

IMPACT OF STAND DENSITY ON SOIL QUALITY IN CHINESE FIR (*CUNNINGHAMIA LANCEOLATA*) MONOCULTURE

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Abstract. It is known that forest management practices and land use affect soil quality worldwide. This study was conducted to assess the potential effects of stand density on soil quality in Chinese fir plantations. Low- (1,450 trees/ha with 2.36 × 2.36 m spacing), intermediate- (2,460 trees/ha with 1.83 × 1.83 m spacing), and high-density (3,950 trees/ha with 1.44 × 1.44 m spacing) stands in a 10-year-old Chinese fir monoculture plantation were examined, and different soil quality indicators were measured. The results indicated that stand density affected nitrogen (N), phosphorous (P), and magnesium (Mg) content, whereas potassium (K) and calcium (Ca) were not affected. Total N and total P contents were higher in the low-density stands, whereas total Mg was higher in the intermediate-density stands. Available N was higher in the low-density stands, whereas available P was higher in the intermediate-density stands. No significant difference was observed in the contents of available K, total K, and total Ca among all densities. Soil organic matter was significantly higher in the intermediate-density stand than in the high- and low-density stands. Soil bulk density increased from the surface layer to the 40-60 cm soil layer. Soil pH was lowest in the surface layer of soils of all three densities and increased from the 0-20 cm layer to the 20-40 cm layer; however, it decreased from the 20-40 cm layer to the 40-60 cm layer. Soil pH differed significantly between soils of different densities but remained within an optimum range (4.1-4.5) for Chinese fir plantations. Soil moisture content was significantly higher in the high-density stand than the other stands. The observed effects of stand density on soil quality may be useful for policy makers and forest managers to implement improved forest conservation practices for preserving soil quality and stand production.

Keywords: *forest conservation, soil health, sustainable forestry, nutrient status, competition*

Abbreviations: SOM–soil organic matter, SMC–soil moisture content, BD–soil bulk density, DBH–diameter at breast height, TN–total nitrogen, TP–total phosphorus, TK–total potassium, TCa–total calcium, TMg–total magnesium, AN–available nitrogen, AP–available phosphorus, AK–available potassium, EC–soil electrical conductivity, SO–silty oxisol

Introduction

Chinese fir (*Cunninghamia lanceolata* (Lamb) Hook) is an indigenous, typically evergreen, sub-tropical conifer species, and it is a widely cultivated timber species in China due to its high yield, excellent timber quality, and fast growth. According to the Eighth National Forest Inventory, the planting area of Chinese fir covers more than 11 million ha, which accounts for about 18.2% of all forest plantations in China, and for 6% of the global forest plantation area (State Forestry Administration, 2014). The yield of Chinese fir plantations has declined continuously over the past years (Yang et al., 2005a), and standing wood volumes in the second and third rotations were 30% and

47% less those in the first rotation, respectively (Bi et al., 2007). Serious concerns have been raised regarding the decrease in yield and the long-term decline in the productivity of Chinese fir (Ma et al., 2007; Zhao et al., 2013; Zhou et al., 2015). In other countries such as Brazil, deforestation rates are either decreasing or stabilizing; however, in China, Malaysia, and Indonesia, deforestation rates are increasing due to the increasing demand for wood-derived products (Margono et al., 2014; Abood et al., 2015).

In forest research, soil quality monitoring has been recognized as a primary aspect for sustainable management. Soil quality can vary due to management and land use practices, which is strongly correlated with physio-chemical, bio-chemical, and biological soil properties (Dudley et al., 2014). Land over-use and intensive cultivation resulted in millions of ha of degraded land, and soil erosion has led to the loss of topsoil and exposure of soils with low nutrient content (Liu and Zhao, 1993; Wei et al., 2006; Zhou et al., 2006). For commercial purposes such as timber production, deforestation continues to be carried out globally on a large scale, leading to significant decreases in soil quality and ecosystem productivity, and Chinese fir plantations are no exception (Wang et al., 2014).

In Chinese fir plantations, surface soil hydrolysable nitrogen (N) and available phosphorous (P) declined under continuous cropping (Horner et al., 2010). Various studies demonstrated a reduction in soil nutrient availability, microbiome structure, microbial enzyme activity (Yang et al., 2010; Vitali et al., 2016; Wang et al., 2017; Zhang et al., 2017b), N stocks, and soil organic carbon after conversion of native forests to plantations (Chen et al., 2013; Marin-Spiotta and Sharma, 2013; Guan et al., 2015; van Straaten et al., 2015). Therefore, a decline in timber yield and productivity under the current management practices of Chinese fir plantations is likely a response to impoverished soils.

