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Effects of Planting Density on Soil Bulk Density, pH and Nutrients of Unthinned Chinese Fir Mature Stands in South Subtropical Region of China

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Abstract: Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) is a fast-growing evergreen conifer with high-quality timber and is an important reforestation and commercial tree species in southern China. Planting density affects the productivity of Chinese fir plantations. To study the effect of five different planting densities and soil depth on soil nutrient contents of a mature *C. lanceolata* plantation, the soil nutrient contents (soil depths 0–100 cm) of 36-year-old mature Chinese fir plantations under five different planting densities denoted A (1667 trees·ha^{-1}), B (3333 trees·ha^{-1}), C (5000 trees·ha^{-1}), D (6667 trees·ha^{-1}), and E (10,000 trees·ha^{-1}) were measured in Pingxiang county, Guangxi province, China. Samples were collected from the soil surface down to a one meter depth from each of 45 soil profiles, and soil samples were obtained at 10 different soil depths of 0–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70, 70–80, 80–90, and 90–100 cm. Twelve soil physical and chemical indicators were analyzed. The results showed that: (1) as planting density increased, the organic matter, organic carbon, total N and P, available N, effective Fe, and bulk density decreased. Soil pH, total K, and effective K increased with increasing planting density. Planting density did not significantly influence the exchangeable Ca and Mg. (2) Soil organic matter; organic carbon; total N and P; effective N, P, and K; exchangeable Ca and Mg; effective Fe content; and bulk density decreased with increasing soil depth. This pattern was particularly evident in the top 30 cm of the soil. (3) Excessively high planting density is not beneficial to the long-term maintenance of soil fertility in Chinese fir plantations, and the planting density of Chinese fir plantations should be maintained below 3333 stems·ha^{-1} (density A or B) to maintain soil fertility while ensuring high yields.

Keywords: Chinese fir; mature stand; planting density; soil profile; nutrient content

1. Introduction

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) is a species characteristic of the subtropical zone and an important reforestation and commercial tree species, occurring throughout the whole southern subtropical zone in China. According to the eighth Chinese National Forest Inventory, Chinese fir plantations occupy almost 8.95 million ha, and they have a standing timber volume of 625 million m^3 [1]. The total plantation area of Chinese fir has increased due to an increased demand for timber. However, the yield and productivity of pure Chinese fir plantations are extremely low due to poor soil fertility and unscientific management practices [2–4]. As Chinese fir litter has a low decomposition rate, nutrients are slow to return to the soil during a short rotation, which may lead to poor soil fertility [5,6]. Some reasonable silvicultural treatments, like harvest residue management [7], fertilization [8], and mixed forests [9], could improve the stand growth environment, and increase the vegetation development and litter decomposition rates in Chinese fir plantations [10], which would help maintain soil fertility.

The response of soil properties to silvicultural treatments [11], including thinning and harvesting regimes, underforest vegetation management, rotation [12–14], and site condition and climate status analysis, can be complex. For Chinese fir plantations, previous studies on the soil nutrients focused on successive planting [15,16], thinning intensity [17,18] and the changes in the soil nutrients in plantations during their different development stages [19,20] in mid-subtropical areas such as Jiangxi and Fujian [21–24]. Thinning is a common stand density management practice used to increase the quality and quantity of merchandisable timber [25]. Thinning can increase [26,27], decrease [28], or have little effect [29] on soil nutrition. However, most of these studies mainly focused on the short-term effects of thinning on soil properties, and long-term studies have generally shown that soil organic matter eventually returns to preharvest levels in most sites during the first rotation [14,30].

Planting density greatly affects plantation productivity [31]. Some studies on loblolly pine have shown that planting density affects biomass accumulation at the stand level [32] and the tree level [33]. We reported the effects of the planting density of Chinese fir stands on basal area growth, timber assortment structure, biomass, and self-thinning [31,34,35]. Due to action on population structure and the competitive situation in forest stands, density control can affect the formation of litter, the biomass, and species diversity of the undergrowth vegetation by affecting the distribution of factors such as light, temperature, and moisture in the forest community [36], which affect the soil nutrients in forests [5]. Planting density has been proven to significantly affect fibrous root reinforcement in soil [37], soil microflora [38,39], enzyme activity [40], and soil nutrient content [41]. However, most studies focused on the effects of planting density on aboveground yield responses and nutrient concentrations [42,43], so little is known about the effect of planting density on soil nutrients.

Guangxi Province is known as a Chinese fir production area in the south subtropics area in China [44], but no studies have been published on the effects of planting density on soil nutrients in these Chinese fir plantations. In view of this, the objective of our study was to quantify the long-term impacts of different planting densities on soil nutrients as well as to determine their distribution according to soil depths in the 36-year-old undisturbed Chinese fir stands under five planting densities in Pingxiang county, Guangxi province. Information on the soil nutrients status under different planting densities will assist forest managers to strategize future management practices and be beneficial for maintenance of the long-term productivity of regional Chinese fir plantations.

2. Materials and Methods

2.1. Experimental Site

The experimental materials were obtained from the Daqingshan Forest Farm (106°43′ E, 22°06′ N, mean altitude 500 m), located in Pingxiang county, Guangxi province, China (Figure 1). The area's main ground feature is low mounts at slopes of 25–30°. This experimental site has a south tropical monsoon climate. The average annual temperature, precipitation, and evaporation in the study area were 19.9 °C, 1400 mm, and 1200 mm, respectively. The site's sandy textured soil formed from granite, which is classified as red soil in Chinese soil classification. The soil thickness is greater than 1 m. Undergrowth vegetation, such as *Aporosa chinensis* (Champ.) Merr., *Rhodomyrtus tomentosa* (Ait.) Hassk., *Cibotiumb arometz* (L.) J. Sm., and *Adiantum capillus-veneris* L., grow on the site.

