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Effect of a Freezing-thawing Cycle on Overall and Inter-variability of Runoff and Soil Loss Components for a Loess Soil

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Research

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Abstract

Background: Because control of runoff generation as well as soil loss is influenced by freezing-thawing, proper knowledge and insight into the freezing-thawing process in combination with other hydrological processes is essential for executives and planners. However, such dynamic phenomenon and corresponding consequences have not been studied adequately. The present study was therefore planned to comparatively analyze the effects of a freezing-thawing cycle on hydrologic behaviors of loess soil from northeast of Iran. Towards that, the small-size (0.5×0.50×0.30 m) erosion plots were subjected to a freezing-thawing cycle in accordance with governing conditions on the region of the origin soil. The plots were subjected to a freezing-thawing treatment through inducing cold air until temperature declined to below -20 °C and lasted for three days using a large cooling compartment system, and then were kept in the laboratory with ambient temperature of above 10 °C for two days. The treated plots as well as untreated (control) plots were then exposed to a simulated rainfall with an intensity of 72 mm h^{-1} and 0.5 h duration while they were placed on a slope of 20%.

Results: The results indicated that the hybrid processes of freezing-thawing, and splash and interrill erosions significantly affected runoff generation and soil loss at small plots. So that the time to runoff reduced by 1.65 times in the freezing-thawing treatment compared to that reported for the control treatment. The runoff volume and soil loss also increased at tune of 1.38 and 2.90 times in treated plots in comparison with those measured for the untreated plots. Laboratorial results indicated significant differences ($p< 0.006$) between runoff and soil loss behaviors in plots subjected to a freezing-thawing cycle and those of control condition.

Conclusion: The performance of ice lenses and freezing fronts and creating near-saturation moisture after completing the cycle were evaluated as the most important factors affecting the different soil behaviors under frozen-thawed cycle.

Highlights

- Effect of a freezing-thawing cycle on soil hydrological behavior was monitored.
- Runoff volume and soil loss significantly increased in small treated plots.
- Changes in soil conditions during freezing-thawing process affected soil hydrology.
- The results helps proper soil and water conservation measures in highland regions.

Background

Natural conditions (i.e., climate change especially the climate warming and humidifying) and anthropogenic interventions increase the engineering risk in cold regions [56]. Soil erosion processes are highly influenced by seasonal climatic fluctuations and soil management practices [4]. The characteristics of soil erosion and its contributors may be different in regions with various terrains and climate features [30]. On sloped fields, water and sediment can be transported downhill as soil loss, runoff and erosion [42]. The high erosion rate of seasonal frozen soils by snow/glacier melt runoff is the primary form of soil erosion in high-altitude and cold regions, such as in America, Europe, Asia and Antarctic Peninsula [5, 15, 22, 46]. So that, the erosion area caused by the freeze-thaw cycle in the Qinghai-Tibet Plateau is approximately 1.64 million km^2 [16]. Along with other factors affecting soil ecosystem susceptibility, the soil freezing-thawing cycle is another serious challenge that causes soil degradation in the lands located in cold areas [17]. Soil freezing-thawing process is a transition phase of soil water in cold and semi-arid areas that influences the soil hydrological behavior. Freezing-thawing processes weakened soil strength by breaking down the structure of soil aggregates to cause more erosion. Further, disruption of soil structure and texture results in a reduction in soil stability and soil particles binding leading to soil degradation. [21] Showed that frequent freeze-thaw cycles over the winter alleviated a majority of soil compaction at the 0-20 cm depth. Detrimental effects of freezing-thawing on soil aggregates have also been reported by [3, 6, 7, 31, 34, 41, 56]. Although, such phenomena repeatedly occur in reality and in the highlands or cold regions, but technology and human activities interfere the governing processes leading to undesirable outcomes of the system [32, 39, 54].

The freezing-thawing cycle of soil is the result of complicated process on the soil surface [14]. During cold seasons, when heat is lost from the soil surface due to air temperature dropping, the soil water content begins to freeze [13], and after increasing the temperature, the upper layer of soil begins to thaw. The freezing-thawing cycle affects soil physical and chemical properties [20]. The snow and/or glacier melt water runs off the frozen soil and/or thawed soil surface in high erosion regions, which could affect surface or subsurface hydrology [24]. So that, they have key role in soil hydrological behavior [44]. To understand the soil freezing-thawing cycle effects on soil systems, many efforts have been conducted. Generally speaking, soil freezing-thawing cycle leads to destroy the original structures and textures of soil surface layers [49], decrease soil aggregate stability [31] and size of aggregates [11]. Additionally, it migrates soil water [50], loses soil organic matter [53], decreases soil infiltration [6, 23], and increases soil erodibility against splash and rill erosion [11, 6, 7, 41, 36]. These changes in/on the soil under impressed by freezing-thawing cycle could be caused an unbalanced state in soil hydrological behavior such as increasing runoff and soil loss [7, 25, 26, 29]. The frequent freezing and thawing occurred in different highlands of Iran with mean elevation of some 1000 m specifically in the Alborz (top crest at Damavand with elevation of 5610 m) and Zagross (top crest at Dena with elevation of 4409 m) mountain regions mainly extended in northern and western parts of the country, respectively. Bojnurd City located on the foothill of the Alborz tail in northeast of Iran has cold winters and moderate summers. A high level of abandoned drylands, highly sensitive geological formations to erosion, and various forms of water erosion, particularly channelized erosions, are the general conditions of the Bojnurd area [7], which is the representative for erosion prone high land areas in northeastern Iran. Due to the high sensitivity of the loess soil in the area after enduring the winter conditions, various types of water erosion take place after the spring rains. Therefore, elucidating the mechanisms of the freezing-thawing processes and its associated soil erosion processes is essential for soil and water conservation and ecological protection.

