

Review

The Influence Mechanism of Freeze-Thaw on Soil Erosion: A Review

Lei Zhang ^{1,2}, Feipeng Ren ^{3,4,5,*}, Hao Li ^{3,4,5}, Dongbing Cheng ^{3,4,5} and Baoyang Sun ^{3,4,5,*}¹ Business School, Hohai University, Nanjing 210098, China; zhanglei@mwr.gov.cn² Science and Technology Promotion Centre, Ministry of Water Resources, P.R.C, Beijing 100089, China³ Changjiang River Scientific Research Institute, Changjiang Water Resources Commission, Wuhan 430010, China; haol@whu.edu.cn (H.L.); xiao2005zhu@163.com (D.C.)⁴ Engineering Technology Research Center of Mountain Flood Geological Disaster Prevention and Control, Ministry of Water Resources, Wuhan 430010, China⁵ Field Scientific Observation and Research Station of Aquatic Ecosystem in the Source Area of Changjiang River, Yushu 815000, China

* Correspondence: feipengren2006@mail.bnu.edu.cn (F.R.); sunbx@mail.crsri.cn (B.S.); Tel.: +86-152-9168-8726 (B.S.)

Abstract: As an important type of soil erosion, freeze-thaw erosion occurs primarily at high latitude and altitude. The overview on the effect of freeze-thaw on soil erosion was provided. Soil erosion was affected by freeze-thaw processes, as thawing and water erosion reinforce each other. Remote sensing provided an unprecedented approach for characterizing the timing, magnitude, and patterns of large-scale freeze-thaw and soil erosion changes. Furthermore, the essence of soil freeze-thaw was the freeze and thaw of soil moisture in the pores of soil. Freeze-thaw action mainly increased soil erodibility and made it more vulnerable to erosion by destroying soil structure, changing soil water content, bulk density, shear strength and aggregate stability, etc. However, the type and magnitude of changes of soil properties have been related to soil texture, water content, experimental conditions and the degree of exposure to freeze-thaw. The use of indoor and field experiments to further reveal the effect of freeze-thaw on soil erosion would facilitate improved forecasting, as well as prevention of soil erosion during thawing in regions with freeze-thaw cycles.

Keywords: freeze-thaw; soil erosion; effect mechanism; soil structure; soil erodibility



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1. Introduction

As the world seeks to achieve the Sustainable Development Goals related to food, health, water and climate, soils are under enormous pressure [1,2]. Soil erosion has been identified as a limiting factor in the development of a sustainable, global and social economy [3,4]. Soil erosion occurred in areas where intense interactions among strata at the surface of land and environmental factors interact including water, wind, freeze-thaw, gravity, etc. [5–7]. Freeze-thaw erosion was the result of frequent changes in temperature, resulting in changes to soil and rock physico-chemical properties and occurs to a greater extent at high altitudes and latitudes in cold regions [8,9].

Significant changes in global mean precipitation and surface temperatures have occurred in recent years and are expected to continue throughout the 21st century [10,11]. Due to the diurnal and seasonal changes of heat, the liquid water in the surface soil was repeatedly frozen and thawed, that is, the freeze-thaw cycles, which was one of the most significant land surface characteristics of seasonal frozen soil ecosystem [11,12]. However, climate warming quietly intensified this process. With the global warming, the freezing date of the permafrost in the seasonal freeze-thaw area was delayed, while the thawing date was generally advanced [13]. This trend had a significant impact on the surface environment, that is, the thawing depth of permafrost increased, water moved to the deep soil layer, and the living environment and soil properties of the surface vegetation changed [14].

Freeze-thaw action cannot eliminate all topsoil but can provide an effective source of material for other types of erosion [15]. The distribution range of effective material sources for other erosion forces was wider than that of pure freeze-thaw erosion [16]. Therefore, cumulative erosion of topsoil was closely related to the degree of freeze-thaw [17]. In the areas of seasonal freeze-thaw, the effect of freeze-thaw damaged the slope soil, increased soil erodibility, and led to the increase of soil erodibility [18–20]. Soil erodibility was affected by soil properties and root growth and had obvious seasonal characteristics, whereby greatest erosion was observed during early spring [21,22]. The frozen layer of soil began to thaw from top to bottom when the surface layer thawed and the underlying soil was not thawed, an impermeable layer will be formed between the thawed and unthawed layers. So, water flowed along the interface, reduced frictional resistance, and soil erosion may occur even when rainfall intensity was low [23].