Soil quality indicators have been assessed in previous studies in different regions of China with the main research focus on different provenances or age of the plantations. These studies are useful, however, there is no comprehensive understanding of soil quality in Chinese fir stands of different planting densities. The current study was conducted to fill this gap by studying different soil quality indicators in Chinese fir monoculture plantations of the same age (ten years) but with different stand densities. The soil quality parameters total soil nutrient and available nutrient content, soil organic matter content (SOM), soil pH, soil bulk density (BD), and soil moisture content (SMC) were analyzed at low-, intermediate- and high-density stands. We hypothesized (1) that due to competition by higher under-story vegetation and higher number of trees in low- and high-density stands respectively, total and available nutrient content should be higher in intermediate-density stands; (2) that stand density should have no effect on soil pH and electrical conductivity (EC), while SOM and SMC should be higher in high-density stands than in low- and intermediate-density stands due to maximum shade and less sun light availability.

Materials and methods

Study site

The Xinkou Experimental Forest Farm was established in 2007 as Chinese fir monoculture plantations, in Sanming City, Fujian Province, China (*Fig. 1*). The study site was located at 26°10' N and 117°27' E. Soils were acidic and the climate of the region was a typical mid-subtropical monsoon climate (Zhou et al., 2015), with mean

annual rainfall of 1,612 mm and a mean annual temperature of 19 °C, according to an on-site meteorological station. The average monthly temperature and precipitation is shown in *Table 1*. Before the plantation was established, the area was cut clear, the debris was piled and burned, and complete tillage was carried out. After this, the surface biomass was burned before establishing stands, and one-year-old Chinese fir seedlings were planted. Three plantation stands with different densities were selected and categorized as low-, intermediate-, or high-density stands. The understory vegetation in the selected Chinese fir stands were *Maesa japonica*, *Woodwardia japonica*, *Callicarpa kochiana*, *Selaginella moellendorffii*, *Ilex pubescens*, and *Alpinia japonica*. Further details on the plantation stands are shown in *Table 2*.

Soil sampling

Soil was sampled in the second week of November 2017. Four plots of 20 × 20 m were established in each stand, and in each plot, four pits were dug diagonally. A soil corer was used to obtain soil samples from 0-20, 20-40, and 40-60 cm depths from each pit. After collection, the soil samples from the four sampling pits were mixed to produce one sample for each soil layer and measure pH. Eight composite samples per density from a 0-60 cm depth were prepared to measure the total and available nutrient content, SOM, and SMC. All samples were sealed in clean, air-tight polythene bags. Three soil samples were collected from each stand to determine soil BD at 0-20, 20-40, and 40-60 cm depths using 200 cm³ volumetric rings.

Table 1. Average monthly temperature and precipitation in Sanming City, Fujian, China

	Average temperature (°C)	Minimum temperature (°C)	Maximum temperature (°C)	Average precipitation (mm)
January	10.4	5.9	14.9	57
February	11.4	7.3	15.5	101
March	15.2	10.9	19.6	180
April	19.9	15.4	24.4	203
May	23.6	19.4	27.9	279
June	26.5	22.1	31.0	276
July	28.8	23.7	34.0	122
August	28.4	23.4	33.4	134
September	26.1	21.5	30.8	108
October	21.3	16.5	26.1	63
November	16.7	12.1	21.3	49
December	11.3	6.5	16.1	40

Table 2. Details of plantation stands. Shown are the means ± SE values of average height and diameters at breast height (DBH). "SO" indicates the soil type silty oxisol

Stand density	Number of trees/ha	Spacing (m)	Altitude (a.s.l)	Avg. DBH (cm)	Avg. height (m)	Soil type
Low	1,450	2.36 × 2.36	206	13.05 ± 0.12	12.41 ± 0.14	SO
Intermediate	2,460	1.83 × 1.83	204	12.46 ± 0.43	12.01 ± 0.30	SO
High	3,950	1.44 × 1.44	210	11.04 ± 0.19	11.63 ± 0.23	SO

