aspects. One aspect is the assumption of the future climate scenarios, considering that plateau regions are generally warming with the same amplitude, and permafrost degradation is known to occur not only on the edge of the permafrost zone, but also around the valley thawing area, and the high plain swamp in the permafrost regions [4] [5] [6]. The second aspect is the speculation of the spatial changes of the permafrost in the limited areas using the drilling or cutting data at limited points [7]. The third aspect of main research content is the spatial changes of the permafrost, or the seasonal frozen soil in the Qinghai-Tibet Plateau [8]. These research results have important academic and application values. However, there have been few-

er experiments conducted regarding the massive measured data of the spatial variation factors on a basin scale which can be utilized for the studying of the freezing-thawing process of soil.

The Qilian Mountain is located on an intersection of three plateaus (*i.e.* the Qinghai-Tibet, Inner Mongolia-Xinjiang and Loess Plateaus), and has a very important geographic position in national forest hydrology and ecology research. A combination of the soil's freezing-thawing hydrologic process as an inevitable hydrological phenomenon in this region, and the insufficient related research, has made it very necessary to carry out related research in this region. During the research regarding the spatial changes of the frozen soil in the Qilian Mountains or upstream of the Heihe River, seven thermometer boreholes were used to set thermometer tubes for ground temperature monitoring for the purpose of studying the frozen soil distribution characteristics [9]. More than 40 years of temperature and soil temperature data at a depth of 5 cm from 11 meteorological stations were adopted to systematically study the monthly seasonal frozen soil distribution from 2000 to 2009, along with the spatiotemporal variation characteristics of the freezing probability [10]. Based on an elevation-response model, the high-resolution elevation data (DEM), longitude data, latitude data, annual average air temperature (MAAT), and vertical lapse rate data (VLRT) were applied for a numerical simulation of the frozen earth distribution in the Qilian Mountains during the last 40 years [11]. Related research has also been conducted in the Sidalong, Binggou, and Pailugou Basins of the Qilian Mountains by the Gansu Research Institute of Water Conservation Forest in the Qilian Mountains [1] [12] [13] [14]. This research focused on the hydrological and inter-annual change characteristics of the freezing and thawing process of soil.

In summary, there were few experimental results available to set the denser sample plots and frozen soil tubes in the basin for the long-term field monitoring of the frozen soil changes. There was also only a small amount of data regarding the changes in the spatial factors such as altitude, slope gradient, slope direction, and crown density factors, by which to study the freezing-thawing process of soil. Accordingly, the monitoring devices were set in typical sample plots with different elevations, slope gradients, slope directions, and forest stands throughout the entire basin to obtain the data for this study. The spatial variation characteristics of the soil's freezing and thawing processes were analyzed to further resolve the stand structure of the basin, along with its function mechanism of water conservation, which provided a scientific basis and reference for the ecological hydrology.

2. Study Area

The Qilian Mountains are located at the intersection of the Qinghai-Tibet, Inner Mongolia-Xinjiang and Loess Plateaus. This mountain range is classified as one of 50 nationally important eco-function areas, and one of 25 key eco-function