At present, there was abundant research on the effects of freeze-thaw on soil properties, and the dynamic changes of soil erosion process and erosion amount have been gradually deepened. However, it was difficult to define the driving mechanism of freeze-thaw and quantitatively evaluate the contribution of freeze-thaw due to the many influencing factors and the complex process of freeze-thaw. Therefore, the research achievements of the effects of freeze-thaw on soil erosion and the mechanism of action were sorted out to provide references for the studies of the mechanism and prevention of freeze-thaw erosion.

2. Methods

Although climate warming has changed the soil freeze-thaw dynamics, almost all the simulations of freeze-thaw effects have been carried out in the laboratory using remolded soil. There was little agreement on how to conduct freeze-thaw simulations, with differences in methods led to many inconsistent or contradictory results. Furthermore, many soil incubations have introduced experimental artifacts that diminished the realism and relevance of the freeze-thaw treatments [24].

2.1. Freeze-Thaw Process of Indoor and Field Experiment

In order to reduce the difficulty of experimental control, indoor freeze-thaw simulation method was mainly used to study the effects of freeze-thaw action on soil physical and chemical properties and erosion process [17–19]. However, natural soil freeze-thaw in the field and simulated freeze-thaw in the room were two completely different ways and processes [23,24]. In the process of soil freezing and thawing in the field, the ambient temperature changed gradually, while the indoor temperature was generally set as a constant temperature [24]. Even if the gradual change process of field temperature was simulated, the rate of change of field temperature cannot be consistent with that of field temperature [22]. During the indoor simulation, the sampling and loading of soil samples, the direction of freezing and thawing, and the side-wall effect under slope scale conditions were all factors affecting the test results [25].

2.2. Soil Moisture of Indoor and Field Experiment

The change of soil water potential during freeze-thaw cycles will lead to water migration, which will affect the next time degree of soil freeze-thaw [26]. In the indoor simulation of freeze-thaw process, a container with a certain volume was generally used to fill soil samples, so the simulation test was a closed system [10]. Different from the open field system, the water inflow and outflow in the freeze-thaw process were limited. Under the same initial water content, the degree of freeze-thaw varied greatly between indoor and outdoor conditions [24]. Even if the open system could be simulated in the field, the specific water supply or loss due to evaporation in the process of freezing and thawing cannot be controlled [27].

2.3. Differences in Freeze-Thaw Conditions

The number of freeze-thaw cycles, soil water content before freeze-thaw, freeze-thaw duration and freeze-thaw temperature were the main variables to be considered in the freeze-thaw simulation test and are also the important factors affecting the degree of freeze-thaw [24,25]. Many studies have been carried out on freeze-thaw tests at home and abroad, but the conclusions were often quite different or even contrary, which was mainly due to the large differences in the design of freeze-thaw conditions [10]. For example, some researchers set the freeze-thaw cycles for several hours or several weeks [28–30]. When the freeze-thaw cycle was set less, it is difficult to reveal the long-term effect and accumulation effect of the freeze-thaw process [27].

Furthermore, under the same freeze-thaw conditions, the conclusions obtained by physical and chemical properties determination and erosion simulation test would be different due to different soil texture or test equipment [24,27].

3. Results

3.1. Effect of Freeze-Thaw on Soil Erosion Process and Amounts

In seasonal freeze-thaw region, freeze-thaw erosion was generally tending to be moderate or mild [10]. However, soil erodibility with different utilization types in thawing period was 2–3 times of that in other seasons, and serious soil erosion may occur even if the rainfall intensity was small [16,17]. Barnes et al. [23] used erosion needle method to monitor the impact of freeze-thaw action on clay gully erosion for a long time in the field and found that freeze-thaw action would significantly increase the amount of erosion in gullies, especially the lateral walls. The erosion characteristics of silt without freeze-thaw and after freeze-thaw were quantitatively studied under different discharge, slope and water content conditions [18]. After freeze-thaw, the average gullies depth, width, sectional area and erosion amount were significantly greater than those of non-freeze-thaw soils, and the difference between the two increased with the increase of initial water content, which was basically the same with previous studies [31]. In addition, soil moisture content increased and soil cohesion decreased in soils which undergo freeze-thaw, resulting in increased erosion [22].