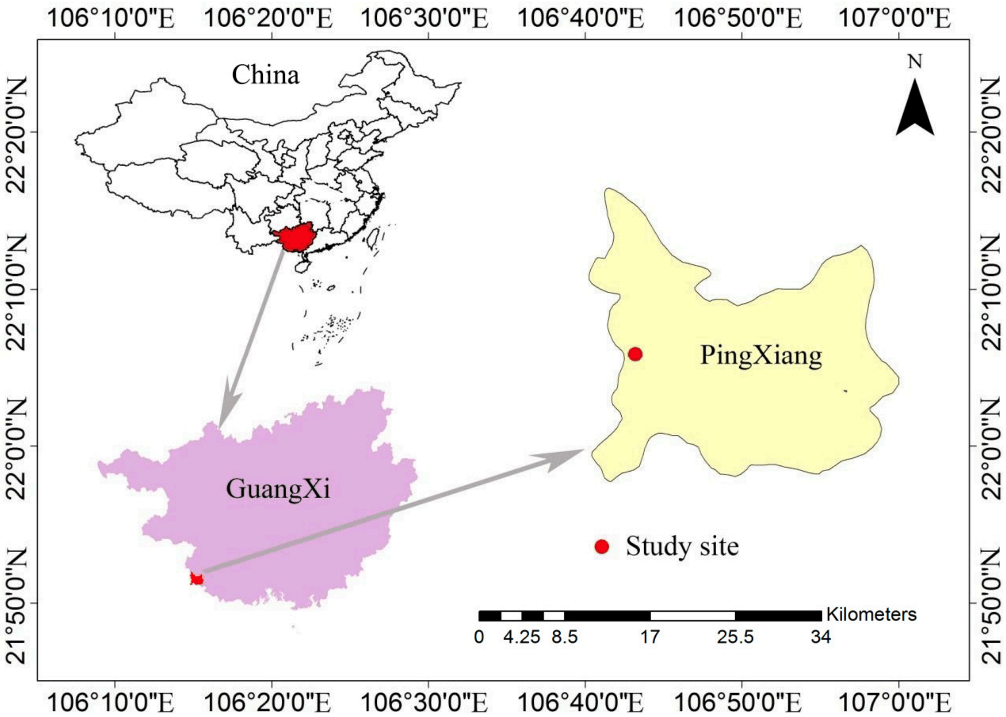

Figure 1. The geographical map of the study site.

2.2. Experimental Design

The Chinese fir stand density experiment was planted with two-year-old seedlings in the spring of 1982. The five planting densities were 1667, 3333, 5000, 6667, and 10,000 trees ha^{-1} with distances between trees of 2 × 3, 2 × 1.5, 2 × 1, 1 × 1.5, and 1 × 1 m, recorded as A, B, C, D, and E, respectively. Plots were installed in a random block arrangement. Each spacing level was replicated three times for a total of 15 plots. Each plot was 20 × 30 m (0.06 ha), with a buffer zone of two rows of the same species density around each plot, and a fixed boundary of concrete piles. The basic information for the different densities of Chinese fir stands is provided in Table 1.

Table 1. The arithmetic mean diameter at breast height (DBH), mean height (H), dominant height (H_d), and understory biomass of stands with different planting densities.

Planting Density (trees ha^{-1})	Stand Density (trees ha^{-1})	Stand Age (years)	DBH (cm)	H (m)	H_d (m)	Understory Biomass (t·ha^{-1})
A: 1667	1044	36	19.76	18.82	15.70	9.76
B: 3333	1428	36	17.26	18.08	15.09	13.56
C: 5000	1533	36	16.28	16.95	14.16	9.71
D: 6667	1511	36	17.61	18.93	16.01	8.11
E: 10000	1356	36	15.67	16.69	14.56	8.05

2.3. Collection and Analysis of Soil Samples

Three soil profiles were selected and diagonally distributed for each of the 15 plots. A total of 45 soil profiles were manually dug when the Chinese fir density experimental stand was 37 years old in the fall of 2016. Each soil profile was 1 m deep. Soil samples were collected at 10 soil depths of 0–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70, 70–80, 80–90, and 90–100 cm, and approximately 500 g of soil at each depth was sampled. In each depth, we measured for the soil: bulk density, pH, organic matter content, total N, alkali-hydrolyzable N, total P, available P, total K, available K, exchangeable Ca, exchangeable Mg and available Fe. Bulk density was determined by inserting a steel cylinder of known volume, 5 cm high and with a 5.046 cm inner diameter, into each depth of the soil profile. A total of 1 350 samples were taken from 15 plots with 45 soil profiles. The dry weight, calculated with fresh weight and water content, divided by the volume of the cylinder is the bulk density expressed as g cm^{-3} [45]. At the same time, 500 g of each of 450 layers was stored in soil bags, transported to the laboratory, air-dried, ground, sieved, and analyzed for soil chemical properties. The soil pH was determined using the potentiometer method of analysis, using soil/saline solution suspensions (soil-KCl 1 mol) in a 1:2.5 proportion [46]. The organic matter was determined by the $K_2Cr_2O_7$-H_2SO_4 oxidation method [45]. The total N and alkali-hydrolyzable N were determined by the Kjeldahl method using a 2300 Kjeltec Analyzer Unit (FOSS, Hilleroed, Denmark) and the alkaline hydrolysis method, respectively. The extraction method for total P and K, available P and K was conducted according to the soil physical and chemical analysis [45]. The exchangeable Ca, Mg, and Fe were determined using an atomic absorption spectrophotometer (Thermo Fisher Scientific, Rockford, IL, USA) [47].

2.4. Data Processing

Both one-way analysis of variance (ANOVA) and multiple comparisons were used to determine the difference in the soil nutrient contents in different planting densities and soil layers.

3. Results and Analysis

3.1. Effects of Planting Density on Bulk Density

Table 2 provides the determined values of the volume weight in the different soil layers for the five planting densities. Table 1 shows that in the 0–20 cm soil layer, the soil bulk density at lower planting densities (A and B) was lower than in D and E densities. In the 0–10 cm soil layer, the soil bulk density in D was significantly higher than in the other four planting densities. We observed a small difference in soil bulk density for the five densities in the soil layers below 20 cm.

Table 2. Soil bulk density in different layers under different stand densities (g·cm^{-3}).

Soil Depth (cm)	Planting Density (trees·ha $^{-1}$)				
	A (1667)	B (3333)	C (5000)	D (6667)	E (10,000)
0–10	1.24 ± 0.07 ^{Aa}	1.27 ± 0.10 ^{Aa}	1.29 ± 0.08 ^{Aa}	1.38 ± 0.05 ^{Ab}	1.29 ± 0.09 ^{Aa}
10–20	1.41 ± 0.14 ^{Ba}	1.45 ± 0.11 ^{Ba}	1.46 ± 0.12 ^{Ba}	1.51 ± 0.06 ^{Ba}	1.48 ± 0.04 ^{Ba}
20–30	1.58 ± 0.04 ^{Ca}	1.58 ± 0.06 ^{Ca}	1.56 ± 0.07 ^{Ca}	1.58 ± 0.04 ^{Ca}	1.54 ± 0.07 ^{Ba}
30–40	1.59 ± 0.05 ^{Ca}	1.59 ± 0.04 ^{Ca}	1.57 ± 0.09 ^{Ca}	1.59 ± 0.04 ^{Ca}	1.55 ± 0.03 ^{Ba}
40–50	1.58 ± 0.05 ^{Ca}	1.59 ± 0.04 ^{Ca}	1.58 ± 0.07 ^{Ca}	1.59 ± 0.04 ^{Ca}	1.53 ± 0.09 ^{Ba}
50–60	1.55 ± 0.06 ^{Ca}	1.57 ± 0.05 ^{Ca}	1.55 ± 0.09 ^{BCa}	1.58 ± 0.10 ^{Ca}	1.51 ± 0.09 ^{Ba}
60–70	1.57 ± 0.02 ^{Ca}	1.58 ± 0.04 ^{Ca}	1.53 ± 0.08 ^{BCa}	1.57 ± 0.07 ^{Ca}	1.54 ± 0.06 ^{Ba}
70–80	1.54 ± 0.07 ^{Cab}	1.59 ± 0.05 ^{Ca}	1.55 ± 0.07 ^{BCab}	1.56 ± 0.03 ^{Cab}	1.53 ± 0.05 ^{Bb}
80–90	1.56 ± 0.07 ^{Ca}	1.60 ± 0.09 ^{Ca}	1.57 ± 0.09 ^{Ca}	1.58 ± 0.06 ^{Ca}	1.54 ± 0.09 ^{Ba}
90–100	1.60 ± 0.09 ^{Ca}	1.59 ± 0.08 ^{Ca}	1.57 ± 0.09 ^{Ca}	1.57 ± 0.04 ^{Ca}	1.55 ± 0.07 ^{Ba}

Notes: The data in the table are average ± standard deviarion (SD). Different lowercase letters in the same line indicate significant differences among different densities at the 0.05 level, and different capital letters for the same density in the same column indicate significant differences among different soil layers at the 0.05 level.