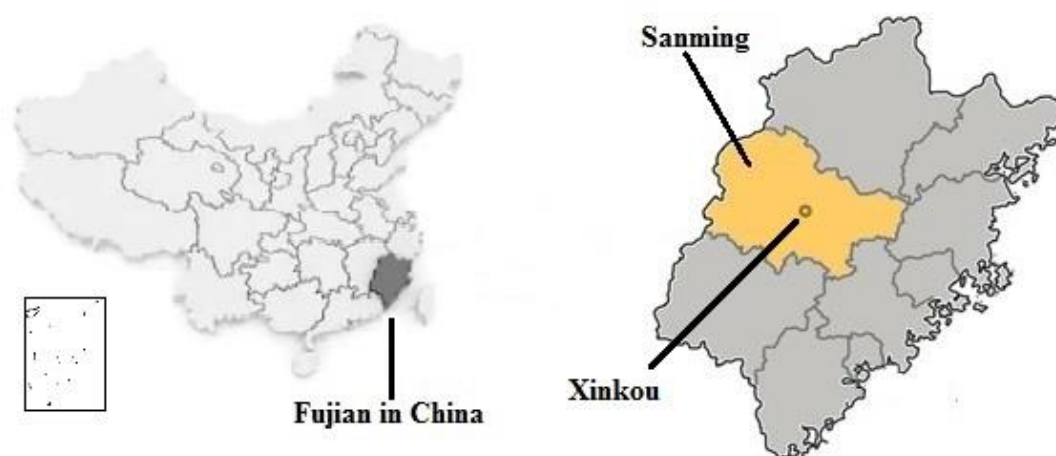


Figure 1. Location of the study area, Xinkou Experimental Forest Farm, in Sanming City, Fujian province, China

Sample preparation

All samples were transferred to a laboratory for further analyses. Debris and roots were removed carefully by hand. The soil samples were air-dried at room temperature and then crushed and passed through sieves of 2 mm and 0.15 mm mesh size for subsequent analyses. To determine soil BD, the samples were weighed and then dried to constant weight before re-weighing.

Laboratory analyses

All measurements were conducted in the key laboratory of soil and water conservation, College of Forestry, Fujian Agriculture and Forestry University, China. The respective analysis methods are shown in *Table 3*.

Table 3. Methods and equipment used for soil quality analyses

Analysis	Method/Equipment
pH	Potentiometric method (1:2.5 soil:water)
Electrical conductivity (EC)	Conductivity meter
Bulk density (BD)	Core method of the Nanjing Institute of Soil Science (1978)
Total nitrogen	CN elemental analyzer
Total phosphorus	Molybdenum-antimony colorimetric method
Total potassium	Flame photometry
Total calcium	CN elemental analyzer
Total magnesium	CN elemental analyzer
Available nitrogen	Kjeldahl method (Ryan et al., 2007)
Available phosphorus	Bray and Kurtz (1945)
Available potassium	Schollenberger and Simon (1945)
C:N ratio	CN elemental analyzer
Moisture content (SMC)	Calculated based on wet and dry weight
Soil organic matter (SOM)	Soil organic carbon was first measured by wet oxidation (CN elemental analyzer) and then calculated as SOM

Statistical analyses

All measurements are reported as mean \pm standard error. A one-way analysis of variance was used to determine correlations between soil quality indicators and stand densities using the SPSS software (SPSS 13.0, SPSS Inc., IL, USA). Means of variables that showed significant differences were compared using Tukey's test at a 5% level of significance. Origin 9.1 and ArcGis software were used to produce graphs and figures.

Results

Variation in total soil nutrient contents

A significant difference in total N and P contents between stands was observed at $P < 0.05$. Total N content was 0.99 ± 0.2 g/kg, 0.74 ± 0.1 g/kg, and 0.92 ± 0.08 g/kg, and total P content was 0.59 ± 0.03 g/kg, 0.48 ± 0.1 g/kg, and 0.59 ± 0.2 g/kg in low-, intermediate- and high-density stands, respectively. Both total N and total P contents were highest in the low-density stand and lowest in the intermediate-density stand.

