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Forest thinning increases soil carbon stocks in China

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ABSTRACT

Thinning is a common forest management practice. However, its impact on soil organic carbon (SOC) stocks is still unknown. Therefore, we conducted a meta-analysis of 270 measurements from 77 articles to evaluate the effect of forest thinning on SOC stocks in mineral soil (0–30 cm) across planted forests in China. The results showed that, compared to reference (non-thinned) plantations, thinning significantly increased SOC stocks in planted forests by 7.2%. Among different thinning intensities, moderate thinning (35–55% of thinning intensity) increased SOC stocks in planted forests (+16.1%) more than other levels of thinning intensity. However, the positive effect of thinning on SOC stock was significant > 5 years after harvesting. In the humidity-restricted areas (humidity index (HI) < 30), the increase in SOC stocks after thinning was significantly higher than that of other areas. In addition, thinning increased the sensitivity (i.e. slope value) of soil total nitrogen (TN) stocks changes to SOC stocks. Therefore, we conclude that forest thinning strategy is potentially a viable silvicultural measure to increase SOC fixation in planted forests. Our results provide a reference for the formulation and implementation of future forest management strategies.

1. Introduction

Globally, soil contains 1500–2300 Pg of organic carbon (C), which is approximately twice the carbon in the atmosphere and three times that in terrestrial plants (Lal, 2004). As an important carbon sink, forests account for 31% of the global land area and store 70% of the soil organic carbon (SOC) (Six et al., 2002; Carvalhais et al., 2014). Thus, even the slightest impact of forest management can influence the global carbon cycle (Davidson and Janssens, 2006; Lal, 2020). Forest thinning, as a widely used forestry management practice, can improve wood yields, reduce wildfire risk, and increase resiliency to disturbances by modifying forest structure (Sohn et al., 2016; Kim et al., 2019). However, thinning can affect ecological processes in forest soils by changing abiotic and biotic attributes (e.g., productivity, root density, solar radiation, and litterfall inputs) (Baena et al., 2013; Dang et al., 2018). For SOC stocks, thinning changes the balance between soil carbon input and output by affecting the characteristics of plant litter and roots and the activity of soil microbes (Borrelli et al., 2015; Kim et al., 2019). Therefore, increasing our understanding of how thinning affects SOC stocks is essential for studying the forest ecosystem carbon cycle and regional vegetation planning, design, and sustainable development.

Previous studies have revealed contrasting results to changes in SOC stocks after thinning (Johnson and Curtis, 2001; James and Harrison, 2016; Zhang et al., 2018). One view is that thinning reduces the competition of species for limited resources (light, water, and nutrients), thereby enhancing the carbon sequestration capacity of the stable pool by increasing the growth and productivity of plants (Roig et al., 2005; Jimenez et al., 2015). A contrary viewpoint is that thinning of forests destabilizes soil structure and alters microclimatic parameters, which in turn stimulates microbial activity and litter decomposition, thereby reducing SOC stocks (Jandl et al., 2007; Trentini et al., 2017). In addition, many studies have shown that these differing results depending on thinning intensity, recovery time, and climatic conditions (Zhou et al., 2013; Zhang et al., 2018). Overall, due to the multiplicity and uncertainty of the influencing factors and complicated interactions between plants and soil, the characteristics of SOC stocks responses to thinning are still unclear.

To mitigate the effects of climate change and land degradation, various large-scale eco-restoration projects have been launched since the 1980s in China, including the Grain for Green project and the Three-

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North Shelterbelt Program (Cao et al., 2011; Yuan et al., 2014). Previous studies have shown that afforestation has significantly increased vegetation coverage and effectively improved ecosystem services in China, such as carbon sequestration, sandstorm prevention, and soil and water retention (Liu et al., 2008; Deng et al., 2014). However, after decades of development, due to the limitation of precipitation and the existence of high forest density, a variety of problems have occurred in plantations, including dry soil layers, low biodiversity, and reduced regeneration (Cao, 2011). For arid and semiarid areas, afforestation activities usually lead to soil moisture shortages and plant degradation due to the limitation of rainfall and the evapotranspiration rate (Feng et al., 2016; Jia et al., 2017; Gong et al., 2020). Under these conditions, adjusting the stand density and structure of planted forests has become a top priority for forest management and sustainable development. Previous studies in China have shown that the thinning of plantation forests can be used to increase plantation biodiversity and ecosystem stability (Dang et al., 2018; Li et al., 2020). However, the question as to whether thinning will increase SOC stocks remains controversial in China (Chen et al., 2016; Dang et al., 2018). Previous studies have mainly analyzed changes in SOC stocks at specific locations or specific vegetation types. In addition,

