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Effects of thinning on soil nutrients in a chronosequence of Chinese fir forests in subtropical China

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Abstract Thinning is a common silviculture technology in forestry, but there is considerable uncertainty about the changes of soil nutrients due to thinning practice in different aged forests. The influence of light thinning (reduction of 20% of stand density) on soil organic carbon (SOC) and other mineral elements (N, P, K, Cu, Fe, Zn, Mn and S), as well as soil pH and soil bulk density were investigated in 6, 13, and 23 years-old growth stands of Chinese fir forests in subtropical China. Six 10 × 10 m plots (three thinning and three non-thinning plots) were set up in each aged forests. Soil samples were taken from different soil layers from these plots for nutrient analysis. Results showed that SOC increased 59.4, 48.9, and 62.0% in topsoil layer (0-30 cm) in 6, 13, and 23 year-old growth stands, respectively when compared to the control, and the content of N increased by 20.5, 44.6, and 54.1% corresponding after two year post-thinning. In the thinned forests, soil P slightly increased at 6 and 23 year-old growth forests dude to microclimates were improved, and K decreased because of leaching. The response of micronutrients Cu, Fe, Zn and Mn to thinning varied in all examined Chinese fir forests. Thinning decreased soil bulk density and soil pH in 23 year-old growth stands. Our study provided scientific references for sustainable management of soil nutrients under forest operations in Chinese fir forest ecosystem in subtropical China.

Keywords: thinning, forest management, macronutrients, micronutrients, soil organic carbon, forest age.

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Introduction

Forests play a crucial role in improving and maintaining soil nutrient status through both aboveground and belowground inputs of little debris to soils. Forest management practices can affect soil fertility by modifying the pathways of nutrients into soil. While the influences of the management practices on aboveground part of a forest are relative easily observed and recognized, the impacts of the human activities on belowground processes are usually hard to be detected. Soil is a significant essential component of forest ecosystems in terms of supplying of nutrients and water for forest productivity, maintaining of microbial community for decomposition processes, and supporting of energy flow and material cycle for ecosystem services. As a result, there is an increasing need to understand the mechanisms that forest management practices affect soil properties and underground processes (Johnson & Curtis 2001, Jandl et al. 2007, Drum et al. 2019, Sewerniak 2020).

Thinning is a common silviculture practice in forest management, which regulates the distribution of growing space and improves forest stands' conditions, so that residual standing trees may benefit for competition, growth and health status (Verschuyl et al. 2011, Salerni et al. 2020). Thinning generally results in decreases of stand density and increases of light and nutrient availability. Thinning is also a practice that improves the overall health of the forest by mitigating disease and insect susceptibility while minimizes catastrophic fire risk. Increasing growth spacing through thinning in forests has shown to increase individual plant growth. Zhang et al. (2006) reported that intensive thinning increased tree height by 13.1% compared with the control, whereas tree diameter and merchantable stem volume per tree increased by > 20-75% in naturally regenerated jack pine forests in Canada. Thomas et al. (1999) pointed out that thinning could have large effects on understory plant diversity and community composition. Removal of portion of forest canopy by thinning significantly affected soil properties, soil organic matter turnover and nutrient budgets (Schlesinger & Andrews 2000), altered temperature and moisture statues (Tang et al. 2005), modified root density and turnover (Bowden et al. 2004) and regulated the quantity and quality of substrate inputs into the soil (Maassen et al. 2006). Sohn et al. (2016) recent demonstrated by using meta-analysis that thinning, in particular heavy thinning was a suitable approach to improve the growth response of trees to drought. In addition, thinning activity enhanced forest ecosystem services capacity, such as promoting carbon (C) sequestration, reducing the wildfire risk and maintaining a healthy forest (Tang et al. 2005). While there seems to be a consensus that thinning improves growth and production of remaining trees, the influences of thinning on soil nutrient statues are conflicts. Some studies indicated that soil nutrient availability including nitrogen (N), phosphorus (P) and potassium (K) was improved post-thinning and the competition for available nutrient resources decreased (Briggs et al. 2000, Zhang et al. 2006). But, Bai et al. (2017) found that thinning practice did not change soil C and N contents in native *Corymbia variegata* and *C. citriodora* open forests in Australia. As a result, further studies are needed for better understanding of the impact of thinning on soil nutrient dynamic and soil fertility.

