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Responses of soil organic carbon, soil respiration, and associated soil properties to long-term thinning in a semiarid spruce plantation in northwestern China

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Abstract

Silvicultural thinning using whole-tree harvesting (WTH) has been an important and common forest management practice for *Picea crassifolia* plantations in the Qilian Mountains of China. However, consequences of this silvicultural practice are still not well known. We examined the influence of three thinning levels on long-term soil carbon storage, soil respiration (Rs), and soil properties. Our results showed that soil carbon stocks decreased significantly with increasing thinning intensity at a soil depth of 0–70 cm, whereas soil water storage increased, especially in the deep soil layers (30–70 cm). Mean Rs rates during the growing season increased significantly with increasing thinning intensity, and the dynamics of Rs coincided with that of soil temperature. Generally, 65% to 73% of the variation in Rs rates in three thinning levels was explained by the changes in soil temperature. WTH significantly increased soil bulk density at the 0- to 30-cm and soil pH at the 0- to 20-cm depths and significantly decreased soil nitrogen and C:N ratio in the 0- to 20-cm layers. As no significant effect of WTH was detected on fine root biomass, we attributed the elevated soil respiration to accelerated decomposition of organic matter as a result of elevated soil temperature and substrate quality. Our results demonstrate the potential for WTH to relieve water deficits in spruce plantations in semiarid regions but suggest that WTH has a negative impact on carbon sequestration.

KEYWORDS

semiarid spruce plantation, soil organic carbon, soil properties, soil respiration, whole-tree harvesting

1 | INTRODUCTION

Silvicultural thinning, the reduction of stand density to increase the availability of growth-limiting resources to residual trees, has been an important and common silvicultural practice for forest ecosystems, especially in plantations (Baena et al., 2013; Tian et al., 2009). Thinning improves resistance to insects and disease (Chase, Kimsey, Shaw, & Coleman, 2016; Louda & Collinge, 1992), reduces the risk of wildfire (Schoennagel, Veblen, & Romme, 2004), relieves soil degradation (especially soil drought), and maintains a healthy forest (Baena et al., 2013) by opening the canopy and changing microclimatic conditions at ground level (Saunders et al., 2012). Stand responses following thinning involve modifications in understory vegetation composition (Dodson, Peterson, & Harrod, 2008), the quantity and quality of organic matter into the soil (Saunders et al., 2012), and root density (including exudates) and turnover (Pang, Hu, Bao, de Oliveira Vargas,

& Tian, 2016; Tufekcioglu, Guner, & Tilki, 2005). Changes to biotic and abiotic conditions can alter the soil carbon (C) cycle and associated soil properties in forest (Borrelli, Märker, & Schütt, 2015; Chatterjee, Vance, Pendall, & Stahl, 2008; Lemenih, Kassa, Kassie, Abebaw, & Teka, 2014).

The influence of silvicultural thinning on soil processes and properties include changes in soil respiration (Rs), soil C and nitrogen (N) stocks, soil temperature, soil water, acidity, nutrient status, and biological activity (Baena et al., 2013; Santiago, Lucas-Borja, Baena, Andrés-Abellán, & Heras, 2016). However, large uncertainty exists about the ecological consequences of silvicultural thinning (Kaarakka et al., 2014; Nilsen & Strand, 2008; Tian et al., 2009). Thinning is initially observed to decrease Rs because of the cessation of root respiration (Nakane, Tsubota, & Yamamoto, 1986; Sullivan et al., 2008). However, Tang, Qi, Xu, Misson, and Goldstein (2005) documented no significant difference in Rs after thinning due to interannual climate variability. An increase in Rs has also been observed following thinning due to an increase in microbial respiration induced by root death and changes in soil microclimate (Cheng, Kang, Han, Liu, & Zhang, 2015; Pang, Bao, Zhu, & Cheng, 2013; Selig, Seiler, & Tyree, 2008). Soil C storage frequently decreased with thinning (Nave, Vance, Swanston, & Curtis, 2010), and the extent of this effect depended on thinning type and intensity, forest type (hardwood vs. coniferous/mixed), soil layer (forest floor vs. mineral), and soil taxonomic order (Cheng et al., 2014; Guo et al., 2010; Tian et al., 2009). A meta-analysis at a global scale by D. W. Johnson and Curtis (2001) revealed significant effects of harvest type on soil C and N, with stem-only harvesting resulting in increases (18%) and whole-tree harvesting (WTH) in decreases (6%) in soil C and N. Many studies have shown that soil water, acidity, and nutrient pools were also sensitive to thinning and the responses were often site-specific (Baena et al., 2013; Kaarakka et al., 2014; Panosso et al., 2011). Currently, most of the studies have focused on responses in the first few years after thinning and changes in topsoil (e.g., 0–10 cm), but long-term effects (>10 years) and responses of subsoil are still not well known (Hu et al., 2014; Jandl et al., 2007; Wall, 2012). Thus, data are needed from long-term thinning experiments in different site conditions and in deep soil layers to extend our knowledge about the consequences of thinning.