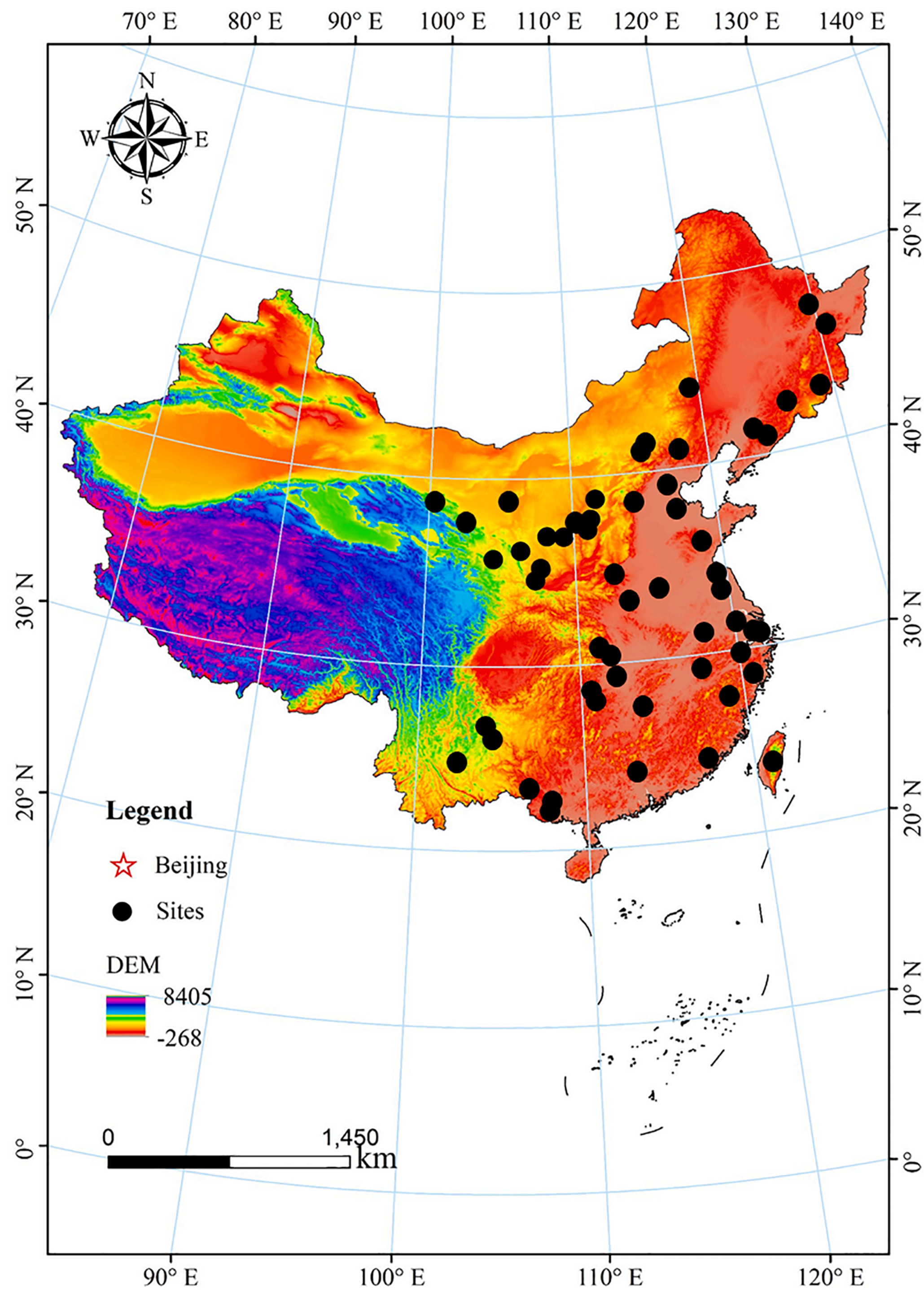

Fig. 1. Distribution of study sites in China. Note: DEM: Digital Elevation Model. The DEM data in this study comes from Resource and Environment Data Cloud Platform (http://www.resdc.cn/Default.aspx).

few studies have focused on how the SOC stocks in thinned artificial forests are affected by thinning intensity, climate, and recovery time.

