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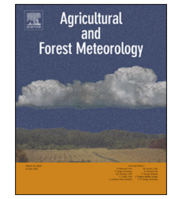

Artificial warming-mediated soil freezing and thawing processes can regulate soybean production in Northeast China

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ABSTRACT

Northeast China with seasonally frozen soil is quite sensitive to global warming. The changes in soil freezing and thawing processes initiated by global warming could alter the hydrological cycle of agricultural fields. A paired-plot experiment was conducted in frozen agricultural soils in Northeast China to examine the impacts of simulated warming on soil freezing and thawing processes and on soybean production. Infrared radiators were used to simulate global warming, rising surface soil temperature (5 cm depth) by 2.86 °C. We showed that, artificial warming caused the freeze duration shortened by 22 days, and the thaw duration shortened by 17 days resulting in the mean duration of soil freezing-thawing significantly shortened by 39 days and the maximum frost depth reduced by about 40 cm. Simulated warming had no significant effect on the average annual freeze-thaw cycle frequency. Warming induced a larger water accumulation in the 0–100 cm soil layer during 2014–2015 soil freezing period. In the dry year of 2015, warming did not significantly affect surface soil moisture during period from sowing date to VC (soybean cotyledon) date. Thus, warming-induced an increase in soybean yield in the dry year may be attributable to the positive effect of enhanced soil temperature on soybean growth (aboveground dry matter accumulation) and consequent on soybean production. In the wet year of 2014, warming decreased surface soil moisture from sowing date to the date of VC stage because warming advanced the soil thaw-end date in 20–60 cm layer by 15 days. This decline in surface soil water availability may potentially offset the positive effects of increased soil temperature on soybean yield, thus warming effects on soybean production was neutral in the wet year. Our findings highlight the potential role of seasonally soil freezing and thawing dynamics in regulating soybean to global warming and suggested that warming effects on soil water dynamics during soil freezing and thawing periods, and subsequent on the surface soil water availability at the early vegetative stage and soybean production were associated with the hydrological year. We conclude that under current precipitation patterns, the no response of soil surface water availability to warming during early vegetative growth, coupled with warming-mediated increases in soil temperature, might improve soybean production during dry years in Northeast China.

1. Introduction

The global mean surface temperature has increased since the late 19th century (IPCC, 2013), and it is certain that the climate is undergoing a warming trend (IPCC, 2013; Wang and Wu, 2013). Northeast China, located at relatively high latitudes, is one of the coolest regions in China with seasonally frozen soil. The climate in this region is sensitive to climate change (Yang et al., 2007; IPCC, 2013). Recent research has shown that important characteristics of climatic change in this region are temperature increasing, precipitation decreasing and drought strengthening (Qian and Zhu, 2001; Liu et al., 2004; Yang et al., 2007). Among features, drought strengthening, in particular, spring drought caused by large precipitation variability and rising temperature has become a serious problem for crop production in Northeast China (Qian and Zhu, 2001; Yang et al., 2007; Liu et al., 2008). The occurrence of spring drought depends on precipitation in the spring season and on soil thawing water (Shen et al., 1980). Therefore, when spring rainfall is too small to meet crop demands, soil thawing water associated with seasonally frozen soil is critical for alleviating spring drought stress in Northeast China (Shen et al., 1980;

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Henry, 2013; Yi et al., 2014).

Seasonally frozen ground involves a soil layer, which freezes and thaws annually, and is profoundly influenced by climate change (Morison et al., 2000; Zhao et al., 2004). As reported by Lemke et al. (2007), in the Northern Hemisphere, the global warming has led to about a 7% reduction in the maximum seasonally frozen ground area since 1900. Therefore, in recent years, there has been an increasing concern of the interaction between climate change and soil freezing. Considerable progress has been made in illuminating the effects of climate change on soil freezing characteristics, including length of the soil freezing period (Cutforth et al., 2004; Sinha and Cherkauer, 2008; Wang and Wu, 2013), depth (Venalainen et al., 2001; Frauenfeld et al., 2004), frequency (Ho and Gough, 2006; Fortin, 2010; Musa et al., 2014), through modeling and field measurements. The seasonally frozen soil in Northeast China has already been influenced by global warming (Chen and Li, 2008; Li et al., 2017), as demonstrated by the reduction in maximum frost depth (Chen and Li, 2008; Li et al., 2017), and the shortening of the duration of the seasonally frozen ground (Chen and Li, 2008) in recent decades. However, few field studies directed specifically on how warming affects soil freezing and thawing dynamics have been performed. Soil freezing and thawing are controlled by complex interactions of energy and water transfer (Flerchinger et al., 2005), which is always accompanied by soil water migration and redistribution, and thus usually induces an increase in total soil water content during the freezing period (Guo et al., 2002; Flerchinger et al., 2005; Zhang and Sun, 2011; Chen et al., 2013) driven by soil matric potential gradients and temperature gradients (Zhao et al., 2000; Tokumoto et al., 2010; Sun et al., 2012; Chen et al., 2013). Zhao et al. (2000) reported that larger temperature and steeper temperature gradient both lead to larger unfrozen water migration during freezing of the active soil layers in the Tibetan Plateau. However, some studies have found that drier soil and lower unsaturated hydraulic conductivity could be responsible for slower soil water migration rates (Fukuda et al., 1983; Kane and Stein, 1983; Flerchinger et al., 2005; Chen et al., 2013). Therefore, freeze-thaw-induced water migration and water accumulation in seasonally frozen agricultural soils is very important for understanding how soil hydrology is affected by global warming (Zhao et al., 2013). There exists a need to artificially heat soil as a way to mimic future warming conditions in order to study warming impacts on soil freezing and thawing and soil hydrology.