Within the 0–30 cm soil layer, the bulk density for the five density stands sharply increased with increasing soil layer depth, presenting a significant progressive increase in four planting densities: A, B, C, and D. The bulk density changed little in the soil layers below 20 cm.

3.2. Effects of Planting Density on Soil pH

The soil pH in high-density stands is higher than in the low-density stands, and the five densities demonstrated a consistent change trend in soil pH in different soil layers, with the basic order of E > D > B > C > A. In the 0–10, 10–20, 20–30, 30–40, 40–50, 50–60, and 60–70 cm soil layers, a significant difference was found in the soil pH ($p < 0.5$) between A density and the other densities, but no significant difference was found between the other four densities, B, C, D, and E, in the different soil layers (Table 3).

The soil pH was 3.50–4.0 at 1 m deep in the soil profile, presenting a rising trend with the increase in soil depth. For different planting densities, a certain difference was observed in the effect of soil layer on soil pH. For the A planting density, a significant difference was found in the soil pH between the 0–60 cm soil layers and the soil layers below 60 cm. In B, C, and D densities, there was no significant difference in the soil pH in the 0–70 cm soil layers, but the soil pH above 70 cm is significantly different from that below 70 cm. In the E density, there was no significant difference in soil pH of the 0–80 soil layers, only the soil pH in the 0–10 cm soil layer had significant difference from the soil layers below 80 cm. High planting density can reduce the difference in the soil pH in different soil layers.

Table 3. Soil pH in different layers under different stand densities.

Soil Depth (cm)	Planting Density (trees·ha $^{-1}$)				
	A (1667)	**B (3333)**	**C (5000)**	**D (6667)**	**E (10,000)**
0–10	3.54 ± 0.19 ^{Db}	3.77 ± 0.13 ^{Ca}	3.74 ± 0.11 ^{Ca}	3.80 ± 0.07 ^{Da}	3.86 ± 0.06 ^{Ca}
10–20	3.58 ± 0.17 ^{CDc}	3.79 ± 0.10 ^{Cab}	3.75 ± 0.11 ^{Cb}	3.85 ± 0.06 ^{CDab}	3.87 ± 0.05 ^{BCa}
20–30	3.60 ± 0.16 ^{CDc}	3.77 ± 0.10 ^{Cb}	3.77 ± 0.10 ^{Cb}	3.86 ± 0.09 ^{CDab}	3.89 ± 0.07 ^{ABCa}
30–40	3.62 ± 0.17 ^{CDc}	3.79 ± 0.10 ^{Cab}	3.76 ± 0.10 ^{Cb}	3.85 ± 0.08 ^{CDab}	3.89 ± 0.08 ^{ABCa}
40–50	3.63 ± 0.18 ^{CDb}	3.79 ± 0.09 ^{Ca}	3.79 ± 0.10 ^{BCa}	3.85 ± 0.10 ^{CDa}	3.90 ± 0.09 ^{ABCa}
50–60	3.66 ± 0.17 ^{CDb}	3.83 ± 0.07 ^{Ca}	3.80 ± 0.11 ^{BCa}	3.86 ± 0.10 ^{CDa}	3.91 ± 0.12 ^{ABCa}
60–70	3.73 ± 0.15 ^{ABb}	3.87 ± 0.07 ^{ABCa}	3.85 ± 0.11 ^{BCa}	3.92 ± 0.13 ^{ABCDa}	3.93 ± 0.12 ^{ABCa}
70–80	3.81 ± 0.14 ^{ABb}	3.92 ± 0.06 ^{ABab}	3.89 ± 0.10 ^{ABab}	3.96 ± 0.14 ^{ABCa}	3.95 ± 0.12 ^{ABCa}
80–90	3.84 ± 0.17 ^{Ab}	3.94 ± 0.08 ^{ABab}	3.91 ± 0.10 ^{Aab}	3.97 ± 0.15 ^{ABa}	3.97 ± 0.11 ^{ABa}
90–100	3.82 ± 0.15 ^{ABb}	3.94 ± 0.09 ^{Aab}	3.92 ± 0.09 ^{Aab}	3.99 ± 0.16 ^{Aa}	3.99 ± 0.12 ^{Aa}

Notes: The data in the table are average ± standard deviation. Different lowercase letters in the same line indicate significant differences among different densities at the 0.05 level, and different capital letters for the same density in the same column indicate significant differences among different soil layers at the 0.05 level.

3.3. *Effects of Planting Density on Nutrient Contents*

3.3.1. Organic Matter

Figure 2 shows that the planting density had an obvious effect on the organic matter in the soil layers, and the surface soil (0–30 cm) in both A and B densities had a higher organic matter content than the soil layers under the other densities. The 0–10 cm soil layer in the A density had more organic matter content than in the other planting densities, indicating that low density is good for the accumulation of soil organic matter. Comparatively, the soil in the D density had the lowest organic matter content, and its organic matter content was significantly less than in the other planting densities ($p < 0.05$).

Figure 2 shows that with the increase in soil depth, the organic matter content declines to different degrees, with different decreasing ranges. A fourfold decrease in organic matter content was recorded in 90–100 cm compared with the 0–10 cm soil layer. The organic matter content in 0–30 cm soil in all five density was higher than in the soil layers below 30 cm, decreasing significantly with the increase in soil depth. The organic matter content decreased less within the 30–60 cm soil layer, but was invariant within 60–100 cm soil layer.