Therefore, we conducted a meta-analysis based on a total of 270 sites and thinning treatment combinations from 77 articles to quantify the impact of thinning on SOC stocks in mineral soil (0–30 cm) in China's planted forests and address the following questions: (a) does forest thinning affect SOC stocks of planted forests? (b) how do thinning intensity, climate and recovery time affect SOC stocks after thinning? and (c) does thinning affect the sensitivity (slope value) of SOC stocks and soil total nitrogen (TN) stocks?

2. Materials and methods

2.1. Data compilation

Peer-reviewed publications related to SOC stocks of non-thinned and thinned forest lands were searched using online databases including Web of Science (United States) and China's National Knowledge Infrastructure (CNKI). The retrieval was performed on March 1, 2020. We used the following combination of terms: "selective cutting" or "silvicultural treatment" or "thinning" or "harvest" or "management treatment" or "forest management" and "soil organic carbon" or "soil organic matter" and "China". To avoid deviations in the results, the following criteria were used for paper selection:

(1) the study included SOC concentrations or SOC stocks, or these metrics could be calculated directly;
(2) the study included both non-thinned forest lands (control sites) and thinned forest lands (experimental sites) under similar soil types, topography and climate conditions;
(3) the study provided forest thinning intensities, or the forest thinning intensities could be calculated from the density of retained trees;
(4) the study used only field experimental data, excluding indoor control experiments and model simulation experiments; and
(5) the study focused only on artificial forestation, excluding natural forests.

According to the topic and the screening criteria of this study, 382 related papers were reviewed, and 270 sites and thinning treatment combinations from 77 peer-reviewed publications were aggregated (Fig. 1 and Appendix Dataset). All original data were obtained from published tables. GetData Graph Digitizer ver. 2.24 (Russian Federation) was used to extract data when the study reported results graphically. Furthermore, detailed information of the experimental site, such as the location (latitude and longitude), topography conditions (elevation and slope angle), climatic factors (mean annual temperature (MAT) and mean annual precipitation (MAP)), plantation age, recovery time (time since thinning) and planted tree species, were also collected from the papers.

2.2. Data calculation

The SOC stocks were calculated as:

$$C_i = SOC_i \times BD_i \times i \times 10^{-1} \quad (1)$$

where C_i, SOC_i, and BD_i represent SOC stocks (Mg·ha^{-1}), SOC concentration (g·kg^{-1}), and soil bulk density (g·cm^{-3}) in the i soil layer, respectively. If the study provided only the soil organic matter (SOM) concentration, then SOC concentration was obtained by multiplying by a conversion factor of 0.58 (Mann, 1986).

Missing bulk density (BD) data were obtained using the empirical relationship between SOC stocks and BD value (Deng et al., 2016b). The formula is as follows:

$$BD = 0.4123 + 1.0326e^{-0.0413SOC} \quad (2)$$

Due to the significant positive correlation between MAT and MAP in China (Yang et al., 2007), the humidity index (HI) was used to analyze the response of SOC stocks to climate (MAP and MAT) in this study (Deng and Shangguan, 2017):

$$HI = \frac{MAP}{MAT + 10} \quad (3)$$

In our collected dataset, soil sampling depths were not always consistent across different studies. Hence, to improve the comparability of data, SOC stocks of different soil layers were converted into SOC stocks of mineral layers (0–30 cm) (Jobbagy and Jackson, 2000):

$$Y = 1 - \beta^d \quad (4)$$

$$X_{30} = \frac{1 - \beta^{30}}{1 - \beta^{d0}} \times X_{d0} \quad (5)$$

where Y is the cumulative proportion of SOC stocks, β is the relative reduction rate of SOC stocks (0.9786), X_{30} is the upper 30 cm SOC stocks, and d_0 and X_{d0} represent the soil depth (cm) and SOC stocks (Mg·ha^{-1}) in the reference study, respectively.