The erosion-prone soil formations like loess soil in the cold and semi-arid regions could accelerate the freezing-thawing cycle interruption impacts on soil hydrological behavior [41]. Although, effects of freezing-thawing cycle on physicochemical properties and erosion variation of loess soils, as a representative for erosion-prone lands, has been studied repeatedly [7, 41, 50, 51, 52, 56], the quantitative impacts of freezing-thawing cycle on hydrological behavior of erosion-prone loess soil is still challenging. The results showed that the freezing-thawing cycle often affected the mechanical and engineering properties of the soil and specially decrease the stability of the soil aggregates. Whilst, studying soil hydrologic behavior viz. runoff starting time, time to runoff peak, runoff volume and coefficient, and sediment concentration under different circumstances is vital, which leads to an awareness of the health and sustainability state of soil system [38]. Accordingly, the present study was designed with the aim of comparative and quantitative analyses of runoff and soil loss components, as soil hydrologic behavior indicators, from small-size plots filled by a loess soil under the influence of with and without freezing-thawing cycle under rainfall simulation conditions. Experimental data can help improve our understanding of the phenomenon. The results of the present study can be used for further detailed studies with optimal planning of study variables at larger scales and more complicated conditions under reality.

Materials And Methods

Study soil

The study soil was collected from a rangeland area in Badranlou area (57° 11' 15" E and 37° 32' 10" N) with a general slope of 20% located at 10 km west of Bojnurd City that a part of Kopet Dagh sedimentary basin located in North Khorasan Province, northeast Iran. The elevation of the sampling site was 1020 m above mean sea level. The mean annual precipitation of the study area is some 227 mm. The minimum, mean, and maximum annual temperatures are -8.2, 14.8, and 40.6 °C, respectively. The coolest and the hottest months are December (4.5 °C) and July (34.4 °C), respectively. Some 82 freezing-days have also been recorded in a year for the region. The soil texture of the region was silty-loam (48% silt, 28% clay, and 24% sand) [7, 41].The organic matter, EC and pH of soil samples were 0.15%, 137.30 μS cm^{-1} and 8.20, respectively.

Experimental setup

The present study was designed with the aim of comparative and quantitative analyses of runoff and soil loss components, as soil hydrologic behavior indicators, from small-size plots filled by a loess soil under the influence of with and without freeze-thaw cycle under rainfall simulation conditions. The average slope of 20 % (11.5°) was selected similar to the that of the area where the soil was sampled. The rainfall event with a constant intensity of some 72 $mm.h^{-1}$ and 30 min duration was also selected based on the analysis of intensity-duration-frequency (IDF) curves for Bojnurd synoptic station located at the vicinity of the origin of the soil. Of course, other intensities and even slopes could be incorporated for the experimental design, but during the present study the effectiveness of an individual freezing and thawing cycle on overall and inter-variability of main components of hydrologic behavior at plot scale was targeted.

The study was carried out under rainfall simulation condition in the Rainfall Simulation and Soil Erosion Laboratory of Faculty of Natural Resources of Tarbiat Modares University (TMU), Iran. Due to the necessity of controlling the freezing-thawing conditions and the possibility of placement of plot in the freezing system, the plots with surface dimensions of 50×50 cm and 30 cm in height, and total volume of 0.075 m^3 were used with the ability to move and deploy in the freezing simulator system specifically manufactured for the study [7]. The plots had iron frames and transparent polycarbonate walls with a high ability to withstand lateral and thermal insulation. In order to optimally simulate the natural conditions, soil stratification was performed based on the actual conditions of the motherland of the study soil [6, 7]. So that, after taking soil from the study area, the air-dried soil was passed through a 3-mm sieve, and then the plots were filled by the study soil. The layered soil was then compacted using a hand-made roller according to the original soil bulk density (1.3 g cm^{-3}) based on methodology presented by [19]. In order to provide conditions for the moisture conditions of the field and appropriate to the natural conditions [1], the plots were placed in large water containers for about 24 h to be saturated from the bottom and then left out for further 24 h to reach moisture conditions of about 30% and similar to that reported for the study region [6, 7]. To increase the validity of the experiments, 6 and 3 replicates were considered for treated and control conditions, respectively.

In order to induce freezing conditions to the study soil, a cold-air cooling system with a rotary air system adapted to the range of temperature variations from -30 to 21 °C [7] was used. The freezing-thawing cycle to the soil plots placed in the cooling system was simulated similar to the natural conditions. So that, the study plots were kept below -20 °C for three days and then two days of thawing in ambient temperature of beyond 10 °C. The induction of cold air was applied to the experimental plots was made from the top and similar to the natural conditions through isolating the sides of the experimental plots using styrofoam sheets [6]. Control treatment plots were also kept without application of freezing-thawing process under lab temperature where the treated plots remained to be thawed. The plots were then placed on standard platforms with 20% slope similar to the slope of soil origin area for consequent experiments.