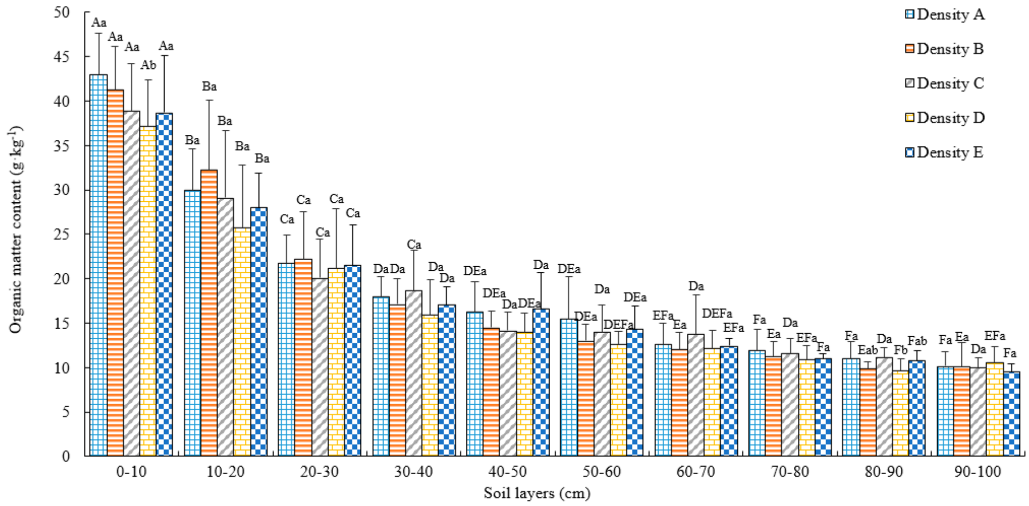

Figure 2. Soil organic matter in different layers under different stand densities (g·kg^{-1}). Note: Different lowercase letters indicate significant differences among different densities at the 0.05 level, and different capital letters for the same density indicate significant differences among different soil layers at the 0.05 level.

3.3.2. Total N and Alkali-Hydrolyzable N

The nitrogen (N) in soil exists in an organic state. The total N is the total content of nitrogen and N supply potential, and alkali-hydrolyzable N refers to the N content that can be absorbed for use by plants. Figures 3 and 4 show that both the soil total N and the alkali-hydrolyzable N consistently changed with Chinese fir planting density. With the increase in density, the total and alkali-hydrolyzable N contents in all soil layers decreased a little as a whole. The total N content in the A density was generally higher than that in the other densities, but the density had no significant effect on the total and alkali-hydrolyzable N contents in the same soil layer.

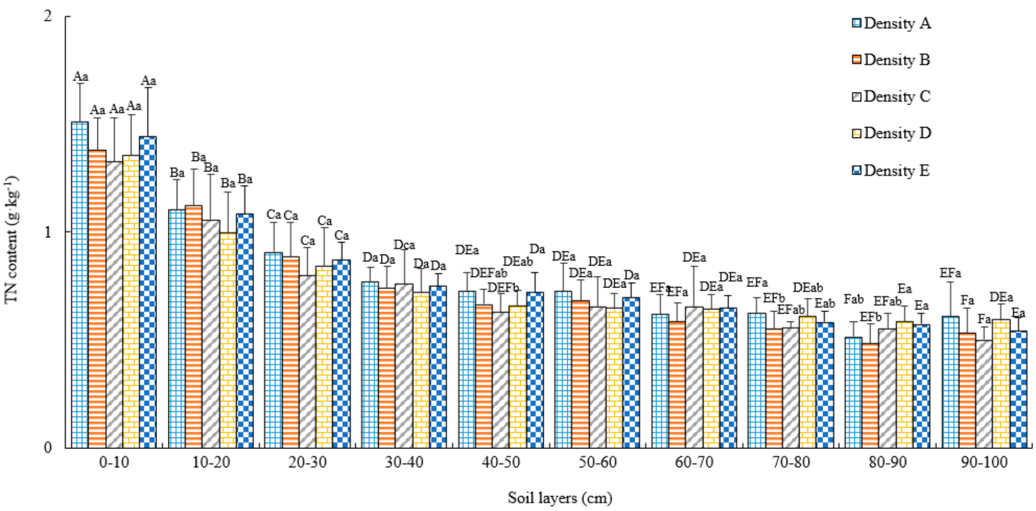

Figure 3. Soil total N in different layers under different stand densities (g·kg^{-1}). Note: different lowercase letters indicate significant differences among different densities at the 0.05 level, and different capital letters for the same density indicate significant differences among different soil layers at the 0.05 level.

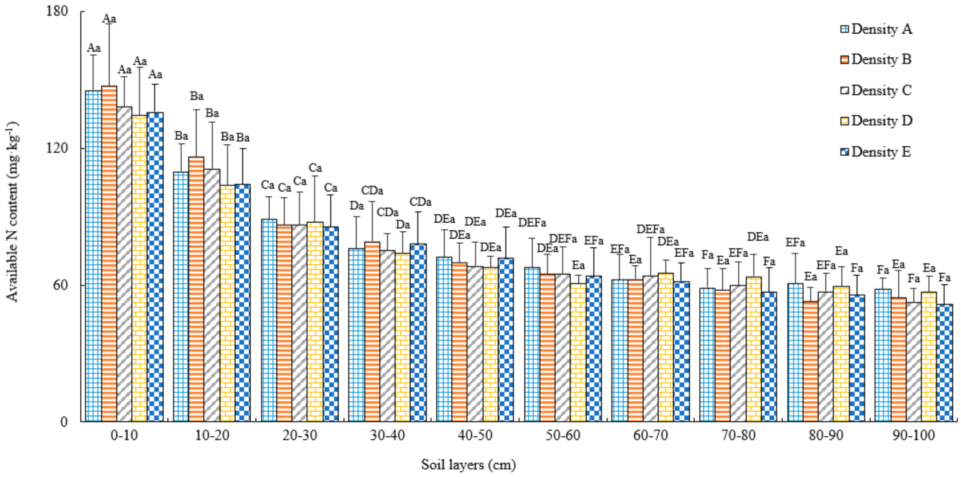

Figure 4. Soil alkali-hydrolyzable N in different layers under different stand densities (mg·kg^{-1}). Note: different lowercase letters indicate significant differences among different densities at the 0.05 level, and different capital letters for the same density indicate significant differences among different soil layers at the 0.05 level.

The soil total and alkali-hydrolyzable N contents in the five density stands decreased with the increase in soil depth. The two contents in the 0–30 cm soil layer were significantly higher than that in the other soil layers ($p < 0.05$). The two contents decreased significantly within the 0–30 cm soil layer with the increase in soil depth, but in the soil layers below 30 cm, they decreased relatively slowly. The soil total and alkali-hydrolyzable N contents in the 30–40 cm soil layer in the lower density A and B stands were significantly higher than that in the soil layer below 60 cm. The two contents in the 30–40 cm soil layer in the relatively higher C-, D-, and E-density stands were significantly higher than those in the soil layers below 70 cm. Both the total and the alkali-hydrolyzable N contents presented no statistically significant difference in the soil layers below 40 cm in different density stands.

3.3.3. Total P and Available P

Figures 5 and 6 shows that no significant difference between A and B density stands existed in the total P content in all soil layers, but their total P content was greater than that in the C, D, and E stands. Among C, D, and E stands, with a relatively higher density, the total P content in the D-density stand was higher than in C and E density stands, and the difference reached a significant level in 10–20 cm soil layer ($p < 0.05$). Different from total P content, the available P content in 10–100 cm soil layers in the C density stand was higher than in A, B, D, and E stands, and the content difference was at a significant level in some layers ($p < 0.05$). Instead, among C, D, and E stands with a relatively higher density, the available P content in D density stand was obviously lower than that in C and E stands.

