COMPARISON OF CALCIUM ACCUMULATION, DISTRIBUTION, AND USE EFFICIENCY AMONG CHINESE FIR (*CUNNINGHAMIA LANCEOLATA* (Lamb.) Hook) CLONES

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Abstract. Screening Chinese fir (*Cunninghamia lanceolata)* clones with efficient calcium utilization is an effective strategy to maintain soil fertility and improve their productivity and adaptability to nutrient stress habitats. The calcium content of 17-year-old Chinese fir progenies was measured, and calcium accumulation, distribution, and utilization efficiency were compared to select clones that had high calcium utilization efficiency (CaUE). Significant differences in calcium content and accumulation were observed in different vegetative organs and clones. The highest average calcium content and accumulation were in needles, and the lowest averages were in stems and dead branches. Clone M43 had the highest total calcium accumulation, whereas clone M37 had the lowest. Among the tested clones, the CaUE of the whole tree for M23, M37, and M25 was significantly high, whereas that for M43 was the lowest. The CaUE of stems was the highest in M23 and lowest in M17. Thus, calcium content and accumulation in the vegetative organs are important factors affecting the CaUE of whole trees and stems of different Chinese fir clones. Considering the comprehensive CaUE and bioaccumulation in whole trees and stems, M23, M25, and M10 were clones with high CaUE that should be used in future studies on high-yield plantations.
Keywords: *Chinese fir, plantation, productivity, nutrient stress adaptation, nutrient accumulation, utilization efficiency*

Abbreviations: NUE, nutrient utilization efficiency; CaUE, calcium utilization efficiency

Introduction

Calcium is an important nutrient essential for plant growth and development. It participates in cell growth, the formation of cell walls, plasma membranes and wood, as well as in the regulation of physiological processes in plants. Calcium ions have evolved over countless mega-anna and formed a relatively rigorous and complex signal regulation mechanism (Hepler, 2005; Lautner et al., 2007; Kudla et al., 2010). The amount of calcium in the soil depends on many factors, such as the parent material, degree of weathering, leaching intensity, and application of lime. Generally, the calcium content in the soil can meet the regular growth needs of plants; however, plants show calcium deficiency owing to the influence of environmental factors, such as high soil acidity or alkalinity, and other causal factors (White and Broadley, 2003; Guo et al., 2022). For example, soil calcium content is low in red soil areas of subtropical regions because of strong soil weathering and leaching. Damp and rainy conditions can easily cause leaching

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and reduce calcium content and oxygen concentrations in the soil, which affects the absorption of calcium and causes calcium deficiency in plants (Huang, 2004). Therefore, these factors gradually restrict the growth of crops and forest trees. Research has shown that improving the nutrient utilization efficiency (NUE), which enables the production of new biomass with minimum nutrient uptake, is a major strategy for adapting to poor environments. Although some scholars in China and abroad have attached great importance to the study of plant NUE, most research has focused on carbon, nitrogen, phosphorus, potassium, and other nutrient elements. Most studies on efficient calcium utilization by plants focus on crops, and only a few have been conducted on forests.

Nutrient utilization is an important factor when studying forest ecosystem productivity and nutrient cycles. Studies have shown that nutrients play an important role in forest productivity as forest nutrients are mainly used in material production (Wu and Ma, 2009). During the growth process, plants are often in a nutrient-stressed environment for various reasons. In the long-term evolution process, they gradually adapt to the varying nutrient resources in their habitats, forming a selectivity to different nutrient levels and nutrient forms. This selectivity is mainly reflected in a series of physiological adaptations, such as nutrient absorption, assimilation, and photosynthesis, as well as the requirements for nutrient content, morphological adaptation, and productivity accumulation. These different adaptation mechanisms are not only observed among different plant species but also among different strains of the same plant. Studies have shown that different plants or different strains of the same plant have significant differences in the absorption and utilization efficiency of soil nutrients (Nourgholipour et al., 2018). Forest site conditions, especially the supply level of soil nutrient elements, are crucial for a genetic response or adaptation mechanism to nutrient deficiency in plants. Therefore, screening forest genotypes with high NUE is an important way to improve forest productivity and the theory and methods of forest nutritional genetics.

The Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) is an important tree species in subtropical regions that is fast-growing, has a high yield per unit area, and has good material quality. For a long time, many researchers have been committed to investigating the selection and breeding of Chinese fir and have screened out many excellent genotypes that have greatly improved the productivity of Chinese fir plantations. In recent years, based on the characteristics of fast growth, fertilizer tolerance, and drought resistance of Chinese fir clones, high-yield varieties that do not require copious amounts of fertilizer and have adapted to different site conditions with high water and NUE have been studied. For example, it is important to screen clones with high utilization of nutrients, such as nitrogen and phosphorus in Chinese fir (Ma et al., 2002; Wu et al., 2011; Zou et al., 2018), and cultivate excellent seed sources of different aluminum-resistant and drought-resistant types of Chinese fir (Li et al., 2020; Xu et al., 2020). Furthermore, reducing the growth pressure of fast-growing tree species is important to forest fertility and alleviating the decline in productivity due to the continuous planting of Chinese fir plantations. Previous studies have shown the importance of screening genotypes with high calcium utilization to enhance plant resistance and improve plant fruit quality. Xing et al. (2020) reported that the accumulation rate of calcium in plant tissues increased concurrently with the calcium supply level. An appropriate amount of calcium can promote the absorption and utilization of nitrogen by improving plant photosynthesis, nitrogen metabolism, and enzyme activity. Nourgholipour et al. (2018) reported there are differences in the absorption of phosphorus and calcium among different varieties of spring oilseed rape under low phosphorus conditions. High calcium absorption can increase the

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bioavailability of calcium-bound phosphate in the soil and promote the absorption and utilization of phosphorus in spring rape seeds. Hippler et al. (2018) identified that a reasonable calcium supply could maintain photosynthesis by directly enhancing the antioxidant system and protecting related antioxidant enzyme activities to minimize the stress damage of copper to plant roots and needles. Calcium application can also promote the nutritional growth and reproductive growth of peanuts, significantly increasing peanut yield and promoting the absorption, utilization, and accumulation of phosphorus in peanut plants (Suo et al., 2021). However, most of these studies focused on crops such as fruits and vegetables, and only a few studies on genotypes of high calcium utilization in trees. Current research shows that because of factors such as acid rain, a large amount of soil calcium is lost, and an appropriate amount of lime or other calcium fertilizer applied to the forest land in acidic soils can alleviate the decline in productivity of *Eucalyptus*, *Pinus*, and other plantations by increasing the effectiveness of calcium (Rochaa et al., 2019). However, adding an appropriate amount of calcium in barren soil can promote the growth of Chinese fir (Rashid et al., 2020) and cypress (Zhang et al., 2020) seedlings, which provides a scientific basis for screening clones with high calcium utilization in forest trees. Therefore, it is very important to screen Chinese fir clones with high calcium acquisition and utilization efficiency. It is not only an effective way to maintain the productivity of Chinese fir plantations in subtropical red soil forest areas and improve their productivity, but also an important strategy to enhance the adaptation of Chinese fir to nutrient stress habitats.

Therefore, based on previous research, we aimed to screen Chinese fir clones with high calcium utilization efficiency (CaUE) from 15 Chinese fir clones (17-year-old) by investigating the calcium nutrient concentration in various organs, the calcium accumulation levels in different Chinese fir stands, and the CaUE of whole trees and stems of different Chinese fir clones, to elucidate the efficiency of Chinese fir to soil calcium and provide a reference for the sustainable management practice of Chinese fir plantations.

Materials and methods

Study site

The study site was located in the Wuyi state-owned forest farm of Zhangping, Fujian Province (117°35'E, 25°15'N), China, which belongs to the general production area of Chinese fir. The annual average temperature is 20.3 °C, the average temperature in the coldest month (January) is 9.7 °C, the average temperature in July is 28.1 °C, the frost-free period is 300 days, the accumulated temperature ≥10 °C is 4956.5 °C, the annual sunshine hours are over 1878 h, and the annual average precipitation is 1508.8 mm (Hu, 2008). In 1991, an experiment on Chinese fir clone determination and afforestation was conducted in the Shibankeng work area of this study site (Wuyi state-owned forest farm). The terrain of the Shibankeng work area is concave, with a southwest slope direction and an altitude of 300 m. The soil is categorized as deep and fertile mountain red soil. The site type belongs to class II, and the previous stubble was pine and miscellaneous forest cuttings.