Rainfall simulation, and runoff and soil loss measurements

A portable rainfall simulator was used for study experiment with a height of about 4 m and BEX: 3/8 S24 W pressure nozzles. The plots were then placed on standard ramps with 20% slope (i.e., 11.5 °C) similar to the slope of soil origin area. According to the intensity-duration-frequency (IDF) curves from the Bojnurd Synoptic Automatic Weather Station, the rainfalls were simulated with an intensity of 72 mm h^{-1} and duration of 30 min [7]. The runoff components were then measured at the onset of the runoff commencement. The runoff was sampled every 2 min for the first 6 min (the first three time steps after beginning of the rainfall simulation i.e., from the time of runoff commencement to minute 6), every 3 min for next 9 min (the second three time steps of the event i.e., from minute 6 to minute 15) and finally every 5 min for last 15 minas (steps until the end of the event from minute 15 to minute 30). The time to runoff and total runoff were also recorded for each individual experiment. Afterward, runoff coefficient was then calculated by dividing runoff volume to rainfall volume. The sediment concentration was then measured using the decantation procedure, oven drying at 105 °C for 24 h and weighing by means of high precision scale (0.0001 g), and divided to the collected runoff volume. The entire soil loss was also calculated for the whole incident. In addition, times to peaks of runoff and sediment concentration, and peak runoff and sediment concentration were also measured in accordance with the methodology proposed by [38].

Data augmentation and statistical analyses

The normality and homogeneity of variances of the measured data were verified using the Shapiroe-Wilk and the Levine's tests, respectively. The independent-samples t-test was performed to test the effect of treatments on time independent runoff and soil loss components. Whereas the comparative analyses for time variant components of runoff and sediment concentration at different times were made using paired t-test. Whole differences were assessed at 95% level of confidence. Data banking and tabular and pictorial presentations; and statistical analyses were conducted with the help of Excel 2013 and he IBM SPSS 19 software packages, respectively.

Results

Time to runoff

The time of creating a runoff stream at the site of the spillover was recorded as the runoff start point (min). Table 1 show the results of measurement of time to runoff in the research treatments. The results show that the study treatment of freezing-thawing cycle averaged 1.65 times of time to runoff than those recorded for the untreated (control) plots. The statistical analyses also verified significant difference ($P<0.004$) between times to runoff of freezing-thawing treatment and control conditions.

Time to peak and peak of runoff

The time to peak as well as peak of runoff as two most important components of hydrograph analysis were also calculated and corresponding results have been shown in Fig. 1. In freezing-thawing treatment, the time to peak of runoff significantly increased over the control ($p<0.002$). The peak of runoff in freezing-thawing plots also significantly ($p<0.001$) decreased in comparison with the controls (Fig. 1).

Runoff volume and runoff coefficient

After sampling of runoff volume in different time steps determined during rainfall event, the runoff volume (ml) was recorded in each experiment .Table 2 and Figs. 2 and 3 show the results for the measurement of runoff volumes and Tabel 3 also shows the state of temporal variation during the rainfall event and analysis of variance to assess the effect of runoff volume. The runoff coefficient in freezing-thawing and control treatments have also been shown in Fig. 4. The results of statistical analyses showed significant differences between mean of total runoff volume ($P<0.006$), and temporal variation ($p<0.001$), and runoff coefficient ($P<0.002$). The significant difference ($p<0.001$) in runoff volume with normalized time spans in treatments was also confirmed. The freezing-thawing treatment increased average runoff volume by 1.38 times in comparison with that recorded for control condition.

Soil loss and sediment concentration

The detailed results of the measuremnet of soil loss and sediment concentration for both the treated and control conditions, temporal variability and associated statistical analyses have been given in Tables 4 and 5, and Figs. 5 to 7. On this basis, the freezing-thawing treatment increased the amount of soil loss on an average of 2.90 times more than that the control plot did. The results of statistical analysis also showed very significant differences ($p<0.001$), in mean soil loss and sediment concentration in all treated and control situations.

Time to peak and peak of soil loss

The statistical comparison of the time to peak of soil loss and the peak of soil loss shows in the freezing-thawing cycles and control treatments have been shown in Fig. 8. The results showed that the time to peak of soil loss significantly increased over the control ($p<0.002$). The peak of soil loss in freezing-thawing cycle plots also significantly ($p<0.001$) decreased in comparison with the controls.

Discussion

The results of this study showed significant and different behaviors of plots treated by a freezing-thawing cycle in comparison with control circumstances in viewpoints of time to runoff, runoff volume, runoff coefficient and soil loss under rain simulation conditions. The freezing-thawing cycle in the soil matrix caused up and down movement of water and soluble materials within top 30 cm of the soil. The water in the soil can reach the frozen ground of the soil, causing the formation of ice lenses and the background to increase runoff and soil loss. In the profile of the soil, physical conditions such as the formation of ice lenses in the space among the particles aggregates and on the border of the ice front, increasing moisture in the surface layer after the cycle, growth of ice crystals with conical shape and forming a lower frozen layer. The similar affecting factors on production of runoff and soil loss due to freezing and thawing processes have been noted by [5, 7, 9, 12, 18, 25, 33, 37, 43, 45, 55] who unitedly verified the negative effects of freezing and thawing on increasing runoff and soil loss.

The process of freezing-thawing consists of two main and interconnected stages. This firstly causes the destruction of the building, reducing the stability and resistance of the voids/solids due to an increase of 9% in the volume of frostbite, and the accumulation of moisture on the surface layer of the soil in the thawing effect of the main indices [28]. Secondly, due to the increase in pressure at the frostbite, the swelling and bloating state at the soil surface, and the destruction of the soil building, the surface shear strength reduces [47]. They both resulted in the loss of soil dynamics [8] and increasing the erodibility. The results obtained by [13] also explained the increase of soil erosion under the influence of freezing-thawing cycles in formation of ice lenses on the ice line boundary in the freezing treatment and swelling state of the soil and finally the degradation of the surface layer of the soil. The existence of an active thawing layer in the surface layer of soil and the formation of a frozen profile with less permeability than the reasons for reducing the runoff time and increasing the volume of runoff can be also noted. This layer has high level of moisture and close to the saturation condition and provides the basis for faster runoff flow and shorter runoff production time. As a result, by reducing the runoff production time in the freezing-thawing cycle treatment, the field has been provided to produce more runoff due to the effect of the freezing and thawing process in the soil. Increasing the amount of runoff volume caused by the existence of this layer on the region of glacial edge region has been confirmed by [51] in China.