The total P content decreases with the increase in soil depth. The total P content the in 0–10 cm soil layer was higher than in the soil layers below 10 cm in all five stands. The content became a significant level in A planting density ($p < 0.05$), and changed a little in the 10–100 cm soil layer, with an insignificant difference. In B, C, D, and E planting densities, the available P content in the 0–10 cm soil layer was significantly higher than in the soil layers below 30 cm ($p < 0.05$). In the 0–30 cm soil layer, the available P level was higher than that in the soil layers below 30 cm. The available P content decreased gradually with the increase in soil depth. This decreasing trend was even more remarkable against the total P level in the 0–30 cm top soil, and declined dramatically in 0–10 and 10–20 cm soil layers. The difference in available P contents in 0–10, 10–20, and 20–30 cm soil layers was significant in all five stands ($p < 0.05$). The available P content in the 30–40 cm soil layer and below did not reach a significant level.

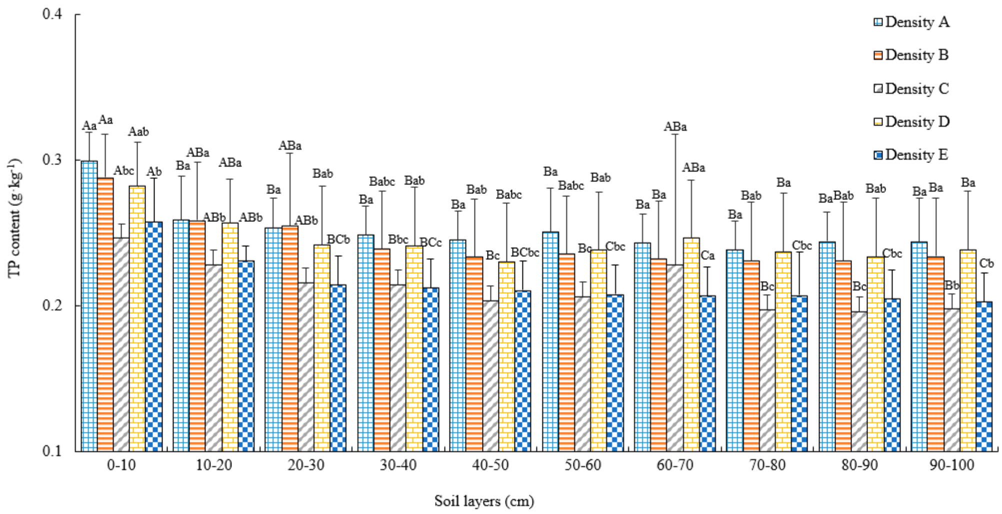

Figure 5. Soil total P in different layers under different stand densities (g·kg^{-1}). Note: different lowercase letters indicate significant differences among different densities at the 0.05 level, and different capital letters of the same density indicate significant differences among different soil layers at the 0.05 level.

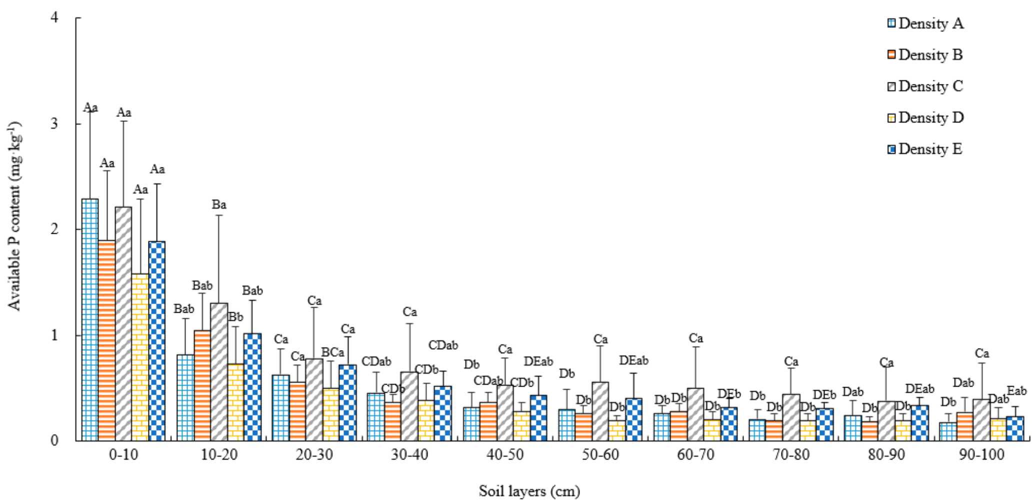

Figure 6. Soil available P in different layers under different stand enmities' (mg·kg^{-1}). Note: different lowercase letters indicate significant differences among different densities at the 0.05 level, and different capital letters of the same density indicate significant differences among different soil layers at the 0.05 level.

3.3.4. Total K and Available K

Figures 7 and 8 show that, besides the 40–50 and 50–60 cm soil layers, the total K content in all soil layers tends to decrease first and then increase with the increase in. The total K content in D and E stands was higher than in the other density stands; the content in the B density stand was the lowest, and highest in the E stand. The total K content in the 10–20, 20–30, 30–40, 40–50, 60–70, 70–80, and 90–100 cm soil layers in the E stand was significantly higher than in the B stand ($p < 0.05$). This indicates that high-density stands are beneficial to the accumulation of soil total K.

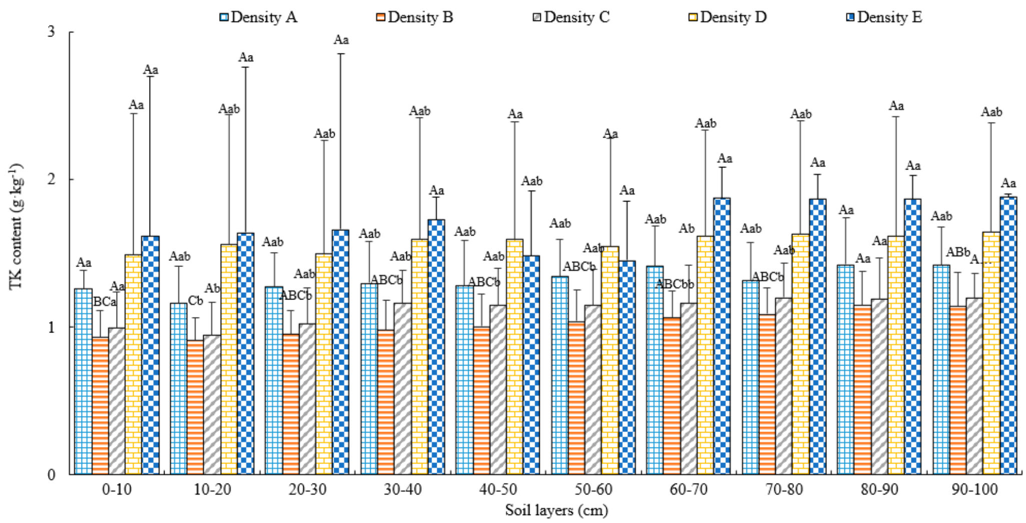

Figure 7. Soil total K in different layers under different stand densities (g·kg^{-1}). Note: different lowercase letters indicate significant differences among different densities at the 0.05 level, and different capital letters of the same density indicate significant differences among different soil layers at the 0.05 level.