The Qilian Mountains are an important forest region (dominated by *Picea crassifolia*) in northwestern China. In recent decades, the area of *P. crassifolia* plantation has been growing to restore mountain vegetation (He, Zhao, Liu, & Tang, 2012). High carbon sequestration potential has been demonstrated for these plantation forests (Chen et al., 2016). However, due to generally high stand densities, water deficits had been often observed following afforestation. Furthermore, soil degradation and low forest productivity are also common in these *P. crassifolia* plantation forests. To relieve soil degradation (especially soil drought), silvicultural thinning using WTH has been an important and common forest management practice for *P. crassifolia* plantation in the Qilian Mountains. However, the effects of this silvicultural practice on the soil C cycle and associated soil properties in these ecosystems are poorly known. Thus, our objectives were to investigate the impacts of long-term WTH on (a) soil respiration, (b) associated soil properties, and (c) soil C, N, and water storage.

2 | METHODS

2.1 | Study sites

The study site was situated in the Guantai protection zones (100°15.277′E, 38°32.597′N) in the middle of the Qilian Mountains, and within Sunan County, Gansu Province. Mean annual temperature and precipitation are 2.5°C and 385 mm, respectively (Zhu, He, Du, Yang, & Chen, 2015). The growing season ranges from June to September. In the study area, forests are mostly found on north-facing slopes (shaded slopes), and grasslands occupy south-facing slopes (sunny slopes) and east- or west-facing slopes (semishaded slopes; Chen, He, Du, Yang, & Zhu, 2015). Since the 1980s, *P. crassifolia* plantations have expanded rapidly on semishaded slopes. *Carex vulpina*, *Potentilla acaulis*, *Elymus cylindricus*, *Urtica triangularis*, and *Achnatherum splendens* are the dominant understory species. Thinning was conducted in 1997 and 1998 by cutting every second row. Trees were whole-tree harvested.

2.2 | Experimental design, vegetation survey, and soil sampling

In mid-August 2013, 15 years after thinning, three treatments were selected in *P. crassifolia* plantation forests, including an unthinned control (4,458 trees ha^{-1}, CK), a light thinning (3,565 trees ha^{-1}, LT), and a high thinning (2,720 trees ha^{-1}, HT). Stands occurred adjacent to each other (separated by roads) and had similar site conditions (Table 1). We randomly established three replicate plots of 30 × 30 m^2 in each study stand.

The characteristics of trees for each plot, including density, height, and diameter at breast height, were determined; 10 subplots of 1 × 1 m^2 were randomly located for the measurements of understory vegetation biomass (Zhu et al., 2015). Soil samples were collected in five soil layers (0–10, 10–20, 20–30, 30–50, and 50–70 cm) at five randomly located points for each plot. In addition, undisturbed soil cores with volume of 100 cm^3 were obtained to determine soil bulk density.

2.3 | Measurements of Rs rate

The *Rs* rate was determined in situ with a Li-8100a soil CO$_2$ flux system. In early May 2014, five polyvinyl chloride collars (20 cm in diameter and 10 cm in height) were randomly installed in each plot. Plants inside the collars were removed before measurements. Measurements of *Rs* were performed on the collars in the middle of every month from May to October (soil was frozen from November to April) in 2014 and 2015; for each collar, the measurement was repeated twice between 09:00 and 11:00 am. The measurements of soil temperature and moisture were concurrent and adjacent to the PVC collars. The relationship between *Rs* and temperature was simulated by the following function (Iqbal et al., 2010; Noh et al., 2010).

$$Rs = Ae^{BT}, \tag{1}$$

$$Q10 = e^{10B}, \tag{2}$$

TABLE 1 Site characteristics for different thinning treatments

Thinning treatment	Slope (°)	Aspect (°)	Altitude (m)	Height (m)	DBH (cm)	Plantation age (year)	Stand density (trees ha^{-1})	Annual production litter (g m^{-2})	Aboveground biomass of mosses (g m^{-2})	Aboveground biomass of herbs (g m^{-2})	Fine root biomass (g m^{-2})
CK	24.06	344.81	2787	5.8 ± 0.89	8.3 ± 1.02	31	4458 ± 37	365.16 ± 46.32 a	614.54 ± 87.23 a	-	321.42 ± 39.92 a
LT	23.25	327.75	2819	6.3 ± 0.69	8.5 ± 0.89	32	3565 ± 75	323.67 ± 49.53 ab	274.50 ± 28.58 b	85.47 ± 8.53	327.74 ± 52.89 a
HT	19.67	336.33	2828	6.1 ± 0.46	8.6 ± 0.76	30	2720 ± 58	262.12 ± 54.19 b	50.33 ± 21.98 c	116.53 ± 10.94	314.71 ± 43.67 a

Note. Values (±SE) followed by different lowercase letters within columns are significantly different at $P < 0.05$. DBH: diameter at breast height.

where *Rs* was soil surface CO_2 flux, *T* was ST (°C), and *A B* were model coefficients, respectively. The *Q*10 value was calculated from the *B* values from the regression equation (1).

2.4 | Litter collection and fine root (<2 mm in diameter) biomass measurements

Five litter traps (1.0 × 1.0 m^2, 50 cm above the ground) were randomly installed in each plot. Litter in traps was collected every 3 months from October 2013 to September 2015. Collected litter was oven-dried at 65°C.

