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The effect of soil water content and erodibility on losses of available nitrogen and phosphorus in simulated freeze-thaw conditions

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ABSTRACT

The effects of soil water content (SWC) and erodibility on available nutrient losses, as well as the influence of freeze-thaw on available nitrogen (AN) and phosphorus (AP) losses from loess soils have rarely been considered. We report on a series of laboratory simulation experiments conducted to determine SWC and soil erodibility effects on AN and AP losses under freeze-thaw conditions. Effect of freeze/thaw compared to unfrozen, two treatments were set (LS: Loess that unfrozen; FTS: Freeze-thawed a loess), and we studied five SWCs, between 10% and 30%, and we divided SWCs into two groups: lower water content areas (10% and 15%), higher water content areas (20%, 25%, and 30%). Overall, significant differences in runoff/sediment associated AN and AP concentrations of different SWCs for two treatments ($p < 0.05$) were noted, while the relationship between SWC and AN and AP loss show a quadratic function change trend ($R^2 > 0.8$). Largest runoff-associated AN and AP losses were found when the SWC was 30% and the largest sediment-associated AN and AP losses were found when the SWC was 10% in the two treatments. The soil erodibility factor (K) of the LS was less than that of the FTS when the SWC was low, and greater in a high water content area. The influence of runoff on sediment was positively linear. The absolute slope of the regression line between runoff rate and sediment yield rate is shown to be suitable as a soil erodibility indicator, while runoff-associated AN losses are mainly controlled by runoff rate, and are weakly affected by soil erodibility ($p > 0.05$). However, soil erodibility significantly influenced sediment-associated AP losses ($p < 0.01$), best described by a positive logarithmic relationship. Since the sediment-associated AP losses dominated the total AP losses for the two treatments, soil erodibility also exhibited a significant influence on total AP losses ($p < 0.01$). The freeze-thaw effect increased the total AN loss when the SWC was 15%, 20%, and 30%, and increased the total AP loss when it was 10% and 15%. The results of this study provide a better understanding of soil and available nutrient loss mechanisms under freeze-thaw conditions.

1. Introduction

Freeze-thaw action is the phenomenon of soil freezing and melting caused by soil temperatures change around the freezing point. This is a widespread, natural phenomenon in high latitudes and mountain regions globally. During the spring thaw period, as surface soil undergoes repeated freezing and thawing, soil cohesive force is reduced, dispersion forces become larger, and soil erosion resistance is reduced. At the same time, freezing and thawing changes the moisture content of soil aggregates and the main compounds in soil (Wang et al., 2013), interferes with soil microbial community evolution, influences soil elements of the biogeochemical cycle, and impacts on the structure and function of soil ecosystems (Sharma et al., 2006). In recent years, global warming trends are obvious and have significantly influenced biogeochemical cycles as well as freezing and thawing soil nutrient processes (Feng et al. 2007; Wu et al. 2010).

The degree of soil freezing and thawing has an important relationship with soil water content (SWC), and soil freezing temperatures and can lead to changes in the physical properties and behavior of soils (Wang and Wu, 2013). Thus, soil moisture and temperature are important factors influencing and controlling seasonal variations in soil organic matter mineralization (Patra et al. 1999); freeze-thaw can increase the desorption capacity of dissolved organic carbon thereby decreasing soil organic carbon concentration. The expansion of ice

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crystals in the soil pores when freezing breaks the connection between the particles, breaking the soil aggregate into small agglomerates, effectively converting large aggregates into smaller ones. Increased microbial availability enhances the decomposition and mineralization of organic matter, consequently increasing the nutrient availability to plants in the soil (Oztas and Fayetorbay, 2003; Teepe et al., 2000). Similarly, as freezing and thawing processes cycle, the release and absorption of phosphorus into soil is closely related to soil moisture content. The change of soil moisture content influenced the diffusion coefficient of phosphorous; the diffusion coefficients increased with the increase of SWC. The trend in diffusion coefficient also varies with SWC, changing slowly when moisture content is low and more rapidly at higher SWC values (Xu et al. 2000). Therefore, the SWC determines the forms of phosphorus in soil; the higher SWC, the greater the proportion of dissolved phosphorus in the soil, and higher phosphorus release to runoff (Li and Meng, 2013; Gore and Snape, 2008).

Numerous research results have shown that the same restriction factors that influence soil nutrients are affected differently by freezing and thawing (Peltovuori and Soinne, 2005; Wang et al. 2007a; Ozgul et al. 2012; Qian et al. 2012). The migration and transformation of soil nutrients are influenced by the combined actions, such as soil components, SWC, freezing and thawing time, cycle index, vegetation types, and the condition of micro-organisms. Thus, the combined effects of many inter-related factors causes variation in the migration and transformation of soil nutrient under freezing and thawing conditions (Lehrsch et al., 1991; Doney and Schimel, 2007; Joseph and Henry, 2008). It is therefore important to study the processes of migration and transformation of soil nitrogen and phosphorus under different water content conditions, as well as to understand soil biogeochemical cycling in cold climates. The effects of freezing and thawing on soil enzyme activity and nutrient availability are likely to be emphasized in future studies (Sjursen et al. 2005; Liu et al. 2010).