We used excellent Chinese fir clones screened by the Fujian Chinese Fir Research Center and Fujian Chinese Fir Progeny Determination Cooperation Group for this study. Spike strips were collected from September to October and were cut in the nursery. Intensive management was conducted from January to March of the following year for

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transplanting. Watering was conducted in the afternoon, once per day for the first 30 days, once per two days after 30 days, and weeding was performed once per month. In the spring of the third year, strong symmetrical seedlings with well-developed roots and a uniform size were selected for afforestation. A randomized block design was adopted for afforestation: two block groups with four Chinese fir trees in each group and six replicates, arranged longitudinally along the mountain in two columns. During afforestation, a random arrangement within and between groups was achieved.

The afforestation of forest land involved grass cutting, mountain refining, and strip land preparation. The belt spacing was 2.0 m, the plant spacing was 1.5 m, an open hole (60 cm × 40 cm × 30 cm) was excavated. Comprehensive weeding and tending were performed 1–2 times a year in the first 3 years after afforestation. One to two rows of *Michelia macclurei* were planted around the trees for protection. In this study, 15 clones (M1, M3, M8, M9, M10, M17, M19, M23, M24, M25, M34, M37, M41, M43, and M45) were selected for analysis. The tested Chinese fir clones were 17 years old, and the growth conditions and treatment methods of the experimental forest were consistent.

Investigation method

The characteristics of the 17-year-old progeny of different Chinese fir clones (15 clones) were measured using a wood gauge. Tree height, average diameter at breast height (DBH), and average tree height of different clones were calculated (*Table 1*). Based on the average wood height and DBH of all trees at the sample site, one standard tree was selected from each sample site and dug out from the roots. The fresh mass of stems, barks, branches, and needles in each section was determined by dividing the stem into 2 m segments. The fresh weight of the root was also determined. All samples were taken back to the laboratory, where they were dried and measured for dry matter weight. After the plant samples were dried, crushed, and sieved, the calcium content of different organs was determined using atomic absorption spectrophotometry (Thermo Scientific iCE 3000), and the calcium accumulation and CaUE of whole trees and stems were calculated using equations 1, 2, and 3, with three replications:

$$\text{Calcium accumulation} = \text{Total dry biomass in different organs of Chinese fir} \times \text{Calcium content in different organs} \quad \text{(Eq.1)}$$

$$\text{CaUE of the whole tree} = \frac{\text{Total dry biomass of the whole tree}}{\text{Calcium accumulation of the whole tree}} \quad \text{(Eq.2)}$$

$$\text{CaUE of stem} = \frac{\text{Total dry biomass of stem}}{\text{Calcium accumulation of the whole tree}} \quad \text{(Eq.3)}$$

Statistical analyses

All measurements are reported as mean ± standard deviation. Microsoft Excel 2016 was used to calculate the data, and IBM SPSS Statistics 19 software was used to analyze the data. At a significance level of 5%, the Tukey test was used to compare the average values of variables showing significant differences, and Origin 2021b (OriginLab) was used for Pearson correlation analysis and mapping.

Table 1. *Comparison of growth among different testing clones of 17-year-old Chinese fir plantations (Tao et al. 2021)*

Clone	diameter at breast height (DBH)/cm	Height/m
M1	22.13 ± 2.84	16.13 ± 1.35
M3	23.99 ± 2.29	16.06 ± 0.56
M8	22.46 ± 3.42	16.47 ± 1.15
M9	19.70 ± 4.78	14.64 ± 3.16
M10	20.58 ± 4.53	15.70 ± 1.80
M17	24.37 ± 2.55	17.15 ± 1.35
M19	21.79 ± 4.24	16.02 ± 1.99
M23	21.40 ± 3.16	16.06 ± 1.67
M24	22.06 ± 2.95	16.00 ± 1.42
M25	19.47 ± 3.42	16.14 ± 1.28
M34	22.32 ± 4.50	15.64 ± 2.93
M37	21.47 ± 3.14	15.31 ± 2.31
M41	20.07 ± 5.39	15.19 ± 3.69
M43	24.17 ± 2.37	17.76 ± 1.36
M45	23.60 ± 2.58	15.58 ± 0.43

Results

Calcium content in vegetative organs of different Chinese fir clones

The calcium content in different vegetative organs of different Chinese fir clones varied greatly. Among the 15 tested clones, the average calcium content in needles was the highest and differed significantly from in the other organs ($P < 0.05$); The average calcium content of bark was the second, but was only 38.98% of that of needles; The average calcium content of living branches and barks was similar, and the difference was only 0.03 g kg^{-1}; The average calcium content of the roots and stems was low, with only 0.04 and 0.01 g kg^{-1}. The calcium content of the stem and root organs of the multiple clones was zero. Among all tested clones, M17 had the highest calcium content, which differed significantly from the other clones ($P < 0.05$), followed by M43, M41, and M24, but there was no significant difference ($P > 0.05$). M23 had the lowest calcium content, which was only 33.90% of the average value. The calcium content of living branches M43, M19, M10, and M41 was higher, and the difference was not significant ($P > 0.05$); The calcium content of M1 living branches was the lowest, with only 9.52% of its average value (*Table 2*).