areas by the National Ecological Function Regionalization and the National Major Function Area Planning, and thereby presents a very important ecological niche. The Dayekou Basin (38°16'N - 38°33'N, 100°13'E - 100°16'E) belongs to the Zhongshan climate zone of the Qilian Mountains, and extends East to Mazongliang, West to Xigouliang, North to Zhengnangou, and South to Pailugou. This basin originated from Yeniu Mountains, Sunan County. Six larger branches, namely Dongcha, Xicha, Toutangou, Xigouliang, Guantaigou and Shengou, converge at the Dayekou Reservoir, with an area of 80 km², and control 98% of the basin catchment area, which indicates a typical closed basin (as shown in **Figure 1**). Due to great elevation variation intervals in the basin, the hydrothermal conditions display large differences in the form of vegetation and soil types, as well as vertical and horizontal gradient differences. From the lowest to highest altitudes, the vegetation types can be described as mountain desert, mountain grassland, mountain forest grassland, subalpine meadow, and mountain snow vegetation. The soil types include mountain sierozem, mountain chestnut soil, mountain gray cinnamonic soil, subalpine shrub meadow soil, and alpine frost desert soil. Among all of the soils, the mountain gray cinnamonic soil and the sub-alpine shrub meadow soil are the soils involved in forest growth, and are distributed in the regions with altitudes of 2400 to 3300 m and 3300 to 4000 m, respectively. Among the edificatories, the Qinghai *Picea crassifolia* is distributed as patches or strips on the shaded and half-shaded slopes, at altitudes between 2400 and 3300 m in the test area, staggered with grassland on the sunny slopes.
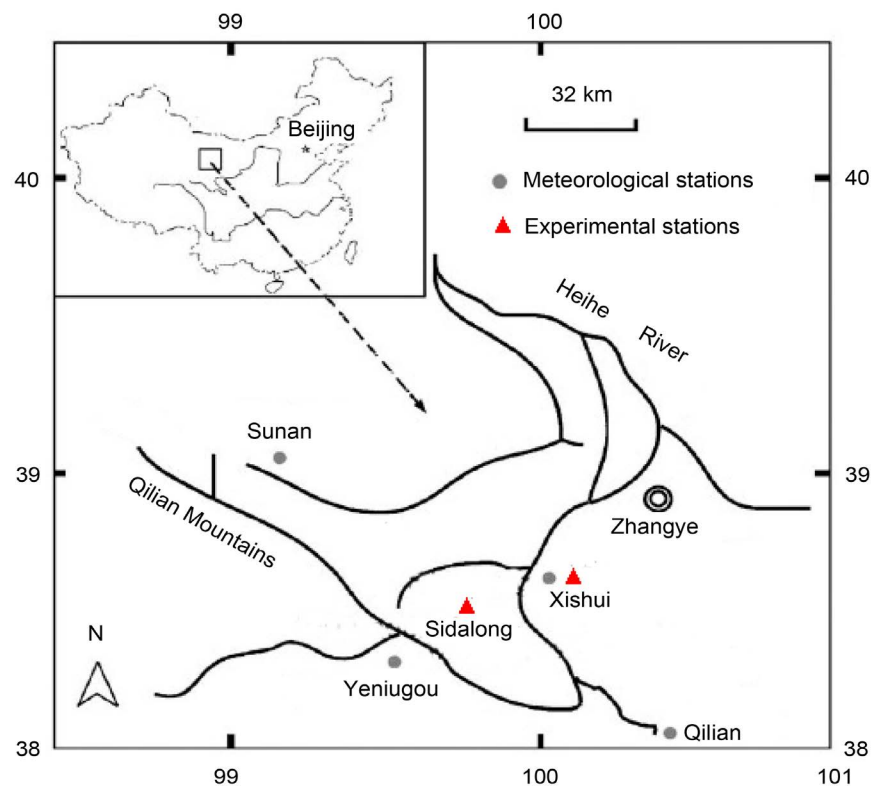
Figure 1. Position sketch map of the Dayekou basin of the Qilian Mountains.

The Qilian *Sibina przewal ski* is distributed as small blocks on the sunny and half sunny slopes. The shrubs which are dominant species include: *Potentilla fruticosa Linn., Caragana jubata (Pall.) Poir, Salix gilashanica C. Wang et PYFu,* and so on. The herbaceous plants mainly consist of *Polygonum viviparum Linn., Carex heterostachya Bge., Stipa capillata Linn.,* and so on. This basin is closed, with soil and vegetation typicality in spatial changes, and is an ideal experimental zone to study basin eco-hydrological processes, with soil freezing and thawing as one of the important ecological factors.

3. Research Methods

3.1. Sample Plot Layout and Instrument Installation

In this research study, in accordance with the different basin elevations, slope directions, slope gradients, and vegetation types, as well as their representatives, 15 sample plots were set up in October of 2013 (the sample plot situation is labeled by a sample plot number in Table 1). In each sample plot, a freezing meter was installed to monitor the phenomenon of soil freezing and thawing as detailed in the following table. Then, according to the thickness of the soil, the outer casings with lengths of 300 cm, 200 cm or 150 cm, and diameters of 5 cm were set into the underground area. Meanwhile, a rubber freezing tube with a diameter of 1 cm equal to the outer casing was injected with water, and the gaps between the outer casing and soil were backfilled to prevent precipitation entering. The changes in the soil's freezing and thawing processes were determined according to the water freezing scale of the freezing meter.

Table 1. Sample number and its basic situation.

Sample No.	Altitude/m	GPS-E	GPS-N	Sample/m	Forest type	Slope direction/°	Gradient/°	Crown density
T_1	2518	100°17'29.2"	38°34'49.4"	20 × 20	Moss spruce forest	9	36	0.69
T_2	2579	100°17'18"	38°34'1"	20 × 20	Shrub grassland	28	6	0.75
T_3	2600	100°18'2.7"	38°32'40.8"	20 × 20	Grass shrub forest	26	34	0.60
T_4	2610	100°17'23.6"	38°34'3.2"	20 × 20	Moss spruce forest	61	32	0.70
T_5	2701	100°17'10"	38°33'11"	20 × 20	Shrub grassland	48	10	0.50
T_6	2720	100°17'6"	38°33'18"	20 × 20	Moss spruce forest	47	30	0.70
T_7	2840	100°17'37"	38°33'5"	20 × 20	Grass spruce forest	56	30	0.82
T_8	2900	100°18'2.7"	38°32'40.8"	20 × 20	Grass shrub forest	61	12	0.50
T_9	2923	100°18'6"	38°32'42"	20 × 20	Moss spruce forest	16	32	0.80
T_{10}	2946	100°17'59"	38°32'47"	20 × 20	Sunny slope grassland	220	33	0.36
T_{11}	3028	100°17'59"	38°32'39"	20 × 20	Moss spruce forest	10	25	0.70
T_{12}	3100	100°18'13"	38°32'31"	20 × 20	Shrub spruce forest	22	27	0.70
T_{13}	3195	100°18'6"	38°32'25"	20 × 20	Shrub spruce forest	69	35	0.66
T_{14}	3300	100°18'16"	38°32'20"	20 × 20	Shrub spruce forest	39	34	0.70
T_{15}	3300	100°18'14.5"	38°32'7.8"	20 × 20	Subalpine shrub forest	41	33	0.80

3.2. Data Acquisition and Processing

1) Every five days, observations were basically carried out from an altitude between 2500 and 3300 m throughout the year.

