Effect of freeze-thaw and the root system on soil detachment capacity of different soils

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Abstract

Soil detachment is one of the most important processes of soil erosion, as it is of great significance for the prevention and treatment of soil erosion in areas subject to seasonal freeze-thaw. However, most previous studies on the effect of freeze-thaw on soil detachment capacity (SDC) of bare soil, little research on SDC under the effect of freeze-thaw and the root system. This study investigated the effects of freeze-thaw and the root system on soil detachment capacity through hydraulic flume experiments to simulate the soil detachment process of two soil types, sand soil and loessal soil, under four treatments, control, freeze-thaw, root system and freeze-thaw + root system. And a prediction model was developed to calculate SDC under the effect of freeze-thaw and the root system. The results illustrated that the SDC of sand soil was higher than that of loessal soil. The SDC of two soils was reduced and increased by the root system and freeze-thaw, respectively, although the former effect was significant ($P < 0.05$) whereas the latter was not. The effect of freeze-thaw in combination with the root system showed that the root system contributed the majority of SDC variability (99.95%); therefore, inhibition of SDC by the root system played a leading role. When comparing shear stress, unit energy of the water carrying section and unit stream power, stream power was found to be the hydraulic parameter that best predicted SDC (R2¬ > 0.84). The inclusion of root weight significantly improve the accuracy of the SDC prediction model developed by hydraulic parameters. A general model based on stream power and root weight was developed to quantify SDC and was shown to have a high SDC prediction accuracy for both soils treated by freeze-thaw and the root system [NSE = 0.88,R2 = 0.90].

1. Introduction

Soil detachment is defined as the separation and dislodging of soil particles from the soil mass surface by the force of raindrops and overland flow (Lautridou, 1990; Wang et al., 2014; Zhang et al., 2002). Scouring by overland flow is the dominant process resulting in detachment and transport of soil particles. The mechanism of soil detachment by open channel flow has become a research focus (Cao et al., 2009; Wang et al., 2016; Xiao et al., 2017). In the case of clear water, maximum soil detachment rate referred to as soil detachment capacity (SDC) is a key parameter used to describe the soil erosion process (Nearing et al., 1991; Sun et al., 2018). SDC is often used to estimate the rate of soil erosion resulting from overland flow and has been widely used in a range of representative erosion models, such as the Water Erosion Prediction Project (WEPP) and other process-based models (Misra and Rose, 1996; Morgan et al., 1998; Nearing et al., 1989). Meanwhile, SDC is to a certain extent affected by the hydraulic parameters of overland flow and the relationship between SDC and hydraulic parameters can be established to quantitatively simulate or predict soil detachment (Nearing et al., 1991; Zhang et al., 2002, 2003). For this reason, past studies have conducted laboratory control experiments to reveal the internal relationship between SDC and hydraulic parameters (Zhang et al., 2002, 2015). The results of these past studies have indicated that soil detachment is strongly influenced, and in some cases controlled, by hydraulic parameters, such as shear stress (Nearing et al., 1991), unit energy of the water carrying section (Hairsine and Rose, 1992a, 1992b), stream power (Wang et al., 2018; Xiao et al., 2017) and unit stream power (Morgan et al., 1998). However, since these studies did not employ standardized experimental conditions, there remains no consensus on the optimal hydraulic parameters to predict SDC and the dynamic mechanism of the soil detachment process remains unclear. For example, Morgan et al. (1998) found that the unit stream power is the best parameter to predict SDC, whereas Nearing et al. (1999) demonstrated the strong relationships of shear stress and stream power with SDC. Therefore, obtaining consensus requires further numerous experiments under different dynamic conditions to reveal the dynamic mechanism of soil detachment driven by overland flow.

Past research has demonstrated that soil type, bulk density, soil moisture, freeze-thaw and the root system all have strong relationships with SDC (Gyssels et al., 2006; Van Klaveren and McCool, 2010; Ye et al., 2017; Zheng et al., 2000). The seasonal soil freeze-thaw process is a common phenomenon in mid-latitude regions, such as the northern part of the Loess Plateau in China. The freeze-thaw process changes soil physical and mechanical properties and reduces the stability of soil aggregates, thus affecting soil SDC (Kværnø and Øygarden, 2006; Sun et al., 2018). And the SDC would be first decreasing and then increasing with an increasing number of freeze-thaw cycles (Sun et al., 2018). The soil freeze-thaw process can result in increased soil and water loss during the spring thawing period of temperate regions to $> 50\%$ of annual loss (Chow et al., 2000; Ellison and D., 1945; Froese et al., 2001). An analysis of soil detachment under the freeze-thaw process can provide an important theoretical basis for developing soil erosion control and prevention mechanisms for the seasonal freeze-thaw region. However, most previous studies on the effect of freeze-thaw on SDC were conducted on bare soil, whereas many affected areas have vegetation, and the extent of area with vegetation is continuous increasing with the implementation of a series of ecological restoration projects (Wang et al., 2014). Past studies have gradually highlighted the importance of the effect of the plant root system on soil properties and soil erosion in this region. The root system plays a key role in increasing soil stability, thereby reducing soil erosion (Baets et al., 2007; Jiao et al., 2012). The root system not only promotes the formation of large soil aggregates by consolidating fine soil particles, but also increases soil organic matter and improve soil structure through root exudates and plant residues (Amezketa, 1999; Burylo et al., 2012; Whalley et al., 2005; Ye et al., 2017). Soil with vegetation can have an SDC that is 23.2–55.3 lower than that of bare soil due to the effect of the root system (Wang et al., 2014). Gyssels et al. (2006) found that the SDC can be reduced by $> 50\%$ through the presence of herbaceous plant root systems compared with that of soil without roots. However, current research on the root system effect on the soil detachment process is mainly focused on non-freeze-thaw conditions, and therefore the relationship between the root system and SDC under freeze-thaw condition remains unclear. Quantitatively analyzing the effect of the root system and freeze-thaw on the soil detachment process and the development of a high-precision SDC prediction model is of great significance for the improvement of soil erosion prevention and control strategies in the seasonal freeze-thaw region and for the accurate assessment of local soil erosion (Laflen et al., 1991; Lal, 1989).