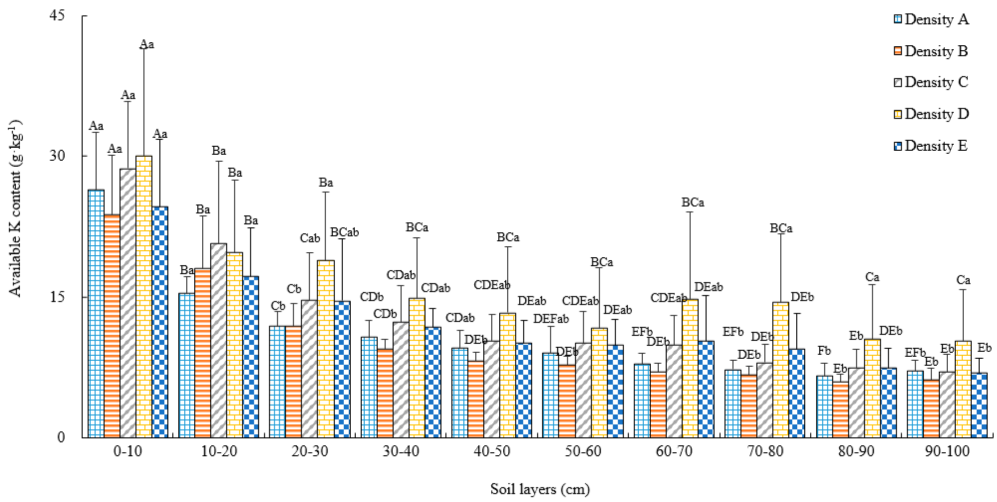

Figure 8. Soil available K in different layers under different stand densities (mg·kg^{-1}). Note: different lowercase letters indicate significant differences among different densities at the 0.05 level, and different capital letters of the same density indicate significant differences among different soil layers at the 0.05 level.

The available K content in soil tended to increase first and then decrease with the increase in density. The D stand had the highest soil available K content, and the available K content in the 20–30 cm soil layer and below was significantly higher than in A or B stands ($p < 0.05$). In the 70–80 and 80–90 cm soil layers, the available K content in the D density stand was significantly higher than that in the other four stands ($p < 0.05$). Different than total K content, the available K content decreased obviously in the E stand compared with the D stand, but was still higher than that in the A and B stands.

The total K content in the five stands tended to increase slowly, but did not present a significant difference in the five different stands. The available K content tended to decrease obviously with the increase in soil depth, where the available K content in the 0–30 cm soil layer decreased faster, but decreasing sharply from the 0–10 and 10–20 cm soil layers. The variance analysis indicated that the available K content in the 0–10 cm soil layer was significantly higher than in the 10–20 cm soil layer in the five densities ($p < 0.05$). The available K content in the 10–20 cm soil layer in the A, B, and C density was significantly higher than in the 20–30 cm soil layer and below ($p < 0.05$).

The available K content varied differently with the soil depth in the different stands. There was no significant difference in available K content in the 50–100 cm soil layer in the A stand, which was also observed for the content in the 40–100 cm soil layer in the B and C stands. However, in the D and E stands, this phenomenon occurred within 30–100 cm, indicating the available K content was relatively stable in the relatively high planting density stand.

3.3.5. Ca, Mg, and Fe

Figures 9 and 10 show that a certain difference was observed in exchangeable Ca and Mg content in soil layers for different stand densities. The variability in exchangeable Ca and Mg content among stand densities in the 0–10 cm soil layer was clearly higher than in the 10–20 cm soil layer and below, and the exchangeable Ca content in the 0–30 cm soil layer in the B stand was lower than in the other four stand densities. However, the variance analysis results showed the effect of density on all soil layers was not significant. Both exchangeable Ca and Mg contents decreased gradually with the increase in soil depth, but decreased sharply in the 0–10 and 10–20 cm soil layers. The exchangeable Ca and Mg contents in the 0–10 cm soil layer were significantly higher than in the 10–20 cm soil layer and below ($p < 0.05$). However, there was no significant difference in exchangeable Ca content in the 10–20 cm soil layer and below for different soil layer depths.

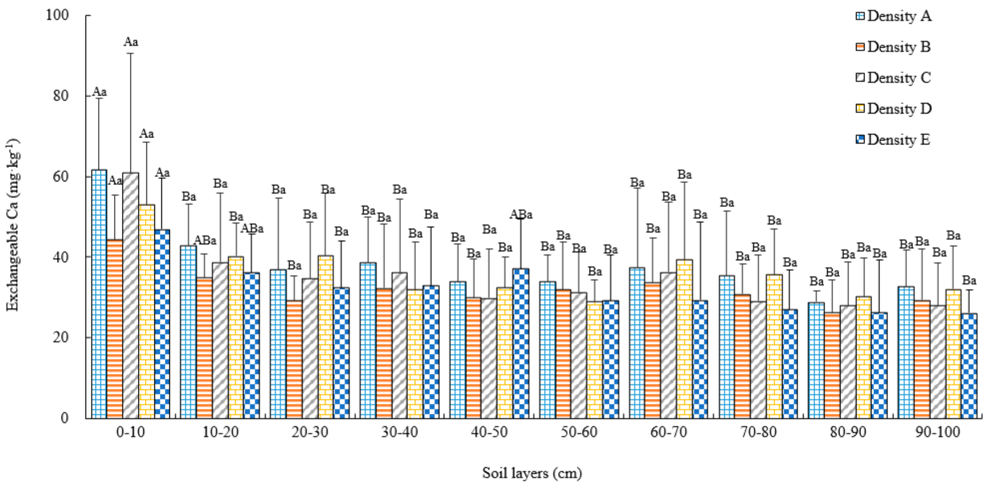

Figure 9. Soil exchangeable Ca in different layers under different stand densities (mg·kg^{-1}). Note: different lowercase letters indicate significant differences among different densities at the 0.05 level, and different capital letters of the same density indicate significant differences among different soil layers at the 0.05 level.

Figure 11 shows that the available Fe content in the 0–30 cm soil layer in A and C stand densities was higher than that in B, D, and E stands, and there was a significant difference in available Fe in the 0–10 cm soil layer in all five stands, but the difference in the available Fe was not significant in the 10–20 cm soil layer and below for different stand densities. Compared with exchangeable Ca and Mg, the available Fe coTABLEntent decreased more obviously with the increase in soil depth, and the content in the 0–40 cm soil layer decreased sharply in all five stand densities. The available Fe content decreased significantly in succession in the 0–10, 10–20 and 20–30 cm soil layers from top to bottom ($p < 0.05$), and the content within 0–30 cm was significantly higher than in the 30–40 cm soil layer and below in the A and C stands ($p < 0.05$). The difference in the available Fe content in the 40–50 cm soil layer and below was not significant in the five stands. In terms of the amount of decrease, the available Fe content in the 60–100 cm soil layer was 20 to 30 lower compared with the 0–10 cm soil layer.