2) The eigenvalue parameter algorithm is shown as below:

$$Cv = \frac{\sigma}{\mu}, \ \mu = \frac{1}{N}\sum_{i=1}^{N} x_i, \ \sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \tag{1}$$

In the equation, μ, σ, and Cv are the average, standard deviation and variation coefficient of the freezing-thawing of soil, respectively; x_i is the measured values of the soil's freezing-thawing process; and N is the statistical number.

A correlation analysis method was used for the correlation analysis and modeling parameter screening of the freezing days, thawing days, freezing rate and thawing rate with altitude, slope direction, slope gradient, and crown density. Then, a stepwise regression analysis method was adopted to determine the regression model of the soil's freezing-thawing and space factor, in order to establish a regression model for the R fitting, F variance, and t regression coefficient tests.

4. Results and Analyses

4.1. Soil Freezing-Thawing Variation Process

4.1.1. Spatial Variation Characteristics

The soil's freezing-thawing process included two stages: soil' freezing, and soil thawing. Driven by the ground temperatures, these two processes occur alternately. In order to facilitate the research, the soil's thickness is shown as an increase over a period of time overall, and is usually referred to as soil freezing. It may be referred to as soil thawing. As can be seen in Table 1 and Table 2, within the soil scope with a depth of 150 cm, the soil's freezing-thawing rate displayed different response degrees to the changes in the different space factors, such as the altitude, slope direction, and slope gradient, as well as the vegetation crown density. As shown in Figure 2, the soil's freezing rate presented a trend of fluctuation increases with the rising altitude, while the soil's thawing rate showed an opposite trend. Then, by utilizing the same method, it was determined that the variation coefficient of the soil's freezing-thawing increased with the altitude, and displayed a trend of increased fluctuations. The ending time of the soil's freezing presented a trend of fluctuation prior to the rising altitude. Meanwhile, the ending time of the thawing displayed an opposite trend. Therefore, during the space change sorting of the soil's freezing-thawing rate, for the variation coefficient, starting time, and ending time (in the cases of the same value), the altitude was taken as a secondary discrimination factor for the evaluation. The soil's freezing rate was sequenced from smallest to largest as follows: the moss spruce forest with an altitude of 3028 m < shrub grassland with an altitude of 2579 m < sunny slope grassland with an altitude of 2946 m < shrub spruce forest

Table 2. Spatial variation features of the rate of soil freezing and thawing in the Dayekou Basin of the Qilian Mountains.

Altitude/m	Freezing rate/cm·d^{-1}					Thawing rate/cm·d^{-1}				
	Average	Standard deviation	Coefficient of variation	Lower limit	Upper limit	Average	Standard deviation	Coefficient of variation	Lower limit	Upper limit
2518	1.3	0.3	0.2	1.0	1.6	1.9	1.7	0.9	0.2	3.6
2579	1.2	0.4	0.3	0.8	1.6	1.8	1.1	0.6	0.7	2.9
2600	2.0	0.7	0.3	1.4	2.7	2.5	2.1	0.9	0.4	4.6
2610	1.8	0.5	0.3	1.3	2.4	2.3	2.6	1.1	0.0	4.9
2701	1.5	0.2	0.2	1.2	1.7	1.3	0.9	0.7	0.4	2.2
2720	1.3	0.4	0.4	0.8	1.7	1.3	1.4	1.1	0.0	2.7
2840	3.1	1.4	0.5	1.7	4.6	0.9	1.7	1.8	0.0	2.6
2900	1.7	0.6	0.3	1.1	2.2	1.2	0.9	0.8	0.3	2.1
2923	1.7	0.6	0.4	1.1	2.3	1.0	1.3	1.4	0.0	2.3
2946	1.2	1.0	0.8	0.2	2.2	4.0	2.9	0.7	1.1	6.9
3028	1.0	0.5	0.5	0.5	1.6	0.8	1.3	1.7	0.0	2.1
3100	1.2	0.4	0.4	0.8	1.6	0.8	1.0	1.3	0.0	1.8
3195	2.1	0.6	0.3	1.5	2.7	0.9	2.0	2.1	0.0	2.9
3300	2.2	2.2	1.0	0.0	4.4	0.8	1.1	1.3	0.0	1.9
3300	4.6	2.4	0.5	2.2	6.9	1.2	1.1	0.9	0.1	2.3
Mean	1.9	0.8	0.4	1.0	2.7	1.5	1.5	1.2	0.2	3.1
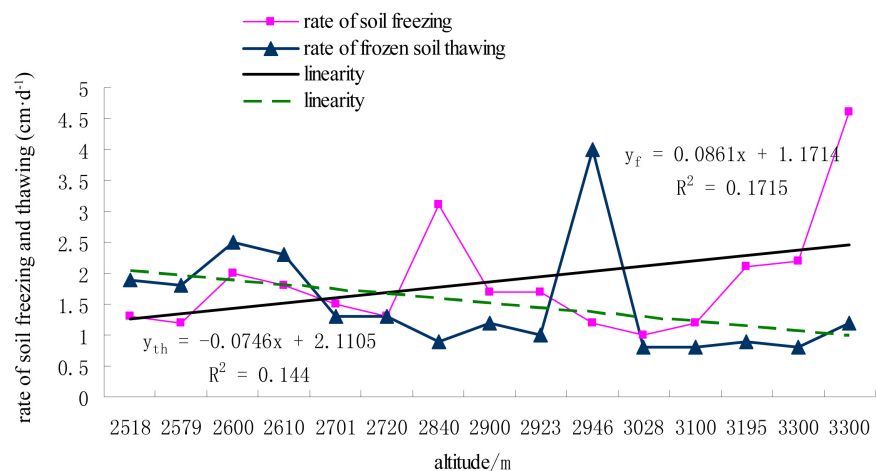
Figure 2. Spatial variation features of the rate of soil freezing and thawing with altitude in the Dayekou Basin of the Qilian Mountains.

