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Effect of snow-straw collocation on the complexity of soil water and heat variation in the Songnen Plain, China

Renjie Hou[a,1], Tianxiao Li[a,1], Qiang Fu[a,b,*], Dong Liu[a], Song Cui[a], Zhaoqiang Zhou[a], Peiru Yan[a], Jiawen Yan[a]

[a] School of Water Conservancy & Civil Engineering, Northeast Agricultural University, Harbin 150030, China
[b] Key Laboratory of Effective Utilization of Agricultural Water Resources of Ministry of Agriculture, Northeast Agricultural University, Harbin, Heilongjiang 150030, China

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ABSTRACT

The goal of this study was to explore the effect of the collocation coverage of snow and straw on the complexity variation of soil water and heat and its appropriate evaluation method during freeze-thaw periods in the Songnen Plain of China. Based on field trials, the characteristics of the spatial variability in soil water and heat and the correlation between the water/heat in snow and in soil were analyzed under conditions of bare land (BL), natural snow (FB0), natural snow plus 5-cm-thick straw (FB5) and natural snow plus 10-cm-thick straw (FB10). Additionally, a spectral entropy algorithm based on Fourier transform was used to calculate the spectral entropy of the soil water and heat sequences, and the spatial variation law of soil water and heat complexity in vertical section was explored; furthermore, the positive effect of straw on the soil water and heat environment was revealed. (1) During the freezing period (i.e., the rapid freezing period and stable freezing period), the collocation coverage of straw and snow weakened the differences between the surface soil and the deeper soil; furthermore, the presence of straw hindered the energy exchange between snow and soil, and as the amount of straw coverage increased, the difference between snow water/heat and that in soil increased. During the melting period, the infiltration of snowmelt water affected the variation of soil water and heat, whereas the straw, due to its water storage characteristics, absorbed large amounts of snowmelt water and provided a stable water supply to the soil. With the increase of straw coverage, the correlation between snow water/heat and that in soil was increased under the FB5 and FB10 treatments. (2) The spectral entropy algorithm evaluation values were in good agreement with the classical statistical analysis, demonstrating that the algorithm can be used to efficiently and accurately evaluate the complexity of soil water and heat time series. The spectral entropy of soil water and heat in the 10-cm soil layer under the treatments of FB0, FB5 and FB10 was less than the corresponding entropy under the BL treatment during rapid freezing and stable freezing periods. As the soil depth increased, the spectral entropy decreased under the different treatments. Affected by the maximum freezing depth, the soil water and heat spectral entropy values peaked in the vertical section during the stable freezing period; as the amount of straw coverage increased, the position of the peak value gradually increased. However, during the melting period, the complexity of soil water and heat under the three snow cover conditions increased significantly relative to that under the BL treatment. As the straw coverage increased, the complexity of soil water and heat decreased. The complexity evaluation method of the spectral entropy algorithm is reliable, and the measurement accuracy meets the evaluation requirements. The algorithm has application value for the evaluation of soil water and heat variation in cold regions.

1. Introduction

It is well known that seasonal frozen soil is part of the atmosphere-cover-soil composite system in nature. In permafrost regions, soil, the main site of energy-water gas exchange between the atmosphere and land surface in such regions, is subjected to freezing and melting every year (Zhang et al., 2013; Li et al., 2014; Brown et al., 2015). The freezing and thawing processes of soil change the sensible heat, latent heat and long-wave radiation effects between soil and the atmosphere. These processes also change the hydraulic properties of soil and directly

* Corresponding author.
E-mail address: fuqiang0629@126.com (Q. Fu).

[1] These authors contributed to the work equllly and should be regarded as co-first authors.

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affect the migration process of soil moisture (Zhou et al., 2008; Roxy et al., 2014). Under the influence of the freezing driving force, the water in soil undergoes a phase transition and redistribution. Under the influence of the water potential gradient, moisture migrates to the frozen front, and the total water content in the frozen area increases (Maurer and Bowling, 2014; Wang et al., 2012a, 2012b). In addition, the infiltration of snowmelt water increases the amount of shallow water resources during the thawing period. Due to the low thermal conductivity and large specific heat capacity of water, the increase in moisture content reduces the soil temperature and reduces the transfer and loss of soil heat, which has positive effects in terms of alleviating water shortages and spring drought and promoting crop seedling growth (Chang et al., 2015; Fu et al., 2015a, 2015b). Snow is an important part of the ecological system in the permafrost region, which has a strong influence on the infiltration and evaporation of soil water during the melting period (Rennert et al., 2007), subsequently changing the soil water and heat flux (Iwata et al., 2010) and thus causing the variation range and cycle time of soil water and heat to present some differences, in turn causing soil water and heat migration trends to show a certain degree of complexity within the freezing range (Fu et al., 2016). However, straw has certain water absorption characteristics that inhibit the ineffective evaporation of soil water and also reduce the interference of precipitation runoff with the soil water and heat status, effectively regulating the variation processes of soil water and heat (Ji and Unger, 2001). Moreover, the transfer and transformation of soil water and heat affect the distribution of nitrogen, organic carbon and other nutrients, thus affecting the fertility level of farmland ecosystems and ultimately determining crop growth and fruit accumulation (Wang et al., 2012a, 2012b). Therefore, it is of great significance to study the temporal and spatial variations in water and heat and the distribution of water and heat complexity in frozen soil under the conditions of collocation coverage with snow and straw, which could result in the effective utilization of the frozen soil resources in cold regions and improvement of the complex adaptability of farmland crops.

