https://doi.org/10.17221/143/2020-SWR

Effects of freeze-thaw on soil properties and water erosion

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Citation: Sun B., Ren F., Ding W., Zhang G., Huang J., Li J., Zhang L. (2021): Effects of freeze-thaw on soil properties and water erosion. Soil & Water Res., 16: 205–216.

Abstract: Freeze-thaw erosion occurs primarily at high latitudes and altitudes. Temperature controlled freeze-thaw events dislodge soil particles and serve as a catalyst for erosion. This review paper provided an overview of the effects of freeze-thaw on soil properties and water erosion. The process of freeze-thaw cycles results in temporary and inconsistent changes in the soil moisture, and affects the soil's mechanical, physical and chemical properties, such as the soil moisture content, porosity, bulk density, aggregates stability, shear strength and organic matter content and so on. The variation trend and range of the soil properties were related to the soil texture, water content and freeze-thaw degree. Furthermore, the soil erosion was affected by the freeze-thaw processes, as thawing and water erosion reinforce each other. However, research of different experimental conditions on indoor simulations have numerous limitations compared with field experiments. The use of indoor and field experiments to further reveal the freeze-thaw effect on the soil erosion would facilitate improved forecasting.

Keywords: erosion amount; erosion process; freeze-thaw cycles; soil properties; soil moisture transport

Soil erosion has emerged as a major environmental problem worldwide, which can lead to soil degradation and reductions in land productivity, affecting the agricultural production and food security (Luca 2015; Šarapatka et al. 2018). With the development of soil erosion research, a lot of research has been carried out on the effects of soil texture, organic matter content, vegetation and gravel cover on slope erosion and sediment yields (Kadlec et al. 2012; Bashari et al. 2013; Qiu et al. 2021). Temperature controlled freeze-thaw (FT) events dislodge soil particles and serve as a catalyst for soil erosion at high latitudes and altitudes (Fu et al. 2016; Sun et al. 2018).

As a result of frequent changes in the temperature, freeze-thaw cycles (FTCs) have led to variations in various physicochemical properties of soils and rocks, and it has occurred at high altitudes and latitudes in cold regions to a greater extent (Ban et al. 2016). As reported in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the mean precipitation and surface temperature of the world have changed significantly in recent years, and these changes are projected to continue throughout the 21st century. Therefore, the FT effects are likely to be exacerbated, along with their related effects on human survival and development (Zhang & Liu 2018).

Supported by the Program of National Key Research and Development of China (2019YFC1510705-05), the Fundamental Research Funds for Central Public Welfare Research Institutes (Grant No. CKSF 2019179/TB, CKSF 2019292/TB, CKSF 2021487/TB, CKSF 2021447/TB), and the National Natural Science Foundation of China (42077062, 41271303, 41807066 and 41877082).

https://doi.org/10.17221/143/2020-SWR

Although freeze-thaw erosion (FTE) is unlikely to remove all topsoil, it can contribute to water erosion. Soil erodibility is an important property which could be used to evaluate the sensitivity to soil erosion. FT affects the soil's physical and chemical properties, such as the soil structure, water stability of soil aggregates, and shear strength, among others (Kværnø & Øygarden 2006; Li & Fan 2014). In areas with seasonal FT, it can damage the slope soil stability, increased soil erodibility, and can lead to an increase in the effective material source for other erosion forces. Thus, the cumulative erosion of topsoil is closely related to the degree of the FT. It is known that soil erodibility follows obvious seasonal trends, whereby the greatest erosion is observed during early spring (Zhang et al. 2001). Furthermore, complex relationships have been observed between the FT and water erosion (Sun et al. 2020). This facilitates large degrees of erosion even with low snowmelt or precipitation. Indeed, the distribution range of the effective material sources for other erosion forces is wider than that of the FTE (Zhang et al. 2009). Therefore, the contribution of FT to water erosion cannot be undervalued.

In this review, a reference for future investigations was provided, based on the current state of research on soil erosion, particularly the FT effect. Additionally, it may serve as a crucial reference for the revision of current erosion prediction models for areas with FTCs, and to further elucidate the intricate relationship between FT and water erosion.

Effects of freeze-thaw on soil properties

Soil moisture content and water transport

The process of soil FT is accompanied by the hydrothermal transport and transfer, and the composition of the solid, liquid and gas phase is the basis of water phase transition and migration in the FT process (Mohanty et al. 2014; Fu et al. 2016). Different densities of water and ice could cause frost heaving, thawing and subsidence in the soil. Phase changes in the soil moisture between the soil particles are the main factor governing soil properties under the FT conditions. Therefore, continuous modifications in the soil moisture during the FTC drives the changes in the physical, chemical and biological properties of the soil (Formanek et al. 1984; Dagesse 2010).