To minimize soil disturbance, fine root biomass was determined only in July 2014 and 2015 (Zhang et al., 2015). For each plot, five soil cores (9 cm in diameter and 20 cm in depth) were obtained and then mixed into one composite sample. Roots were gently separated from the soil manually, washed, and oven-dried at 65°C to a constant weight.

2.5 | Measurements of soil water content

Soil water content was measured semi-monthly from May to October in 2014 and 2015 with five replicates for each plot. The soil was sampled in five soil layers (0–10, 10–20, 20–30, 30–50, and 50–70 cm) to determine the gravimetric soil water content. Soil water storage (SWS) was calculated as follows (Zhang & Zhao, 2015):

$$VSWCi = SWCi \times Bi, \tag{3}$$

$$SWSi = VSWCi \times Di, \tag{4}$$

where *SWSi*, *SWCi*, *VSWCi*, *Bi*, and *Di* were, respectively, SWS (mm), gravimetric soil water content (%), volumetric soil water content (VSWC; %), bulk density (g cm^{-3}), and thickness (mm) of the layer *i*.

2.6 | Soil analysis

Soil pH was determined by the method of acidity agent (Deng, Zhang, & Shangguan, 2014). Soil organic carbon (SOC) was measured with the $K_2Cr_2O_7$–H_2SO_4 oxidation method developed by Walkley-Black (Nelson, Sommers, Page, Miller, & Keeney, 1982); total nitrogen (TN) was determined by the Kjeldahl method (Jackson, 1973); total phosphorus (TP) was determined colorimetrically after wet digestion with H_2SO_4 + $HClO_4$ (Parkinson & Allen, 1975).

2.7 | Calculation of soil C and N storage

SOC and TN stocks for a soil profile were calculated using the following equation (Chen et al., 2015; Rytter, 2012):

$$SOCSh = \sum_{i=1}^{n} Di \times Bi \times SOCi \times \frac{(1 - \theta i)}{10}, \tag{5}$$

$$TNSh = \sum_{i=1}^{n} Di \times Bi \times TNi \times \frac{(1 - \theta i)}{10}, \tag{6}$$

where *SOCSh* and *TNSh* were SOC and TN stocks of a soil profile with a depth *h* (cm); *SOCi*, *TNi*, *Di*, *Bi*, and *θi* were, respectively, SOC concentration (g kg^{-1}), TN concentration (g kg^{-1}), thickness (cm), bulk density (g cm^{-3}), and the volumetric percentage of the fraction >2 mm (%) at the layer *i*.

2.8 | Statistical analysis

One-way ANOVA was adopted to detect the differences among stands with thinning levels in soil properties, Rs, soil temperature and moisture, SOC and TN stocks, and SWS. Additionally, we employed ordinary least squares regression to examine the relationships between Rs and soil temperature, and soil moisture. Pearson correlation analysis was performed to determine the relationships between Rs and other soil biotic and abiotic properties such as SOC, TN, TP, soil C:N ratios, soil pH, soil bulk density, and fine root biomass.

3 | RESULTS

3.1 | Changes in soil properties

Soil temperature showed similar seasonal variability among the different thinning levels and was significantly influenced by thinning treatment over the course of both growing seasons (Figure 1). As thinning intensity increased, mean soil temperature (0–10 cm) increased significantly ($P < 0.05$) from 2.79°C (CK) to 4.58°C (LT) and 4.95°C (HT) in 2015, and from 3.03°C (CK) to 4.75°C (LT) and 5.15°C (HT) in 2014. However, soil moisture (0–10 cm) did not differ significantly among stands with different thinning levels (Table 2).

Soil OC and TN tended to decrease with increasing thinning levels (Table 3); consequently, SOC in the 0- to 30-cm soil layer and TN in the 0- to 20-cm soil layer were significantly ($P < 0.05$) higher in CK than in HT. Similarly to SOC and TN, C:N ratios also decreased with increasing thinning levels, and C:N ratios in HT were significantly lower than that in LT and CK in the 0- to 20-cm layers, although no significant difference was detected in TP across the sampled soil depth (0–70 cm) among stands with different thinning levels. Soil bulk density increased with increasing thinning levels except for the 50- to 70-cm soil layer, and soil bulk density in the 0- to 30-cm layers in HT was significantly ($P < 0.05$) higher than that in CK. Thinning also resulted in an increase in soil pH in the upper layer (0–20 cm), and soil pH in the 0- to 20-cm layers in LT and HT was significantly ($P < 0.05$) higher than that in CK, although fine root biomass did not differ significantly among stands with different thinning levels (Table 1).