Therefore, the northern part of the Loess Plateau, China, as a typical seasonal freeze-thaw region, was selected by the current study as the study area. The current study investigated the sand and loessal soils that are widely distributed in this area. A flume experiment was conducted to explore the effect of the root system and the freeze-thaw cycle on SDC. In addition, an SDC prediction model was developed based on hydraulic parameters. The objectives of this study were to: (1) investigate and compare the effects of the root system, freeze-thaw and freeze-thaw combined with the root system on the soil detachment process, (2) develop a model to simulate SDC under the effects of the root system, freeze-thaw and freeze-thaw combined with the root system.

2. Material and methods

2.1 Test location and soil

Experiments were conducted within the Simulated Rainfall Hall at the Institute of Soil and Water Conservation, Chinese Academy of Sciences. The soil types tested were sand and loessal soils, sourced from Dalad

Banner Province, Inner Mongolia, which intersects the Hobq Desert and the Loess Plateau (110°31'17" E longitude, 39deg58'12"N latitude) and from Ansai, Shaanxi Province (110deg10'30"E longitude, 38deg165'08"N latitude), respectively. The soil samples were collected from the 0 cm–20 cm soil layer in abandoned cropland. Table 1 shows the soil mechanical composition, bulk density and organic carbon. Air-dried soil samples were filtered through a 2 mm mesh to remove stones, residual roots and other debris.

2.2 Experimental design

The SDC experiment was conducted in a scour flume. Field investigation showed that the slope of abandoned land in the study area was generally less than 15 deg and that the main plant species was *Bothriochloa ischaemum* . Therefore, the current study selected a scour test slope of 10 deg and the root system of *Bothriochloa ischaemum* . Furthermore, the flow rate was set to 6 L min^{-1}, 12 L min^{-1}, 18 L min^{-1} and 24 L min^{-1} based on previous research in the study area (Sun, 2018).

Four tests treatments were conducted on each soil, and for each treatment, the soil was placed into an iron box, for a total of eight boxes, with the length, width and depth of each box of 1.5 m, 1.5 m and 0.2 m, respectively. Soil was compacted into each box to obtain a bulk density equal to that of the soil in the field. The inner walls of the boxes were coated with a thermal insulation material. Several small holes were drilled into the bottom of each box to prevent water accumulation. The four boxes filled with sand were labeled as S1, S2, S3 and S4, whereas the four boxes filled with loessal soil were labeled as L1, L2, L3 and L4, with, S1 and L1 representing the control group of each soil with no treatment measures (C), S2 and L2 representing the soils treated by freeze-thaw (FT), S3 and L3 representing soil with root systems (R) and S4 and L4 representing soils treated by freeze-thaw combined with root systems (FT + R). The seeds of *Bothriochloa ischaemum w* ere planted in the S2, S4, L2 and L4 treatments at the optimal density of 50 individuals m^{-2} to represent the field growth in the study area. The *B. ischaemum* plants were cultivated indoors, with maturity being reached in October, 2016. During the cultivation period, all test soil samples were watered twice month to ensure consistent initial water conditions among the different soil samples. Subsequent to the *B. ischaemum* reaching maturity, the S3 and L3 treatments without grass and the S4 and L4 treatments with grass were placed outdoors to expose them to natural freeze-thaw conditions from November, 2016 to March, 2017. The S1, S2, L1 and L2 treatments cultivated indoors were watered with the amount of water representative of any outside precipitation and snow during this period. A cylindrical sampler (dimeter and depth of 10 cm and 5 cm, respectively) was used to collect soil samples for scouring in April, 2017. The aboveground parts of *B. ischaemum* plants were removed from the treatments to eliminate their effects on the test results, with only the root system retained. A total of 8 soil samples were collected from each box, for a total of 64 soil samples.