Total Mg contents were highest in intermediate-density stand and lowest in the low-density stand. No significant differences between stand densities were found in total K and Ca contents. Total K contents were 22.5 ± 7.5 g/kg, 21.2 ± 8.2 g/kg, and 21.8 ± 2.5 g/kg and total Mg contents were 7.41 ± 3.9 g/kg, 8.51 ± 3.7 g/kg, and 7.91 ± 0.5 g/kg in low-, intermediate-, and high-density stands, respectively. Total Ca contents were 2.23 ± 0.4 g/kg, 2.25 ± 1.09 g/kg, and 2.14 ± 0.9 g/kg in low-, intermediate-, and high-density stands, respectively (Fig. 2).

Variability in available soil nutrient contents

Available N and available P were significantly different between soils of different stand densities, whereas available K contents did not differ significantly. Available N contents in soils of low-, intermediate- and high-density stands were 67.69 ± 2.2 mg/kg, 59.04 ± 3.0 mg/kg, and 54.07 ± 1.9 mg/kg, respectively, and available P contents were 3.92 ± 0.2 mg/kg, 5.16 ± 0.4 mg/kg, and 4.79 ± 0.5 mg/kg, respectively. Available K contents in soils of low-, intermediate- and high-density stands were 87.23 ± 2.1 mg/kg, 81.44 ± 3.9 mg/kg, and 87.30 ± 5.4 mg/kg, respectively.

Available N was highest in the low-density stand and lowest in high-density stand, whereas available P was highest in the intermediate-density stand lowest in the low-density stand. Available K did not differ significantly between the low- and high-density stand, both of which differed significantly from the intermediate-density stand (Fig. 3).

Soil pH, BD, SOM, EC, and SMC

Modest variations in the pH values were observed between stands in each soil layer (Fig. 4a). Soil pH in the 0-20 cm soil layer was 4.21 ± 0.1 , 4.28 ± 0.04 , and 4.27 ± 0.2 in the low-, intermediate-, and high-density stands, respectively. The soil pH values in the 20-40 cm soil layer were 4.27 ± 0.03 , 4.37 ± 0.02 , and 4.29 ± 0.1 , respectively. In the 40-60 cm layer, the pH values were 4.15 ± 0.04 , 4.28 ± 0.02 , 4.27 ± 0.1 in the low-, intermediate-, and high-density stands, respectively. The soil pH values in the 0-20 cm layer was lower in intermediate- and high-density stands compared to the 20-40 cm and 40-60 cm layers (Fig. 4a). Soil pH was higher in the 20-40 cm layer and lower in the

40-60 cm layer. There was no consistent decline from the 0-20 and 40-60 cm layers in the intermediate- and high-density stands, however, these layers differed significantly different in the low-density stand.

Soil BD generally increased with increasing stand density, which was consistent in the 0-20 cm, 20-40 cm, and 40-60 cm soil layers (Fig. 4b). In the surface layer, soil BD was $1.06 \pm 0.1 \text{ g/m}^3$, $1.24 \pm 0.04 \text{ g/m}^3$, and $1.36 \pm 0.2 \text{ g/m}^3$, and in the 20-40 cm layer soil BD was $1.19 \pm 0.2 \text{ g/m}^3$, $1.24 \pm 0.1 \text{ g/m}^3$ and $1.34 \pm 0.3 \text{ g/m}^3$ in low-, intermediate-, and high-density, respectively. Furthermore, in the 40-60 cm layer, soil BD was $1.04 \pm 0.1 \text{ g/m}^3$, $1.15 \pm 0.3 \text{ g/m}^3$, and $1.29 \pm 0.1 \text{ g/m}^3$ in the low-, intermediate-, and high-density stand, respectively. In the surface layer, soil BD differed significantly between stands and increased from the low- to the high-density stand. Soil BD in the 20-40 cm and 40-60 cm layers was higher in the high-density stand and lowest in low-density stand (Fig. 4b).