3.2 | Changes in Rs and its relationship with soil temperature, soil moisture, and other soil variables

Generally, Rs showed similar seasonal variability among stands with different thinning levels, and the dynamics of Rs paralleled that of soil

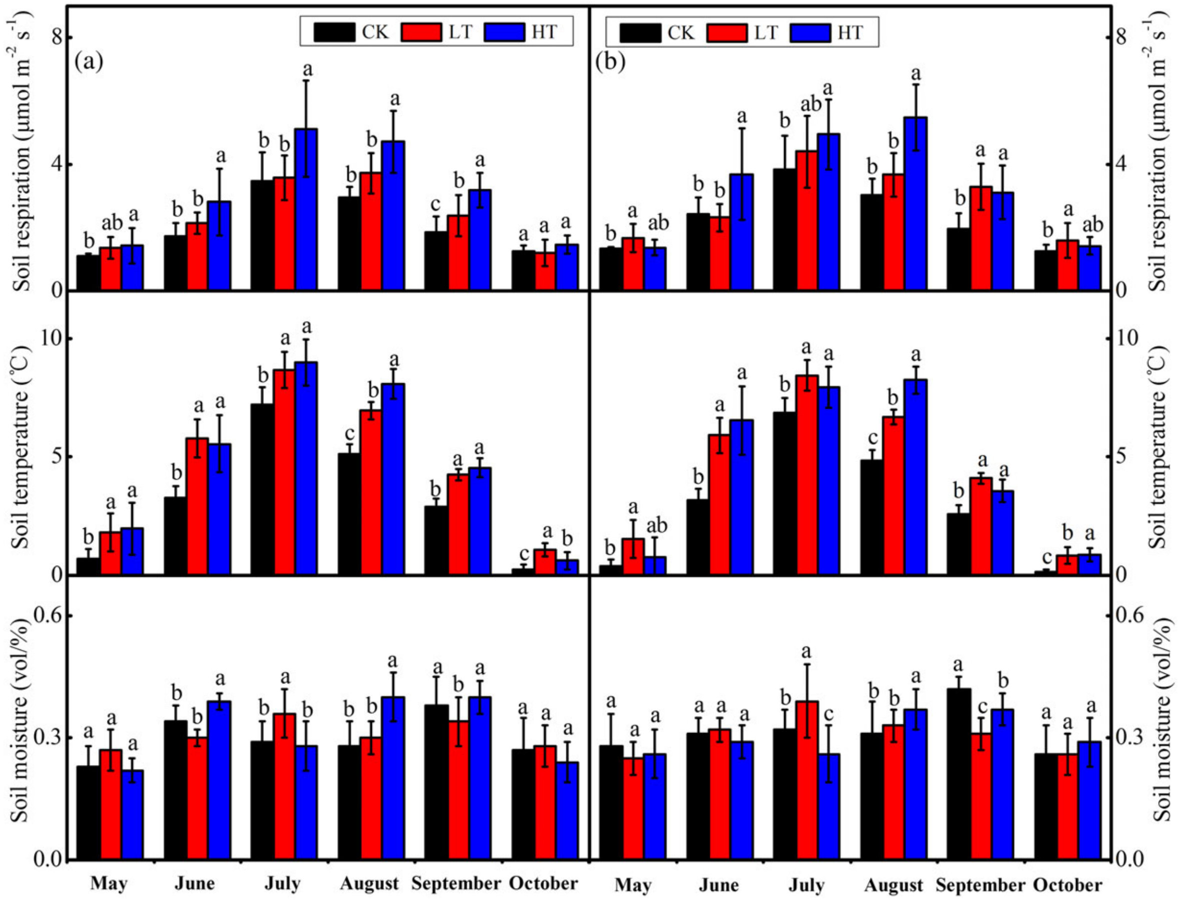

FIGURE 1 Seasonal variation in soil respiration, soil temperature, and soil moisture at a depth of 10 cm in different thinning treatments during the growing seasons of 2015 (a) and 2014 (b). Error bars represent standard errors of the means (n = 15). Different lowercase letters above the bars indicate significant differences at $P < 0.05$ [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Comparison of mean soil respiration rate (Rs, *n* = 15), mean soil temperature (ST, *n* = 15), and mean soil moisture (SM, *n* = 15) during the growing season at a depth of 10 cm, and soil water storage (SWS) at a depth of 0–70 cm (*n* = 15) among stands with different thinning levels

Year	Thinning treatment	Rs (μmol m^{-2} s^{-1})	ST (°C)	SM (%)	SWS (mm)
2015	CK	1.89 ± 0.79 b	2.79 ± 2.29 b	0.28 ± 0.05 a	126.59 ± 13.10 c
	LT	2.51 ± 1.02 a	4.58 ± 2.69 a	0.28 ± 0.04 a	142.99 ± 16.90 b
	HT	2.97 ± 1.54 a	4.95 ± 3.09 a	0.29 ± 0.04 a	157.58 ± 27.46 a
2014	CK	1.96 ± 0.85 b	3.03 ± 2.34 b	0.27 ± 0.05 a	125.53 ± 16.44 b
	LT	2.39 ± 1.07 ab	4.75 ± 2.65 a	0.26 ± 0.06 a	140.61 ± 18.25 a
	HT	3.12 ± 1.57 a	5.15 ± 2.99 a	0.30 ± 0.03 a	151.75 ± 23.85 a

Note. Values (±SE) followed by different lowercase letters within columns are significantly different at $P < 0.05$.