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) is an important native evergreen coniferous species in China with a planting history extending more than 1000 years (Yu 2006). With the features of fast growing, relative short rotation (~25 years), high productivity and good timber quality, Chinese fir has been widely chosen as a silvicultural tree species in southern China, and the Chinese fir forests have covered more than ten provinces in the nation. The plantation area of Chinese fir forests was about 9.21

million ha, which accounted for one third of the total plantation area in China (Lei 2005). Given the huge area, Chinese fir forests not only provided large economic benefits to local farmers and governments, but also provided considerable ecosystem services at regional and national levels. In the past years, numerous studies have been conducted to examine the influence of thinning practices on tree growth and timber yield (Dang et al. 2018), understory vegetation biodiversity (Xu et al. 2014) and soil properties (Zhao et al. 2012) in Chinese fir forests. However, little information was available on the effects of thinning on the situation and availability of soil nutrients status in the Chinese fir forest ecosystems. Particularly, the influences of thinning activity on soil nutrient dynamics in an age sequence of Chinese fir forests were not fully understand.

In the current study, the impacts of thinning practice on the amount and distribution of soil nutrients were investigated in a series of aged stands of Chinese fir forests. The purpose of this project was to further understanding of how does forest management (such as thinning) effect the belowground processes (such as soil nutrient availability and dynamics) in Chinese fir forests. The specific objectives of this study were: (1) to quantify amount and distribution of soil macronutrients and micronutrients in different aged Chinese fir forests under thinning treatments, and (2) to compare soil nutrient status and soil properties between thinning and un-thinning stands of Chinese fir forests.

Materials and Methods

Study site

The study was conducted at Fushou Mountain Forestland, located in Pingjiang County of Hunan province, China (28°3′00″N-28°32′30″N, 113°41′15″E-113°45′00″E) (Figure 1). Topography of the study area is mountainous with the elevation of ranging 835-1573 m, and the slope ranging at 22°-27°. The total area of the studied forestlands is about 1295 km^2. Mean annual temperature is 12.1°C, with mean January and July temperatures of -1.5°C and 33°C, respectively. Mean annual precipitation is 1345.6 mm. Soils vary in texture from clay loams to sandy loams, with an average pH of 5.1, and are classified as mountain yellow soil.

The study area is a typical representative of subtropical second-growth forests in southern China, with most artificial plantation forests.

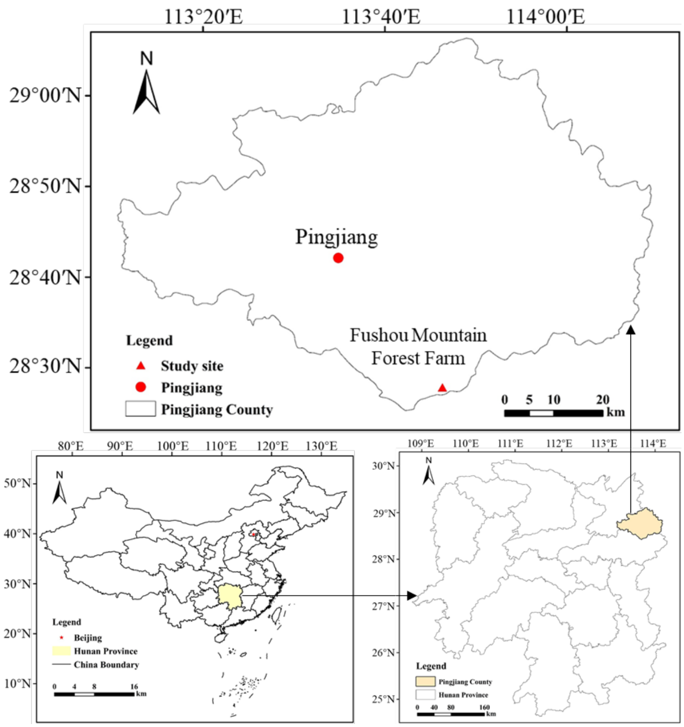


Figure 1 Location of the study site.