Calcium accumulation in different Chinese fir clones

Calcium accumulation in different vegetative organs of Chinese fir clones also varied greatly. The average calcium accumulation in the needles was the highest, which differed significantly from that in the other organs ($P < 0.05$). The average calcium accumulation in the cortex was 46.01% of that in the needles; the average calcium accumulation of living branches, stems, roots, and dead branches decreased successively, with dead branches showing the lowest, at only 7.06% of that in the needles. The average calcium

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accumulation in the roots and stems was 11.16% and 12.83%, respectively, and many clones showed no calcium accumulation in the stem and roots. The calcium accumulation pattern of the needles, living branches, and bark of vegetative organs were similar in all clones, with high calcium accumulation in M17, M41, and M43 and the lowest in M45, M1, and M23. Calcium accumulation in the 15 tested clones was significantly different among the different Chinese fir clones. Clone M43 had the highest calcium accumulation in the whole plant, which differed significantly from that in the other clones ($P < 0.05$) and was 1.95 times the average of all tested clones. The calcium accumulation of M17 and M41 was 5.98% and 17.45% lower than M43, respectively. M37 had the lowest calcium accumulation in the whole plant, with only 24.76% of that of M43 (*Table 3*).

Table 2. *Comparison of calcium content among different organs in different Chinese fir clones (g kg^{-1})*

Clone	Needle	Living branch	Dead branch	Bark	Stem	Root
M1	1.44 ±0.02Abcd	0.04 ± 0.06CDc	0.41 ± 0.10Bab	0.29 ± 0.05BCcde	0.00 ± 0.00Da	0.09 ± 0.11CDab
M3	1.13 ±0.01Acde	0.39 ± 0.07Bbc	0.13 ± 0.02CDc	0.24 ± 0.21BCde	0.00 ± 0.00Da	0.00 ± 0.00Db
M8	0.99±0.01Acdef	0.54 ± 0.03Bab	0.21 ± 0.01CDbc	0.34 ± 0.15Cbcde	0.01 ± 0.01Ea	0.03 ± 0.04DEab
M9	1.17 ±0.39Acde	0.52 ± 0.06BCabc	0.19 ± 0.01CDbc	0.83 ± 0.04Aba	0.00 ± 0.00Da	0.04 ± 0.06Dab
M10	1.43 ±0.21Abcd	0.61 ± 0.15Bab	0.25 ± 0.12CDbc	0.42 ±0.09BCabcde	0.02 ± 0.02Da	0.06 ± 0.06Dab
M17	2.21 ± 0.18Aa	0.48 ± 0.09Babc	0.60 ± 0.14Ba	0.56 ± 0.18Babcd	0.00 ± 0.00Da	0.03 ± 0.03Dab
M19	0.86 ±0.04Adef	0.61 ± 0.14Bab	0.20 ± 0.02Dbc	0.41 ± 0.04Cabcde	0.05 ± 0.05Da	0.02 ± 0.04Dab
M23	0.40 ± 0.01Af	0.16 ± 0.09Bbc	0.20 ± 0.04Bbc	0.06 ± 0.05Be	0.05 ± 0.06Ba	0.03 ± 0.05Bab
M24	1.54 ± 0.04Abc	0.29 ± 0.05Cbc	0.32 ± 0.01Cbc	0.58 ± 0.12Babcd	0.02 ± 0.03Da	0.00 ± 0.00Db
M25	0.77 ± 0.18Aef	0.24 ± 0.09Cbc	0.29 ± 0.01BCbc	0.46 ± 0.05Babcde	0.00 ± 0.00Da	0.00 ± 0.00Db
M34	0.87 ±0.06Adef	0.32 ± 0.02Bbc	0.40 ± 0.06Babc	0.41 ± 0.20Babcde	0.06 ± 0.01Da	0.01 ± 0.02Db
M37	0.62 ± 0.20Aef	0.37 ± 0.16ABbc	0.30 ± 0.03Bbc	0.20 ± 0.04BCde	0.00 ± 0.00Ca	0.00 ± 0.00Cb
M41	1.57 ± 0.04Abc	0.60 ± 0.06Bab	0.28 ± 0.07BCbc	0.60 ± 0.12Babcd	0.00 ± 0.00Ca	0.13 ± 0.12Cab
M43	1.96 ± 0.17Aab	0.86 ± 0.08Ba	0.29 ± 0.11CDbc	0.72 ± 0.11BCabc	0.00 ± 0.00Da	0.17 ± 0.18Da
M45	0.78 ± 0.12Aef	0.24 ± 0.30Bbc	0.29 ± 0.01Bbc	0.77 ± 0.01Aab	0.00 ± 0.00Ba	0.06 ± 0.09Bab
Means	1.18 ± 0.51	0.42 ± 0.23	0.29 ± 0.12	0.46 ± 0.23	0.01 ± 0.03	0.04 ± 0.08