TABLE 3 Comparison of soil organic carbon (*n* = 15), soil total nitrogen (*n* = 15), soil total phosphorus (*n* = 15), soil carbon/nitrogen (C:N) ratios (*n* = 15), pH value (*n* = 15), and soil bulk density (*n* = 15) among different thinning treatments in different soil layers

Soil property parameters	Soil depth (cm)	CK	LT	HT
Soil organic carbon (g kg^{-1})	0–10	72.63 ± 5.02 a	63.03 ± 4.14 b	50.33 ± 4.52 c
	10–20	66.83 ± 3.75 a	53.57 ± 3.95 b	44.52 ± 3.10 c
	20–30	51.58 ± 5.42 a	46.56 ± 3.83 ab	41.61 ± 2.51 b
	30–50	40.95 ± 2.65 a	39.26 ± 3.40 a	35.50 ± 2.98 a
	50–70	34.14 ± 3.64 a	30.98 ± 2.00 a	29.36 ± 1.76 a
Soil total nitrogen (g kg^{-1})	0–10	4.38 ± 0.20 a	4.02 ± 0.39 ab	3.56 ± 0.21 b
	10–20	4.25 ± 0.13 a	3.61 ± 0.29 b	3.30 ± 0.10 b
	20–30	3.54 ± 0.31 a	3.37 ± 0.20 a	3.12 ± 0.18 a
	30–50	2.85 ± 0.24 a	2.80 ± 0.16 a	2.77 ± 0.21 a
	50–70	2.36 ± 0.30 a	2.25 ± 0.15 a	2.22 ± 0.08 a
Soil total phosphorus (g kg^{-1})	0–10	0.85 ± 0.05 a	0.83 ± 0.05 a	0.82 ± 0.04 a
	10–20	0.77 ± 0.04 a	0.75 ± 0.07 a	0.73 ± 0.05 a
	20–30	0.65 ± 0.05 a	0.67 ± 0.05 a	0.68 ± 0.07 a
	30–50	0.59 ± 0.06 a	0.61 ± 0.06 a	0.63 ± 0.05 a
	50–70	0.66 ± 0.07 a	0.63 ± 0.05 a	0.67 ± 0.06 a
C/N	0–10	16.58 ± 0.54 a	15.71 ± 0.49 a	14.11 ± 0.48 b
	10–20	15.72 ± 0.45 a	14.83 ± 0.17 a	13.50 ± 0.92 b
	20–30	14.04 ± 0.62 a	13.70 ± 0.55 a	13.52 ± 0.90 a
	30–50	14.37 ± 0.43 a	14.00 ± 0.43 a	13.67 ± 0.88 a
	50–70	13.90 ± 0.48 a	13.76 ± 0.39 a	13.26 ± 0.69 a
pH value	0–10	7.40 ± 0.06 b	7.55 ± 0.07 a	7.64 ± 0.05 a
	10–20	7.73 ± 0.07 b	7.90 ± 0.07 a	7.93 ± 0.06 a
	20–30	7.93 ± 0.06 a	7.95 ± 0.04 a	8.02 ± 0.07 a
	30–50	8.28 ± 0.05 a	8.23 ± 0.06 a	8.30 ± 0.06 a
	50–70	8.44 ± 0.04 a	8.49 ± 0.09 a	8.46 ± 0.03 a
Soil bulk density (g cm^{-3})	0–10	0.78 ± 0.08 b	0.83 ± 0.03 ab	0.93 ± 0.04 a
	10–20	0.90 ± 0.03 b	0.92 ± 0.08 ab	0.97 ± 0.03 a
	20–30	0.89 ± 0.04 b	0.94 ± 0.02 b	1.01 ± 0.04 a
	30–50	0.92 ± 0.05 a	0.93 ± 0.04 a	0.98 ± 0.03 a
	50–70	0.98 ± 0.04 a	0.96 ± 0.05 a	1.01 ± 0.02 a

Note. Values (±SE) followed by different lowercase letters within rows are significantly different at $P < 0.05$.

temperature (Figure 1), with maximum Rs and soil temperature occurring in July and August. It appeared that Rs did not covary with soil moisture. As thinning intensities increased, mean Rs rates increased significantly ($P < 0.05$) from 1.89 μmol m^{-2} s^{-1} (CK) to 2.51 μmol m^{-2} s^{-1} (LT) and 2.97 μmol m^{-2} s^{-1} (HT) in 2015, and from 1.96 μmol m^{-2} s^{-1} (CK) to 2.39 μmol m^{-2} s^{-1} (LT) and 3.12 μmol m^{-2} s^{-1} (HT) in 2014 (Table 2).

Significant correlations existed between Rs and soil temperature in each stand ($R^2 = 0.65$ for CK; $R^2 = 0.73$ for LT; $R^2 = 0.68$ for HT), and the relationships were characterized by exponential functions (Figure 2). The Q_{10} values increased in the order of CK (3.94), LT (4.37), and HD (4.66). However, Rs showed no significant relationships with soil moisture (data not shown).

Correlation analyses between Rs and other soil biotic and abiotic properties are shown in Table 4. There were significant positive correlations between Rs and soil pH ($P < 0.05$) and significant negative correlations between Rs and C:N ratios ($P < 0.01$). However, no significant correlations were detected between Rs and SOC, TN, TP, soil bulk density, and fine root biomass ($P > 0.05$).