In China, soil erosion process under freeze-thaw conditions has been studied mainly in seasonal freeze-thaw areas such as the Loess Plateau and the black soil area in Northeast China through laboratory simulation experiments, and a lot of results have been obtained in recent years [32]. Soil detachment was the initial stage of soil erosion, and it was also the stage that was most affected by freeze-thaw action. Through scouring test, it was found that freeze-thaw action had a significant effect on soil detachment capacity [33]. Chen et al. [34] found that the flow velocity increased significantly after the surface of the loess slope was frozen, leading to a significant increase in the amount of erosion in the lower slope through indoor simulated freeze-thaw and rainfall tests. The intensity of sediment yields on loess slope increased with the increase of soil mass moisture content and the number of freeze-thaw cycles [35]. Wu et al. [36] found that in the Sanjiang Plain of Northeast China, the soil infiltration rate of thawing slopes in April was less than that in the rainy season, leading to the increase of runoff and erosion. Different from the Loess Plateau, the permafrost in the Qinghai-Tibet Plateau was relatively thick, which required long-term field location monitoring and large scale indoor simulation tests for mutual verification [37]. Li et al. [38] found that the erosion resistance of the Qinghai-Tibet Plateau was significantly lower than that of other regions, which was related to the degree of freeze-thaw and soil properties, but the specific influencing mechanism remained unclear.

3.2. Effect of Soil Erosion on Freeze-Thaw Action

During the thawing period, soil freeze-thaw action and erosion feed each other (eg. freeze-thaw action indirectly intensified the degree of erosion, and the result of erosion will affect the degree of freeze-thaw action) [10]. The contribution of freeze-thaw action to soil erosion was mainly reflected in the change of soil properties and retard of infiltration [13,14].

In the process of soil erosion, the humus and organic matter contents in the surface soil were lost, and the water distribution in the soil profile on the slope, as well as the transport and accumulation of sediments will change the response of soil to freeze-thaw action [39]. In the process freeze-thaw cycles, freeze-thaw action and water erosion feed-back processes usually occurred simultaneously or alternately [10]. Therefore, soil erosion under freeze-thaw action was generally more intense.

3.3. Different Scales Monitoring of Freeze-Thaw and Soil Erosion

Under the impetus of the global warming, cold region was experiencing the profound change, and different scales monitoring have made some achievements, but the thawing permafrost and soil erosion needed more accurate interpretation. At the slope scale, through the situ monitoring and simulation of freeze-thaw action, the increase of thawing depth, soil initial water content before freeze-thaw and the number of freeze-thaw cycles will all lead to the increase of erosion amount [23]. Based on watershed scale monitoring, the freeze-thaw action not only led to the development of rills into shallow rills and gullies, but also increased erosion rate at the head of gullies. The freeze-thaw action accelerated the gravity erosion of gully side walls, and the sediments formed by the collapse will produce greater erosion when the rainfall was high [40–42].

Remote sensing provided an unprecedented approach for characterizing the timing, magnitude, and patterns of large-scale environmental changes [43]. The multi-sensor data fusion method was expected to overcome the shortcomings of single sensor observation and enhanced the ability of monitoring and detecting environmental changes in cold regions [11,44]. The Freeze-Thaw Earth System Data Record (FT-ESDR) was developed encompassing a larger global domain, longer data record and refined classification algorithms. The expanded FT-ESDR enabled new surveys of land areas dominated by snow and ice, while longer records and better accuracy allow for fine-grained assessments of global change, better distinguished between transient extreme weather, landscape phenology changes and climate anomalies from long-term trends lasting several decades [45]. Liu et al. [46] applied GPS interference reflection technology to multipath signal-to-noise ratio data collected by a GPS receiver in continuous operation in the depths of permafrost in Barrow, Alaska, and obtained diurnal changes in surface elevation caused by the dynamics of active layer and near-surface permafrost during July and August from 2004 to 2015. This method could be potentially extended to numerous continuously operating global navigation satellite system receivers in cold regions.

4. Discussion

The essence of soil freeze-thaw was the freeze and thaw of soil moisture in the pores of soil. Due to the different densities of water and ice, the constant phase change of soil water made soil frost heave and thaw sink frequently occurred, which led to the change of soil physical, chemical and biological properties [10]. Freeze-thaw action mainly increased soil erodibility and made it more vulnerable to erosion by destroying soil structure, changing soil water content, bulk density, shear strength and aggregate stability, etc.