With the onset of thawing, the frost is thawing from the surface to the depth of the retreat [27] and replacing it with the active layer [51]. The heterogeneity of soil permeability variations due to the change in the hydrodynamic properties of the soil during the rainfall event and the high erodibility due to the formation of the upper layer has had significant effects on the amount of runoff generation, and more effectible impact on the soil loss [7, 13, 41].

In this study, the time to runoff reduced by 1.65 times in freezing-thawing treatment compared to control (Table 1). In addition, the study treatment led to a higher level of soil loss and at tune of 2.90 times more than that recorded for control conditions. Increase of the amount of runoff in the freezing-thawing cycle compared with the control treatment was also ascertained (Table 4) as similarly approved by [6, 10]. This finding is consistent with the results presented by [6, 35, 47] who reported the incremental rates of 2.65, 11.92, and 1.10, respectively. The analyses of Figs. 3 and 5 also showed the average time variation of runoff volume and soil loss in freezing-thawing and untreated (control) treatments. The significant effect of these processes on temporal variations emphasizes the hydrological variation.

Accordingly, a wide range of potential strategies can be considered as an effective modifier of soil physical and chemical properties leading to better performance in soil and water conservation in frost and permafrost areas subjected to frequent freezing and thawing. In this regard, the use of soil additives and stabilizers has been introduced as one of the basic strategies, environmental and economic environment of soil erosion management [6, 7, 40].

Conclusions

Based on the results obtained and statistical analyses employed during the present study, it can be concluded that the freezing-thawing processes detrimentally affected hydrological behavior of the small-sized plots under a design simulated rainfall. Although, such phenomena repeatedly occur in reality and in the highlands or cold regions, but human activities might interfere the governing processes leading to undesirable outcomes of the system. The results of the current study or similar endeavors may therefore provide appropriate pipelines to the managers, decision makers and planner for the better management of the soil and water resources in the regions subjected to the frequent freezing and thawing cycles. Better understanding of the governing processes and conservation approaches is an important task for proper planning and management of natural resources. Accordingly, further detailed studies with variables affecting factors in combination with freezing-thawing cycles at larger scales and under field investigations are recommended. With regard to mountainous conditions in Iran as well as many other upland watersheds in the world, continuing similar researches in different and more extensive dimensions is strongly recommended.

Declarations

Ethics approval and consent to participate: Not applicable.

Consent for publication: Not applicable.

Availability of data and materials: All data used in the present study have been either collected by the authors or obtained from public domains available to anybody, which have been referred in the context.

Competing interests: The authors declare that they have no competing interests.

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Authors' contributions: S G contributed in methodology, investigation, data curation, software, writing-original draft and formal analysis SHR S contributed in conceptualization, methodology, investigation, resources, writing, editing and finalizing manuscript, supervision, project administration, funding acquisition; A N contributed in conceptualization, supervision, project administration; B Z contributed in methodology, investigation, project administration; H K contributed in methodology; A M contributed in project administration. All authors read and approved the final manuscript.

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Authors' information (optional)

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Tables

Table 1. Times to runoff (min) for the study treatments in the experimental plots

Coefficient of variation (%)	Standard deviation	Mean	Replication						Treatment
			6	5	4	3	2	1	
24.81	1.51	6.10	8.35	5.24	7.13	4.03	5.58	6.25	Freezing-thawing cycle
4.96	0.50	10.08	-	-	-	10.48	9.52	10.24	Control

Table 2. Runoff volume (ml) and runoff coefficient for the study treatments in the experimental plots												
Coefficient of variation of runoff coefficient	Mean runoff coefficient	Coefficient of variation	Mean	Replicate						Time (min)	Interval	Treatment
				6	5	4	3	2	1			
33.96	12.44	33.96	72.50	51	64	60	120	76	64	1	1	Freezing-thawing cycle
21.34	22.98	21.34	134.00	98	102	156	166	150	132	2		
25.20	31.90	25.20	186.00	116	194	208	250	198	150	3		
28.05	40.38	28.05	353.33	195	315	422	460	308	420	1	2	
21.99	45.92	21.99	401.83	298	384	485	374	340	530	2		
20.76	55.18	20.76	482.83	424	405	520	482	402	664	3		
14.60	55.85	14.60	814.33	684	850	840	668	862	982	1	3	
9.37	61.96	9.37	903.33	850	916	900	854	836	1064	2		
8.07	67.73	8.07	987.50	1012	1062	968	902	896	1085	3		
9.32	7.66	9.32	44.67	–	–	–	46	40	48	1	1	Control
47.80	20.35	47.80	118.67				90	82	184	2		
15.76	25.67	15.76	149.67				152	125	172	3		
50.71	23.09	50.71	202.00	–	–	–	136	150	320	1	2	
38.98	29.64	38.98	259.33				188	215	375	2		
22.43	37.33	22.43	326.67				250	334	396	3		
30.62	33.79	30.62	492.67	–	–	–	330	628	520	1	3	
5.28	50.43	5.28	735.33				778	726	702	2		
3.48	56.15	3.48	818.67				838	832	786	3		