3.3 | Changes in SOC, nitrogen, and water storage

Generally, SOC stocks tended to decrease with increasing thinning levels (Figure 3), and SOC stocks in CK were significantly ($P < 0.05$) higher than those in HT at all soil depths; SOC storage in the 0- to 70-cm soil profile for CK, LT, and HT was 297.21, 271.53, and 261.04 Mg ha^{-1}, respectively. In contrast to SOC stocks, TN stocks (kg m^{-2}) generally did not differ significantly among stands with different thinning levels (Figure 3), and TN storage in the 0- to 70-cm soil profile for CK, LT, and HT was 20.04, 19.11, and 19.62 Mg ha^{-1}, respectively.

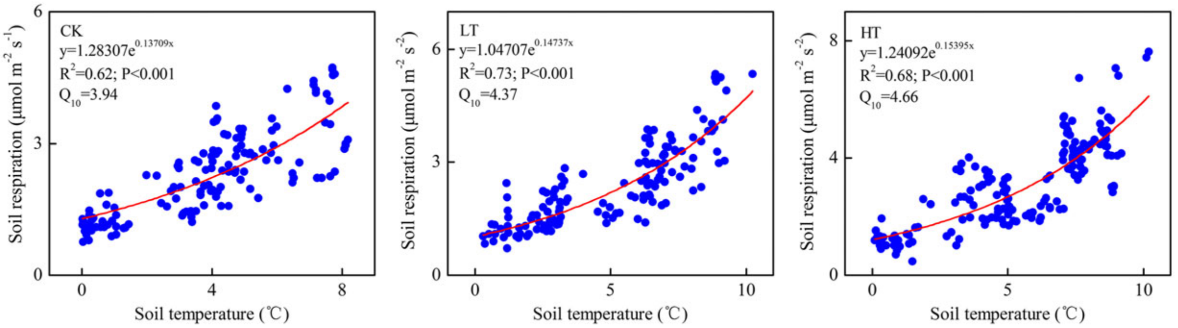

FIGURE 2 The relationships between soil respiration and soil temperature at a soil depth of 10 cm during the growing seasons of 2014 and 2015 for stands with different thinning levels [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Pearson's correlation coefficients between soil respiration rate and soil properties in the 0- to 10-cm soil layers and fine root biomass

Soil property parameters	Soil respiration rate
Soil organic carbon	−0.363
Soil total nitrogen	−0.229
Soil total phosphorus	−0.107
C/N	−0.882**
pH value	0.531*
Soil bulk density	0.039
Fine root biomass	−0.162

*Correlation significant at the 0.05 level (two-tailed).

**Correlation significant at the 0.01 level (two-tailed).

SWS in the 0- to 70-cm soil profile increased with increasing thinning intensity, and thinning significantly ($P < 0.05$) increased SWS (Table 2): 125.53 mm for CK, 140.61 mm for LT, and 151.75 mm for HT, respectively, in 2014; and 126.59 mm for CK, 142.99 mm for LT, and 157.58 mm for HT, respectively, in 2015. Generally, VSWC showed similar variation trends in 2014 and 2015; VSWC in the 0- to 30-cm layers did not differ significantly among stands, whereas VSWC in the 30- to 70-cm layers increased significantly ($P < 0.05$) with increasing thinning intensity (Figure 4).

4 | DISCUSSION

4.1 | Response of SOC, nitrogen, and water storage to thinning

A net SOC and TN decrease was frequently observed following the removal of organic residues and the effects dependent upon harvesting types (Hu et al., 2014; Nave et al., 2010). Due to a greater export from the site of the nutrient-rich aboveground biomass, especially needles and twigs, WTH was often associated with a decline in soil C and N pools (Saarsalmi, Tamminen, Kukkola, & Hautajarvi, 2010). In this study, we found that WTH had significant and negative impacts on SOC and TN, with SOC in the 0- to 30-cm and TN in the 0- to 20-cm soil layer decreasing significantly with increasing thinning intensities (Table 3), confirming the results of previous research. Additionally, we found that the impacts of WTH on SOC and TN were greater in the upper than in the lower soil, which was also observed in numerous studies in temperate zones (Hu et al., 2014; Nave et al., 2010). Soil organic matter in forest systems often has lower molecular complexity and shorter turnover times in topsoil than in subsoil, and the abundance of labile substrate in the topsoil may stimulate a more quick microbial response following disturbance, which would cause the topsoil to be more vulnerable to organic matter decline than the subsoil following logging (Hu et al., 2014).

WTH involves a great removal of organic residues from forest sites. In addition, a decrease in the production of litter and biomass of understory vegetation and an increase in Rs were observed with increasing thinning intensity in this study (Tables 1 and 2). Thus, the significant decrease in soil C stocks with increased thinning intensity may be attributed to the lower C input via litter production and understory vegetation, and larger C outputs through Rs. In contrast to soil C stocks, we did not observe a significant decrease of soil N stocks following WTH, supporting earlier results observed in conifer stands (Olsson, Staaf, Lundkvist, Bengtsson, & Rosen, 1996) and northern hardwoods (C. E. Johnson, 1995). Due to lower stand transpiration, an increase in soil moisture had been generally observed following the removal of a portion of tree biomass (Chase et al., 2016; Stogsdil, Wittwer, Hennessey, & Dougherty, 1992). In this study, WTH had resulted in a significant increase in SWS (Table 2), confirming the results of previous research.