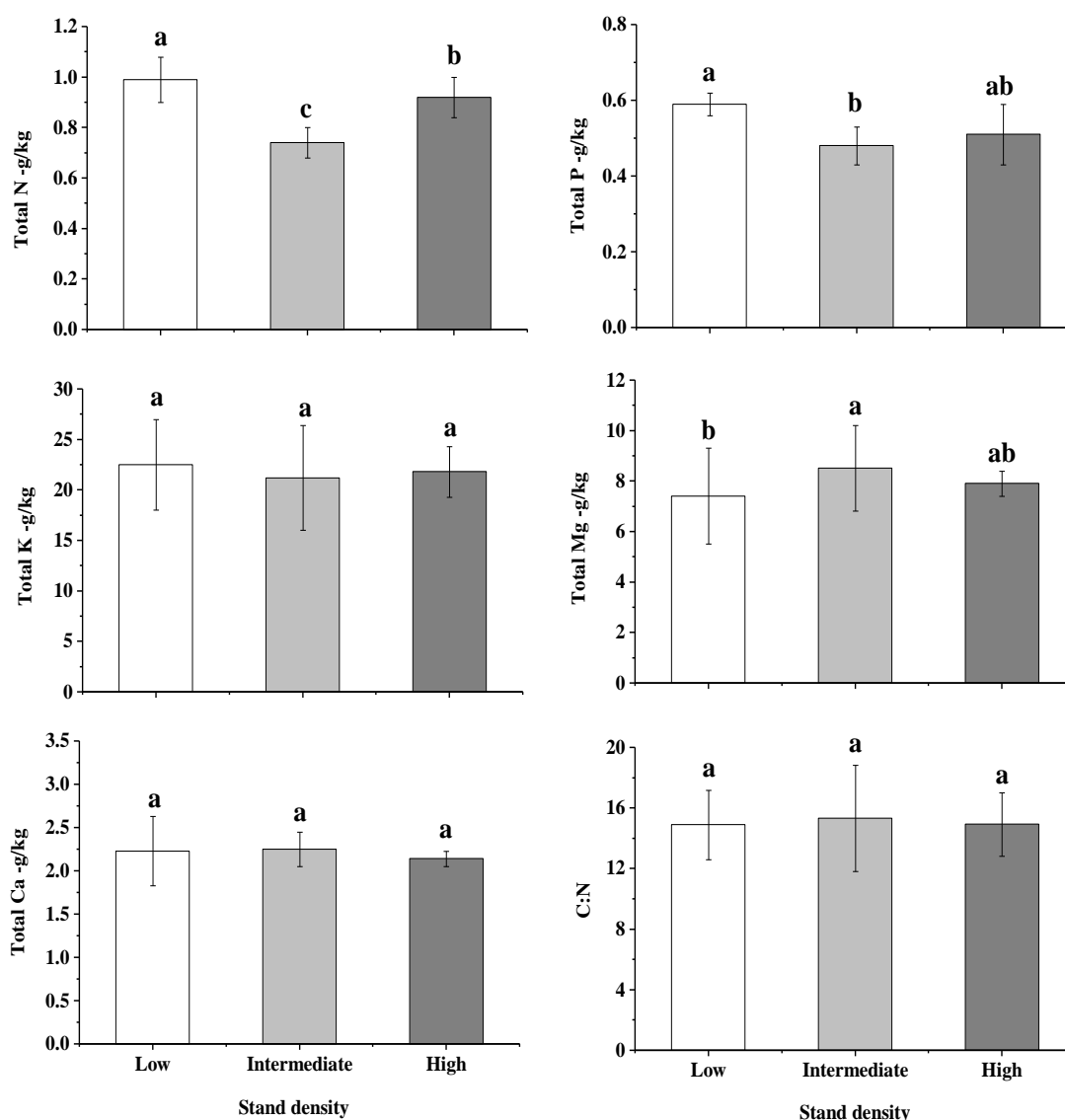


Figure 2. Variation among total soil nutrient contents in low-, intermediate-, and high-density stands ($N = 24$). Columns indicate mean \pm SE, different letters indicate significant differences at $P < 0.05$