Dominant tree species include Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) representing > 80% of basal area), *Pinus taiwanensis* Hayata, *Phyllostachys pubescens* (Carrière) J.Houz., *Sassafras tzumu* (Hemsl.) Hemsl., *Alnus trabeculosa* Hand.-Mazz. and *Carya cathayensis* Sarg. The main understory shrubs and herbaceous species are *Eurya japonica* Thunb., *Vaccinium bracteatum* Thunb., *Vaccinium vitis-idaea* L., *Rhus chinensis* Mill, *Lespedeza bicolor* Turcz., *Ilex purpurea* Hassk., with herbs and ferns of *Cortaderia selloana* (Schult. & Schult.f.) Asch. & Graebn., *Miscanthus floridulus* (Labill.) Warb. ex K.Schum. & Lauterb., *Houttuynia cordata* Thunb., and *Polygonatum kingianum* Collett & Hemsl.

Experimental design

The study was treated as a split-plot design where the age of Chinese fir forests was the main plot effect, and thinning vs. non-thinning (control) was the sub-plot effect. Three aged Chinese fir forests, planted in year 1989, 1999 and 2006 were selected in this study. The thinning treatments were performed in these forests during the period of 2012-14. Thus, the selected stands represented as young aged stands (~6 year-old growth), middle aged stands (~13 year-old growth), and near matured aged stands (~23 year-old growth) of Chinese fir forests. Three 10 × 10 m replicated thinned plots were set up for each aged stand, with a space of at least 10 m apart in order to avoid edge effects. Three 10 × 10 m replicated non-thinned plots were also established. Therefore, 36 sample plots were selected in the study site. The light thinning intensity was manually conducted by handsaw in all studied forests, with a reduction of about 20% of stand density.

Field measurements

Two years later after thinning performance, the diameter at the breast height (DBH), tree heights, and width of canopy of all individual trees within the plot were measured. The characteristics of the examined stands were presented in Table 1.

In each thinned and non-thinned plot, soil samples were randomly taken from three locations within the plot with about 5 m apart each other. The soil samples were taken by a soil auger (5 cm in diameter) from 0-15 cm, 15-30 cm and 30-45 cm, and 45-60 cm depth, respectively. The three soil samples of the same layer in each plot were mixed as one sample. Soil samples were stored in airtight tubes and delivered to the laboratory for further chemical analysis.

In the laboratory, soil samples were air dried. The soil samples were grounded and passed through a 0.25-mm sieve. Soil bulk density (SBD) for each soil depth was estimated using the cutting ring method. Soil pH was measured using a glass electrode in a saturated soil water paste, with a soil solution ratio of 1:2.5. SOC content was estimated according to Ball (1964). The N concentration was determined by Kjeldahl acid-digestion method after extraction with sulfuric acid (Sparks et al. 1996). The P concentration was determined colorimetrically using a UV-visible spectrophotometer (model UV-2300,

Table 1 Characteristics of different aged stands of Chinese fir forests in the study site.

Stand age (Year)	Treatment	Plot number	Stand density (tree/ha)	DBH (cm)	Tree height (m)	Mean canopy width (m^2)
6	Thinning	3	2650	3.9	3.2	1.2
	Non-Thinning	3	3300	3.2	2.6	0.9
13	Thinning	3	2100	11.5	7.3	4.8
	Non-Thinning	3	2600	9.7	6.8	4.0
23	Thinning	3	1700	15.9	12.2	9.0
	Non-Thinning	3	2100	12.3	9.4	5.6

Techcomp Com, Shanghai, China) after the digestion with H_2SO_4 and $HClO_4$ (Parkinson & Allen 1975). The content of K, Ca, Cu, Fe, Zn, Mn, and B was determined by using flame atomic absorption spectrophotometer under the wavelength of 766.5, 422.7, 324.7, 248.3, 213.9, 279.5, and 249.7 nm, respectively.

Statistical analysis

Statistical tests for the effects of forest ages since plantations, thinning vs. non-thinning (control) location, temporal (year-to-year) variation, and their interactions on N, P, K, Ca, Cu, Fe, Ze, Mn, B, soil pH, SOC, and SBD were performed using analysis of variance (ANOVA). The original macronutrients and micronutrients data were log-transformed to satisfy the normality and homoscedasticity assumptions of ANOVA. No transformation was necessary for soil pH, SOC and SBD. Statistical analyses were conducted using the SAS statistical package (SAS Institute, Inc. Cary, NC 1999-2001).

Results

Overall, forest ages, thinning treatments and their interactions had no significantly effects on SOC and N content in soil profile ($p > 0.05$), but had significantly effects on the contents of P, K, Cu, Fe, Zn, Mn, B, and soil pH in the studied forests ($p < 0.05$, Table 2). There was likewise a significant difference in P and K, Cu, Fe, Mn, B, and soil pH among the different aged stands ($p < 0.05$, Table 2).