The pore water (Figure 1A) in the soil medium froze below 0 °C, the liquid water phase turns into ice, and the volume increases by 9% (Zhao et al. 2004). The formation of ice squeezes the surrounding particles, and the expansion of ice crystals in the soil pores during freezing breaks the connection between the soil particles, which destroys the soil structure (Dagesse 2010) (Figure 1B). Generally, the movement of the soil moisture in the liquid or gaseous state is driven by the water potential of the soil during the

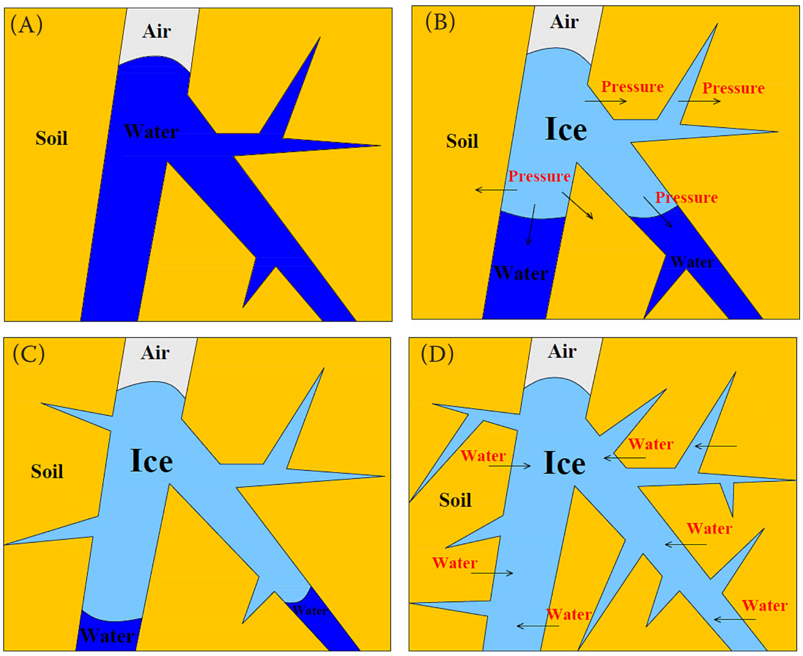

Figure 1. Soil moisture phase change and migration during the freezing-thawing process (Gao et al. 2016)

https://doi.org/10.17221/143/2020-SWR

FT process (McMinn et al. 2003; Zhao et al. 2015). Freezing first occurs in the surface of the soil, and then gradually extends downwards (Fu et al. 2016) (Figure 1C). Moreover, water is transported from the surroundings, which have high water potentials, to the freezing interface (Figure 1D). This movement of moisture to the interface gradually increases the moisture contents of the frozen layer (Wang et al. 2019). During thawing, the melted water on the surface evaporates and moves downward to the layers with the lower water potential, resulting in a reduced soil moisture content (Chen et al. 2013). These shifts are more significant in soils with higher moisture contents and high FTC counts (Perfect et al. 1990). According to the characteristics of temperature changes and the hydrothermal transfers in the active layer of the permafrost on the Qinghai-Tibet Plateau, Zhao et al. (2000) found that the hydrothermal coupling characteristics in the active layer were the most complex in the process of melting and initial freezing, and the moisture migration was the greatest.

Soil's physical properties

Soil bulk density and porosity. The reaction forces generated during water phase transitions – such as ice crystal growth and water migration (Figure 1) – result in the destruction of the soil structure during the FTCs (Zheng et al. 2015). Frequent phase changes slowly alter the porosity ratio of the soil, causing modifications in the bulk density (Jie & Tang 2018). Through CT scanning and digital image processing technology, the three-dimensional structure of the soil aggregates was visually studied, and the connectivity and complexity of the internal pores of soil aggregates were quantitatively characterised (Figure 2). The black soil porosity increased from 7.8% to 23.34 % after the 20 FCTs (Jiang et al. 2019).