It should be noted that due to the difference in SOC distribution through the soil profile, the standardization of this dataset may introduce potential uncertainties. However, Jobbagy and Jackson (2000) indicated that for the distribution of soil C with depth, there were no significant differences between different vegetation types and the global average. Similarly, Yang et al. (2011) and Li et al. (2012) concluded that depth correction did not alter the overall pattern of soil C stock dynamics.

2.3. Meta-analysis

Since the measure of variance was not reported and the sample size differed among the studies, we used unweighted meta-analysis (Powers et al., 2011; Deng et al., 2016a). The response ratio (RR) was used in this study to indicate the relative change in SOC stocks between the treatment (X_e) and control plots (X_c) (Zhang et al., 2018; Gong et al., 2020). The formula is defined as follows:

$$RR = \frac{X_e}{X_c} - 1 \quad (6)$$

The 95% confidence interval (CI) was estimated using the following equation (Luo et al., 2006; Su and Shangguan, 2019):

$$SE_R = \sqrt{\frac{V_R}{N}} \quad (7)$$

$$95\%CI = 1.96 \times SE_R \quad (8)$$

where SE_R represents the standard error of the response ratio for SOC stocks and V_R and N denote the variance and the number of the response ratio for SOC stocks, respectively. If the 95% CI does not overlap 0% change, then the observed effect ratio is considered significantly different from 0% change.

2.4. Factor classification

To analyze the effects of thinning intensity, recovery time, and climate on the SOC stocks, we grouped the data, as follows: (1) Different thinning intensities were divided into three groups according to the removed proportion of basal area, biomass or stems: light thinning (<35%), moderate thinning (35–55%), and heavy thinning (>55%) (Li et al., 2020). (2) The recovery time was categorized into three stages: early stage (<5 yr after thinning), medium stage (5–10 yr after thinning), and late stage (>10 yr after thinning) (Zhou et al., 2013). (3) The

HI was divided into three groups: low-humidity area (HI < 30), middle-humidity area (30 ≤ HI ≤ 50), and high-humidity area (HI > 50).

2.5. Data analysis

The Shapiro-Wilk test and Levene's test were used to examine the normality and homogeneity of the variances, respectively. When data were not normally distributed, they were log-transformed to achieve conditions required for statistical analysis. In addition, values outside 3 standard deviations of the mean were identified outliers and eliminated from the analysis (Li et al., 2020). An analysis of variance (ANOVA) was used to test whether the response ratio of SOC stocks significantly differed among different categorical variables (thinning intensities, recovery times and HIs), and significant differences for multiple comparisons were obtained with the least significant difference (LSD) test. Meanwhile, t-tests were conducted to evaluate whether thinning intensities, recovery times and HIs significantly affected SOC stocks under different forest management practices (thinned and non-thinned forest lands). A regression analysis was performed to examine the sensitivity (slope value) of SOC stocks and TN stocks to forest thinning. Significance levels were evaluated at $P < 0.05$. All statistical analyses were performed in SPSS Version 24.0 software (SPSS Inc., USA) and the figures were drawn using Origin 9.0 (OriginLab Ltd., USA).

3. Results

Overall, compared with the non-thinned forest lands, forest thinning significantly increased SOC stocks in planted forests by 7.2% (95%CI: 2.8%) (Fig. 2). For different thinning intensities, light and moderate thinning significantly increased SOC stocks in planted forests by 7.5% (95%CI: 4.0%) and 16.1% (95%CI: 5.9%), respectively, while heavy thinning had a negative effect on SOC stocks (−3.4%, 95%CI: 3.6%). In addition, the response ratio of SOC stocks under moderate thinning was significantly higher than that under light thinning and heavy thinning (Fig. 2).

Different recovery times significantly affected the response ratio of SOC stocks (Fig. 3a, $P = 0.037$). Specifically, thinning significantly increased SOC stocks in planted forests in the medium (+6.3%, 95%CI: 5.3%) and late (+13.1%, 95%CI: 5.4%) stages of recovery, while thinning effected on SOC stocks in the early (+4.4%, 95%CI: 4.5%) stage of