Table 3. Results of analysis of variance to assess the effect of study treatments on the runoff volume in the experimental plots						
Variation Sources		Sum of squares	Degree of freedom	Mean square	F-value	Level of Significance.
Freezing-thawing cycle	Between Groups	121446.136	2	60723.068	69.717	0.000
	Within Groups	44420.934	51	870.999		
	Total	165867.070	53			
Control	Between Groups	32235.722	2	16117.861	16.431	0.000
	Within Groups	23542.664	24	980.944		
	Total	55778.387	26			

Table 4. Soil loss (g) for the freezing-thawing and control treatments in the experimental plots												
Coefficient of variation (%)	Mean sediment concentration	Coefficient of variation (%)	Mean soil loss	Replicate						Time (min)	Interval	
				6	5	4	3	2	1			
30.15	0.129	26.57	0.09	0.071	0.107	0.080	0.092	0.061	0.125	1	1	Freezing-thawing cycle
50.52	0.107	55.16	0.15	0.152	0.202	0.120	0.059	0.074	0.273	2		
72.84	0.206	79.16	0.38	0.254	0.397	0.193	0.98	0.213	0.251	3		
55.39	0.132	56.43	0.45	0.416	0.795	0.254	0.111	0.452	0.67	1	2	
57.69	0.165	53.31	0.63	0.529	1.252	0.250	0.523	0.563	0.641	2		
44.91	0.179	41.87	0.84	0.543	1.315	0.341	1.052	0.852	0.92	3		
37.55	0.182	34.97	1.46	0.835	1.935	1.794	1.168	1.026	2.012	1	3	
0.081	0.230	32.85	2.08	0.886	2.146	2.72	1.719	2.477	2.537	2		
0.077	0.262	48.38	2.57	0.979	4.395	2.522	1.43	2.816	3.286	3		
17.27	0.088	22.93	0.04	–	–	–	0.040	0.030	0.048	1	1	Control
36.42	0.115	34.34	0.13				0.160	0.078	0.147	2		
29.91	0.118	30.84	0.18				0.149	0.140	0.238	3		
74.81	0.143	50.60	0.25	–	–	–	0.280	0.112	0.361	1	2	
52.37	0.125	28.60	0.29				0.293	0.208	0.375	2		
52.45	0.094	28.65	0.29				0.257	0.223	0.379	3		
20.08	0.112	13.11	0.53	–	–	–	0.548	0.585	0.451	1	3	
6.69	0.081	9.89	0.60				0.588	0.545	0.662	2		
6.61	0.077	6.71	0.63				0.619	0.589	0.672	3		

Table 5. Results of analysis of variance to assess the effect of the study treatment on the soil loss in experimental plots						
Variation sources		Sum of Squares	Degree of freedom	Mean Square	F-value	Level of significance
Freezing-thawing cycle	Between Groups	0.855	2	0.428	21.525	0.000
	Within Groups	1.013	51	0.020		
	Total	1.869	53			
Control	Between Groups	0.016	2	0.008	10.685	0.000
	Within Groups	0.018	24	0.001		
	Total	0.034	26			

Figures

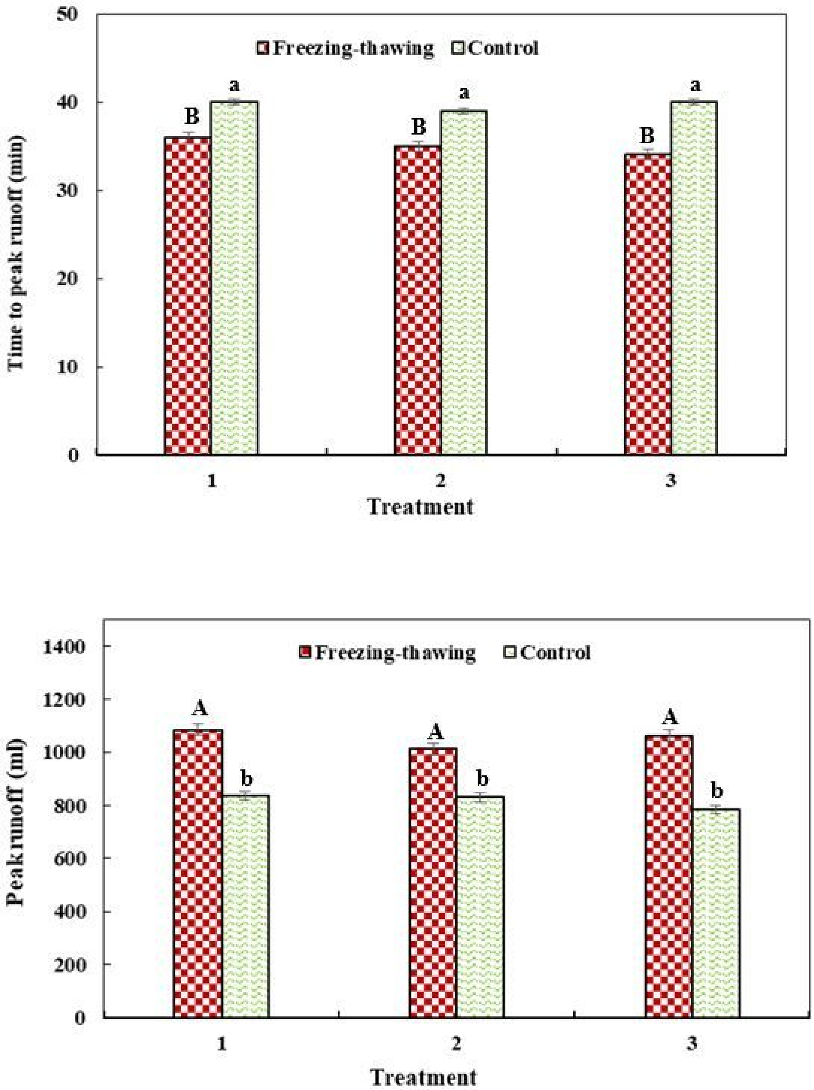


Figure 1

Time to peak (top) and peak (bottom) of runoff in freezing-thawing treatment and control after different time spans For each time span, bars with the same small or capital similar letters show non-significant difference (t-Test, $p>0.002$), otherwise they show significant difference (t-Test, $p<0.002$).