In general, the development of a stable state in the soil bulk density is related to the soil texture and initial bulk density (Sahin et al. 2008; Xiao et al. 2014; Starkloff et al. 2017). The bulk density of saline-sodic soil increases when the initial value is lower, while soils with larger initial values become looser in the structure and decrease in the bulk density. In contrast, soils with a moderate bulk density do not change significantly in this regard (Sahin et al. 2008). Starkloff et al. (2017) found that in both silt and sandy soils, the FT had a negative effect on the macropore properties (e.g., reduction in the macroporosity, thickness and specific surface area

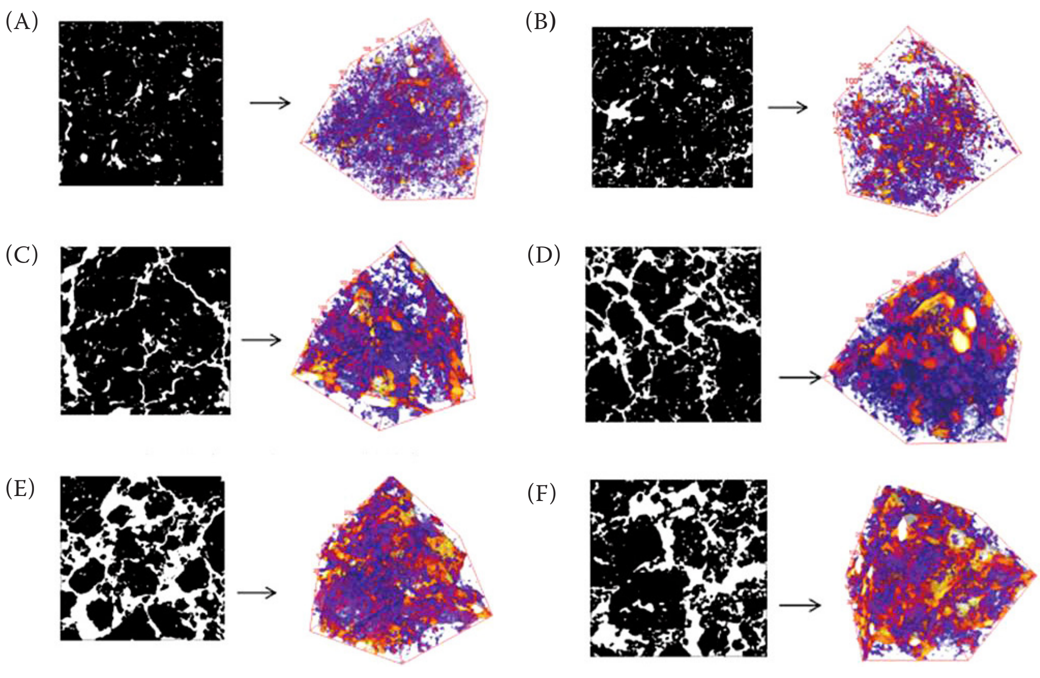

Figure 2. 2D and 3D visualisations of the soil aggregate structures under different freeze-thaw cycles (Jiang et al. 2019): before the freeze-thaw (A), after the first freeze-thaw cycle (B), after 5 freeze-thaw cycles (C), after 10 freeze-thaw cycles (D), after 15 freeze-thaw cycles (E), after 20 freeze-thaw cycles (F)

The white part of the two-dimensional image is the pore, and the black part is the solid particle; the yellow part of the three-dimensional image is the cube edge pores, and the purple part is the inner pores of the macropores). In loess soils, porosity appears to decrease and then increase to a stable state after 10 cycles (Xiao et al. 2014). With increased FTCs, the soil macroporosity presented a decreasing-increasing-decreasing trend, the decrease in the soil macroporosity by FTCs was mainly formed in the first FTC (Zhao & Hu 2020). However, some scholars have also found that independent of whether the initial soil structure was loose or dense, the soil porosity ratio decreases to a constant value after 1–3 FTCs, which range from 0.31 to 0.40 (Viklander 1998).

On the other hand, the moisture content is also an important factor that affects the soil bulk density and porosity. A higher moisture content and moisture transport potentiates the FT process, causing greater frost heave and destruction of the soil structure, and results in larger changes in the soil bulk density and porosity (Wang et al. 2020). Research has shown that after 15 FTCs, the bulk density of a black soil decreased by 0.053, 0.050 and 0.058 g/cm^3, the porosity ratio increased by 1.749%, 1.636% and 1.916%, respectively, when the soil's initial moisture content was 20%, 30% and 40% (Liu 2009). Therefore, the effects of the FT on soil bulk density and porosity should be analysed according to the soil moisture, texture and properties.