4.2 | Response of soil properties to thinning intensity

In the present study, soil temperature (0–10 cm), soil C:N ratios, soil pH, and soil bulk density in both topsoil and subsoil (below 10 cm) were also significantly altered 15 years following WTH (Table 3). Many studies on the impacts of thinning focused mainly on the forest floor and topsoil (e.g., 0–10 cm), and information about changes below this depth remains scarce (Brandtberg & Olsson, 2012). Our results provided evidence that WTH had the potential to alter soil properties in the long term in both topsoil and subsoil in semiarid spruce plantation forests.

Higher soil temperatures have often been observed in harvested treatments (Baena et al., 2013; Tufekcioglu et al., 2005). Thinning opened forest canopy and allowed more solar and thermal radiation to penetrate to ground level (Pang et al., 2016). Thus, increased soil

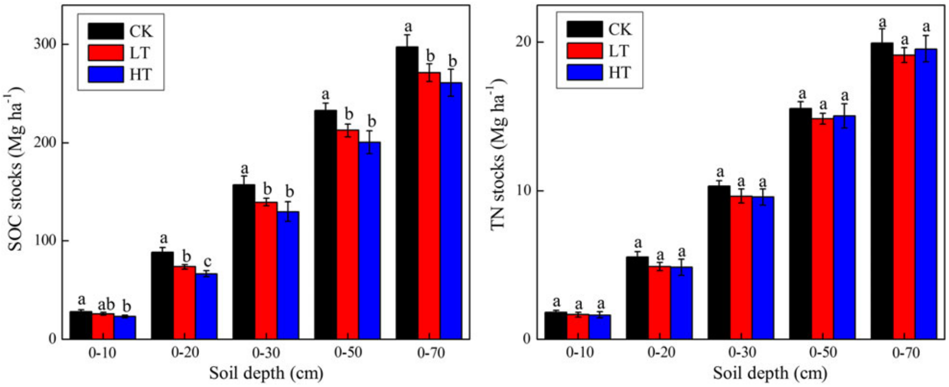

FIGURE 3 Comparison of soil organic carbon (SOC) and soil total nitrogen (TN) stocks among stands with different thinning levels in different soil layers. Error bars represent standard errors of the means (n = 15). Different lowercase letters above the bars indicate significant differences at P < 0.05 [Colour figure can be viewed at wileyonlinelibrary.com]

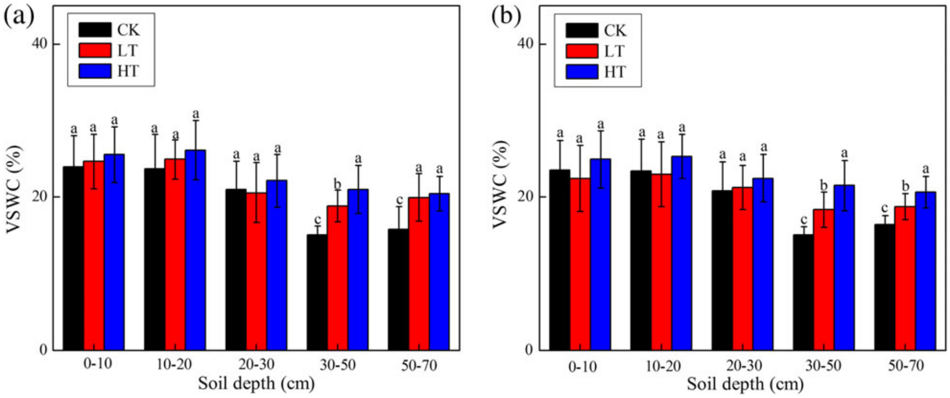

FIGURE 4 Comparison of volumetric soil water content (VSWC) among stands with different thinning levels in different soil layers during the growing seasons of 2015 (a) and 2014 (b). Error bars represent standard errors of the means (n = 15). Different lowercase letters above the bars indicate significant differences at P < 0.05 [Colour figure can be viewed at wileyonlinelibrary.com]

temperatures observed in the topsoil were attributed to canopy openness created by thinning. Our results confirmed those of previous research, and the topsoil temperature increased significantly with increasing thinning intensity.

Soil C:N ratios provide a signature of the quality of organic matter into the soil and the extent of mineralization (Black & Harden, 1995; D. W. Johnson & Curtis, 2001). Due to the incorporation of woody residues with high C:N ratios from the felled trees, soil C:N increased initially following thinning and then decreased as a result of enhanced carbon mineralization (Bolat, 2014; Olsson et al., 1996). In the present study, soil C:N ratios decreased with increasing thinning intensities, and a significant decrease was detected in HT in the 0- to 30-cm layers, which can be partially explained by the accelerated mineralization rates of soil organic matter caused by WTH. In addition, WTH also reduced litter production and altered the composition of understory vegetation, with the biomass of herbs increasing while that of moss decreasing significantly with thinning intensity (Table 1). Generally, herbs have lower C:N ratios and faster decomposition rates than coniferous detritus and mosses (Corbeels, O'Connell, Grove, Mendham, & Rance, 2003; Finzi, Van Breemen, & Canham, 1998; Xu, Tian, & Hui, 2008). Thus, modifications in the quality of substrate inputs into the soil may have also contributed to the decline of soil C:N ratios.