with an altitude of 3100 m < moss spruce forest with an altitude of 2518 m < moss spruce forest with an altitude of 2720 m < shrub grassland with an altitude of 2701 m < grass shrub forest with an altitude of 2900 m < moss spruce forest with an altitude of 2923 m < moss spruce forest with an altitude of 2610 m < grass shrub forest with an altitude of 2600 m < shrub spruce forest with an altitude of 3195 m < shrub spruce forest with an altitude of 3300 m < grass spruce forest with an altitude of 2840 m < subalpine shrub forest with an altitude of

3300 m, averaged at 1.9 cm·d^{-1}. The soil's thawing rate was sequenced from smallest to largest as follows: the shrub spruce forest with an altitude of 3300 m < shrub spruce forest with an altitude of 3100 m < moss spruce forest with an altitude of 3028 m < shrub spruce forest with an altitude of 3195 m < grass spruce forest with an altitude of 2840 m < moss spruce forest with an altitude of 2923 m < subalpine shrub forest with an altitude of 3300 m < grass shrub forest with an altitude of 2900 m < moss spruce forest with an altitude of 2720 m < shrub grassland with an altitude of 2701 m < shrub grassland with an altitude of 2579 m < moss spruce forest with an altitude of 2518 m < moss spruce forest with an altitude of 2610 m < grass shrub forest with an altitude of 2600 m < sunny slope grassland with an altitude of 2946 m, averaged at 1.5 cm·d^{-1}.

The variation coefficient was an indicator to study the variation degree of the freezing-thawing process of soil (Table 2). Within the soil scope with a depth of 150 cm, the soil freezing variation was sequenced from smallest to largest as follows: the moss spruce forest with an altitude of 2518 m < shrub grassland with an altitude of 2701 m < shrub grassland with an altitude of 2579 m < grass shrub forest with an altitude of 2600 m < moss spruce forest with an altitude of 2610 m < grass shrub forest with an altitude of 2900 m < scrub spruce forest with an altitude of 3195 m < moss spruce forest with an altitude of 2720 m < moss spruce forest with an altitude of 2923 m < shrub spruce forest with an altitude of 3100 m < grass spruce forest with an altitude of 2840 m < moss spruce forest with an altitude of 3028 m < subalpine shrub forest with an altitude of 3300 m < sunny slope grassland with an altitude of 2946 m < shrub spruce forest with an altitude of 3300 m, averaged at 0.4. The soil's thawing change was sequenced from smallest to largest as follows: the shrub grassland with an altitude of 2579 m < shrub grassland with an altitude of 2701 m < sunny slope grassland with an altitude of 2946 m < grass shrub forest with an altitude of 2900 m < moss spruce forest with an altitude of 2518 m < grass shrub forest with an altitude of 2600 m < subalpine forest with an altitude of 3300 m < moss spruce forest with an altitude of 3300 m < moss spruce forest with an altitude of 2720 m < shrub spruce forest with an altitude of 3100 m < shrub spruce forest with an altitude of 3300 m < moss spruce forest with an altitude of 2923 m < moss spruce forest with an altitude of 3028 m < grass spruce forest with an altitude of 2840 m < shrub spruce forest with an altitude of 3195 m, averaged at 1.2.