4.1. Soil Moisture

Soil freeze-thaw process was accompanied by water and heat migration and transfer, and the composition of solid, liquid and gas was the basis of water phase change (Figure 1a) and migration in the process of freeze-thaw, freeze-thaw cycle made the water and heat conditions in the soil have complex transfer changes [26,47]. In the process of freeze-thaw, soil water content was mainly affected by the distribution of soil water potential and ground temperature [48]. The pore water in the soil medium (Figure 1b) froze below 0 °C and the liquid water phase changed to ice, increased in volume by 9% [49]. Under the drive of water potential, soil water moved in the form of liquid phase water and vapor phase water [50]. The formation of ice compressed the surrounding particles, and the expansion

of ice crystals in soil pores during freezing destroyed the connections between soil particles (Figure 1c), thus damaged the soil structure [51,52].

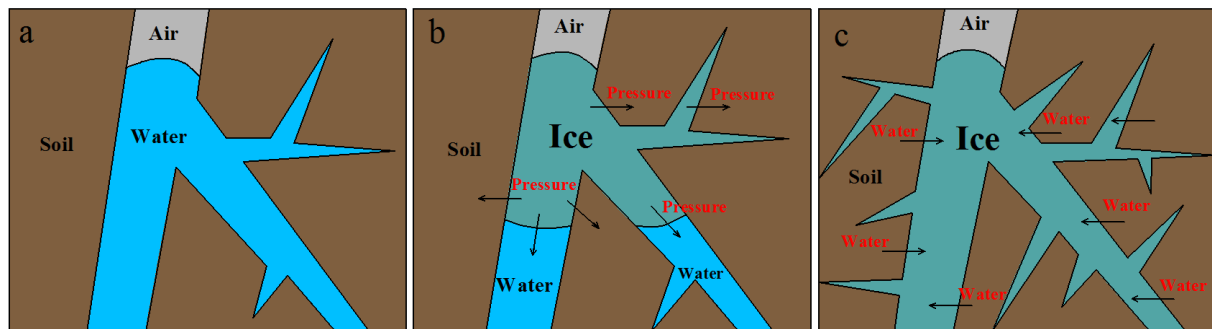


Figure 1. The phase change and migration of soil moisture during freezing process. (a) Three-phase distribution of solid, liquid and gas in soil before freeze; (b) During the freezing process, the upper layer of soil pore water begins to freeze, producing pressure on the surrounding soil and the lower layer of water; (c) After the pore water freezes, ice crystals grow and destroy the soil structure [51].

During the freezing process, the soil moisture moved from the lower layer of the soil with high water potential to the upper frozen layer of the soil with low water potential, and the soil moisture in the frozen layer increased gradually. During the thawing process, the melting water evaporated from the surface of the soil and moved to the lower layer driven by the gravity gradient, resulted in the accumulation of water in the vertical soil profile [53]. These changes were more significant in soils with higher water content and higher freeze-thaw cycles [54].

4.2. Soil Structures

The fundamental cause of soil structure destruction by freeze-thaw was the reaction forces of water phase change, ice crystal growth and water migration on soil particles and pores [55,56]. Generally, soil porosity increased slowly with the increase of freeze-thaw cycles, while bulk density changed in the opposite way [57]. Starkloff et al. [58] found that in both silt and sandy soils freeze-thaw had a negative effect on properties of macropore (Figure 2). In loess soils, porosity appeared to decrease and then rise to a stable state after 10 cycles [59]. With the increased of freeze-thaw cycles, the soil macroporosity presented a trend of decrease-increase-decreased, the decrease of soil macroporosity by freeze-thaw cycles was mainly formed in the first freeze-thaw cycle [60]. Sahin et al. [61] found that bulk density of saline-sodic soil would increase when the initial value was lower, while soils with larger initial values would become looser in structure and decreased in bulk density. In contrast, soils with moderate bulk density will not change significantly in this regard. So, development of a stable state in soil bulk density was related to soil texture and initial bulk density [62].

Soil aggregates were important components of soil structure, and their composition and stability were important evaluation indexes of soil erodibility [63,64]. Many studies have been carried out at home and abroad on the effects of freeze-thaw action on the stability of aggregates, and many achievements have been made, but the results vary greatly (Table 1). The influence of freeze-thaw action on the stability of aggregates was determined by the degree of freeze-thaw in soil [21]. The number of freeze-thaw cycles and the initial soil water content were the main factors affecting the degree of freeze-thaw [65]. Therefore, the effects of freeze-thaw on soil aggregates should be analyzed according to soil moisture, texture and properties.