Soil aggregate structure. Soil aggregates are important components of the soil structure, as their composition and stability influence the soil erodibility (Barthes & Roose 2002; Zádorová et al. 2011; Li & Fan 2014). Since the 1950s, many studies have investigated the effects of the FT action on the stability of soil aggregates. However, the results have varied quite dramatically, with both positive and negative effects (Table 1).

Table 1. Research results of the effect of the freeze-thaw (FT) on the soil aggregates

No.	Reference	Soil types	Main results
1	Mutchler and Carter (1983)	stability of black soil aggregates	Initial soil moisture influenced stability the most, followed by the freeze-thaw cycle (FTC) times and freezing temperature.
2	Perfect et al. (1990)	powder loam soils	FTCs increased the soil aggregate stability, but the magnitude of the increase was affected by the initial moisture.
3	Staricka and Benoit (1995)	clay loam	Moisture content was the most important factor influencing the aggregate stability.
4	Lehrsch (1998)	0–15 mm soil aggregates of black soil	Soil aggregates at the soil surface increased with the increasing FTCs, peaking after 2–3 cycles.
5	Bochove et al. (2000)	clay soil	The negative effects of the FT on the aggregate stability are more pronounced for an aggregate larger than 0.25 mm.
6	Oztas and Fayetorbay (2003)	soils formed on different parent materials	Wet aggregate stability increased when the FTCs increased from 3 to 6, but decreased after that point. The percentage of the water-stable aggregates in all the soils at –18 °C was less than that at –4 °C.
7	Kværnø and Øygarden (2006)	wet sieve or rainfall	Stability of all the soil aggregates significantly decreased following the FT induced by a wet sieve or rainfall.
8	Wang et al. (2007)	clay loam	By experimenting with 96 groups, the water stability of the aggregates in clay loam decreased following the FT.
9	Sahin et al. (2008)	saline-sodic soils mixed with sewage sludge or fly ash	Soil aggregate stability was determined by the degree of the FT, which, in turn, was mainly dictated by the number of FTCs and initial soil moisture.
10	Edwards (2010)	loam, sandy loam and fine sandy loam	In loamy soils and fine sandy loam soils with high contents of aggregate, the content of aggregate larger than 4.75 mm decreased, while that of aggregate smaller than 0.5 mm increased from 19% to 70% following 15 FTCs.
11	Li and Fan (2014)	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 an increase in the FTCs.
12	Jin et al. (2019)	black soil in China	Aggregate porosity increased with the increasing FTCs, ranging from 32.4% to 41.4%. The aggregate porosity was important in the aggregate stability under the FT condition.

https://doi.org/10.17221/143/2020-SWR

In addition to the soil texture, the times of the FTCs and test methods, and the soil moisture conditions had different effects on the soil aggregate stability (Li & Fan 2014). Without water supplementation, the content of dry sieve aggregates (> 5 mm) and wet sieve aggregates (> 0.25 mm) increased 7.98–29.41% and 36.11–44.44%, respectively, whereas opposite results were obtained when water was supplemented which decreased by 10.88–25.52% and 1.02–3.40%, respectively (Wang et al. 2010). This was likely due to the increase in the soil moisture, as water was frozen as ice crystals and expanded in the soil pores, which resulted in the destruction of the cohesive forces and the reduction in the aggregate stability (Figure 1C). When the soil moisture decreased, soil particles shrank, and the adhesion of intergranular increased as the soils dry. Generally, soil moisture migration tends to concentrate in the upper frozen soil, while deeper layers have decreased moisture and become drier throughout the FTC (Fu et al. 2016). These opposite processes occur at different locations, so a differing stability of the soil aggregates can be found in the same soil.

Soil mechanical properties

Soil strength, especially the shear strength, is an important index to estimate the soil resistance to erosion (Zhou et al. 2018). After 15 FTCs, the cohesion of loess decreased significantly from 51.20 to 25.11 kPa, while the internal friction angle changed from the original 11.49° and increased to 21.8°. Moreover, after 50 FTCs, the shear strength of the undisturbed loess was close to that of the remoulded loess (Ni & Shi 2014). However, Dong et al. (2010) observed the shear strength of the loess generally reached its lowest point following 3–5 FTCs, and tended to stabilise gradually with a constant water content. The effect of FTCs on the soft-soil results in the permeability of the soil increasing despite the change in the void ratios and decreases the shear strength of the soft soil. Also, increasing the FTCs showed a higher ductility nature in the soil (Karumanchi et al. 2020). The soil uniaxial compressive strength of the Qinghai-Tibet Plateau has decreased from 252.3 kPa of the unfrozen soil to 177.3, 98.7, 86.4 kPa as the volume and porosity of the soil increased after 1, 3 and 6 FTCs (Xie et al. 2015). Compared to the unfrozen soil, which did not experience the FTCs, the highest decrease in the rate of the elastic modulus was about 26–45% and it reached at 32–45% for failure strength. The cohesion decreased after the first few FTCs and then kept nearly stable after about 9–12 cycles. The effect of the FTCs on the shear strength of the silty loam soil was greater than that of the freezing temperature (Liu et al. 2016).