Northeast China has the largest soybean production area (Liu et al., 2008). The soybean production in this area often suffers from drought stress in the spring season (Yang et al., 2007), which can cause losses in soybean yield (Liu et al., 2008). Although soil freezing and thawing may provide soil water useful for relieving crop water stress (Shen et al., 1980), there is little observational evidence on how warming-induced changes in soil freezing and thawing processes affect soybean production in this region. Therefore, the purpose of this study is to compare soil freezing-thawing dynamics, and soil profile water dynamics under current climate conditions with those under simulated climate warming conditions, thus elucidating the role of soil frost dynamics on regulating soybean production responses to global warming. The specific research objectives are to: (1) examine the impact of simulated global warming during two winter seasons on soil freezing-thawing characteristics of an agricultural soils, (2) investigate the responses of water dynamics during the soil freezing and thawing periods and growing seasons to artificial warming, (3) identify how warming-mediated changes in soil freezing and thawing processes alter soybean production in Northeast China.

2. Materials and methods

2.1. Study site

The field experiment was performed at the Hailun National Field Station (47°26′N, 126°38′E), Chinese Academy of Sciences, in Heilongjiang province, China. The field site is located in the Mollisols region of Northeast China, where it is known as the 'bread basket' of China (Chen et al., 2011). The climate is a typical temperate continental monsoon climate with long and cold winters. The soil freezing and thawing process lasts from the end of October to the following June (Wang et al., 2008). The maximum frost depth is in the range of 160 ~ 230 cm (Wang et al., 2008). From 1953 to 2013, the annual mean temperature is 2.0 °C increasing at a rate of about 0.27 °C per decade (China Meteorological Data Sharing Service System). The mean air temperature during the freezing and thawing stages (i.e. October-June) is −3.45 °C (Fig. S1a). Soybean is one of the dominant economic crops, and it is planted in May. The average water consumption is 459 mm (Meng and Zhang, 1997). Averaged over the 3 years, the groundwater level is about 17 m deep (National science & technology infrastructure, National Ecosystem research Network of China), and it does not supply water to crops. Agricultural production in this region completely depends on natural precipitation. The mean annual precipitation is 558 mm (China Meteorological Data Sharing Service System), with about 67% of the total precipitation occurring from June to August (Fig. S1b). The average precipitation during the soil freezing and thawing season is 220 mm (Fig. S1a). Based on annual precipitation, 2014 was a wet year (680.2 mm), and 2015 was a dry year (429.8 mm) (Figs. S1b, S1c). The frequency and total amount of precipitation during growing season (May to September) in 2015 was lower than those in 2014 (Fig. S1b). The daily average wind speed during growing season in 2015 was larger than that in 2014 ($P < 0.001$), but there were no differences in both daily mean vapor pressure deficit (VPD) and daily total solar radiation between 2014 growing season and 2015 growing season (Table S1) (China Meteorological Data Sharing Service System). Before the experiment, undisturbed soil cores (5 cm long, and 5 cm diameter) with three replications were sampled at a depth increment of 10 cm from 0 cm to 100 cm depth and 20 cm from 100 to 260 cm depth to determine soil physical characteristics. Bulk density and saturated water content were obtained by the oven drying method. The saturated hydraulic conductivity was measured by the constant head method (Klute and Dirksen,1986). A pressure chamber was used to measure the field capacity (Yi et al., 2014). In addition, the disturbed soil samples were collected from the same depths to analyze soil texture by the pipette method (Gee and Bauder, 1986). The soil texture is silty clay loam, according to the USDA soil taxonomy (Soil Survey Staff 2010). Selected soil physical characteristics are shown in Table1.

Table 1
Soil physical characteristics at the experimental site.

Soil depth (cm)	Soil texture			Bulk density ($g\ cm^{-3}$)	Saturated water content ($cm^3\ cm^{-3}$)	Saturated hydraulic conductivity ($cm\ d^{-1}$)	Field capacity ($cm^3\ cm^{-3}$)
	Sand (%)	Silt (%)	Clay (%)				
0-30	35.4	35.4	29.2	1.24	0.45	31.28	0.35
30-60	26.3	42.8	30.9	1.39	0.44	11.06	0.36
60-120	29.0	41.9	29.1	1.38	0.43	11.94	0.36
120-160	31.8	39.6	28.6	1.44	0.41	8.65	0.34
160-260	30.9	41.8	27.3	1.54	0.41	5.52	0.36