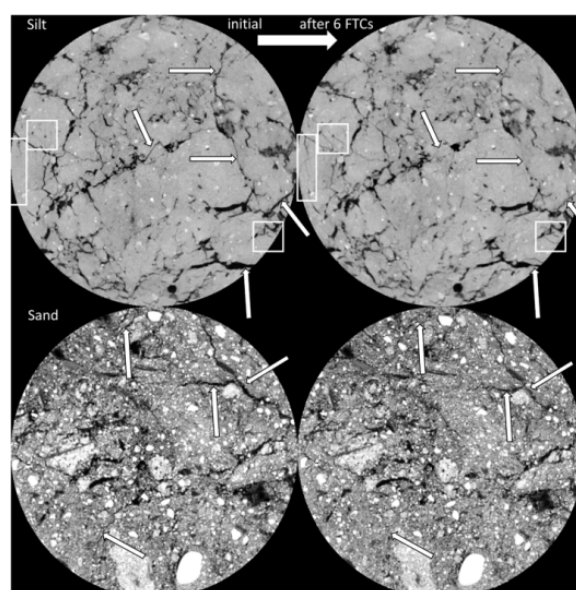


Figure 2. Horizontal cross-section through four greyscale images. Note: The upper two are images of the more compacted lower regions of a silt sample before the first FTC (left) and after six FTCs (right). The lower images show the same for a sand sample. Arrows show pores which became thinner and rectangles show where new voids occurred [58].

Table 1. Researches of the effect of freeze-thaw on soil structure.

Number	Authors	Soil Types	Main Results	Citations
1	Viklander	Silty soil	Soil porosity ratio decreased to a constant value after 1–3 FTCs	[57]
2	Xiao et al.	Loess soil	Soil porosity appeared to decrease and then rise to a stable state after 10th cycles	[59]
3	Jiang et al.	Black soil in China	The soil porosity increased from 7.8 to 23.34% after 20th FCTs	[66]
4	Staricka & Benoit	Clay loam	Moisture content was the most important factor influencing aggregate stability	[67]
5	Lehrsch	Black soil in China	Soil aggregates at the soil surface rose with increasing freeze-thaw cycles, peaking after 2–3 cycles	[68]
6	Bochove et al.	Clay soil	The negative effects of freeze-thaw on aggregates stability were more pronounced for aggregates larger than 0.25 mm.	[69]
7	Oztas & Fayetorbay	Soils formed on different parent materials	Wet aggregate stability increased when freeze-thaw cycle s increased from 3 to 6, but decreased after that point. The percentage of water-stable aggregates in all soils at -18°C was less than that at -4°C .	[70]
8	Kvaerno & Oygarden	Wet sieve or rainfall	Stability of all soil aggregates significantly decreased following freeze-thaw induced by wet sieve or rainfall	[12]
9	Wang et al.	Clay loam	By experimenting with 96 groups, the water stability of aggregates in clay loam decreased following freeze-thaw	[71]
10	Edwards	Loam, sandy loam and fine sandy loam	In loamy soils and fine sandy loam soil with high contents of aggregate, content of aggregate larger than 4.75 mm decreased, while that of aggregate lesser than 0.5 mm increased from 19 to 70% following 15th freeze-thaw cycles.	[19]
11	Li, G.Y. and Fan, H.M.	Black soil in China	Water-stable aggregates of the four larger particle size groups (>5 , 5–3, 3–2, and 2–1 mm) decreased while those of the two smaller particle size groups (1–0.5 and 0.5–0.25 mm) increased with the increase of freeze-thaw cycles.	[21]
12	Jin et al.	Black soil in China	Aggregate porosity increased with increasing freeze-thaw cycles, ranging from 32.4 to 41.4%. Aggregate porosity was important in the aggregate stability under freeze-thaw condition.	[72]

4.3. Soil Properties

Soil strength, especially shear strength was an important index to estimate soil resistance to erosion. After repeated freeze-thaw cycles, the shear strength of undisturbed soil appeared to be similar to that of remolded soil [73]. And the permeability of soil increased desperate the change in void ratios and decreased the shear strength of soft soil [74]. Dong [75] observed shear strength of loess generally reached its lowest point following 3–5 freeze-thaw cycles, and tended to stabilize gradually with constant water content. Soil cohesion and uniaxial compressive strength of Qinghai-Tibet Plateau decreased as the volume and porosity of the soil increased after experiencing various freeze-thaw cycles, especially in the first six freeze-thaw cycles [9]. The effect of freeze-thaw cycles on the shear strength of silt loam soil was greater than that of freezing temperature [76]. Generally, as freeze-thaw cycles increased, cohesive forces between soils particles were gradually destroyed, the particles were rearranged, soil structure become looser, and the mechanical properties and microstructure of soil changed significantly. Additional deformation occurred when external pressure exceeded gravity stress. However, additive (e.g., lime, fibers, quartz sands and sodium silicate et al.) can improve the strength behavior of frozen-thawed soil, and the reinforcing mechanism was still not fully understood [77,78].