Table 2 Analysis of variance of soil nutrients, pH, soil organic carbon (SOC) and soil bulk density with stand age, thinning treatment and location in the study site.

Source	DF	N	P	K	Cu	Fe	Zn	Mn	B	pH	SOC	Soil bulk density
Age	2	0.4205	0.0027*	<0.0001*	0.0017*	<0.0001*	0.0514	0.0143*	0.222	<0.0001*	0.3038	0.0015*
Thinning	1	0.9131	0.1682	0.0007*	0.5548	0.602	0.0327*	0.2308	0.0009*	0.0276*	0.0947	0.0966
Age×Thinning	1	0.3217	0.0005*	0.8794	0.0027*	0.0008*	0.4742	0.3144	0.2681	0.1542	0.4674	0.1211

*Represent significant difference at the 0.05 level. Data in table represents the P value.

Specifically, thinning treatment led a significant increase of SOC and N content in the upper soil layers (0-30 cm) in all aged stands of Chinese fir forests compared to the control ($p < 0.05$, Figure 2), except SOC in 0-15 cm in 13 year-old growth and 15-30 cm in 13 year-old growth forests, and N content in 15-30 cm at 6 year-old growth forests. On average, SOC increased 59.4, 48.9, and 62.0% in 0-30 cm in 6, 13, and 23 year-old growth stands of Chinese fir forests, respectively when compared to the control. The content of N in soil increased by 20.5, 44.6, and 54.1% in 0-30 cm in 6, 13, and 23 year-old growth stands of Chinese fir forests, respectively when compared to the control. Thinning significantly increased soil P content in the young aged stands but decreased soil P content in the middle-aged stands. The effect of thinning operation on P content varied in near matured aged stands. The K content in soil was significantly reduced in thinning treated plots in almost all aged stands compared to the non-thinning treated plots.

Thinning decreased Cu contents in soil in all aged stands ($p < 0.05$), except in the 15-45 cm soil layers at the near matured stands where Cu contents increased in the thinned plots but the differences were not significant (Figure 3). Soil Fe contents decreased significantly in 6 year-old growth forests in the thinned sites, but increased significantly in the 13 and 23 year-old growth forests when compared to the control ($p < 0.05$). The content of Zn in soil was reduced in thinned stands in almost aged