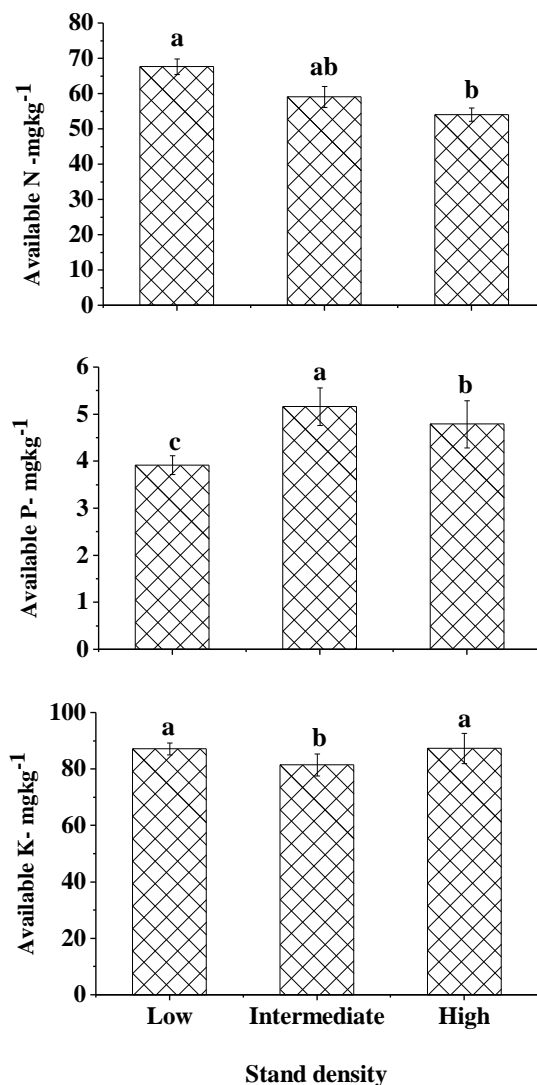


Figure 3. Available N, available P, and available K at low-, intermediate-, and high-density stands ($N = 24$). Columns indicate mean \pm SE, different letters indicate significant differences at $P < 0.05$

At a 0-60 cm soil depth, the soil pH was highest in the intermediate-density stand and lowest in the low-density stand. In both the intermediate- and the high-density stands the soil pH values were significantly different from the low-density stand. Soil pH values were 4.21 ± 0.04 , 4.31 ± 0.03 , and 4.27 ± 0.03 in the low-, medium- and high-density stands, respectively. Soil BD was highest in the intermediate-density stand and lowest in the high-density stand. Soil BD was 1.22 ± 0.07 , 1.28 ± 0.01 , and 1.16 ± 0.09 in low-, medium-, and high-density stands, respectively, and differed significantly between stands (*Table 4*).

No significant difference in soil EC was observed among the stands. SOM was higher in the intermediate-density stand and lower in low-density stand; the SOM values were 31.90 ± 1.34 g/kg, 36.56 ± 1.61 g/kg, and 35.47 ± 0.8 g/kg in the low-, intermediate-, and high-density stands, respectively. No significant difference was observed between the intermediate- and high-density stands; however, both were significantly different from the low-density stand. SMC was higher (17.2%) in the high-

density stand than in the intermediate- (9.53%) and low-density (11.49%) stands. SMC in the high-density stand differed significantly from the intermediate- and the low-density stands (Table 4).