The scouring device comprised a water supply tank, flow meter, steady flow section and flume, and had a length, width and depth of 400 cm, 15 cm and 8 cm, respectively (Fig. 1). Before the scouring experiment for loessal soil was initiated, dry loessal soil was filtered through a 2 mm mesh, following which the soil particles were evenly glued to the surface of the flume bed to simulate the grain roughness of the soil surface under natural conditions. The same procedure was conducted for the scouring experiment for sandy soil. For each experiment, the cylindrical sampler packed with the soil sample was placed into the test area of the flume, with the soil surface aligned with the flume bed surface. The surface of the soil sample was covered with a cover panel to prevent the scouring of soil samples during the adjustment of the flow rate. The panel was removed once the experiment setup was complete and the flow rate had stabilized to allow the detachment experiment to begin. Experiments were terminated when the depth of the eroded soil in the cylindrical sampler reached 2.0 cm, with the duration recorded. For the soil samples containing root systems, the binding effect of the root systems made it difficult to measure the eroded soil depth. Therefore, for these samples, the experiment was halted at 15 min regardless of scour depth. Wet soil was oven-dried at 105 for 24 h and then weighed. Two groups of scour tests were conducted for each flow rate as experiment repetitions, and a total of 64 groups of tests were conducted for a total of 128 tests.

2.3 Determination of hydraulic parameters and SDC

2.3.1 Water depth and velocity

The below measurements were conducted once for each experimental group, as defined in the above section.

At flow stabilization, flow depth was measured using a level probe (+- 0.01 mm) at points 1.2 m, 2.2 m and 3.2 m above the lower end of the flume. At each distance, depths were measured three times, at points 1.0 cm from each side and at the center of the flume, resulting in a total of 9 positions and 27 measurements for each experiment. The mean flow depth for the experiment was defined as the average of the 27 depth measurements.

Velocity of the flow was determined using $KMnO_4$ as a tracer. Velocity measurements were replicated three times for each experiment group. The water temperature was monitored following which the Reynolds number (R_e) was calculated. It was found that the flow regime was mainly laminar flow (Re < 500) and transitional flow (500 [?] Re [?] 2000). Where the flow was laminar, the mean flow velocity was obtained by multiplying the surface velocity by 0.6, whereas it was multiplied by 0.70 when the flow was transitional (Abrahams et al., 1985). The mean velocity was defined as the average corrected velocity of the three times measured velocity for each experiment group.

2.3.2 Hydraulic parameters

The shear stress (τ), unit energy of the water carrying section (E), stream power (ω) and unit stream power (P) were calculated as follows:

$\tau = \rho g h S$ (1)

$E = \frac{\alpha v^2}{2g} + h\cos\theta$ (2)

$\omega = \tau v$ (3)

$P = v \times J$ (4)

In Eq. (1)–Eq. (4), τ is the shear stress (Pa), E is the unit energy of the water carrying section (cm), ω is the stream power ($N\cdot m^{-1}*s^{-1}$), P is the unit stream power ($m*s^{-1}$), ρ is the water density ($kg\cdot m^{-3}$), g is the gravitational acceleration ($m*s^{-2}$), h is the flow depth (m), S is the sine value of slope gradients, V is the mean flow velocity ($m*s^{-1}$), α is the kinetic energy correction factor (α = 1) and ϑ is the slope gradient (°).

2.3.3 SDC

SDC by overland flow (expressed in $kg\cdot m^{-2}*s^{-1}$) was calculated as:

$D_c = \frac{W_w - W_d}{t \times A}$ (5)

In Eq. (5), W_W and W_d are the weights of the dry soil before and after testing, respectively (kg),t is the duration of the test (s) and A is the sample cross-section area (m^2).

2.4 Root weight

After each group of scouring experiments, roots within each soil sample were collected by washing over a sieve (1 mm), following which they were weighted after oven-drying for 12 h at 65 degC (Li et al., 2015).

2.5 Statistical analysis

All statistical analyses were conducted using Excel 2010 and SPSS20.0 software. One-way analysis of variance (ANOVA) was conducted using SPSS20.0. SigmaPlot12.0 was used for equation regression and mapping. The general linear model (GML) was used to analyze the effects of soil type, freeze-thaw, root system and their interactions on the SDC. The following statistical parameters were used to evaluate the performance of simulated results:

$NSE = 1 - \frac{\sum (Q_i - P_i)^2}{\sum (Q_i - O)^2}$(6)

$$R^2 = \frac{\left[\sum_{i=1}^{n}(O_i - O)(P_i - P)\right]^2}{\sum_{i=1}^{n}(O_i - O)^2 \sum_{i=1}^{n}(P_i - P)^2} (7)$$

In Eq. (6) and Eq. (7), *NSE* is the Nash–Sutcliffe efficiency index (Wang et al., 2016), R^2 is the coefficient of determination, O_i is the measured value, P_i is the predicted value,O is the average measured value,P is the average predicted value and $n$is the sample number.