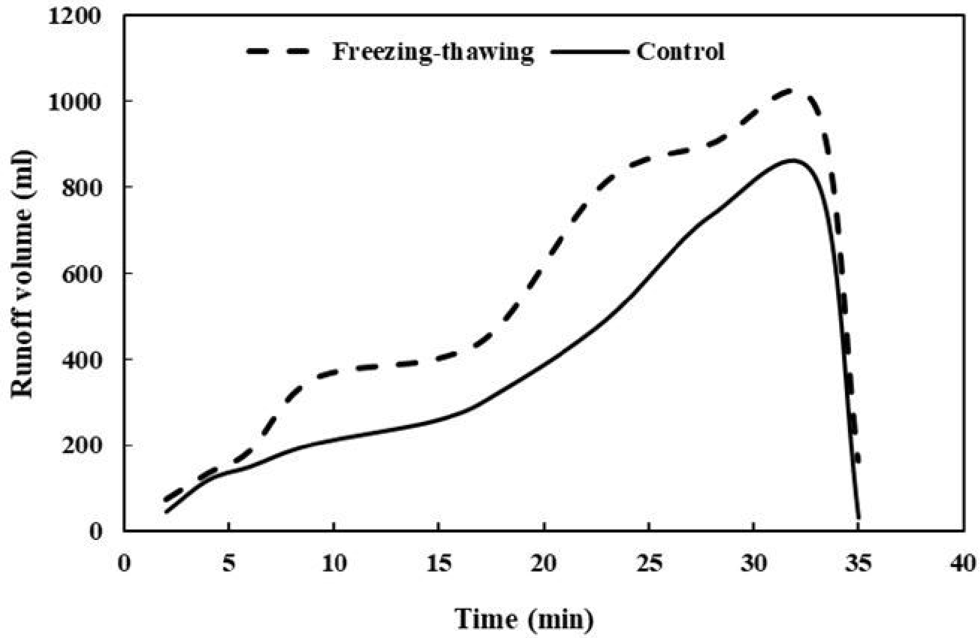


Figure 2

Time variations of runoff volume in freezing-thawing and control plots

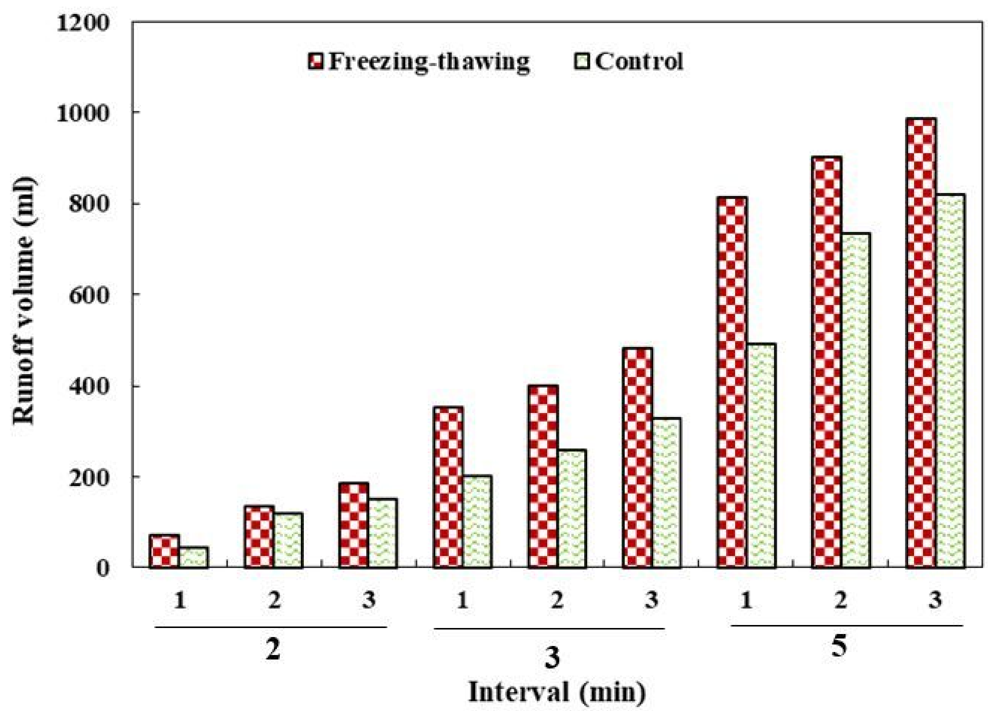


Figure 3

Comparison of mean runoff volume in experimental interval

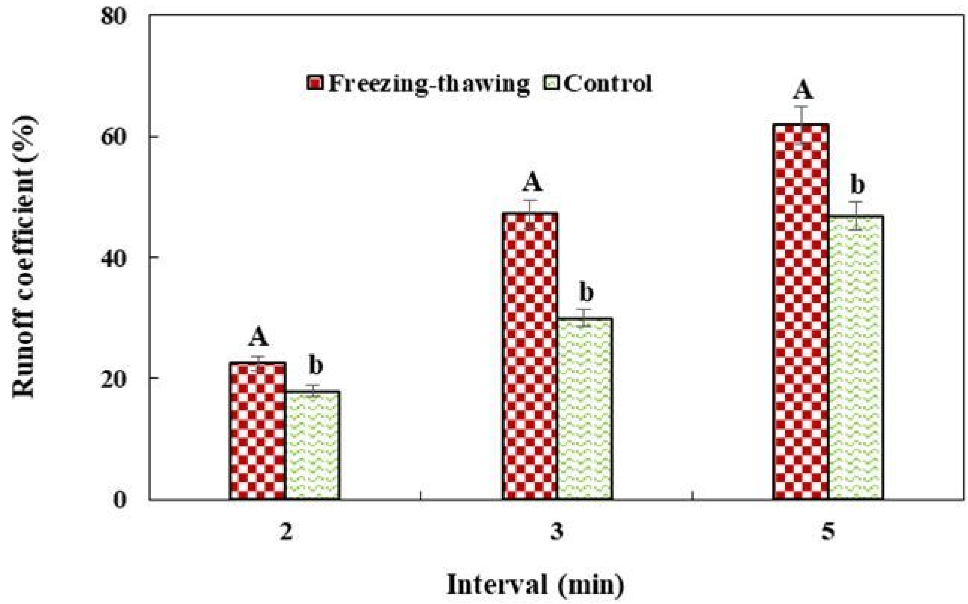


Figure 4

Comparison of mean runoff coefficient in experimental interval

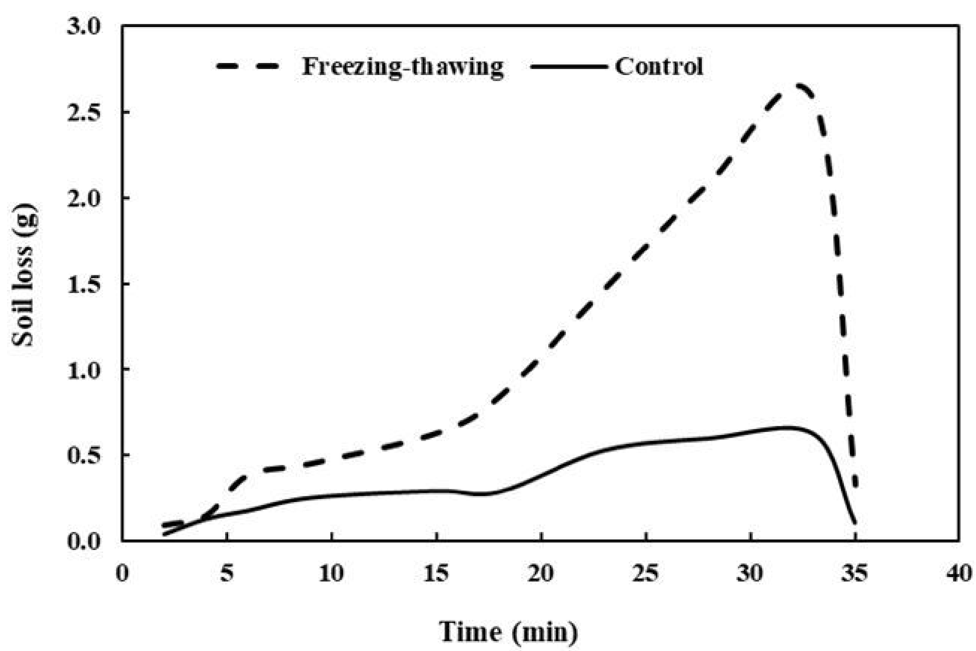