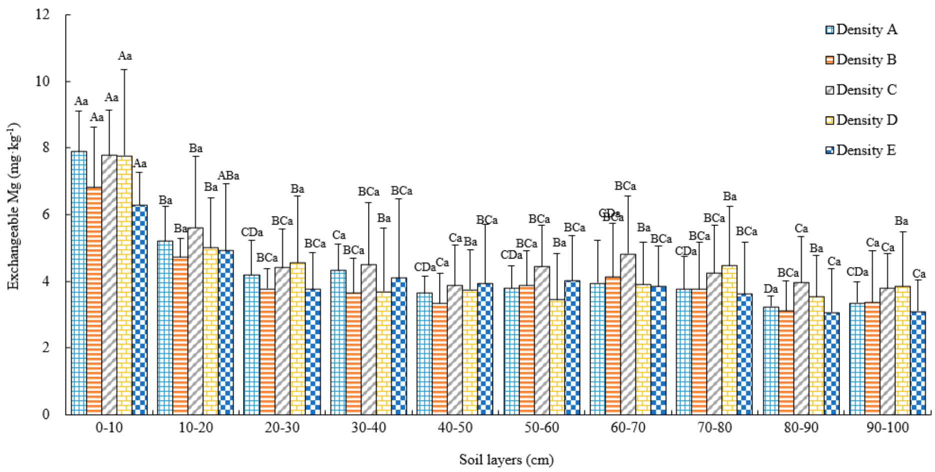

Figure 10. Soil exchangeable Mg in different layers under different stand densities (g·kg^{-1}). Note: different lowercase letters indicate significant differences among different densities at the 0.05 level, and different capital letters of the same density indicate significant differences among different soil layers at the 0.05 level.

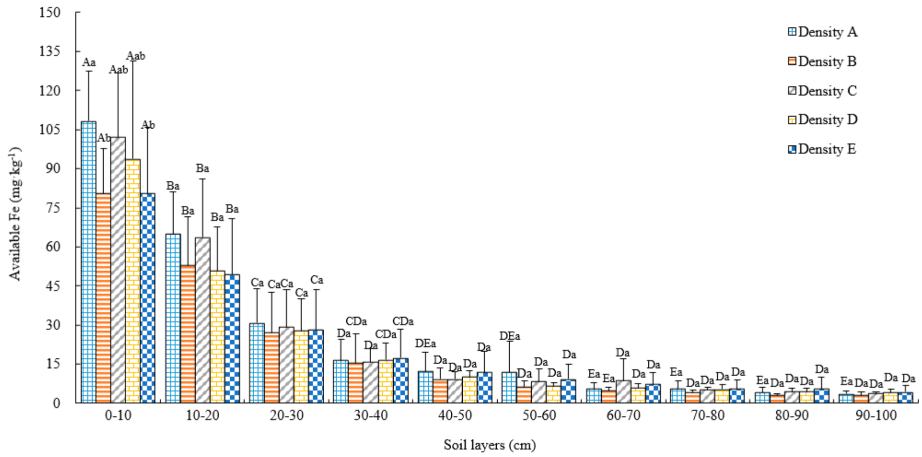

Figure 11. Soil available Fe in different layers under different stand densities (mg·kg^{-1}). Note: Different lowercase letters indicate significant differences among different densities at the 0.05 level, and different capital letters of the same density indicate significant differences among different soil layers at the 0.05 level.

3.4. Correlation Analysis Among Soil pH, Bulk Density, and Nutrients

Table 4 provides the correlation analysis results of soil bulk density, pH, and nutrient elements. Soil bulk density has a highly significantly positive correlation with soil pH, indicating that soil pH increases with soil bulk density. The soil bulk density has a highly significant negative correlation with organic matter, organic C, total N, alkali-hydrolyzable N, available P, exchangeable Ca, exchangeable Mg, and available Fe in soil, and also a highly significantly negative correlation with available K in soil, but no significant correlation with total K.

A highly significant positive correlation exists between any two of the nutrients, such as organic matter, total N, total P, alkali-hydrolyzable N, available P, exchangeable Ca and Mg, and available Fe in soil. The correlation coefficient was 0.7 or higher between organic matter and total N, alkali-hydrolyzable N, available N, available K and available Fe, larger than the correlation coefficient of organic matter with total P and exchangeable Ca and Mg. Total K has a highly significant negative correlation with organic matter, total N, alkali-hydrolyzable N, available P, and available Fe, but a significant positive correlation with total P, available K, and exchangeable Ca.

Table 4. The correlation analysis of soil nutrition and stand factors.

	pH	Organic Matter	Total N	Total P	Total K	Alkali-hydrolyzable N	Available P	Available K	Exchangeable Ca	Exchangeable Mg	Available Fe
pH	1										
Organic matter	−0.356 **	1									
Total N	−0.315 **	0.96 **	1								
Total P	−0.266 **	0.403 **	0.423 **	1							
Total K	0.349 **	−0.171 **	−0.125 **	0.148 **	1						
Alkali-hydrolyzable N	0.308 **	0.935 **	0.913 **	0.375 **	0.118 **	1					
Available P	0.211 **	0.86 **	0.839 **	0.291 **	0.183 **	0.823 **	1				
Available K	0.088	0.726 **	0.735 **	0.439 **	0.151 **	0.768 **	0.66 **	1			
Exchangeable Ca	0.196 **	0.396 **	0.378 **	0.289 **	0.108 *	0.484 **	0.316 **	0.528 **	1		
Exchangeable Mg	0.131 **	0.593 **	0.589 **	0.195 **	0.028	0.616 **	0.564 **	0.591 **	0.697 **	1	
Available Fe	0.378 **	0.916 **	0.879 **	0.36 **	0.155 **	0.899 **	0.829 **	0.7 **	0.45 **	0.572 **	1
Bulk density	0.213 **	0.726 **	0.714 **	0.434 **	0.084	0.69 **	0.699 **	0.565 **	0.323 **	0.456 **	0.715 **

Note: * and ** in the table stand for 0.05 and 0.01 significance level, respectively.

4. Discussion

Soil nutrients are important for the establishment of profitable timber plantation stands. Unfortunately, most tropical soils have low levels of nutrient reserves and low nutrient retention ability for some elements such as C, N, and P [48]. The southern subtropical region is one of the main timber production districts for Chinese fir. Good cultivation measures are needed to best maintain soil fertility while ensuring high yield.

The findings showed that soil bulk density in the 0–10 cm soil layer were influenced by stand planting density. The increase in soil bulk density, found in D and E stands in comparison with A, B and C stands (with the relatively low planting density), clearly suggest the direct effect of planting density on soil compaction. Some studies have found the silvicultural treatment and its disturbance strength could increase soil compaction [49,50]. The overall consequences of soil compaction, is a decrease of soil permeability, growth and nutrient supply of root systems.

The site soil of sandy texture is formed from granite, which is classified as red soil in Chinese soil classification. It is highly acidic at a soil pH of 3.5–4.0 (Table 2), which is lower than the most suitable soil pH for Chinese fir stands of 4.5–6.5 [44]. The pH increases with the increase in stand density and soil depth. This might be because the litter decomposes rapidly to produce plenty of acidic matter, gathering in the top soil at relatively low density with more suitable sunlight and temperature conditions [51].