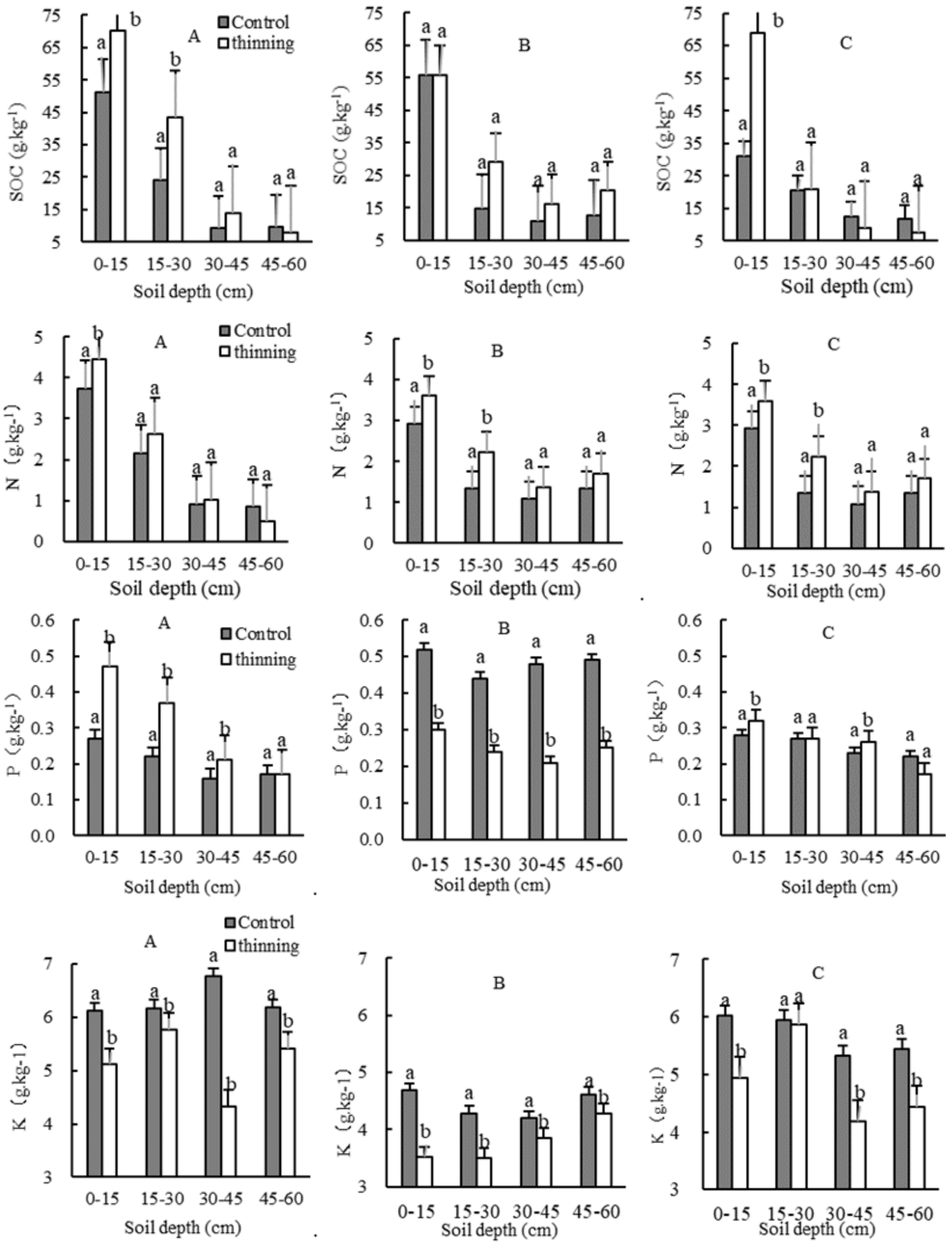
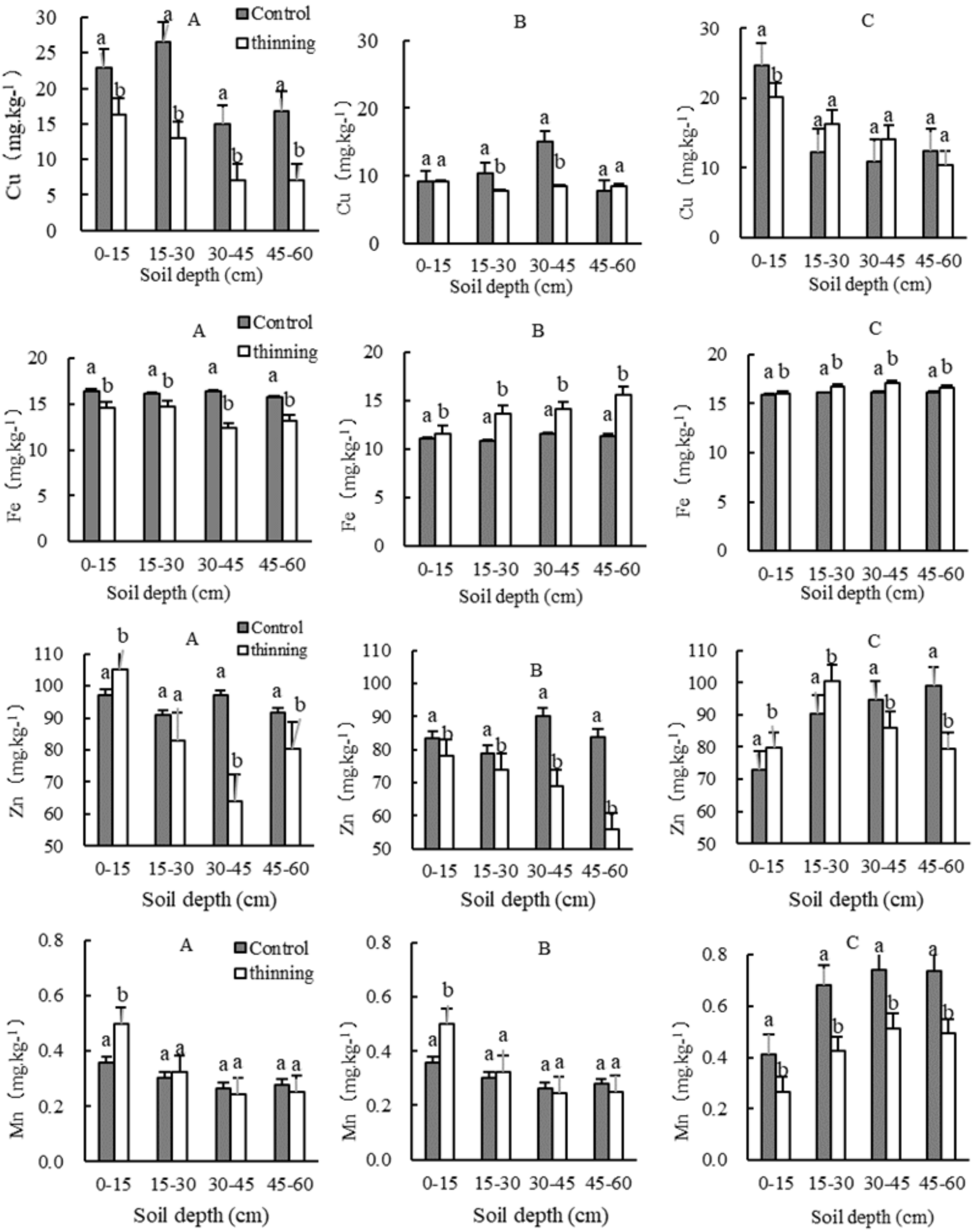