Figure 5

Time variation of soil loss in freezing-thawing and control plots

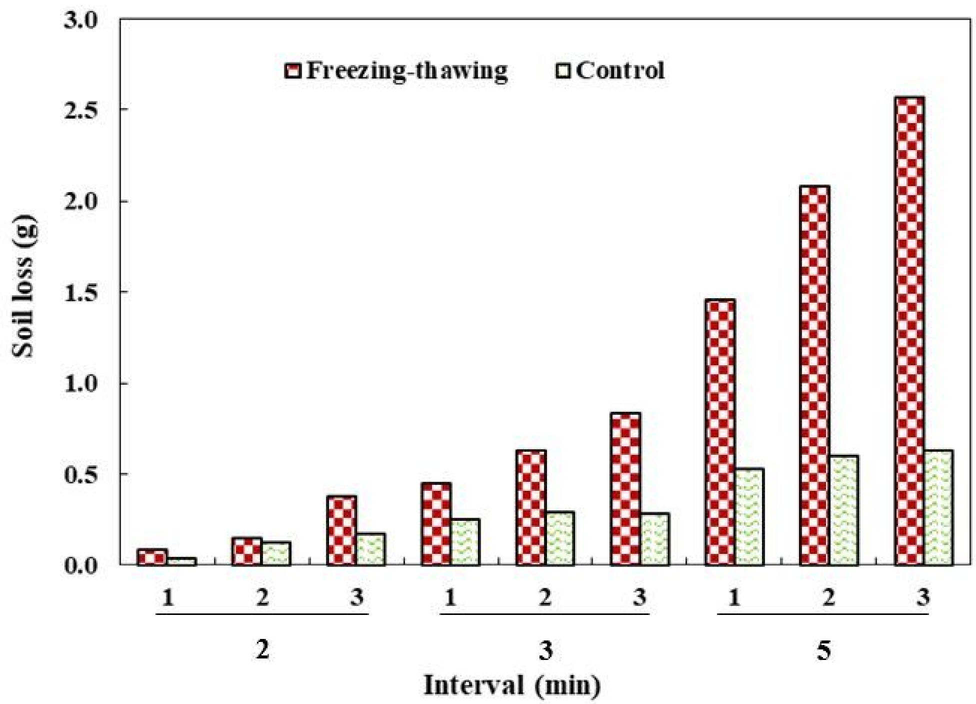


Figure 6

Comparison of mean soil loss in experimental interval

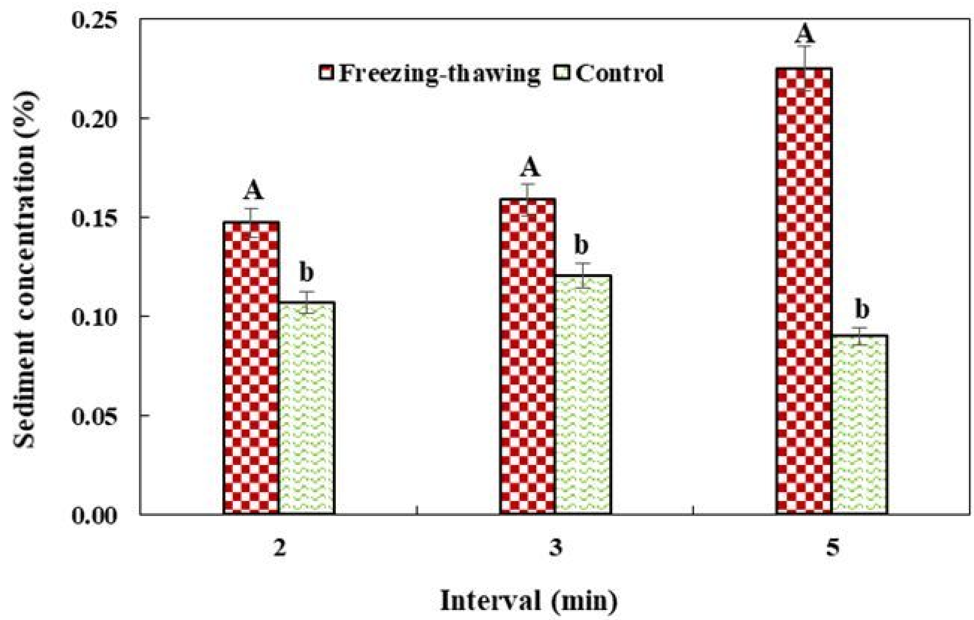
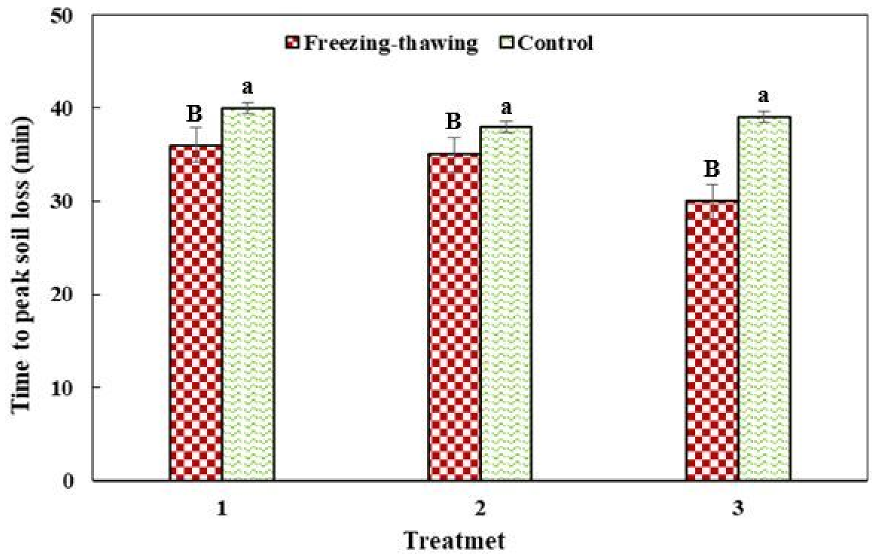


Figure 7

Comparison of mean sediment concentration in experimental interval



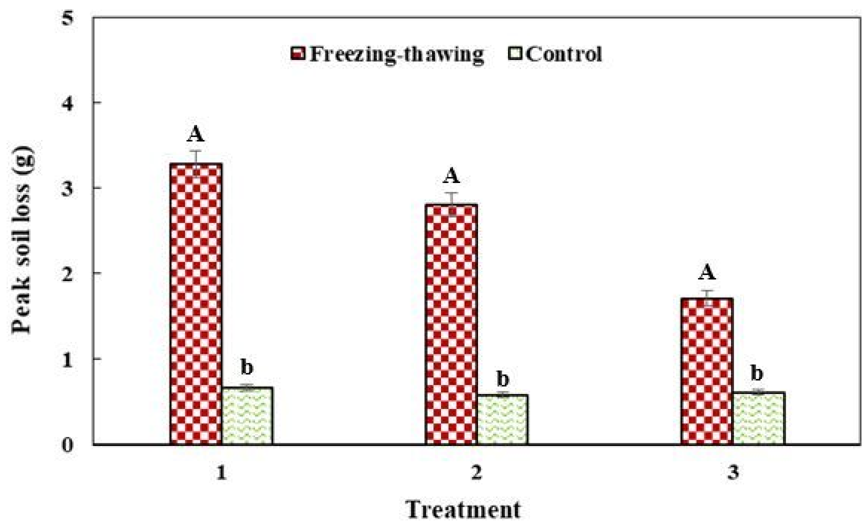


Figure 8

Time to peak (top) and peak (bottom) of soil loss in freezing-thawing treatment and control after different time spans. For each time span, bars with the same small or capital similar letters show non-significant difference (t-Test, $p>0.002$), otherwise they show significant difference (t-Test, $p<0.002$).

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