In areas experiencing seasonal frost, to improve the mechanical behaviour under FT conditions, some effective and reliable techniques have been reported, such as adding cement, lime, fly ash, and fibre to the soil. Nguyen et al. (2019) found the FTCs significantly decreased the mechanical strength of the samples and lime treatments were used to improve the FT resistance of fine-grained soils by X-ray computed tomography observations. The addition of both bassanite and coal ash improved the strength and durability of the stabilised soils significantly, and retained 65–85% strength after the first to second FTC compared to corresponding non-frozen stabilised soils and when no additives were used, it was about 50% (Shibi & Kamei 2014). The inclusion basalt fibre (0.75% of the dry weight of the soil) to the weak soil increased the strength by 41.2% before freezing and by 27.1% after the 15 FTC (Kravchenko et al. 2018). Likewise, the unconfined compressive strength of a straw fibre-reinforced soil decreased exponentially with the number of FTCs. After 20 FTC, the peak stress of the unreinforced samples decreased by 37.58%, it was approximately 25.55% and 23.20%, respectively, for the reinforced samples with 0.2% and 0.4% fibre content (Liu et al. 2020). Similar to natural fibres, artificial fibres, such as polypropylene, glass, and steel fibres, have been used to reinforce FT soil because of their high tension and corrosion resistance (Tang et al. 2007; Zaimoglu 2010).

Generally, when the soil structure becomes looser, the mechanical properties and microstructure of the soil change significantly (Figure 2), and additional deformation occurs when external pressure exceed the gravity stress after the FTCs (Liu et al. 2016; Karumanchi et al. 2020). However, additive components could improve the strength behaviour of FT soils, though the reinforcing mechanism is still not fully understood (Nguyen et al. 2019; Liu et al. 2020).

Soil chemical and biological properties

FT not only affects the soil structure, but may also change the chemical and biological properties by promoting soil nitrification, releasing dissolved organic acids and affecting the microbial activity and so on. As such, the variation in the soil organic matter under FT conditions has been affected by

https://doi.org/10.17221/143/2020-SWR

physical, chemical and biological actions (Cheng et al. 2018). FT regulates the mineralisation of soil organic matter by altering the soil particle size as well as the microbial abundance and activity by affecting the temperature change rate of the medium, and the moisture and migration characteristics of nutrients (Gao et al. 2016). FT breaks the soil macroaggregates, exposed carbohydrates, fatty acids and sterols, and increases their contact and utilisation by microorganisms. Extractable nutrients have been observed to increase by 2–3 times (Song et al. 2016). Moreover, an increase in the fine particulate or clay, which have large surface areas and a strong adsorption capacity for organic matter, result in the redistribution or dissolution of the organic matter (Mohanty et al. 2014). During FT, water transport can mobilise the organic matter, and thus the organic matter at the frozen surface increases with a higher moisture content (Slavik et al. 2012). The phase changes of water lead to the contraction of the organic matter, the destruction of the bonds with the soil particles, and lead to an increased release in the organic matter. At low temperatures, the death of some microbial cells releases the available carbon sources such as sugars and amino acids and increases the release of the dissolved organic matter (Grogan et al. 2004).

At freezing temperatures, the pore water freezes, and the unfrozen water migrates to the ice surface, result in the dehydration and death of microorganisms (Gao et al. 2016). In addition, due to the lack of water, the mobility and availability of the substrate is limited, which makes it difficult for microorganisms to maintain their activity under such conditions, resulting in a decrease in the microbial biomass (Hu et al. 2011). However, with an increase in the FTCs, microorganisms adapt to the environment by changing the length of the carbon chain of the matrix or the saturation of fatty acids, the fungi and bacteria recovered as much as 93% of the soil activities after 8 FTCs (Feng et al. 2007). Repeated FTCs can change the soil microbial community from a fungal community with a high C/N ratio to a bacterial community with a low C/N ratio, thus, changing the decomposition and retention ability of the organic matter in the soil (Larsen et al. 2002).