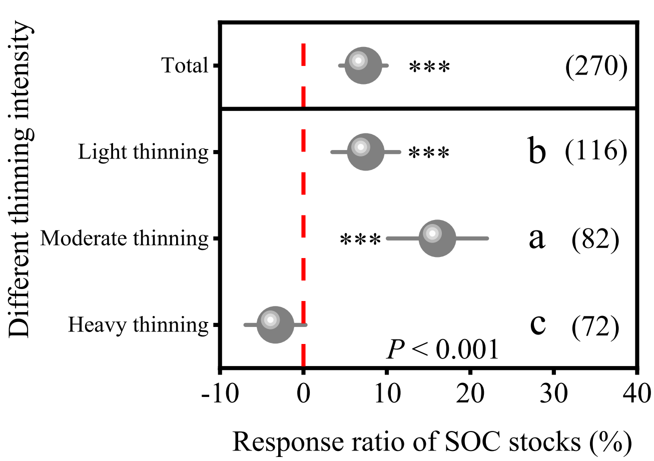

Fig. 2. Changes in SOC stocks after thinning as influenced by different thinning intensities. Note: Dots with error bars denote the mean response ratio ± 95% CIs. Asterisks refer to significant differences from zero (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$). Different lower-case letters mean significant differences at the $P < 0.05$ level among different thinning intensities. The red dashed line is the reference of a response ratio of zero, and numbers of observations are in the parenthesis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

recovery did not differ significantly from zero (Fig. 3a). Moreover, the response ratio of SOC stocks in the late stage of recovery was significantly higher than that in the early and medium stages of recovery (Fig. 3a). Compared with non-thinned forest lands, SOC stocks in planted forests did not significantly change under different thinning intensities in the early stage of recovery (Fig. 3b). However, in the medium and late stages of recovery, both light and moderate thinning significantly increased SOC stocks and the effect was most pronounced in the moderate thinning (Fig. 3b). In addition, in the early and middle stages of recovery, differences in the response ratio of SOC stocks under different thinning intensities were not significant (Fig. 3b; for early stages of recovery $P = 0.126$, for medium stages of recovery $P = 0.059$). By contrast, different thinning intensities significantly affected the response ratio of SOC stocks in the late stage of recovery (Fig. 3b, $P = 0.022$), and the response ratio of SOC stocks under moderate thinning was significantly higher than light thinning and heavy thinning (Fig. 3b).

Humidity indices also significantly affected the response ratio of SOC stocks after thinning (Fig. 4a, $P = 0.001$). Specifically, compared with non-thinned forest lands, SOC stocks in planted forests did not significantly change in the middle- (+3.5%, 95%CI: 4.2%) or high-humidity areas (+4.6%, 95%CI: 4.7%) but increased significantly in the low-humidity areas (+29.5%, 95%CI: 5.8%) (Fig. 4a). In addition, in the low-humidity areas, the response ratio of SOC stocks was the highest and was significantly higher than that in the middle- and high-humidity areas (Fig. 4a). For different thinning intensities, light (+18.4%, 95% CI: 9.6%) to moderate (+24.1%, 95%CI: 9.2%) thinning had a positive effect on SOC stocks in planted forests in the low-humidity areas, while heavy thinning significantly decreased SOC stocks by −4.8% (95%CI: 3.6%). In the middle-humidity areas, different thinning intensities did not significantly change SOC stocks compared with the non-thinned forest lands. In the high-humidity areas, only light thinning significantly increased SOC stocks by 10.9% (95%CI: 8.3%). In addition, in low-humidity areas, thinning intensities had a significant impact on the response ratio of SOC ($P = 0.022$), and the response ratio of SOC stocks under moderate thinning was the highest and was significantly higher than that to heavy thinning, but there was no significant difference from light thinning. However, no significant difference was found for the response ratio of SOC stocks under different thinning intensities in middle- and high-humidity areas.

Overall, SOC stocks were significantly positively correlated with TN stocks, indicating that the change in SOC stocks was closely related to the change in TN stocks ($P < 0.01$, Fig. 5). In addition, the sensitivity (slope value) of TN stocks changes to SOC stocks after thinning (slope = 0.09) was significantly higher than that of non-thinned forest lands (slope = 0.06) (Fig. 5a). For different thinning intensities, the sensitivity of TN stocks changes to SOC stocks under moderate thinning (slope = 0.11) was significantly higher than that under light thinning (slope = 0.07) and heavy thinning (slope = 0.06) (Fig. 5b).