4.1.2. Variation Characteristics of the Starting and Ending Time

The changes in the different space factors, such as altitude, slope direction, and slope gradient, as well as the vegetation crown density, were found to have different effects on the starting and ending time of the soil's freezing-thawing process. As can be seen in Figure 3 and Figure 4, the starting time of the soil's freezing-thawing had only a minimal difference. However, the freezing time of the soil with a depth of 150 cm was found to be quite different (shortened to soil freezing time in this study). The soil freezing began on approximately October 20th, and the soil freezing rate gradually decreased over time. The freezing time
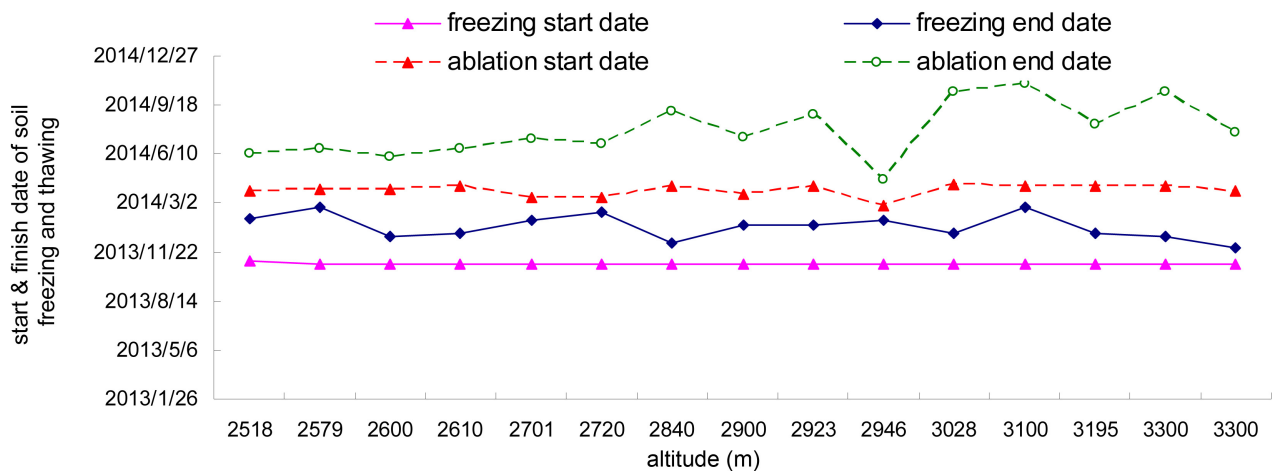
Figure 3. Spatial variation features of the star in end time of the soil freezing and thawing in the Dayekou Basin of the Qilian Mountains.
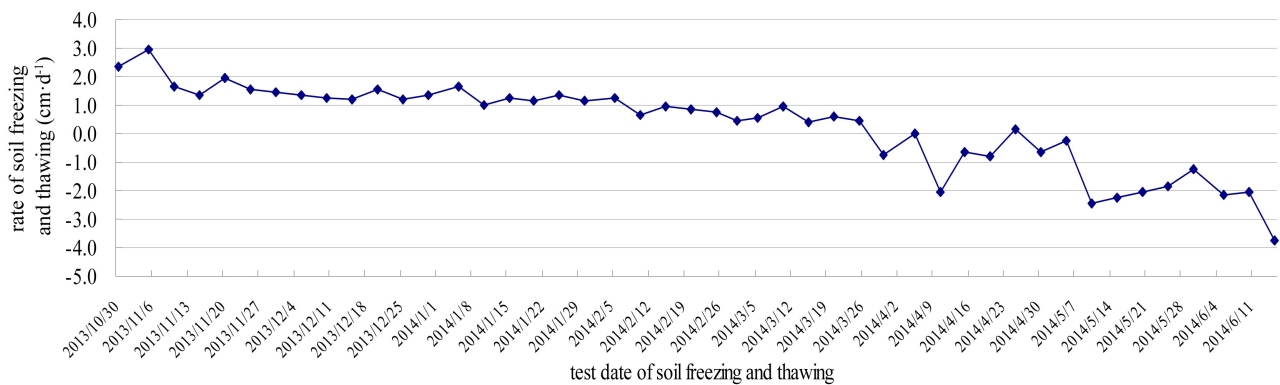
Figure 4. Time representations of the soil's freezing and thawing process in the Dayekou Basin of the Qilian Mountains. Note: **Figure 4** was prepared using the data of the typical T_2, T_5 and T_6 sample plots.