Different lowercase letters in the same column indicate significant differences between different clones ($P < 0.05$); different uppercase letters in the same row indicate significant differences between different organs ($P < 0.05$)

CaUE of different Chinese fir clones

The calcium utilization efficiency of whole tree and stem varied greatly among different Chinese fir clones, with an average of 7011.95 and 4140.60 g g^{-1}, respectively. The utilization efficiency of the whole tree and stem of M23, M37, and M25 were 1.79, 1.66, and 1.39 times and 1.86, 1.57, and 1.38 times their average values, respectively, which were significantly higher than the other tested clones ($P < 0.05$). The CaUE of the whole tree and stem of clone M43 was 51.79% and 52.33% of their average values, respectively, which were the lowest among the tested clones, and significantly different from that of the other clones ($P < 0.05$) (*Fig. 1*).

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Table 3. *Comparison of calcium accumulation among different organs in different Chinese fir clones (g per plant)*

Clone	Needle	Living branch	Dead branch	Bark	Stem	Root	Whole tree
M1	13.11 ± 0.33Aef	0.47 ± 0.02Eg	1.15 ± 0.03Dbc	4.31 ± 0.04Bi	0.00 ± 0.00Fg	2.17 ± 0.09Cc	21.21 ± 0.44de
M3	16.76 ± 0.90Ad	5.82 ± 0.32Bd	0.32 ± 0.01Dj	2.19 ± 0.08Cj	0.00 ± 0.00Dg	0.00 ± 0.00Dg	25.10 ± 1.30d
M8	14.52 ± 0.44Ae	8.34 ± 0.33Bc	0.72 ± 0.02Dfg	4.73 ± 0.12Ci	0.88 ± 0.02Df	1.18 ± 0.08De	30.36 ± 0.96c
M9	8.55 ± 0.45Ai	4.82 ± 0.04Be	0.45 ± 0.02CDi	8.41 ± 0.43Ac	0.00 ± 0.00Dg	1.06 ± 0.09Cef	23.29 ± 1.03d
M10	8.99 ± 0.12Ahi	4.20 ± 0.15Ce	0.68 ± 0.02Fg	4.94 ± 0.10Bhi	2.23 ± 0.04Dd	1.78 ± 0.07Ed	22.81 ± 0.48d
M17	31.17 ± 2.07Aa	9.64 ± 0.47Bb	2.45 ± 0.06Ca	9.23 ± 0.30Bb	0.00 ± 0.00Dg	1.00 ± 0.07CDef	53.50 ± 2.96a
M19	11.64 ± 0.52Afg	8.38 ± 0.11Bc	0.65 ± 0.02Dg	5.57 ± 0.18Cgh	6.08 ± 0.10Cc	0.75 ± 0.01Df	33.07 ± 0.49c
M23	5.61 ± 0.10Bj	2.49 ± 0.08Cf	0.78 ± 0.01Df	0.75 ± 0.02Dk	6.70 ± 0.58Ab	1.21 ± 0.07De	17.54 ± 0.86ef
M24	11.83 ± 0.58Afg	2.87 ± 0.14Cf	0.93 ± 0.05De	7.69 ± 0.51Bcd	1.61 ± 0.02De	0.00 ± 0.00Eg	24.93 ± 1.29d
M25	7.83 ± 0.23Ai	3.10 ± 0.11Cf	1.19 ± 0.05Db	6.14 ± 0.16Bfg	0.11 ± 0.00Eg	0.00 ± 0.00Eg	18.38 ± 0.54e
M34	10.68 ± 0.12Agh	4.56 ± 0.17De	1.11 ± 0.02Ebcd	6.78 ± 0.23Cef	7.68 ± 0.37Ba	0.20 ± 0.02Fg	31.00 ± 0.92c
M37	5.42 ± 0.09Aj	5.03 ± 0.09Bde	1.04 ± 0.03Dd	2.59 ± 0.09Cj	0.00 ± 0.00Eg	0.00 ±.00Eg	14.09 ± 0.30f
M41	21.23 ± 0.82Ac	10.01 ± 0.76Bb	0.54 ± 0.01Dh	10.38 ± 0.44Ba	0.00 ± 0.00Dg	4.80 ± 0.20Cb	46.97 ± 2.21b
M43	24.87 ± 0.63Ab	15.20 ± 0.49Ba	0.88 ± 0.03Ee	9.68 ± 0.31Cab	0.00 ± 0.00Eg	6.27 ± 0.42Da	56.90 ± 1.87a
M45	5.36 ± 0.38Bj	2.20 ± 0.07Cf	1.09 ± 0.03Dcd	7.42 ± 0.31Ade	0.00 ± 0.00Eg	1.63 ± 0.08Dd	17.70 ± 0.80ef
Means	13.17 ± 7.39	5.81 ± 3.77	0.93 ± 0.49	6.06 ± 2.80	1.69 ± 2.70	1.47 ± 1.78	29.12 ± 13.05