Generally, the increase in soil pH, observed in the upper soil layer following WTH, was ascribed to the decomposition of organic acids (Thiffault et al., 2011; Vanguelova, Pitman, Luiro, & Helmisaari, 2010). We found that WTH was associated with a significant increase in soil pH in the 0- to 20-cm layer. Furthermore, soil pH exhibited a significant positive correlation with Rs (Table 4). Organic matter, such as acidic litter and canopy leachates, are the primary organic acid inputs in coniferous forests (Jobbágy & Jackson, 2003); thus, the increase in soil pH can be explained by the accelerated organic matter decomposition caused by WTH to some extent. Due to soil compaction and a decline in SOC, soil bulk density has often been observed in harvested treatments (Carter, Dean, Wang, & Newbold, 2006; Wall, 2012). Our results from WTH confirmed those of previous research. The increase in bulk density and decline in SOC generally weaken soil water-holding capacity, both of which would be unfavorable to the increase in soil water content.

4.3 | The response of Rs to thinning intensity

The influence of silvicultural thinning on Rs was determined by many interactive factors including microclimate, soil properties, and fine root dynamics (Cheng et al., 2014; Pang et al., 2013). Generally, thinning can stimulate organic matter decomposition due to an improvement of microclimate and substrate availability, among others; this process would result in an increase in Rs (Cheng et al., 2015; Tang et al., 2005). Thinning can also reduce Rs rates due to an initial decrease in the biomass of respiring roots caused by the removal of trees (Sullivan et al., 2008). We found that WTH in our study had significant and positive impacts on Rs. Autotrophic respiration mainly depends on fine root biomass (Cheng et al., 2013; Widén & Majdi, 2001), whereas heterotrophic respiration is controlled by microbial decomposition of organic matter (Selig et al., 2008). As no significant effect of WTH was detected on fine root biomass (Table 1), we attributed the elevated Rs to the effects of WTH on heterotrophic respiration. The thinning treatments (LT and HT) exhibited favorable conditions for microbial decomposition of soil organic matter, including elevated soil temperature and substrate quality compared with CK. In our study, the dynamics of Rs paralleled those of soil temperature, and a significant positive correlation was detected between Rs rate and soil temperature for each stand; this indicated an accelerated decomposition of organic matter due to increased soil temperature. In addition, soil C:N ratios were also strongly correlated with Rs (Table 4). As previously stated, the modifications in the quality of organic inputs induced by WTH had resulted in a decrease in soil C:N ratios. Generally, substrates with lower C:N ratios are more vulnerable to decomposition by soil microbes than other substrates (Corbeels et al., 2003; Xu et al., 2008). Thus, the improved substrate quality may have also contributed to the increase in Rs.

The Q_{10} values in this study also increased with an increase in thinning intensity. The values were consistent with those obtained from similar sites in the eastern Tibetan Plateau (Pang et al., 2013) and those observed in managed temperate forest (Olajuyigbe, Tobin, Saunders, & Nieuwenhuis, 2012; Saiz et al., 2006). The Q_{10} values are important indicators of the sensitivity of Rs to elevated temperature (Cheng et al., 2013; Olajuyigbe et al., 2012). The higher Q_{10} values in LT and HT than in CK suggested that more CO_2 efflux may be expected from soils following WHT under climate warming. Many studies have reported higher Q_{10} values in harvested than in nonharvested treatments; the increase in sensitivity with thinning has been attributed to the improved quantity and quality of the respiring components (such as fine roots and associated soil microbes) as well as the increase in sensitivity of the involved processes (Epron, Ngao, & Granier, 2004; Olajuyigbe et al., 2012). As there was no evidence of enhanced root growth following WTH in the present study, the higher Q_{10} values observed in the thinned stands were more likely due to the increase in sensitivity of microbial respiration to temperature.

5 | CONCLUSIONS

Generally, our results provided evidence that WTH had the potential to alter soil properties in the long term in both topsoil and subsoil in semiarid spruce plantation forests. Our results demonstrate the potential for WTH to relieve water deficits, especially in the lower soil layers. The significant increase in SWS with increasing thinning intensities would alleviate competition for water for the residual trees, thus promoting stem-level growth and sustainable development of these plantations. However, a significant decrease in SOC stocks was observed with increasing thinning intensities; the negative effects of WTH on SOC stocks can be attributed to the lower C inputs from litter production and understory vegetation and higher C outputs through Rs. In addition, our results demonstrated the close relationships between Rs and associated soil properties (such as temperature and C:N ratios), and the increase in Rs with thinning intensities can be explained by the accelerated decomposition of organic matter as a result of elevated soil temperature and substrate quality. The effects of forest thinning on Rs involve changes in components and processes (autotrophic and heterotrophic respiration). Further studies are needed to predict soil CO_2 efflux in *P. crassifolia* forests more accurately and to clarify CO_2 efflux drivers.

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