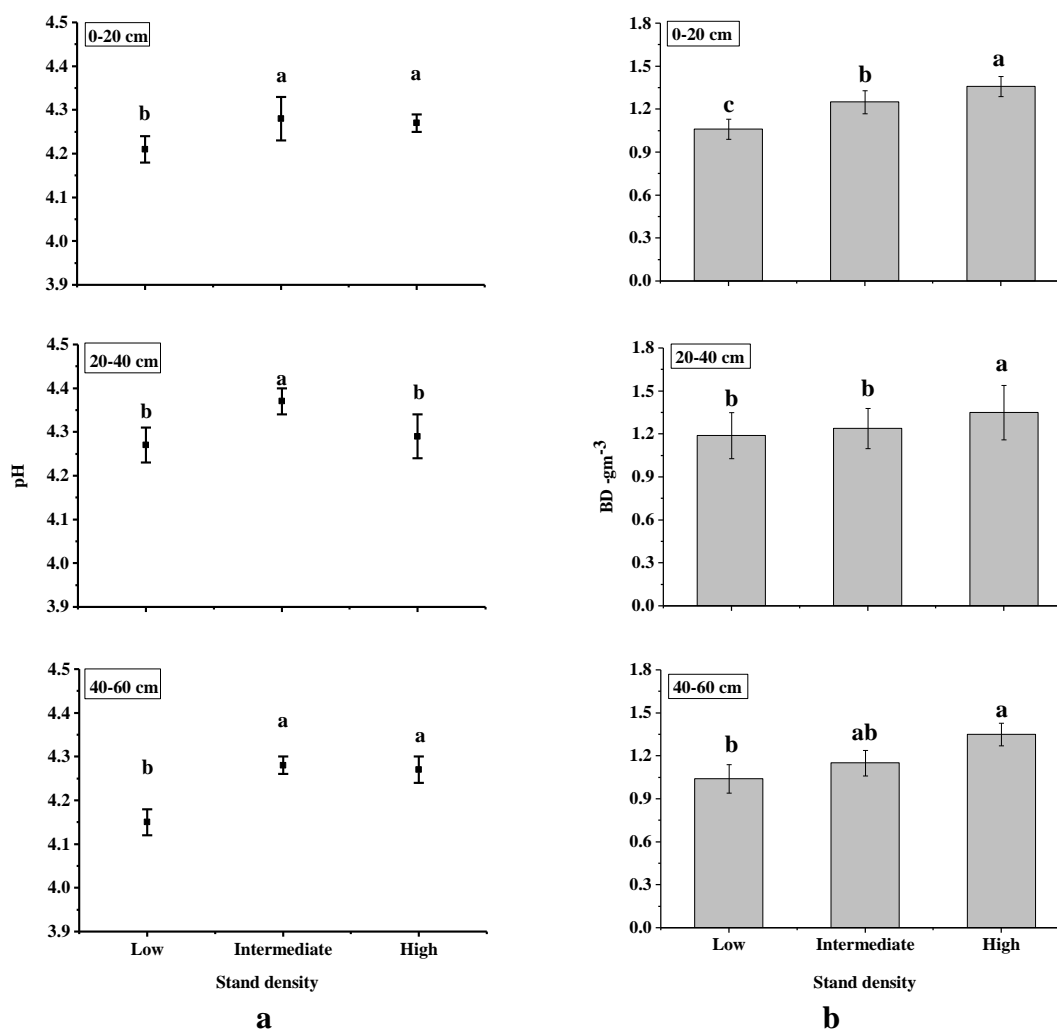


Figure 4. Soil pH and soil BD in low-, intermediate-, and high-density stands. Columns indicate mean \pm SE, different letters indicate significant differences among densities at $P < 0.05$

Table 4. Soil pH, soil electrical conductivity (EC), soil bulk density (BD), soil organic matter (SOM) and soil moisture content (SMC) in low-, intermediate-, and high-density stands at a 0-60 cm soil depth ($N = 24$)

Soil parameters	Stand density		
	Low	Intermediate	High
pH	4.21 \pm 0.04 b	4.31 \pm 0.03 a	4.27 \pm 0.03 a
BD (g/m ³)	1.22 \pm 0.07 ab	1.28 \pm 0.01 a	1.16 \pm 0.09 b
EC	0.02 \pm 0.01 a	0.02 \pm 0.01 a	0.02 \pm 0.01 a
SOM (g/kg)	31.90 \pm 1.34 b	36.56 \pm 1.61 a	35.47 \pm 0.74 a
SMC (%)	11.49 b	9.53 b	17.2 a

Note: Shown are the mean \pm SE, different letters indicate significant differences between the stands at $P < 0.05$

Discussion

In forest conservation and management, stand density is an important factor influencing the trees' competition for growth space, light, and below-ground resources (nutrients and water) (Farinelli and Lemos, 2012; Fan et al., 2014; Sitienei et al., 2016). The soil quality indicators used in the current study were successfully used in previous studies on different forest ecosystems (Kay and Grant, 1996; Wei et al., 2009; Bautista-Cruz et al., 2012; Zhijun et al., 2018), suggesting that these parameters can be used for effective soil quality evaluation.

Watt et al. (2005, 2008) identified total P as important soil quality indicator due to its pivotal role in biochemical reactions and in the nutrient cycling of plantation systems (Reganold and Palmer, 1995; Turrión et al., 2007). In the present study, stand density had a significant effect on total N, available N, total P, available P, and total Mg but had no significant effect on total Ca, total K, and available K. In these plantations of ten years of age, both total N and total P were higher in the low-density stand and lower in the intermediate-density stand. Available N content was higher in the low-density stand and lower in the high-density stand, whereas available P content was higher in the intermediate-density stand and lower in the low-density stand. Our results contradicted those of Fang et al. (2017) who found that stand density had no significant effect on total soil N and on C:N ratio. Cancellier et al. (2011) reported that varying planting density influenced the soil chemical properties, and in low planting density, available P and exchangeable Mg, N, and Ca concentrations were significantly higher than at other planting densities, but little difference was observed in soil organic matter content. Furthermore, our results support the assumption that total P is an important indicator of soil quality for conifer plantations (Yang et al., 2004; Ma et al., 2007; Ross et al., 2009).