Figure 2 Variation of SOC, soil nitrogen (N), phosphorus (P), and potassium (K) contents in different soil depths under thinning and non-thinning (Control) treatments at 6 year-old stands (A), 13 year-old stands (B), and 23 year-old stands (C) of Chinese fir forests in the study site. Different lowercase letters indicate significant differences between thinned and non-thinned (control) forests ($p < 0.05$).

stands but increased at the topsoil lay (0-15 cm) in 6 and 23 year-old growth forests. It seemed that thinning practices had no impact on soil Mn content in young and middle stands, expect at the topsoil where Mn content significantly increased in the thinning sites. Soil Mn content was significantly reduced in the near matured stand due to the thinning. Thinning significantly decreased B content in all soil depths in all stages of stands in all soil depth (Figure 3).



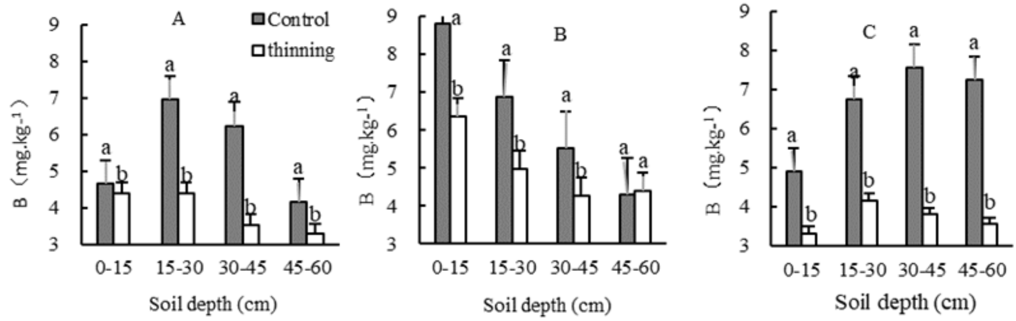


Figure 3 Variation of soil micronutrient elements (Cu, Fe, Ze, Mn, B) contents in different soil depths under thinning and non-thinning (Control) treatments at 6 year-old stands (A), 13 year-old stands (B), and 23 year-old stands (C) of Chinese fir forests in the study site. Different lowercase letters indicate significant differences between thinned and non-thinned (control) forests ($p < 0.05$)

The changes in soil bulk density due to thinning varied, depending on soil depths and forest ages. Thinning increased soil bulk density at young forest stands but decreased soil bulk density at middle aged and near matured aged forest stands (Figure 4). The mean soil pH was consistently higher in control plots than in thinning treated plots for all aged stands compared to the control, excepting the 13 year-old stands when soil pH at topsoil (0-30 cm) was higher in thinned forests than non-thinned forests (Figure 4).