These above studies indicated that there was no inevitable trend in the change of the soil's chemical and biological properties in the FT environment. Due to different conditions, such as organic matter in the environmental medium, their reactions to the FT process were also different, and ultimately led to a different release of organic matter and pollutants in the medium. Overall, FTCs appeared to have consistent effects on the properties of the soil, including an increased porosity, a decreased bulk density (BD), changes in the soil moisture (SM) content, shear strength and aggregate stability, and ultimately an increased soil erodibility. Therefore, FTCs result in more erosion of vulnerable soils. However, due to the heterogeneity in experimental conditions, the soil textures and degree of the FT, the research conclusions on the FT effects on the soil erodibility varied widely and were even opposite.

Effects of freeze-thaw on soil erosion

In seasonal FT regions, the FT activity could alter the properties of the slope's surface soil, especially those which influence the soil erodibility, and soil erosion will increase sharply when heavy rainfall occurs (Coote et al. 1988; Wang et al. 2020). Chow et al. (2000) observed that soil erosion during periods of thawing was 2–3 times higher than that of the other seasons. Frozen soil melts from the surface downwards, and an impermeable layer forms at the boundary while the underlying soil remains frozen. Due to the decreased friction at this border, water could easily flow, and soil erosion could occur even during periods of low rainfall (Wang et al. 2018; Gatto 2000). Via laboratory simulation experiments, Ferrick and Gatto (2005) found that the amount of soil erosion and the size of the erosion gully were greater in the FT than the unfrozen soil, with values that generally increased with the slope and flow. A dramatic increase of 1.02, 2.4, 3.0 and 5.0 times in the average sediments after the FT than with the unfrozen period with 4–5%, 16–18%, 27–30%, 37–40% soil moisture was seen, respectively. Barnes et al. (2016) used an erosion needle method to monitor the impact of the FT on the gully erosion of a clay soil in the field over prolonged periods of time, and found that the FT significantly increased the erosion of the gullies, especially the lateral walls. The change in the FT resulted in a 9.78 mm mean erosion pin length, but in the absence of FT days, the erosion was projected at 6.51 mm.

In the loess plateau region of China, the runoff yield time of the FT hillslope was delayed by 30.18% and the runoff rate of the FT hillslope was 16.69% lower while the sediment yield of the FT slope was 4.67% higher than that of slope with no FT (Li et al. 2015). In addition, the infiltration rate of the FT slope was greater than that of the no FT hillslope and the stable infiltration rate of the FT slope was twice that of the no FT hillslope (Wang et al. 2018). Through indoor simulations of FTCs with rainfall, Wei et al. (2015) demonstrated the sediments yield on the slope increased with the soil moisture content and the FTCs. When the soil moisture mass fraction was 10%, and the FTCs were 3 and 6, the amount of the total runoff generation increase were 3.52% and 4.71%, respectively, and the amount of the total sediment yield increase were 6.13% and 16.95%, respectively. Soil detachment was the initial stage of soil erosion, and the most affected by the FT activity. In addition to the gradient and flow discharge, the initial soil moisture and FT strength were the main factors with a 6.92% and 3.67% contribution, which affected the soil detachment capacity under the FT conditions by the statistical analysis with the help of the Taguchi method (Sun et al. 2018). The soil detachment capacity basically increased with an increase in the slope and flow rate. The mean value after the FT (5.28 ± 2.48 g/(cm^2·min)) was significantly higher than before the FT (2.39 ± 1.71 g/(cm^2·min)). The variation trend in the soil detachment capacity with the times of the FTCs was significantly different. Only when the slope and flow rate were both small (10° and ≤ 18 L/min) or large (15° and ≥ 18 L/min), the trend increased significantly (Figure 3) (Sun et al. 2020). Furthermore, the flow velocity was about 25%, 30%, and 40% higher on the frozen soil than on the thawed slope on 5°, 10°, and 15° slopes, respectively, and about 30% higher over the frozen slope at all flow rates. Similar trends in the slope velocity were observed as rock content increased, as measured with an electrolyte tracer method (Ban et al. 2017). On the slope scale, the FT and rainfall simulation have demonstrated that an increased thawing depth, initial moisture content, and FTC times results in the increased erodibility of black soils (Fan et al. 2010; Liu et al. 2017). At the watershed scale, the FT could lead to the development of shallow gullies from rills, and increased erosion at gully heads. These result in the increased gravity erosion of the gully edge walls, along with the formation of debris due to the collapse of the gully edge walls, which can produce greater erosion with increased rainfall (Oygarden 2003; Nadal-Romero et al. 2008).