of the soil with depths of 150 cm was sequenced from early to late as follows: the subalpine shrub forest with an altitude of 3300 m < grass spruce forest with an altitude of 2840 m < grass shrub forest with an altitude of 2600 m < scrub spruce forest with an altitude of 3300 m < moss spruce forest with an altitude of 2610 m < moss spruce forest with an altitude of 3028 m < shrub spruce forest with an altitude of 3195 m < grass shrub forest with an altitude of 2900 m < moss spruce forest with an altitude of 2923 m < shrub grassland with an altitude of 2701 m < sunny slope grassland with an altitude of 2946 m < moss spruce forest with an altitude of 2518 m < moss spruce forest with an altitude of 2720 m < shrub grassland with an altitude of 2579 m < shrub spruce forest with an altitude of 3100 m, averaged on January 12th. The data of soil's thawing of the 150 cm deep soil also displayed small differences, and was averaged on March 27th. The soil's thawing rate was observed to increase gradually over time, and is marked by a negative value in **Figure 4**. The ending time of soil's thawing was sequenced from early to late as follows: the sunny slope grassland with an altitude of 2946 m < grass shrub forest with an altitude of 2600 m < moss spruce forest with an

altitude of 2518 m < shrub grassland with an altitude of 2579 m < moss spruce forest with an altitude of 2610 m < moss spruce forest with an altitude of 2720 m < shrub grassland with an altitude of 2701 m < grass shrub forest with an altitude of 2900 m < subalpine shrub forest with an altitude of 3300 < shrub spruce forest with an altitude of 3195 m < moss spruce forest with an altitude of 2923 m < grass spruce forest with an altitude of 2840 m < moss spruce forest with an altitude of 3028 m < shrub spruce forest with an altitude of 3300 m < shrub spruce forest with an altitude of 3100 m, averaged at July 27th.

4.1.3. Duration Variation Characteristics

Within the soil scope with a depth of 150 cm, the soil's freezing-thawing duration displayed different responses to the changes in space factors, such as altitude, slope direction, and slope gradient, as well as the vegetation crown density. As shown in Figure 5, the total durations of the soil freezing, soil's thawing and freezing-thawing were averaged 77, 121 and 199 days, respectively.

4.2. Correlation Analysis between the Freezing-Thawing Process of the Soil and the Space Factors

The sample plot observations of the different space factors in the basin were selected for the correlation analysis. In the case of $a = 0.1$ ($P < 0.1$), the Chad threshold $F_{0.1}(1, 14)$ was 3.102, and the correlation coefficient threshold $r_{0.1} = \sqrt{F_{0.1}(1,15)/(F_{0.1}(1,15)+15)}$ was substituted to obtain $r_{0.1}$ at 0.441. If the correlation coefficient was found to be greater than the critical value, it indicated a significant correlation. Meanwhile, if it was less than the critical value, this indicated insignificant correlations (the values with "*" in Table 3 indicate significant correlations, while the values with no "*" indicate insignificant correlations). As shown in Table 3, the freezing days displayed significant correlations with the slope gradient, moderate correlations with the altitude, and rather weak correlations with the other factors. The thawing days displayed significantly positive correlations to the altitude and crown density, while negative correlations
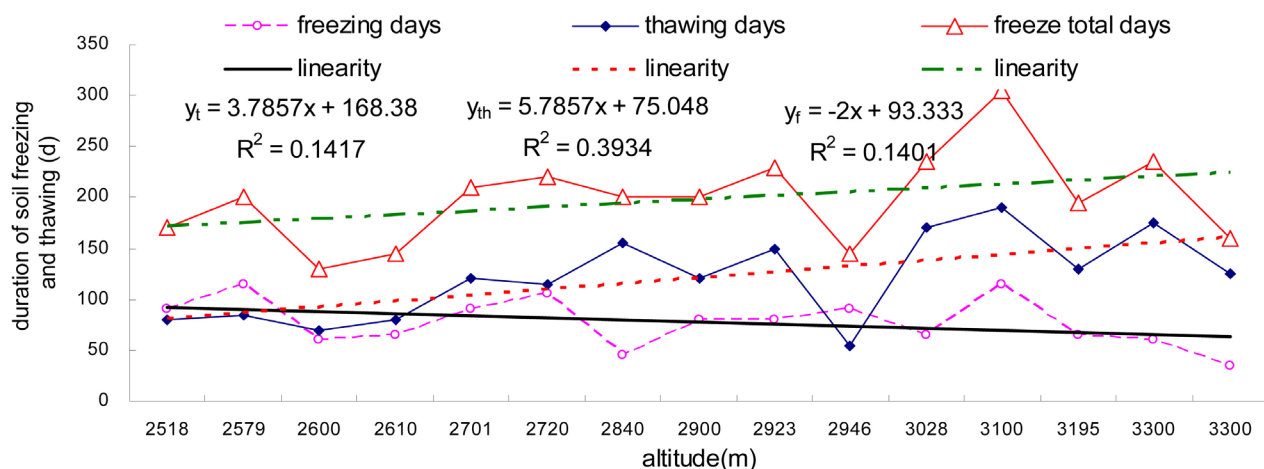
Figure 5. Durations of the soil's freezing and thawing process in the Dayekou Basin of the Qilian Mountains.

Table 3. Correlation coefficient of the soil's freezing-thawing process and the spatial factors in the Dayekou Basin of the Qilian Mountains.