4. Discussion

4.1. Changes in SOC stocks after forest thinning

Our study revealed that thinning could significantly increase mineral SOC stocks (0–30 cm) in planted forests in China (Fig. 2). Several mechanisms could explain the results of this research. Firstly, litterfall and fine roots are the main elements for the formation of SOC (Laik et al., 2009). Thinning can enhance the primary productivity of plants, thereby increasing the sources of SOC by increasing the quantity and quality of litter, fine root density (including exudates) and turnover (Saunders et al., 2012; Pang et al., 2016). Secondly, thinning is known to stimulate the activity of microorganisms and soil enzymes by increasing soil temperature and moisture, which can catalyze the biodegradation of litters and roots, thereby accumulating SOC stocks (Waldrop et al., 2003; Adamczyk et al., 2015; Wu et al., 2019). Additionally, understory

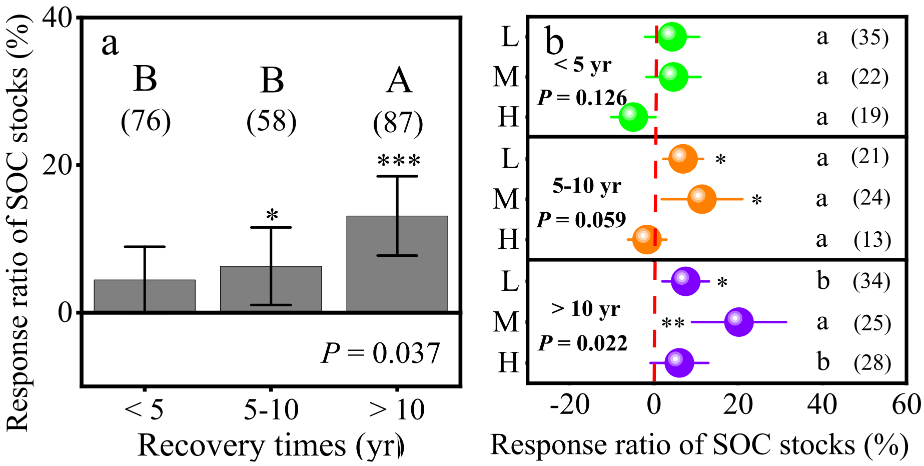

Fig. 3. Changes in SOC stocks after thinning as influenced by different recovery times. Note: L, light thinning; M, moderate thinning; and H, heavy thinning. Dots with error bars denote the mean response ratio ± 95% CIs. Asterisks refer to significant differences from zero (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$). Different upper-case letters mean significant differences at the $P < 0.05$ level among different recovery times, and different lower-case letters mean significant differences at the $P < 0.05$ level among different thinning intensities. The red dashed line is the reference of a response ratio of zero, and numbers of observations are in the parenthesis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

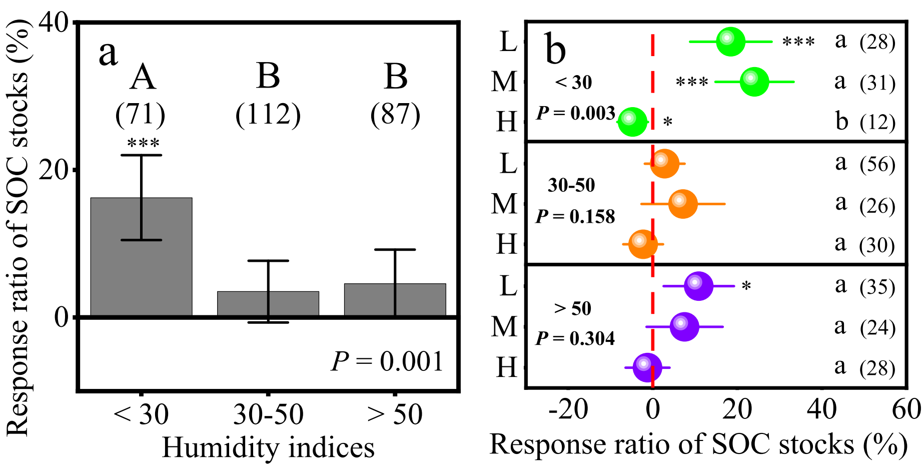

Fig. 4. Change in SOC stocks after thinning as influenced by different humidity indices. Note: L, light thinning; M, moderate thinning; and H, heavy thinning. Dots with error bars denote the mean response ratio ± 95% CIs. Asterisks refer to significant differences from zero (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$). Different upper-case letters mean significant differences at the $P < 0.05$ level among different humidity indices, and different lower-case letters mean significant differences at the $P < 0.05$ level among the different thinning intensities. The red dashed line is the reference of a response ratio of zero, and numbers of observations are in the parenthesis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