To sum up, the FT action aggravated the development of the gully erosion and increased the risk of soil erosion on the slope and watershed scale. In fact, the soil FT and water erosion mutually aggravate each

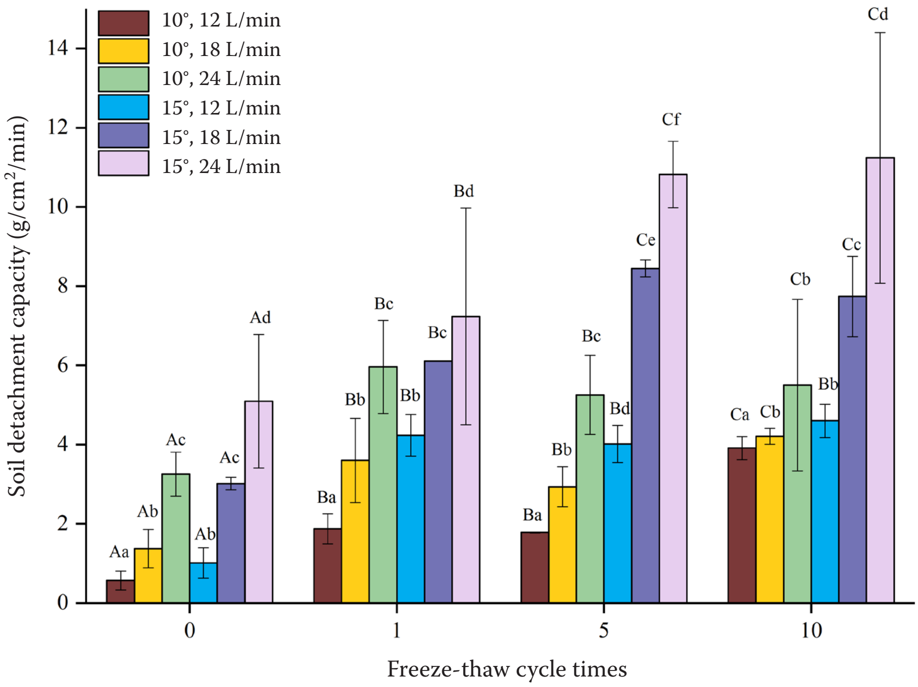

Figure 3. The relationship between the soil detachment and the freeze-thaw cycles (Sun et al. 2020)
Different capital letters indicate a significant difference in the test results among the different freeze-thaw cycle times at a 0.05 level, and the different lowercase letters indicate a significant difference in the test results among the same freeze-thaw cycle times at a 0.05 level

https://doi.org/10.17221/143/2020-SWR

other (e.g., the results of water erosion will affect the degree of FT action). During FTCs, changes in the thaw depth directly impact the snowmelt infiltration and rainfall runoff in the soil, which, in turn, affect the infiltration of the runoff and sedimentation on the slopes (Zhang & Liu 2018). However, during water erosion, humic and organic matter are lost in the soil surface. Over time, the response of the soil to the FT changes due to the redistribution of the water in the slope, as well as the sediment migration and accumulation. In the thawing period, the FT and water erosion usually occur simultaneously or alternately. Therefore, these phenomena must be accounted for when studying the effects of the FT on water erosion.

Deficiencies of the current research

Insufficient of field experiment

At present, the cost control and practicality have led to indoor FT simulations to be the main method used to assess the impact of the FT on soil properties and erosion (Gao et al. 2016). However, a natural FT is different from indoor studies in multiple ways. For example, the ambient temperature changes gradually during the soil freezing and thawing in the field, while indoor temperatures are generally constant. The results of the two-way studies are hardly comparable (Table 2). Moreover, the natural variability of this aspect in the field is difficult to match in simulations (Henry 2007).

Soil moisture is a key factor affecting the FT degree. During the FTC, changes in the soil water potential lead to water migration, modifying the degree of the FT of the soil for the next cycle (Fu et al. 2016). In indoor FT simulations, soil samples are generally filled with specific volumes in containers – a closed system – which behave differently from open systems in the field with water inputs and outputs from various sources (Ferrick & Gatto 2005). Furthermore, even if open systems could be simulated, the specific water supply or loss cannot be controlled during the FT. Indoor simulations are also affected by the collection and loading of soil samples, the FT direction, and the effect of the side walls (Henry 2007; Zhang & Liu 2018). Consequently, field experiments are required to validate and verify observations made in indoor simulations.