The hilly and gully region on the northwest loess plateau of China is characterized by a warm temperate continental monsoonal climate that features significant winds, four seasons, and a temperature below freezing for between 105 days/a and 125 days/a (about one-third of the year). The average annual rainfall in this region is between 300 mm/a and 600 mm/a, and the flood season accounts for > 70% of the year. Seasonal freeze thaw erosion is especially serious in the winter and spring; during the thawing period in the spring, temperature rises and due to incomplete thawing at the soil surface, a water-tight stratum is formed that reduces soil infiltration capacity and produces more surface runoff. In addition, soil physical and chemical properties as well as structure and texture change due to the repeated action of freezing and thawing (Wang et al. 2009). These factors all influence soil erodibility and cause soil nutrient loss.

To date, a number of important results have been generated from research on soil nutrient loss on non-freeze-thawed slopes. At the same time, however, research on freeze-thaw erosion has focused on changes in soil physical properties as well as effects on erosion intensity. Much less work has been carried out on soil nutrient loss from frozen slopes. Therefore, the main focus of this study is on loess, which was tested via indoor freeze-thaw and simulated rainfall in order to observe runoff, sediment, AN and AP loss characteristics under different SWCs. We also analyze the effect of soil erodibility on AN and AP, as our aim is to provide a theoretical basis for the optimal management of water and soil resources as well as optimal agricultural fertilization during the spring thaw cycle.

2. Materials and methods

2.1. Soil and soil flume preparation

The soil used in this study is loess, collected from the Xi'an region in Shannxi Province, China. Subsequent to sample collection from original sites, soils were air-dried and passed through a 10 mm aperture square-hole sieve to remove coarse rocks and organic debris. The properties of original soil are summarized in Table 1. Soil particle composition was measured using a Mastersizer 2000 particle size analyzer (Malvern Instruments, Malvern, UK), and was described in terms of clay (< 0.002 mm), silt (between 0.002 mm and 0.05 mm), and sand (between 0.05 mm and 2 mm) percentages. Soil bulk density was then measured using the ring method, while AN and AP concentrations were determined with an Auto Discrete Analyzer (Clever Chem2000, Germany).

Table 1
Physical and chemical properties of selected soil samples.

Soil type	Particle sizes (mm)			Bulk density (g/cm^3)	The organic carbon(g/kg)	AP (mg/kg)	AN (mg/kg)
	Clay	Silt	Sand				
Loess	1.19	91.14	7.67	1.25	1.042	6.07	11.31

We constructed soil flumes (i.e., 0.9 m × 0.45 m × 0.15 m; length × width × height) out of wood to collect runoff at one end (Fig. 1), and used a permafrost freezer device to simulate ultra-low temperature permafrost (1.15 m × 0.72 m × 0.85 m; length × width × height) at temperatures between −10 °C and − 40 °C. In this experiment, 6 flumes were constructed, and they were repeatedly filled.

We then prepared a series of soil materials that contain different antecedent moisture content. Thus, SWC was first determined before corresponding water needs were computed to configure the required moisture content control. Soil was then spread evenly, sprayed with replenished water to the surface with a watering can, fully stirred, covered with plastic sheeting, and left to sit for 24 h. This process enabled us to obtain soil material with an even moisture distribution and water content values that meet control requirements. We therefore set experimental concentrations at 10%, 15%, 20%, 25%, and 30% water content.

In order to ensure that permeability is close to that of natural slopes and to ensure uniform soil moisture infiltration, a layer of gauze was then placed on the bottom of the soil flumes embedded in 2 cm thick natural sand, the particles are composed of: clay 0%, silt 18.5% and sand 81.5%. To control the consistency of test slope soil physical properties and prevent the appearance of stratification ensure a uniform soil, a 5 cm thickness of layered fill soil material was inter-layered with a rough cast contact area. The bulk density was controlled at about 1.25 g/cm^3, before experiment, the bulk density of soil materials was measured, and the volume of soil for filling the soil flume could be calculated according to the control bulk density (Wang et al. 2007b). Soil materials were then filled to a depth of 10 cm layer-by-layer, holding the soil surface and collecting runoff trough in the same horizontal position. Finally, when loading was complete, the soil surface was covered with plastic wrap in order to prevent surface soil moisture content changes due to evaporation.

Two treatments were prepared. One was loess control (LS): the soil flumes filled with loess, and another was freeze-thawed (FTS), where soil flumes were filled with loess then placed into an ultra-low temperature freezer set to −20 °C, frozen for 24 h, brought to room temperature of 12 °C, and thawed for the same period. Further, in order to simulate the actual situation more closely, insulated material was placed in a surrounded soil bin before freezing in order to ensure that the soil began to thaw from the top and bottom.

2.2. Experimental rainfall setup

Our rainfall experimental equipment setup incorporates a needle rainfall-type that was designed by the Xi'an University of Technology Institute for Water Resources (Lu et al. 2011). A schematic representation of this experimental setup is shown in Fig. 1. The raindrop