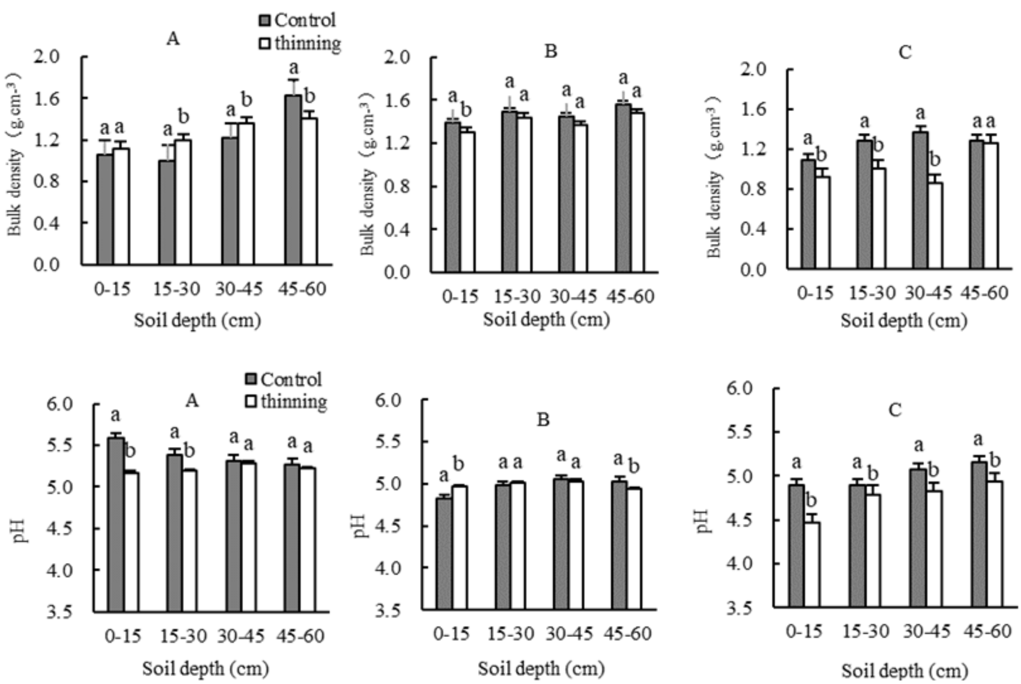


Figure 4 Variation of soil bulk density and pH in different soil depths under thinning and non-thinning (Control) treatments at 6 year-old stands (A), 13 year-old stands (B), and 23 year-old stands (C) of Chinese fir forests in the study site. Different lowercase letters indicate significant differences between thinned and non-thinned (control) forests ($p < 0.05$).

Discussion

In this study, we found that SOC and soil N content were higher in thinning treated plots than in control plots in all studied 6, 13, and 23 year-old stands. Particularly, the thinning effects occurred significantly in the top soil layers (0-30 cm), with 50-60% increase for SOC and 20-50% increase for N in all aged Chinese fir forests compared to the control (Figure 2). The results were consistent with previous studies. Dang et al. (2018) reported that SOC and total N concentrations significantly higher in both moderate-intensity thinned stands (30% of the trees removed) and high-intensity thinned stands (45% of the trees removed) than in the control in a mature Chinese pine plantation. Especially, the contents of SOC and N increased by about 28% and 21% in the high-intensity thinned stands. Zhou et al. (2019) pointed out that thinning operations increased the soil total C concentration by 48.7-50.3% and soil N by 1-1.4 times higher when compared to the control in a larch plantation. Recently, Gong et al. (2021) conducted a meta-analysis for the impact of thinning on SOC stocks in China's planted forests and found that forest thinning significantly increased SOC stocks by 7.2% in planted forests compared with non-thinned forest lands. Moreover, the influence of thinning on SOC stocks in the late stage of recovery was significantly higher than that in the early and medium stages of recovery. The increase of SOC and soil N content in thinned forests were likely attributed to the following reasons: (1) thinning increased the primary productivity of remaining trees in the sites, which increased the above and below ground litter inputs as sources of SOC, (2) thinning provided a large environmental and nutrient spacing for various plant species within the forests, leading an increase of diversity and richness of understory plant species which enhanced the availability and cycle of nutrients, and (3) thinning modified microclimate conditions within the forests, such as light radiation, air and soil temperature, and soil moisture, which were favorable to activity of soil organisms for accelerating nutrient cycling of soil and the accumulation of SOC and N pools (Merila et al. 2002, Richards & Hart 2011).