Differences in experimental conditions

Factors such as the FTC times, soil moisture content and temperature affect the FT degree, and have been

Table 2. Studies on soil erosion under different freeze-thaw (FT) test conditions

No.	References	FT way	Soil types	Number of cycles	Main results
1	Chow et al. (2000)	field	gravelly loam soil	thawing season	The soil erodibility factor was two to three times higher during March and April, which coincides with the winter-spring thaw period, than during the rest of the year.
2	Ferrick and Gatto (2005)	indoor	silt soil	1	Average sediments increased 1.02 to 5.0 times after the FT than unfrozen with 4–30 %, 37–40 % soil moisture.
3	Li et al. (2015)	indoor	loessal soil	1	Runoff rate of the FT hillslope was 16.69% lower while the sediment yield of the FT slope was 4.67 % higher than that of the slope with no FT.
4	Wei et al. (2015)	indoor	loessal soil	3, 6	After 3 and 6 FTCs, the total runoff generation amount increased 3.52% and 4.71%, the total sediment yield amount increased 6.13% and 16.95%, respectively.
5	Barnes et al. (2016)	field	clay soil	thawing season	The change in the FT resulted in a 9.78 mm mean erosion pin length, but in the absence of FT days, the erosion was projected at 6.51 mm.
6	Wang et al. (2018)	indoor	loessal soil	1	The total amount of the sediment yield, the loess slope after the freeze-thaw was 0.9 times of the loess slope without the freeze-thaw.

https://doi.org/10.17221/143/2020-SWR

the focus of most experimental simulations (Table 2). The conclusions of the currently available research varied greatly, likely due to significant differences in the experimental design and conditions (Zhang & Liu 2018). For example, some researchers set the FTCs on the time scale of hours, while others used weeks. For example, Winter et al. (1994) reported a higher microbial biomass in soils stored frozen for 7 days than those stored for 1 day, which may be due to the increased dispersal of the soil aggregates caused by the long-term freezing, resulting in improved efficiency of chloroform fumigation/extraction. Shorter FTCs hinder the extrapolation to long-term trends and cumulative effects (Henry 2007). Furthermore, experiments that employed the same FT conditions have attained varying results regarding properties and erodibility with soils of different textures (Xiao et al. 2014; Starkloff et al. 2017). Therefore, the FT test conditions and soil sample types must be considered in the design of the FT experiments and when comparing results.

Effect mechanism of freeze-thaw on soil erosion

Soil erosion is the combined result of the FT and water in areas which experience annual FT. The mechanisms of water erosion have been well characterised. However, the mechanisms underlying the FT or the combination of the FT and other forces remains unclear (Zhang & Liu 2018). Comprehension of the mechanisms of soil erosion due to the FT would provide an empirical basis for understanding the complex relationships among the FT and other erosion forces, and facilitates the quantification of cumulative erosion (Gatto 2000). Overall, it has been demonstrated that FTCs indirectly influence the degree and intensity of the water erosion of soils by altering their intrinsic properties (Li et al. 2015). To date, research has focused on the effect of the FT on the soil properties, or dynamic changes of the soil erosion processes and severity (Karumanchi et al. 2020). However, the quantitative relationships between the soil erodibility or intensity and soil properties have seldom been evaluated under FT conditions.

CONCLUSION

To sum up, although the FT is a physical process of water phase change, it causes changes in the soil erodibility by affecting the physical structure, chemical properties, microbial population and structure of the medium, and eventually leads to an increase in the soil erosion amounts. The frequent occurrence of global extreme climate events, and the currently available depth of understanding of other forms of erosion means the further investigation of the effects of the FT on erosion in soils with different textures is warranted. Future studies on soil erosion during thawing in seasonal areas with the FT should focus on the following aspects:

(1) Long-term *in situ* studies provide real-world data, but are limited by the lack of control of the system. Combined indoor and field experiments may be a good solution.

(2) To reveal the effect mechanism of the FT on the water erosion, soil properties which affect the soil erodibility should be investigated. This means determining the important relationships between the soil erosion and different degrees of the FT. Quantitative relationships should also be established between the soil erodibility and soil properties in order to provide a reference for soil erosion predictions under FT conditions.

(3) Generally, environments which experience severe seasonal FT are fragile and difficult to control. As human activities have intensified, evaluating and controlling the soil erosion in these sensitive areas has become a priority.

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Received: October 20, 2020
Accepted: April 26, 2021
Published online: June 14, 2021