3. Results

3.1 SDC of different treatments

The SDC of sand soil under each treatment was relatively higher (1.02–3.40 times) compared to that of the treatments of loessal soil, although the differences were not significant ($P > 0.05$). The SDC values of the two soils showed a similar order of variation among the four treatments, with R < R+FT < C < FT (Table 2). Freeze-thaw increased the SDC of sand soil and loessal soil under the FT treatment by 5.99% and 20.39%, respectively compared with C, while that under the R + FT treatment increased by 135.29% and 380.00%, respectively compared with R. However, the effect of freeze-thaw on SDC was not significant ($P > 0.05$) compared to the control. Due to the effect of the root system, the SDC of sand soil and loessal soil under the R treatment were reduced by 99.00% and 99.66%, respectively compared with C, whereas that under the R + FT treatment were reduced by 97.82% and 98.76%, respectively compared with FT. Therefore, the root system reduced SDC significantly ($P < 0.05$) compared to the control. During the combined effect of freeze-thaw and the root system, the contribution of the root system to SDC dominated. The SDC values of sand soil and loessal soil under the R+FT treatment were reduced significantly by 97.64% and 98.38% compared with C, respectively.

The relative contributions of soil type, freeze-thaw, root system and their interactions to the variability of SDC was calculated according to variance component analysis of the general linear model (GLM). The contributions of soil type, freeze-thaw and the root system on SDC were calculated to be 99.95%, 10.64% and 6.00%, respectively; therefore, the root system had the most significant effect on SDC. The interactions between the root system and freeze-thaw also explained the variability of SDC to a high degree (36.90%). whereas the interactions among other factors explained SDC variability to a much lower degree.

3.2 Predicting SDC using hydraulic parameters

Four hydraulic parameters, namely shear stress (τ), unit energy of the water carrying section (E), stream power (ω) and unit stream power (P) are often used to describe the soil detachment process in soil erosion models. Table 3 and Table 4 shows the regression relationships between SDC and the hydraulic parameters of sand soil and loessal soil under four treatments, respectively. The two soil types showed similar regression relationships between SDC and hydraulic parameters. Shear stress and stream power explained variation in SDC well in a positive linear function, whereas unit energy of the water carrying section and unit stream power explained SDC using a power function. However, there was a weak relationship between the hydraulic parameters and the SDC of sand soil under the R and R + FT treatments, with all relationships achieving an $R^2 < 0.01$.

3.3 Comparison of the responses of SDC to the different hydraulic parameters

Table 5 and Table 6 show the prediction accuracies of the regression equations for SDC of sand soil and loessal soil, respectively. Due to the fact that the hydraulic parameters showed weak relationships to the SDC of sand soil treated by R and R+FT, the prediction accuracies of the regression equations representing the C and FT treatments were analyzed. Although shear stress and stream power were found to be good predictors of SDC, shear stress was only a good predictor for rootless soil, whereas stream power was a good predictor for both rootless soil and root soil. Therefore, stream power was identified as the most suitable hydraulic parameter to predict SDC (Fig. 2, Fig. 3). In addition, the hydraulic parameters had stronger relationships to the SDC of loessal soil compared to sand soil.

The model to predict SDC of sand soil under the R and R+FT treatments utilized the regression relationships of both the root weight and stream power with SDC. The simulation results showed that the regression relationship effectively predicted the SDC of sand soil treated by R and R+FT (*NSE* > 0.6904, R^2> 0.7024) (Table 7). Similarly, root weight and stream power were used to predict the SDC of loessal soil under the R and R+FT treatments. The prediction accuracies of the models based on the two factors of steam power and root weight were greatly improved compared to those based on either steam power or root weight. Under the R treatment, the *NSE* was increased from 0.9144 to 0.9756, whereas theR^2 was increased from 0.6477 to 0.9767 under the two-factor regression compared to the single factor regression for loessal soil. Under the R + FT treatment, the difference in *NSE*and R^2 between the two-factor and single factor regression was minimal, although this model still showed a high SDC prediction accuracy. In summary, the prediction accuracy of the model was improved when the second factor of root weight was added to steam power within the SDC prediction model for SDC based on hydraulics parameters.

The present study explored whether the SDC of root soil and rootless soil (root weight was set to 0) could be simulated accurately by the above model. A portion of the test data of SDC, stream power and root weight under the four treatments in two soils was selected to develop an SDC prediction model applicable both to sand soil and loessal soil (Table 8). The results of this model showed higher prediction accuracies for both the *NSE* and R^2 . The model was validated using the remaining portion of data not used in model development. The model validation *NSE* andR^2 prediction accuracies of SDC for loessal soil were 0.7611 and 0.7861, respectively (Fig. 4a), whereas those for sand soil were 0.6734 and 0.8513, respectively (Fig. 4b). These results indicated that the model could simulate the soil SDC under the four treatments relatively well. A single model applicable to simulating the SDC of both sand and loessal soils was developed using data that were a combination of SDC, stream power and root weight data for both soil types. This model obtained *NSE* and R^2prediction accuracies of 0.8248 and 0.8299, respectively. Therefore, the single model applicable to both soil types had higher prediction accuracies relative to the two models developed specifically for the sand and loessal soils.