In contrast, several previous studies found that thinning had less impacts on SOC and N contents in soil. For instance, only timber-removed thinning had little effects on SOC and N pools in an old-growth red pine forest and an old-growth northern hardwood forest (Jurgensen et al. 2012). There were no differences of total SOC pools between thinning and non-thinning treatments in a Mediterranean maritime pine forest (Ruiz-Peinado et al. 2013). Soil labile C did not differ between non-thinned and thinned ponderosa pine forests after 15 years thinning (Grady & Hart 2006). Laik et al (2009) pointed out that litter impacts of thinning on total SOC might be due to the similar above and below ground litter inputs and soil environmental conditions in the thinned and non-thinned plots.

Soil P contents were higher in thinning treated plots than in control plots in both 6 year-old and 23 year-old forests, but the situation was reversed in 13 year-old forests where the soil P content was lower in thinned plots than in control plots. This phenomenon might reflect a complex supply-demand relation of nutrients during the growth and development of Chinese fir forests. Thinning enhanced plant diversity and primary production of understory community and improved microenvironments within the forests, causing nutrient supply excessing demand and leading an increase of P availability in soils. However, the middle-aged stands of Chinese fir forests were in a timber fast growing stage, when demand excesses supply and large nutrient elements including P were uptake, leading a decline of P content in soils. In this study, soil K content significantly decreased in the thinned forests at all aged stands compared to the control. Such decrease of K element was mainly resulted from both uptake and leaching processes during the period of study. Swiftet al. (1979) pointed out that leaching processes involved nutrient release and were especially important for elements such as K and P in forests. In our previous study, we also found that P and K were more susceptible elements than other macronutrients in soils for leaching loss after the disturbance of the Chinese fir forest ecosystems (Kang & Tian 2002, Tian 2005).

The contents of micronutrient elements in the thinned forests showed high variability in different soil depth layers and different aged stands of Chinese fir forests (Figure 3). Although little information was available to explain the variation of soil micronutrient elements after thinning, their effects were resulted from the complex processes, depending on the property of individual elements, thinning intensity, and operation methods. The thinning may affect micronutrients concentrations in leaves and twigs, and then alter soil micronutrients via litterfall and the nutrient release through litter decomposition (Segura et al. 2017). The variation of these soil micronutrients in thinning plots were likely resulted from the reduction of plant debris in forest floor post-thinning (Sang et al. 2017). However, a number of studied indicated that the dry mass of forest floor was higher in control whereas the nutrient concentration increased in thinned plots. It was a particular case for P, K, Mg and Mn elements in moderate thinned plots (Ma et al. 2018).

Soil bulk density could indirectly reflect the status of soil compaction, and therefore it should be related to human activity during the thinning operation. Jurgensen et al. (2012) pointed out that soil bulk density increased with increased cutting intensity. In our study, the forest floors and topsoil layer were actually not seriously compacted during and after the thinning operation due to implication of no heavy cutting and transportation machines were employed. In addition, partial thinned debris and trashes were left on the sites and they prevented the forest floor and soils from impaction. The impact of thinning on soil bulk density is also related to the recover ability of the forests under different thinning intensity. Cheng et al. (2017) found that soil bulk density significantly decreased in the surface soils (0-20 cm) under the heavy thinning intensity treatments (stand density reduced by 33%) compared to the control treatment in Chinese fir plantations in eastern China. However, no significant difference of soil bulk density was observed between the moderate thinning and control treatments in their study. The reduction of soil pH in the thinned forests was probably related to the increasing leaching of cations in the thinning sites. Baena et al. (2013) indicated that thinning resulted in the removal of vegetation and organic debris and caused the processes of washing and solubilization of salts in the soil, leading a decrease of pH and carbonates, especially in wet season.

Conclusions

Knowledge of the mechanisms controlling soil properties is essential for understanding the impact of forest management practices on soil chemical and physical conditions. Our study provided evidence that thinning in Chinese fir forests led to a significantly changes in soil macro and micronutrient elements, as well as soil properties such as SOC, soil pH and soil bulk density. The influence of thinning on soil property was complex, depending on soil layers, forest age, and the period since the thinning operation was applied. The reduction of soil nutrients by thinning resulted mainly from the large uptake, leaching process and reduction of nutrient returning by plant residues. The increase of soil nutrients was primarily attributed improvement of microclimate within the forests, which enhanced soil organism activity and accelerated litter decomposition. Our study are important for sustainable management of forest ecosystems in terms of how to make suitable forest operations in different aged stands and how to protect soil fertility and health efficiently.

Acknowledgements

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