SOM acts as a storage reservoir for soil nutrients and is an important parameter for assessing sustainable forest management (Haynes and Beare, 1996; Tanaka et al., 2005). Availability of C and N in soil is crucial regarding SOM and abundance of the microbial biomass (Xing et al., 2010; Zhang et al., 2017a). According to our results, SOM was affected by stand density and was significantly higher in the intermediate-density stand than in the other stands. Moreover, previous studies showed that in Chinese fir plantations SOM increased due to a large quantity of debris input following artificial thinning (Lin et al., 2001; Ma et al., 2014). Besides stand population density, continuous rotations can also have a significant impact on soil fertility (Black, 2013). Huang et al. (2004) stated that in Chinese fir plantations SOM decreased significantly with continuous cultivation (by 10% and 15% in second and third rotation, respectively). Soil enzyme activity and microbial diversity decreased with successive rotations (Chen and Wang, 2003; Liu et al., 2010). According to a different study, continuous planting does not necessarily affect soil degradation, SOM, total P, total K, and available N content; it was therefore hypothesized that sustainability and soil fertility could be consolidated under a continuous cropping regime if plantation stand density was optimized (Wei et al., 2012). In contrast to our results, Wright (1992) reported that plant density has no substantial effect on soil fertility. Taken together, the relationship of plant density and soil fertility seems not to be entirely consistent.

Soil pH is an important indicator of soil quality, influencing plant nutrient availability and soil chemical reactions (Schoenholtz et al., 2000; Cheng et al., 2016). Previous studies have emphasized the importance of pH as a soil quality indicator for assessing different land use and forest conservation practices (Doran and Parkin, 1994; Bautista-Cruz et al., 2012; Yu et al., 2017). Soil pH was lowest in the surface layer of

soils of all three densities and increased from the 0-20 cm layer to the 20-40 cm layer; however, it decreased from the 20-40 cm to 40-60 cm layer. No significant difference in pH was observed between intermediate-density and high-density stands, both of which differed significantly from the low-density stand; however, the pH values generally remained within the optimum range for Chinese fir plantations (Zhou, 1985). Soil BD increased from the surface to the 40-60 cm soil layer, and significant differences between the stands were observed in each layer. Our results differed from those of Fang et al. (2017) who found that stand density had no significant effect on soil pH and BD.

The understanding of stand density and soil health under continuous cropping conditions have become important for understanding forest productivity, plant population dynamics, and land use for sustainable production (de Bello et al., 2010; Van der Putten et al., 2013). Nutrients are typically removed from growing sites due to stem harvesting and clear cutting (Chen et al., 2013). Yang et al. (2005b) found that nutrient removal due to clear-cutting was higher than that due to pre-burning; furthermore, the total N and organic C contents of topsoil were reduced by 19% and 17%, respectively. Therefore, besides fertilization, plant residues should be buried on site to replenish the soil nutrient contents. A lack of sufficient soil remediation may lead to a reduction in soil nutrient availability, which may, in turn, limit harvesting potential to only a few rotations (Zhou et al., 2016).

Conclusions

Assessing the effect of stand density may help maintain and enhance sustainable crop production and soil health. Our results indicated that stand density had a significant impact on total and available N and P but not on total and available K. Moreover, total Ca was not affected by stand density. Total P may be a useful indicator for assessing soil quality in Chinese fir plantations. A significant difference in soil pH between stand densities was observed; however, soil pH was within the optimum range for Chinese fir plantations. Soil BD was higher in the intermediate-density stand, and SMC was higher in the high-density stand; SOM was higher in the intermediate-density stand and lower in the low-density stand. No significant difference in the SOM was found between intermediate- and high-density stands, both of which were significantly different from the low-density stand. Soil nutrients typically decline due to clear cutting; therefore, the residues should be buried on site to increase soil fertility. A long-term strategy for maintaining and improving yield and sustainable land use requires that policy makers and managers have access to information on the quantitative relationship between stand density and soil quality. To preserve soil quality and ensure high timber production, variations in soil quality parameters, which are affected by stand density, may help policy makers develop better management practices. Moreover, the influence of aspects, such as enzymatic activity, biological variables and microbiological communities, on soil functioning should also be investigated.

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