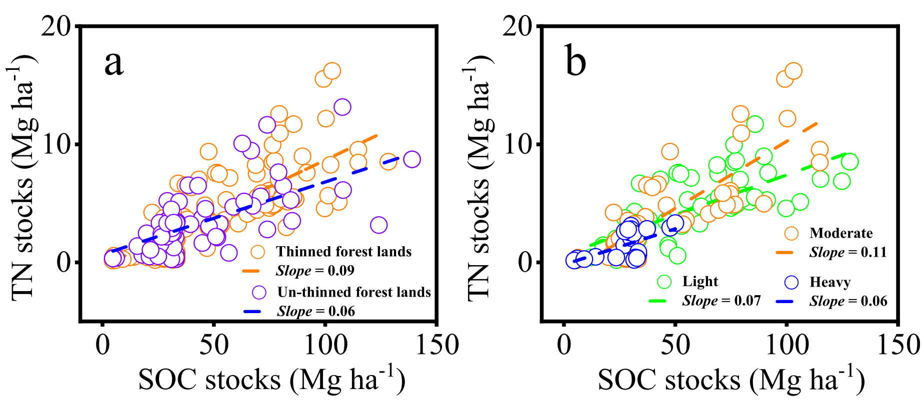

Fig. 5. Effects of thinning on the relationship between SOC and TN stocks. Note: Dotted lines represent the regression model fits.

vegetation, which is an important part of forests, often plays an important role in the cycling of soil C and nutrients (Nilsson and Wardle, 2005; Chen et al., 2019). Thinning often increases the richness of understory species and the quality of community structure by increasing the availability and heterogeneity of resources, thereby promoting nutrient cycling in forest ecosystems (Ma et al., 2018b; Li et al., 2020).

4.2. Effects of different thinning intensities on SOC stocks

Different thinning intensities were also an important factor affecting SOC stocks (Fig. 2). We found that light (thinning intensity < 35%) and moderate thinning (35–55% of thinning intensity) significantly increased SOC stocks, whereas heavy thinning (thinning intensity > 55%) caused a decline in SOC stocks (Fig. 2). This decline may be attributed to the decrease in litter production and root biomass after heavy thinning (He et al., 2018). Moreover, due to the large canopy openings, heavy thinning may increase soil temperature, which acted as the detriment of soil microbial abundance and diversity, thereby reducing the decomposition ratio of inputted litterfall (Saura-Mas et al., 2012; Pang et al., 2016; Bravo-Oviedo et al., 2017). In addition, higher machine traffic associated with heavy thinning may increase bulk density and break up soil water-stable aggregates, thereby causing the loss of SOC (Zhang et al., 2016; Liu et al., 2019; Federico et al., 2020).

4.3. Influence of recovery times on SOC stocks after thinning

According to this study, forest thinning was found to increase SOC stocks significantly after five years of recovery (Fig. 3a), which may be due to new SOC inputs from litters and roots in the older recovery stage (Bastida et al., 2019; Qiu et al., 2020). Similarly, Pregitzer and Euskirchen (2004) indicated that it may take decades for SOC stocks to return to pre-thinning levels. Nave et al. (2010) suggested that thinning may take decades or even longer to significantly affect soil C storage. Moreover, our meta-analysis also showed that heavy thinning (thinning intensity > 55%) was not significantly different from those in non-thinned forest lands at different recovery times (Fig. 3b). This phenomenon may be due to heavy thinning usually took longer period of time to restore above- and belowground plant biomass than light and moderate thinning (Campbell et al., 2009; de Avila et al., 2017). However, due to the limitations of temporal data, our examination on the effect of recovery times on SOC stocks after thinning is insufficient. Overall, long-term observations on how thinning affects SOC stocks needs to be strengthened.