4. Discussion

The current study found that the SDC values of sand soil under all four treatments were higher than those of loessal soil. Previous studies have similarly found that SDC may be influenced by soil type (Su et al., 2014). Line and Meyer (1989) showed that resistance of soil to erosion increased with increasing soil clay particle content. In the current study, the clay contents of sand soil and loessal soil were 6.82% and 17.59%, respectively. Thus, it may be concluded that the lower SDC for loess soil was due to its higher clay content. However, the response of SDC of sand soil to hydraulic parameters was weaker compared to that of loessal soil. In particular, there was a weak relationship between the hydraulic parameters and the SDC of sand soil with roots. Thus, the SDC of soil may be strongly affected by the root system distribution and soil properties. Soil particles bounded by the root system are likely to be strongly consolidated and therefore would not easily be detached by water erosion, whereas soil not consolidated by the root system would be highly susceptible to erosion. In addition, the root system increases the roughness of the soil surface, thereby reducing the energy of runoff, decreasing flow velocity and increasing soil water infiltration (Zheng et al., 2009). Soil that is not consolidated by the presence of a root system experiences stronger scouring erosion, resulting in the rapid detachment of erodible soil particles. Since the root system of*B. ischaemum* is mainly distributed in the surface soil, the roots of this plant protect the surface soil as well as the soil in deeper layers. Under this scenario, there would be little variation in SDC with increasing flow intensity until such a time that the flow is sufficiently strong to dislodge the surface soil layer bounded by the concentrated root system. Therefore, predicting the SDC of sand soil containing a root system requires both hydraulic parameters as well as a parameter reflecting root weight. However, due to the higher clay content and lower erodibility of loessal soil, the soil detachment characteristics of loessal soil both with and without a root system are similar. Hence, models that considered only hydraulic parameters were better able to predict the SDC of loessal soil with roots.

Although the SDC of soils both with and without roots increased under the freeze-thaw effect, the effect was not significant. This result is consistent with that of previous research (Sun et al., 2018). The stability of soil aggregate is an effective index to measure the SDC of soil subjected to freeze-thaw (Bryan, 2000; DiAz-Zorita et al., 2002) as the soil aggregate is broken down by successive freeze-thaw cycles (Lehrsch et al., 1991; Oztas and Fayetorbay, 2003), and it has been shown that soil SDC is increased with the destruction of soil macro-aggregate (Edwards, 1991). However, once the number of freeze-thaw cycles exceed 5, factors such as flow and slope become increasingly important for explaining the contribution of freeze-thaw to soil SDC. This is why the contribution of freeze-thaw to the SDC was not significant (Sun et al., 2018). The clear consolidation effect of the root system on soil results in a significant negative correlation between root density and SDC (Wang et al., 2014), indicating that the root system reduces the SDC of soil significantly. The present study found that SDC of both unfrozen soil and freeze-thaw soil was reduced by 97.82–99.66% due to the presence of a root system. This result is supported by the research results of Gyssels et al. (2006), who found that the roots of cereal plants reduced SDC by $> 90\%$. The main reason for root systems reducing SDC is due to consolidation of soil particles and the increase in soil adhesion and stability by the presence of roots (Baets et al., 2006, 2007). A second reason is the influence of the root system on increasing soil infiltration capacity by increasing the soil surface roughness and thereby reducing the velocity of surface runoff (Gyssels et al., 2006; Viles, 1990). Thus, the SDC would be decreased by root system.

Although soil detachment was increased and decreased by freeze-thaw and the root system, respectively, the inhibition effect of the root system dominated when the effects of freeze-thaw were combined with that of the root system. The SDC under the effect of freeze-thaw in combination with the root system was 5 times higher than that of soil under only the influence of the root system, but 295 times lower than that of the soil affected only by freeze-thaw. On the one hand, the root system significantly increased resistance to overland flow velocity during the process of erosion, thereby weakening the SDC driven by stream scour. On the other hand, the effect of soil disturbance through the freeze-thaw cycle was weakened by the root system to some extent (Gao et al., 2015). The freeze-thaw process has been shown to weaken bare soil by 20.6%, whereas it only weakened soil containing a root system by 7.3% (Li et al., 2012). Meanwhile, the present study found that combined factors of freeze-thaw and the root system explained 36.9% of SDC variation, whereas freeze-thaw as a single factor only explained 10.64% of SDC variation. This result suggests hints at the complexity of the composite effect of freeze-thaw and the root system on soil detachment and the need for further research.