Previous studies found that soil freezing was the result of meteorological factors. Based on changes in meteorological factors, dynamic simulations of water and heat in frozen and thawing soil have been conducted. Musa et al. (2016) studied the characteristics of soil water migration during a freezing period and found that the freezing and thawing processes resulted in the enrichment of soil moisture in the frozen layer and could have a beneficial effect on the vegetation restoration of dune land. Shiklomanov and Nelson (2002) used the Stefan method to perform high-precision mapping of the active layer in the Kuparuk watershed, Alaska, USA; they also used a frozen index to characterize the effect of climate change on the thickness of the frozen activity. Quinton et al. (2010) found that during soil freezing and melting and the smooth transition period, the changes in the thermal characteristics of soil and latent heat release and absorption strongly affected the energy distribution of the surface soil. Henry (2008) demonstrated that soil freezing was strongly influenced by air temperature and snow insulation and that the depth of soil freezing increased as the average freezing temperature increased; they also studied the effect of climate change on soil freezing dynamics using linear regression model interpolation. Kahimba et al. (2009) used the modified SHAW model to predict the soil moisture content during the freezing period with high accuracy and true reliability and accurately predicted the soil moisture content during spring melting. Peng et al. (2016) proposed the use of frozen and thawed meteorological indicators to estimate the thickness of the soil layer in which hydrothermal migration activity occurs and the soil freezing depth. Based on the measured data of 12 meteorological stations and soil surface temperature in the Heihe River Basin of China, the variability in the freezing index and soil freezing depth over time and space was analyzed, and the freezing driving mechanism of seasonal frozen soil was revealed. Yang et al. (2002) used GAME-Tibet to obtain high-resolution soil temperature and water content data and found that the distribution of soil water content at each observation site did not increase or decrease with depth but instead appeared in a high aquifer in the vertical profile. Chen and Sun (2004) assessed the current land surface models, which considered the climate system in terms of snow, soil water and heat transfer, vegetation and various physical changes in the turbulent boundary layer, and then constructed a process model to not only describe the energy exchange and transmission mechanism between soil and the atmosphere but also to reflect different land surface process models under the condition of ground-gas exchange processes. Chang et al. (2014) found that there was a significant Boltzmann function between the ground temperature and the water level dynamics in the permafrost activity layer and that changes in the hydraulic relationship between groundwater and surface water caused changes in hydrological processes. Tang et al. (2012) analyzed the long-term observation data of the environmental observer (ENVIS) and found that the main controlling factors of soil moisture during seasonal freezing and thawing processes were temperature and relative air humidity. The main controlling factors of soil temperature are temperature, saturated vapor pressure and upward net radiation.

In addition, some research has focused on the effects of covering on the spatial distribution and variability of soil water and heat. Guglielmin et al. (2008) proposed that the relationship between hydrothermal variation processes and vegetation in permafrost is a significant indicator of climate change. Changes in permafrost and hydrothermal processes affect the degree of vegetation development, and vegetation cover can also affect the hydrothermal processes of permafrost. Endrizzi et al. (2014) used Geotop, which is a sophisticated network model, to predict soil moisture and heat under snow cover; this model describes the energy exchange between soil moisture and the atmosphere in three dimensions and considers radiation and turbulent flux. In addition, this model also describes the highly non-linear relationship between soil freezing and thawing water and energy. Iwata et al. (2008) noted that snow cover hindered the transmission of energy between the atmospheric environment and soil and that it slowed down the loss of soil heat. At the same time, the snow cover inhibited the supply of energy from atmospheric radiation to the soil. The thickness of the snow layer affected the development and decrease of the frozen front and controlled the output of the water flux below the frozen layer. Granberg et al. (1999) established a process of using meteorological data, precipitation and temperature data as driving variables to simulate the redistribution of water and heat in freeze-thaw soils and demonstrated that winter snow cover can reduce soil freezing. Li et al. (2010) found that, during the freeze-thaw phase changes of soil water, water responds significantly to changes in vegetation coverage. Due to the effects of vegetation transpiration, surface evapotranspiration and the soil temperature gradient, the moisture content of the soil profile during the melting period exhibited upward and bottom migration. Liang et al. (2015) used different field coverage and performed a fall irrigation freeze-thaw test in the Inner Mongolia Hetao Irrigation District; they found that coverage affected the response relationship between soil freezing depth and the environmental cumulative negative temperature. They also confirmed that coverage measures promoted the development of crop seedlings.

Most previous studies have focused on the water and heat transfer laws and the regulation effect of coverage on soil, while ignoring the influence of snowmelt water infiltration, leading to a complex and disorderly trend in the laws of soil water and heat in the melting period under the conditions of natural snow cover. However, in view of previous research, some scholars have focused on evaluation of soil water and heat complexity. Hu et al. (2006) used classical statistical principles to analyze the variability of soil moisture and temperature by means of standard deviations and coefficients of variation and found that the complexity of soil water and heat in sunny slopes was increased relative to that in shady slopes. Migała et al. (2014) analyzed the differences in soil temperature and moisture content under different cover treatments and explained the influences of vegetation on soil water and heat