The formations of soil aggregate structure depend on organic matter and nutrients released by mineralization [51]. Freeze-thaw breaks soil macro-aggregates, exposes carbohydrates, fatty acids and sterols, and increases their contact with and utilization by microorganisms. Extractable nutrients have been observed to increase by 2–3 times [79]. Moreover, the increase of fine particulate or clay, which has large surface areas, has strong adsorption capacity for organic matter, resulting in redistribution or dissolution of organic matter [80]. During freeze-thaw process, water transport can mobilize organic matter, and thus organic matter at the frozen surface increased with higher moisture content [81]. The phase changes of water lead to contraction of organic matter, destruction of bonds with soil particles, and led to increased release of organic matter. At low temperatures, the death of some microbial cells releases available carbon sources such as sugars and amino acids and increases the release of dissolved organic matter [82].

4.4. Soil Erodibility

Soil erodibility reflect the sensitivity of soil to erosion, and its value was relatively constant for specific soil species (or subspecies), but it depends on the change of soil properties [83]. During the thawing period in the alpine region, soil erodibility could reach the minimum value of the whole year [84]. Sun et al. [25] found that rill erodibility was negatively correlated with water stable aggregates and shear strength, but positively correlated with soil porosity under the condition of freeze-thaw by means of indoor simulation freeze-thaw and runoff scour tests (Table 2). When the snowmelt amount was large, the overland current or concentrated water flow increased, which promoted the development of rills [41]. Knapen et al. [15] found that the changes of soil moisture content, cohesion and other properties were the main reasons that affected the seasonal changes of soil erodibility. Studies have found that when the silt content was high, it was easy to form capillary, water transport was faster, and the damage degree of freeze-thaw will increase. Therefore, the sensitivity of silt erodibility to freeze-thaw was the highest [36]. However, some scholars have found that even sandy soil, as long as the soil compaction was moderate, still had a high sensitivity to freeze-thaw [85]. The mulching of straw ($60 \text{ g} \cdot \text{m}^{-2}$) reduced the runoff coefficient from 65.6 to 50.5%, the sediment concentration from 16.7 to $3.6 \text{ g} \cdot \text{L}^{-1}$ and the soil erosion rates from 439 to 73 g. So, mulching could be used as a useful management practice to control freeze-thaw action and soil erosion rates by slowing down water and heat transfer transport and reducing runoff generation [86]. Hence, due to heterogeneity in experimental conditions, soil textures, land use and degree of freeze-thaw, research conclusions on the effects of freeze-thaw on soil erodibility indices varied widely and have even been opposite.

Table 2. Correlation between soil erodibility and soil physical and chemical properties under freeze-thaw conditions.

Erosion Resistance	Correlation	Clay	Silt	Sandy	Bulk Density	Porosity	Generalized Soil Structure	Water Stable Aggregates	Shear Strength	Hardness	Soil Organic Matter
Soil erodibility	Correlation Coefficient Value of <i>p</i>	−0.64	−0.03	0.64	−0.95	0.95	0.80	−0.98	−0.96	−0.86	−0.01
		0.36	0.97	0.36	0.054	0.047 *	0.20	0.02 *	0.04 *	0.14	0.99

Note: * indicates soil erosion resistance is significantly correlated with soil physical and chemical properties at $p = 0.05$ level [25].

5. Conclusions

Areas with seasonal freeze-thaw were widely distributed and were generally found to have poor soil and undergo severe erosion. Freeze-thaw actions indirectly affect soil erosion, and its largest contribution to soil erodibility occurs during thawing of freeze-thaw cycles. The effect of freeze-thaw on soil properties should be further investigated, in order to provide valuable information on factors affecting soil erosion and erodibility. Multiple tests could be carried out to compare and corroborate the results of laboratory simulations and field experiments. Different scales Monitoring of freeze-thaw cycles and soil and water loss during periods of thawing should be conducted to produce evidence of the magnitude of erosion and provide a basis for the promotion of studies on the mechanisms of erosion.

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