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Characteristics of soil freeze–thaw cycles and their effects on water enrichment in the rhizosphere

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ABSTRACT

The freeze–thaw process can lead to water enrichment in freezing layers of soil, and may have beneficial effects on vegetation restoration efforts in sandy land habitats. This study determined the characteristics of soil water migration in dunes and interdune areas during freeze–thaw process, and discussed its potential application to the restoration and recovery of sandy land plant communities. In this research, the mobile sand dunes and interdune lowlands were chosen as the study objects in Horqin Sandy Land, north China. We investigated the soil temperature and moisture content on depths of 20 cm, 50 cm, 100 cm and 150 cm during soil freeze–thaw period (from September 20, 2010 to April 9, 2011), and determined the migrated water during freezing–thawing processes on soil of sand dunes and interdune lowlands, and discussed its potential application on plant recovery processes. Results showed that the soil freeze–thaw process occurred mostly at a depth of 0–100 cm, and the longest period of soil that remained frozen is 104 days at a depth of 20 cm and the shortest period is 39 days at a depth of 100 cm in sand dunes. The number of freeze–thaw cycles was not different between sand dune and interdune area over winter. Most freeze–thaw cycles occurred in the thawing process, and mostly at a depth of 0–50 cm. The freeze–thaw cycles of interdune areas only occurred in the thawing process, but the freeze–thaw cycles of sand dunes occurred both in the process of freezing and thawing. More water of the interdune areas apparently migrated than did in the sand dunes. The range of soil water storage content at depths of 0 to 100 cm increased to 92.4 mm on interdune, and 10.8 mm on sand dunes during the freeze–thaw process. A negative correlation was found between soil temperature and moisture at depths of 100 cm and 150 cm, and while a positive correlation existed at depths of 20 cm and 50 cm. The freeze–thaw process can lead to water enrichment in freezing layer of soil on sand dunes and interdune. Soil texture affected the quantity of soil water migrating during the freeze/thaw process, and more water migrated in interdune areas than in sand dune habitat.

1. Introduction

Seasonal or diurnal freezing and thawing of soil, or freeze–thaw cycles, are a repeated process that occurs in topsoil and extends to a certain depth. When soil freezes, water begins to freeze from the surface and extends down to the deeper soil layers. The soil water potential gradient causes the constant transfer of water from unfrozen to frozen soil, with condensation occurring along a freeze front. As a result, the moisture content of frozen soil increases (Zhang and Sun, 2011). On the soil thaw process, the upper and lower layers of frozen soil begin to melt first. However, the water from melted ice in the upper layer becomes obstructed by the middle frozen layer, allowing the upper soil moisture content to increase in the upper layer (Xiao and Chen, 1983; Yang et al., 2008). The redistribution of soil moisture caused by the migration of water during the freeze/thaw period may be an important process for soil management (Liu, 2010; Xu, 1982).

Recently, many research studies have mainly focused on the mechanisms that control the migration of moisture that occurs when soil is in the process of freezing. Other studies have addressed physical and geological disasters that have been caused by the freeze–thaw process. These studies have used a variety of models to simulate the transfer of water and heat during the soil freeze–thaw process. For instance, Harlan (1973) created the first soil coupled heat and moisture migration model in 1973, based on the idea that the migration of unfrozen water in partially frozen soil was similar to the migration of moisture in unsaturated soil. Flerchinger and Saxton (1989) used the concept of conversation of energy, the concept of variations in entropy and the orthogonal fundamental relationship between the rate of flow and a free boundary to create an equation of coupled heat and mass transfer that simulated and calculated the

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process of melting in permafrost. Zhao and Gray (1997) studied the processes and mechanisms of infiltration in frozen soil. Dai and Zeng (1997) proposed the IAP94 land surface process model that described how soil moisture vapor, liquid and solid phases interact during the process of phase transition. Zhang and Ding (1997) established the LPM.ZD model that was based on the BAT model, and calculated soil temperature and moisture using a combination of methods including physical equations and empirical analytical formulas. Moreover, Yang and Liu (2000) conducted permafrost hydrology observation tests, which included the investigation of variations in the levels of underground water, the freeze–thaw process and employed hydraulic parameters in the active permafrost layer at Binggou Basin in the upper reaches of the Heihe River in the Qilian Mountains, China. Furthermore, Chang et al. (2001) studied the regularity of freeze–thaw patterns in seasonal permafrost and the hydrological function of freeze/thaw patterns in the forested region of the Qilian Mountains based on soil freeze–thaw patterns, temperature and runoff. These studies mainly simulated the freeze/thaw process of soil from the aspect of soil hydrothermal mechanisms and used mathematics to describe the process, providing a mostly theoretical description of this phenomenon.