4.4. Effects of different humidity levels on SOC stocks after thinning

Climate usually affects SOC stocks by affecting ecological processes related to organic matter production and decomposition rates (Iglesias et al., 2012). Our research found that in low-humidity areas (HI < 30), thinning could significantly increase SOC stocks in planted forest compared with non-thinned forest lands, and the increase in SOC stocks was significantly higher than that in middle- (30 ≤ HI ≤ 50) and high-humidity areas (HI > 50) (Fig. 4a). Thinning reduces the competition for resources among vegetation by regulating vegetation density (Tejedor et al., 2017). For arid areas, in particular, soil moisture is not only an important variable that affects plant morphology and function, but also represents a key factor that promotes the cycling of soil nutrients (D'Odorico et al., 2010; Legates et al., 2011). Thinning tends to mitigate water stress in trees by reducing the evapotranspiration of vegetation, increasing soil infiltration and streamflow, thereby promoting the growth of vegetation and the circulation of soil nutrients (del Campo et al., 2019; Tague et al., 2019). In addition, thinning could increase the water use efficiency of plants by improving the physiological and growth characteristics of plants to drought (e.g., radial growth, leaf-water potential) (McDowell et al., 2008; Sohn et al., 2016). For example, Manrique-Alba et al. (2020) found that thinning reduced growth dependence on water stress and improved the drought resistance in pine trees. We also found that the increase in SOC stocks under moderate thinning (35–55% of thinning intensity) in the low-humidity area (HI < 30) was significantly higher than that in other areas (Fig. 4b), further indicating that moderate thinning (35–55% of thinning intensity) was a suitable approach to increase SOC stocks, especially for regions with limited humidity (HI < 30).

4.5. Effects of thinning on the sensitivity of SOC stocks and TN stocks

Due to the stoichiometric relationship between vegetation and soil, additional nitrogen is needed to support the accumulation of terrestrial carbon; therefore, whether carbon can be sustained depends, in part, on the availability of nitrogen (Li et al., 2012; Bai et al., 2017). This meta-analysis found that thinning could significantly increase SOC stocks in planted forests (Fig. 2) and that these SOC stocks were positively correlated with TN stocks (Fig. 5). In addition, we also found that the sensitivity (i.e. slope value) of TN stocks changes to SOC stocks was significantly better after thinning than that of non-thinned forest lands (Fig. 5a), which can be explained by the following mechanism. Firstly, the vegetation residue caused by thinning increases the input of persistent compounds into the soil, thereby increasing the soil nitrogen content (Weedon et al., 2009; Huang et al., 2011). Secondly, microclimate warming and humidity caused by thinning may increase biological nitrogen fixation (Zheng et al., 2019). Thirdly, thinning usually reduces the competition of plants for water and nitrogen, which, in turn, could increase the utilization of these resources within the soil microbial community, thereby increasing the utilization of readily leachable inorganic nitrogen in the soil (Dannenmann et al., 2006; Tejedor et al., 2017). In addition, we found that the relative sensitivity of SOC stocks and TN stocks under moderate thinning (35–55% of thinning intensity) was significantly higher than that under light (thinning intensity < 35%) and heavy thinning (thinning intensity > 55%) (Fig. 5b). A previous study had also shown that moderate thinning could reduce nitrogen solubility and limit nitrogen losses (Ma et al., 2018a). This phenomenon further supports our conclusion that moderate thinning (35–55% of trees removed) showed the greatest SOC and TN conservation benefits.

5. Conclusion

Forest thinning, in particular moderate thinning (35–55% of thinning intensity) is an effective management practice to increase SOC stocks in planted forests in China. In addition, SOC stocks responses to thinning are significantly affected by thinning intensity, recovery time, and humidity index. In particular, thinning significantly increase SOC stocks in humidity-restricted areas (HI < 30) by reducing the competition of species for limited resources. However, this positive effect of thinning on SOC stock was significant after five years of recovery. In addition, TN stocks is a key factor in the regulation of SOC stocks, and forest thinning can improve the sensitivity (slope value) of TN stocks changes to SOC stocks. These results provide a reference for science-based management of planted forests. In the context of global warming and frequent droughts, forest thinning is a suitable forest management practice to increase the capacity of soil carbon sequestration. Moreover, more long-term observations should be made in the future to study the changing characteristics of SOC stocks over extended recovery times, so as to further understand the dynamics of SOC stocks to forest thinning.

Author contributions

C.G., Q.T., G.L. and M.X. conceived this study, C.G. and M.X. conducted the experiment, C.G. and G.L. analyzed the results, all authors wrote and edited the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2020.118812.

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