	Altitude /m	Slope direction/°	Gradient/°	Crown density	Freeze days/d	Thawing days/d	Freezing rate/cm·d⁻¹	Freezing rate/cm·d⁻¹
Altitude/m	1.000							
Slope direction/°	0.114	1.000						
Gradient/°	0.283	0.116	1.000					
Crown density	0.122	−0.688*	0.218	1.000				
Freeze days/d	−0.395	0.029	−0.455*	−0.264	1.000			
Thawing days/d	0.643*	−0.447*	0.011	0.460*	−0.127	1.000		
Freezing rate/cm·d⁻¹	0.448*	−0.055	0.296	0.414	−0.779*	0.132	1.000	
Freezing rate/cm·d⁻¹	−0.424	0.711*	0.134	−0.613*	0.151	−0.859*	−0.223	1.000

Note: The values with * indicate significant correlations.

to the slope direction. The freezing rate had a significantly positive correlation with the altitude, a moderate correlation with the crown density, and rather weak correlations with the other factors. The thawing rate displayed a significantly positive correlation with the slope direction, a significantly negative correlation with the crown density, a moderate correlation with the altitude, and rather weak correlations with the other factors. Therefore, the freezing days with altitude and slope gradient; the thawing days with altitude, slope direction, and crown density; the freezing rate with altitude and crown density; and the thawing rate with altitude, slope direction, and crown density were preliminarily selected for this study's regression analysis.

4.3. Fitting and Variance Analysis of the Freezing-Thawing Process of the Soil and the Space Factors

Table 4 shows the F test values, and the significant level of regression fitting and variance analysis. Generally speaking, in accordance with the complex phase relation interpretation standard, when the multiple correlation coefficient $|R| > 0.95$, significant correlations are indicated; $0.95 \leq |R| \geq 0.8$ indicates high correlations; $0.5 \leq |R| < 0.8$ indicates moderate correlations; $0.3 \leq |R| < 0.5$ indicates low correlations; and $|R| < 0.3$ indicates rather weak correlations, which are considered as non-correlations [15]. Therefore, the fitting of the freezing days with altitude and slope gradient, as well as the freezing rate with altitude and crown density, belonged to moderate correlations, and the fitting of the thawing days with altitude, slope direction, and canopy density, as well as the thawing rate with altitude, slope direction, and crown density, belonged to high correlations. The established model passed the R fitting test with ideal fitting results. The multiple determination coefficients showed that the independent variable could explain the weight of the dependent variable. It can be seen from **Table 5** that the altitude, slope direction, and crown density could be used to predict 68.8% of the thawing duration variances. The adjusted multiple determination coefficients confirmed that the independent variables were able to explain the weight

Table 4. Matching coefficients of the soil's freezing-thawing process and the spatial factors in the Dayekou Basin of the Qilian Mountains.

Dependent variables	Independent variables	R	R^2	$\overline{R^2}$	Standard error	F test value	Significance level
Freeze days	Altitude, gradient	0.533	0.284	0.165	21.840	2.379	0.135
Thawing days	Altitude, slope direction, crown density	0.830	0.688	0.603	25.981	8.098	0.004
Freezing rate	Altitude, crown density	0.575	0.331	0.220	0.821	2.971	0.090
Thawing rate	Altitude, slope direction, crown density	0.875	0.766	0.702	0.480	11.991	0.001

Table 5. Partial regression coefficients of the duration of the soil's freezing-thawing and spatial factors in the Dayekou Basin of the Qilian Mountains.

	Coefficients	Standard error	T Stat	P-value	Lower limit 95.0%	Upper limit 95.0%
Constant	−179.923	85.148	−2.113	0.058	−367.332	7.485
Altitude	0.110	0.028	3.961	0.002	0.049	0.171
Slope direction	−0.416	0.196	−2.120	0.058	−0.848	0.016
Crown density	7.225	78.399	0.092	0.928	−165.329	179.779

of the dependent variables' variations, and that the altitude, slope direction, and crown density could be used to explain 60.3% of the thawing duration changes. The remainder could be explained by other factors, such as the micro topography changes of the land surface. The standard error indicated that the average error was between the predicted and measured values. The smaller the value was, the more ideal the fitting degree was. The F value shown in Table 4 is the test value of the variance analysis as the ratio of regression mean square error and residual mean square error. Therefore, if the regression mean square error is larger, and residual mean square error is smaller, the results should be expected to be more ideal. The greater the F value was, the more ideal the predicted results of the model were. It can be seen from Table 4 that the level of $a = 0.05$ ($P < 0.05$) could be used for another screening. The fitting of the thawing days with altitude, slope direction, and crown density, as well as the thawing rate with altitude, slope direction, and crown density, displayed significance levels of $P < 0.05$, which finally determined that the thawing days and thawing rate model passed the F test of variance. Therefore, the regression models of the thawing days with altitude, slope direction, and crown density, as well as the thawing rate with altitude, slope direction, and crown density, were determined for the partial regression coefficient analysis of this study.