Soil organic matter is the repository providing nutrients for the growth and development of plants. Its content is closely related to the soil fertility level and is one of important indices used to evaluate soil nutrients. The organic matter content is higher in A and B stands than the other stands in the topsoil. This increase in soil organic matter in the low-density stands can be linked to the fact that the organic matter content in forest soil mainly depends on and originated from aboveground litter and the biomass of the vegetation in the forest [36,44,46]. Based on our survey of understory vegetation in sample sites, abundant herbal and bush plants live in the low-density A and B stands, with an understory vegetation biomass of 9.76–13.56 $t \cdot hm^{-2}$ and good light-admission (Table 1). In a low-density environment, animal, microorganism, and enzyme activities in soil increase, and litter decomposes rapidly, which can significantly improve soil fertility, especially in surface soil [23].

The total N in soil is mostly sourced from organic matter, and it has the same changing trend as organic matter: they decrease with the increase in planting density. Alkali-hydrolyzable N, total P, and available P contents decrease with the increase in stand density in the 0–10 cm soil layer, which may be related to the kind and coverage of understory vegetation [44]. Studies on Chinese fir and Masson pine had showed that the amounts of these nutrients in low-density stands are greater than in middle- and high-density stands [52,53]. At a lower tree density, the concentrations of nitrate, sulphur, nitrogen and general carbon ions in the soil were found to be higher [54]. The P deficiency in acidic soil becomes a main factor restricting the growth of Chinese fir stands [44]. In this sense, low-density afforestation is important for phosphorus maintenance and phosphorus availability [40,48]. Both total K and available K contents change irregularly with the increase in stand density. The maximum value of the total K content was found in the E stand, whereas the maximum value of available K content was observed in the D stand. The total N, alkali-hydolyzable N, available P, and available K contents in soil decreased significantly with the increase in soil depth. However, the soil total K content changed differently, increasing with the increase in soil depth, which may be related to the soil parent rock. Our results are similar to the results of research on the soil layer effect of soil nutrients in artificial *Eucalyptus grandis* W. Hill ex Maiden forest of different ages [55]. The total P content remained unchanged in different soil depths because of the minimal phosphorus mobility after leaching down the soil profile [56].

Compared with the macro elements, information about the effects of forest management measures on Ca, Mg, and Fe is lacking [54]. Exchangeable Ca and available Fe in soil reached the highest level in the A stand density. The content of Ca, Mg, and Fe displayed an obvious decreasing trend with the increase in soil depth. As the nutrient elements after decomposition gather along the soil surface, the nutrient content in the 0–10 cm soil layer is significantly higher than in the other soil layers.

The planting density was confirmed to have a significant impact on the chemical composition, especially in the top soil layer. At a lower planting density, the concentrations of organic matter, total N, alkali-hydrolyzable N, total P, and available Fe in the soil were higher, and, by contrast, the pH value and bulk density were lower. A similar result was reported when studying the relationship between planting density and selected elements of the chemical composition of the top soil layer in a 30-year-old Scots pine stand [54]. The proper reduction of stand density by intermediate cuttings could maintain soil fertility [57] and improve the growing environment of the stands [58]. Too high a stand density might lead to decreased understory growth as well as a significant decrease in soil organic matter, total N, total P, hydrolyzable N, and available P [10,59]. Compared with the results from another planting density test forest of Chinese fir in Shaowu county [39], the contents of soil organic matter, total N, available N, available P, available K, and pH in this study (Pingxiang county) were all lower than corresponding indices in Shaowu county (Figure 12), which is consistent with the fact that the timber productivity of Chinese fir stands in Pingxiang county in the southern subtropical zone is lower than in Shaowu county in the mid-subtropical zone [60]. The positive correlation of pH, bulk density, and available K with planting densities of Chinese fir plantations in Pingxiang county is consistent with that in Shaowu county. Contrary to the positive correlation in Shaowu county, the relativities between available N, available P, available K, and planting densities are negative in Pingxiang county, which may be caused by the climate difference, and shows that the effects of planting density on soil nutrients are different under different climate conditions.

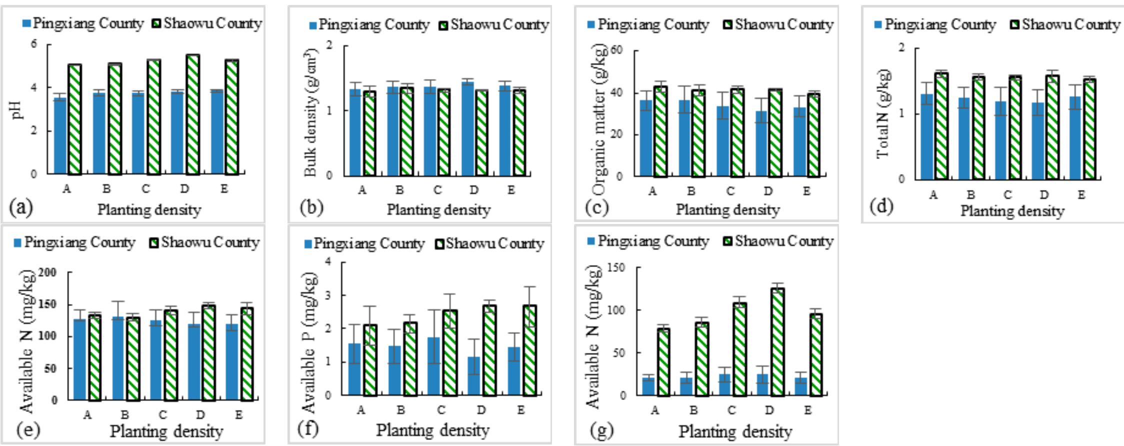

Figure 12. The comparison of (**a**) soil pH, (**b**) bulk density, (**c**) organic matter, (**d**) total N, (**e**) available N, (**f**) available P, (**g**) available K in the 0–20 cm soil layer between two sites (Pingxiang county and Shaowu county) under five different stand densities.

5. Conclusions

Planting density has a significant impact on the soil chemical composition, especially in the top soil layer. Chinese fir stands with a lower planting density have higher concentrations of organic matter, total N, alkali-hydrolyzable N, total P, and available Fe, and lower pH and bulk density after 36 years of natural growth. An excessively high planting density is not beneficial for the long-term maintenance of soil fertility in Chinese fir plantations. The planting density of Chinese fir plantations should be controlled below 3333 stems·ha^{-1} (A or B density) to maintain soil fertility while ensuring high-yield and high-quality stands, and a long rotation period must be considered to promote nutrient return. Because the contents of organic matter, total N, alkali-hydrolyzable N, total P, available P, available K, exchangeable Ca and Mg, and available Fe decrease significantly with the increase in soil depth in the 0–30 cm soil layer, a soil layer at least 40 cm thick should be studied to determine exactly the variation in soil nutrients along the soil profile in southern subtropical Chinese fir plantations. Our results suggest that the lower planting density in southern China will be beneficial to the improvement of soil physical property and minimize soil nutrients losses, which should help sustain the long-term productivity of forests in this region.

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