Previous research has been conducted in different regions and environments. Therefore, the quantity of water found migrating in soil due to freeze/thaw processes varied with location. For example, Jing et al. (2007) found soil water storage increased by 26–38 mm at a depth of 1 m. Yang et al. (2008) and Jing et al. (2008) found soil moisture content increased by 10% at about a 20 cm depth while Xiao and Chen (1983) found that it increased by 20–40% at a 20 cm depth. Meanwhile, the variations in soil texture and mulching also affected the quantity of water that migrated during the freeze/thaw process. For example, plastic film or straw mulching allowed more water to be transferred to the upper layer when compared with bare plots during the freeze–thaw process (Yang et al., 2008; Zheng et al., 2009). As for soil texture, heavy clay soil could transfer more soil water than sandy soil (Gao et al., 2000; Wang et al., 2007). For practical application, some researchers tried to take advantage of the migration water during the seasonal freeze/thaw to improve the spring soil moisture content of farmland (Yi et al., 1997) and woodland (Pei et al., 1994), and to increase the survival rate or productivity of plantations. However, currently little attention has been paid to the transfer of soil water as part of the process of freeze–thaw, and related conditions, quantity of water, and the spatial and temporal characteristics of its occurrence. Research addressing the actual quantity of water and the conditions influencing soil water movement has been limited; therefore, the practical application of the effect of freeze/thaw patterns on plant production and soil organisms has been difficult. Furthermore, little research has addressed the variations of soil moisture content that was caused by the action of freeze–thaw even though it may be possible to take advantage of the increasing availability of water created by specific conditions.

In arid sandy regions, with little precipitation and strong evaporation, shallow soil moisture serves important ecological purposes (Li et al., 2001; Wang et al., 2002). Shallow soil water may make water available for shallow-rooted sandyland plants allowing them to thrive (Wang et al., 2003; Zhao, 2002). Especially in arid and semi-arid sandyland regions, relatively severe sandstorm and drought conditions in spring will influence the germination and growth of vegetation. Variations in shallow soil moisture have relatively direct and obvious impacts on the survival of vegetation. If the migration of water during the soil freeze–thaw process makes supplementary water available to plants, then this water could be used in shallow sandyland areas, and this may benefit vegetation restoration efforts in these areas. This study analyzed typical mobile sand dunes and interdune areas in the Horqin Sandy Land (HSL), in northern China. We determined the characteristics of soil water migration in dunes and interdune areas, and discussed its potential application to the restoration and recovery of sandyland plant communities through investigating the temperature and moisture content of shallow soil during the soil freeze–thaw period.

2. Material and methods

Research was conducted in the Horqin Sand Land, located at 42°41′–45°15′N, 118°35′–123°30′E, mostly in Inner Mongolia, but extending slightly into Jilin and Liaoning provinces, China. The HSL covers about 5.17×10^4 km^2, and stretches about 400 km east to west, in north China. The semi-arid climate has an average annual temperature of 6.2 °C, with the coldest month in January (mean January temperature is −11.7 °C) and the warmest month in July (mean July temperature is 23.6 °C). The annual precipitation is 284.4 ± 82.4 mm (year 1982–2008) with about 70% of this falling in June to August. The annual potential evaporation exceeds 2300 mm. The peak of precipitation coincides with the high temperature during June to August. Annual wind speed averaged 4.2 m s^{-1}, with the strongest instantaneous wind speed of about 31 m s^{-1}. Drought and drying winds coincide in the spring season (March to May). The dunes moved southeastward at a speed of 4–7 m yr^{-1}. The areas have large and dense reticulate dune chains composed of loose and impoverished mobile sands with an insistent moisture content ranging from 3 to 4%. Precipitation is usually the only source of water, and groundwater exists at a deep depth (>8 m) and is not available to support vegetation living on sand dunes.

Typical sand dunes and interdune areas were selected as experimental sites in the HSL. Generally the sand dune and interdune connected together, so we selected three pairs of sand dune and interdune unity as sample plots. The sand dune sample plots were approximately 160–200 m × 230–260 m, the interdune sample plots were approximately 300–350 m × 400–450 m, and all sample plots were within 5 km. The sample plots in sand dunes were set up on the windward slope of a dune with the average slope of approximately 20°, where the dominant plant species were *Artemisia wudanica*, *Corispermum thelegium*, *Agriophyllum squarrosum*, *Setaria viridis*, etc., and with the vegetation cover of less than 15%. The sample plots of interdune area were set up on the north (upwind) side of a sand dune, where 23 plant species occurred with an average vegetation cover of more than 90%. The depth to groundwater was 2.5 m. Table 1 provides a detailed soil profile of sand dunes and interdune areas.

Three 2 m × 2 m quadrats were set up on each sand dune and interdune sample plots of three pairs of sand dune and interdune unity. Time domain reflectometry soil water probes (TDR-3) and temperature probes (PTWD-2A) were buried at different depths (20 cm, 50 cm, 100 cm and 150 cm) in each quadrat with an attempt to minimize the destruction of topsoil vegetation and soil structure. The 24-channel PC-2ST data acquisition devices (Jinzhou Sunshine Technology, Co. Liaoning of China) were used to collect the soil temperature and soil moisture in sand dunes and interdune areas, respectively. We measured and recorded the soil temperature and water content once at 60 min intervals at different soil depths (20 cm, 50 cm, 100 cm and 150 cm) in every quadrat between September 20, 2010 and April 9, 2011.

We calibrated the TDR soil water probes by using oven drying method, and building relationship formula between TDR observations and the actual soil water content by regression analysis. The formulas were showed as below:

For sand dune soil, the formula was: $y = 1.504\times - 7.447$ ($R^2 = 0.89$, $p < 0.0001$).

RMSE of the residuals from the regression lines is 0.53% for sand dune soil.

For interdune soil, the formula was: $y = 0.637\times + 1.995$ ($R^2 = 0.93$, $p < 0.0001$).

RMSE of the residuals from the regression lines is 0.72% for interdune soil.

And on the formula, the “y” is actual soil water content (%), “x” is the TDR observations, and R^2 is the correlation coefficient.