4.4. Partial Regression Coefficient Analysis of the Soil's Freezing-Thawing Process and the Space Factors

In Table 5 and Table 6, the P-value indicates the significance degree of the partial regression coefficient. The smaller the P-value is, the more significant the variation in the partial regression coefficient is. In Table 5 and Table 6, the

Table 6. Partial regression coefficients of the duration of the soil's freezing-thawing and spatial factors in the Dayekou Basin of the Qilian Mountains.

	Coefficients	Standard error	T Stat	*P*-value	Lower limit 95.0%	Upper limit 95.0%
Constant	5.946	1.574	3.777	0.003	2.481	9.410
Altitude	−0.002	0.001	−3.293	0.007	−0.003	−0.001
Slope direction	0.013	0.004	3.534	0.005	0.005	0.021
Crown density	−0.298	1.449	−0.206	0.841	−3.488	2.892

P-values of the crown density are all greater than 0.5, which did not pass the *t* test, thus these were eliminated. Then, a stepwise regression analysis method was used to screen the thawing days with altitude and slope direction, as well as the thawing rate with altitude and slope direction, by again using the *t* test method (as in Table 5 and Table 6). The results showed that the *P*-values of the thawing-days model with altitude and slope direction were all less than 0.05, and those of the thawing rate model with altitude and slope direction were all less than 0.005. The regression models all passed the *t* test with a confidence level of 99% or more.

In this study, the results of the above *R* fitting test were combined with those of the *F* variance and *t* regression coefficient tests, and the regression models of the thawing duration and thawing rate could be obtained as follows:

$$T_a = 0.111a - 0.429e - 176.527 \left(R^2 = 0.830, P < 0.001 \right) \tag{2}$$

$$V_a = 0.013e - 0.002a + 5.805 \left(R^2 = 0.875, P < 0.001 \right) \tag{3}$$

In the equation, T_a and V_a represent the soil's thawing duration (d) and thawing rate (cm·d^{-1}) with the different altitudes and slope directions, respectively; a and e are the basin's altitude (m) and slope direction (˚), respectively.

5. Discussions and Conclusions

5.1. Discussions

It was determined in this study that the seasonal frozen soils were widely distributed in the Qilian Mountains, and were mainly comprehensively affected by topography, altitude, slope direction, slope gradient, slope position, soil type, composition, and structure, as well as other factors, which caused great differences in the freezing-thawing process within the basin. In particular, the spatial variation characteristics of the soil's freezing and thawing displayed seasonal variation laws over time. However, under the influence of different space factors, the presented characteristics were found to not be identical. The soil's freezing and thawing process is complex. The soil's freezing process and the soil's thawing process display different response sensitivities to space factor changes. It was preliminarily determined in this study that the altitude and slope direction had the most significant effects on the soil's thawing process. The soil layer in the alpine glacier permafrost zone and the seasonal frozen soil layer in the mid-low mountains were determined to be the links to connect the "solid reservoir",

"green reservoir", and river water systems. Due to the unique hydrothermal properties, a special underlying surface is formed which is beneficial to the river runoff, and thereby plays a role in water conservation and river runoff regulation. In this study, the fitting relationship between the soil's freezing-thawing process and the topographic space factors was considered as a rough estimation relationship, with more focus on a single factor, and less focus on comprehensive factors. In the future, scientific research in this area should pay closer attention to the spatial inter-annual and seasonal changes in the soil freezing and thawing process, as well as the response characteristics to latitude and longitude. Therefore, through further research, the exploration of the spatial response relationship between global climate warming and soil's freezing-thawing may potentially provide reference data for human responses to worsening ecological environment problems.

5.2. Conclusions

1) The soil freezing rate showed a trend of fluctuation increases with rising altitude, while the soil's thawing rate displayed the opposite trend. The soil's freezing-thawing variation degree presented a trend of fluctuation increase with rising altitude. The ending time of the soil freezing showed a trend of fluctuation in advance with the rising altitude, while the trend of the thawing was found to be the opposite.

2) In the spatial sequence, the soil's freezing rate averaged at 1.9 cm·d^{-1}. The soil's thawing rate averaged at 1.5 cm·d^{-1}. The soil freezing variation degree averaged at 0.4. Finally, the soil's thawing variation degree averaged at 1.2.

3) The soil freezing began on approximately October 20th, and the soil freezing rate became gradually reduced. The frozen soil thickness reached 150 cm averaged on January 12th. The soil's thawing to a soil depth of 150 cm had smaller time differences, averaged on March 27th. Then, the soil's thawing rate gradually increased. The soil's thawing ended and averaged on July 27th. The average durations of the soil's freezing, soil's thawing, and total soil's freezing-thawing were 77, 121, and 199 days, respectively.

4) The established thawing duration and thawing rate regression models all passed the R fitting, F variance, and t regression coefficient tests.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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