Shear stress and stream power had positive linear relationships with SDC, whereas unit energy of the water carrying section and unit stream power showed power function relationships with SDC. This result is consistent with the previous research (Wang et al., 2016; Zhang et al., 2002, 2003, 2008). The present study found that stream power was the hydraulic parameter best able to explain SDC under the effect of freeze-thaw and the root system. This result is consistent with the findings of Cao et al. (2009) and Su et al. (2014). Since the root system is an important parameter that cannot be ignored when representing the process of soil detachment within model development (Wang et al., 2016), the present study developed an SDC prediction model for different soil types and treatment measures based on stream power and root weight. While the model developed in the present study is similar to those developed in previous studies (Li et al., 2015; Wang et al., 2014), some important differences exist. First, since soil parameters were not considered in the present study, only root weight and stream power were included in the prediction model. Secondly, the present study improved the regression relationship between the root system and SDC as an improved correlation between the SDC and the square of root weight was obtained. This result may be related to change to soil permeability resulting from the root system (Gyssels et al., 2006). Although the presence of a small root system in the soil limits the consolidation effect of the root system on soil particles, mechanical interludes of the root system can destroy soil structure, thereby increasing water infiltration. This can result in the collapse of the soil structure, particularly in low-viscosity soils such as sand, resulting in an increase in stream scour-driven SDC after water infiltration volume exceeds a certain critical value. However, an increase in the root system above a certain threshold density will result in great improvement in the soil consolidation capacity of the root system, thereby enhancing soil cohesion and reducing the detachment and transport capacity of stream scour on soil particles and reducing SDC (Xu et al., 2019). Therefore, the present study identified a prediction model based on the square of root weight and stream power that had a higher prediction accuracy compared to models developed in previous research (NSE = 0.8488) (Li et al.,2015). The model developed in the present study could provide accurate prediction for SDC under different conditions in the seasonal freeze-thaw region. Of course, further field tests are required to verify the practicability of this model in areas subject to seasonal freeze-thaw.

5. Conclusions

The present study investigated the SDC of four treatments, namely a control, freeze-thaw, root system and freeze-thaw + root system group by a scouring test. The relationships of hydraulic parameters and root weight with SDC were explored. The present study made the following conclusions:

(1) The SDC of sand soil was higher than that of loessal soil, with both soils showing similar relative SDC responses to the four treatments. While SDC can be increased by freeze-thaw, the increase was not significant. In contrast, SDC was significantly reduced by the root system effect. Under conditions of a combined effect of freeze-thaw and the root system on SDC, the effect of the root system dominated. Among the three factors, the strength of relationships to SDC were: root system> freeze-thaw > soil type.

(2) Positive linear relationships existed for SDC with shear stress and stream power, whereas the relationships of SDC with unit energy of the water carrying section and unit stream power could be represented by a power function. In addition, stream power among the hydraulic parameters was found to have the strongest relationship with SDC under the different treatments.

(3) The SDC model prediction accuracy was improved by including root weight into the model based on stream power.

(4) The model for simulating SDC based on both root weight and stream power was found to be a stronger predictor of SDC when simultaneously considering the root system and freeze-thaw conditions. Furthermore, field observation experiments of SDC driven by stream scour should be increased in the future to verify the practicability of this model.

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Table 1 Mechanical compositions and properties of the two soil types

Soil type	Mechanical composition (%)	Mechanical composition (%)	Mechanical composition (%)	Bulk density (g·c
	Clay (< 0.002 mm)	Silt (0.002 mm–0.05 mm)	Sand (0.05 mm–2 mm)	
Sand soil	6.82	31.56	61.37	1.36
Loessal soil	17.59	68.63	13.78	1.19

Table2 Soil detachment capacity (SDC) of two soil types under different treatments

Treatment	Soil detachment rate (kg·s^{-1}*m^{-2})	Soil detachment rate (kg·s^{-1}*m^{-2})
	Sand soil	Loessal soil
C	1.702 ± 1.193[a]	1.476 ± 1.021[A]
FT	1.804 ± 1.376[a]	1.777 ± 1.128[A]
R	0.017 ± 0.035[b]	0.005 ± 0.006[B]
R + FT	0.040 ± 0.064[b]	0.024 ± 0.016[B]

[a] C, FT, R, R + FT stand for the control, freeze-thaw, root system and root system + freeze-thaw treatments, respectively.

[b] Lowercase letters in this line indicate a significant difference for different treatments of sand soil at $P<$ 0.05. The capital letters in this line indicate a significant difference for different treatments of loessal soil at$P < 0.05$.

Table 3 Regression relationships between soil detachment capacity (SDC) and hydraulic parameters of sand soil

Treatment	Flow shear stress (τ)	Flow shear stress (τ)	Unit energy (E)	Unit energy (E)	Stream power (ω)
	Equation	R^2	Equations	R^2	Equation
N	D_c=0.3363(τ-1.90)	0.81	D_c =0.2823 $E^{1.28}$	0.79	D_c =0.2980(ω-0.04)
FT	D_c=0.5693(τ-4.08)	0.91	D_c =0.2554$E^{1.34}$	0.77	D_c =0.3921(ω-1.48)
R	D_c =0.0001(τ+42.00)	0.02	D_c =0.0031 $E^{0.25}$	0.06	D_c =0.0001(ω+43.00)
R+FT	D_c =0.0034(τ-1.82)	0.03	D_c =0.0096 $E^{0.09}$	0.001	D_c =0.0022(ω+2.27)

C, FT, R, R + FT stand for the control, freeze-thaw, root system and root system + freeze-thaw treatments, respectively.

Table 4 Regression relationships between soil detachment capacity (SDC) and hydraulic parameters of loessal soil

Treatment	Flow shear stress (τ)	Flow shear stress (τ)	Unit energy (E)	Unit energy (E)	Stream power (ω)	Str
	Equation	R^2	Equation	R^2	Equation	R^2
C	y=0.3343(τ-3.25)	0.98	D_c =0.0274 $E^{2.58}$	0.92	y=0.2986(ω-1.58)	0.9
FT	y=0.3815(τ-2.36)	0.85	D_c =0.1742 $E^{1.51}$	0.89	y=0.3252(ω-0.49)	091
R	y=0.0019(τ-3.68)	0.89	D_c =0.0003 $E^{2.23}$	0.85	y=0.0017(ω-2.00)	0.9
R+FT	y=0.0045(τ-1.62)	0.66	D_c =0.0009 $E^{2.22}$	0.84	y=0.0040(ω-0.60)	0.9

C, FT, R, R + FT stand for the control, freeze-thaw, root system and root system + freeze-thaw treatments, respectively.

Table 5 Prediction accuracies of the regression equations between soil detachment capacity (SDC) in sand soil and hydraulic parameters

Treatment	Flow shear stress (τ)	Flow shear stress (τ)	Unit energy (E)	Unit energy (E)	Stream power (ω)	Strea
	NSE	R^2	*NSE*	R^2	*NSE*	R^2
C	0.8233	0.7713	0.8034	0.7518	0.8446	0.792
FT	0.9080	0.9080	0.8114	0.7713	0.8392	0.820

C, FT and *NSE* stand for the control treatment, freeze-thaw treatment and Nash-Sutcliffe Efficiency, respectively

Table 6 Prediction accuracies of the regression equations between soil detachment capacity (SDC) in loessal soil and hydraulic parameters

Treatment	Flow shear stress (τ)	Flow shear stress (τ)	Unit energy (E)	Unit energy (E)	Stream power (ω)	Strea
	NSE	R^2	*NSE*	R^2	*NSE*	R^2
C	0.9782	0.9782	0.7958	0.4907	0.9746	0.974
FT	0.8864	0.8531	0.8532	0.8752	0.9088	0.908
R	0.5707	0.6528	0.7847	0.6979	0.9144	0.647
R+FT	-0.1228	0.9135	0.9253	0.9625	0.9503	0.950

C, FT, F, R + FT and *NSE* stand for the control treatment, freeze-thaw treatment, root treatment, freeze-thaw + root treatment and Nash-Sutcliffe Efficiency, respectively

Table 7 Regression equations showing the relationships of stream power and root weight with soil detachment capacity (SDC) for two different soil types

Soil type	Treatment	Linear functions	*NSE*	R^2
Sand soil	R	$D_c=e^{(50.09R\text{-}27.95R\hat{}2\ \text{-}27.39)}\ \omega^{0.21}$	0.7465	0.7503
	R + FT	$D_c=e^{(10.69R\text{-}3.44R\hat{}2\ \text{-}11.76)}\ \omega^{0.21}$	0.6904	0.7024
Loessal soil	R	$D_c=e^{(3.97R+1.53R\hat{}2\text{-}10.02)}\ \omega^{1.68}$	0.9756	0.9767
	R + FT	$D_c=e^{(\text{-}1.61R+0.76R\hat{}2\text{-}5.91)}\ \omega^{1.50}$	0.9177	0.9500

R, R + FT and *NSE* stand for the root treatment, freeze-thaw + root treatment and Nash-Sutcliffe Efficiency, respectively

Table 8 Soil detachment capacity (SDC) prediction models for different soils

Soil type	Linear functions	*NSE*	R^2
Sand soil	$D_c=e^{(4.54R\hat{}2\text{-}10.43R\text{-}1.65)}\ \omega^{1.14}$	0.8492	0.8632
Loessal soil	$D_c=e^{(3.79R\hat{}2\text{-}10.06R\text{-}3.89)}\ \omega^{2.22}$	0.9095	0.9387
Sand or loessal soil	$D_c=e^{(4.24R\hat{}2\text{-}10.14R\text{-}2.48)}\ \omega^{1.48}$	0.8488	0.9023

NSE stands for Nash-Sutcliffe Efficiency

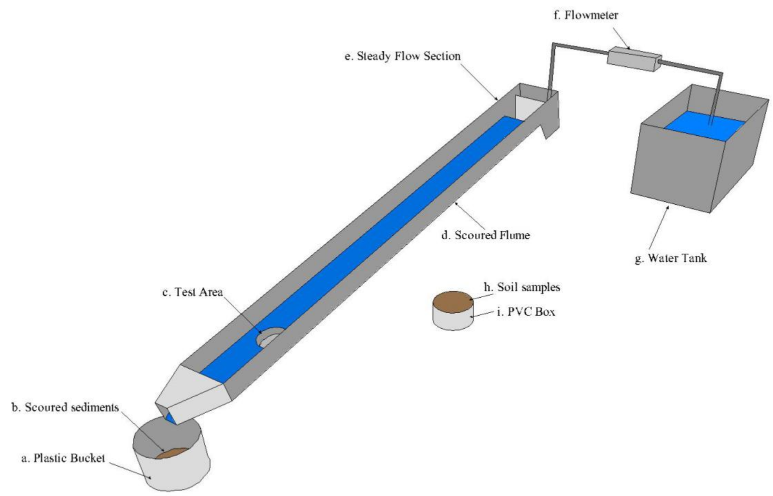

Fig.1. Schematic diagram of the experimental setup (Sun et al., 2018)

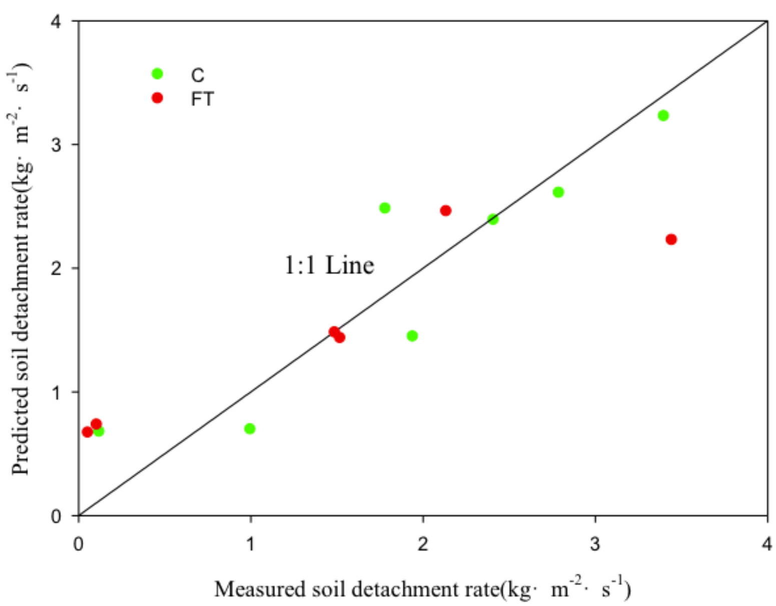

Fig. 2. Comparison between measured and predicted soil detachment capacity (SDC) in sand soil where steam power was used to predict SDC

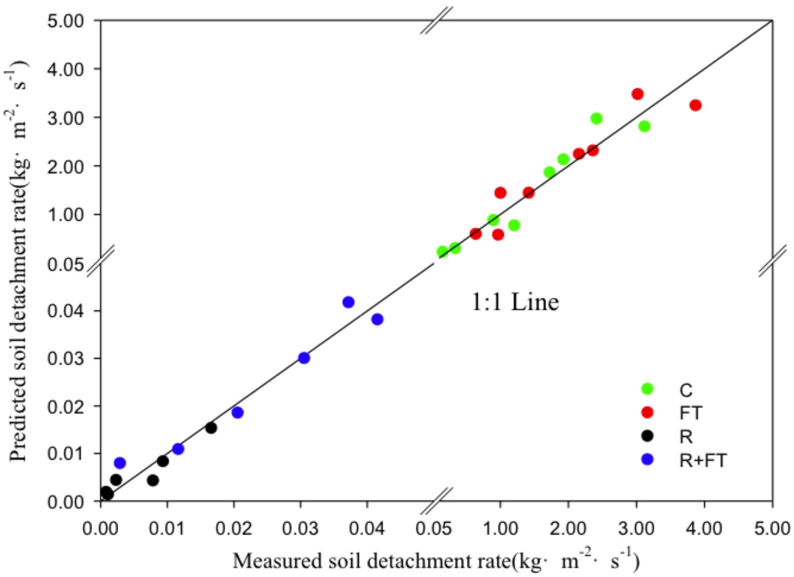

Fig. 3. Comparison between measured and predicted soil detachment capacity (SDC) in loessal soil where steam power was used to predict SDC. (a) C and R treatment; (b) R and R+FT treatment

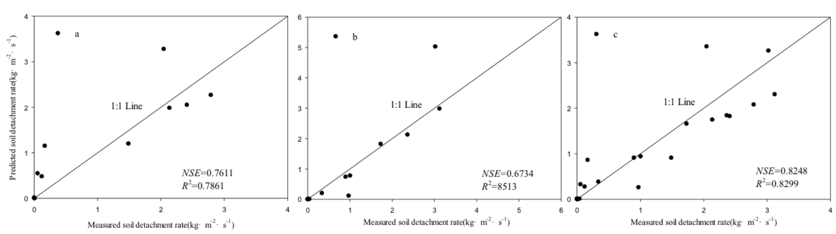

Fig. 4. Comparison between observed and simulated soil detachment capacity (SDC) for regression models based on soil type. (a) sand soil; (b) loessal soil; (c) sand or loessal soil