Different lowercase letters in the same column indicate significant differences between different clones ($P < 0.05$); different uppercase letters in the same row indicate significant differences between different organs ($P < 0.05$)

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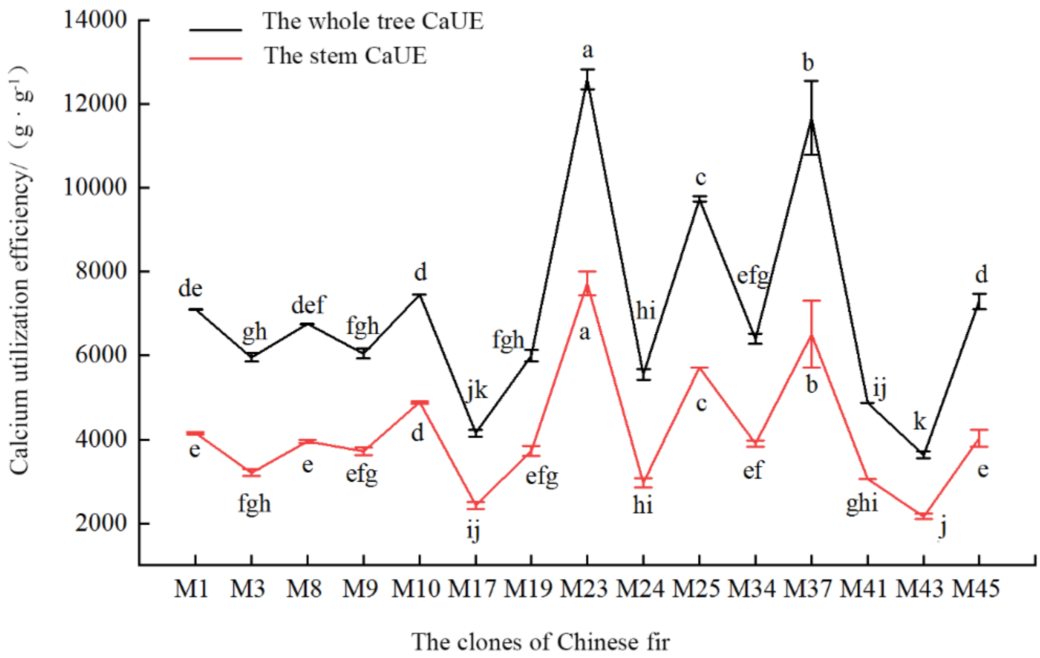

Figure 1. *Comparison of calcium use efficiency among different clonal test plantations of Chinese fir. Different lowercase letters indicate significant differences between different clones (P < 0.05)*

Correlation between calcium accumulation and CaUE among different Chinese fir clones

The CaUE of different Chinese fir clones showed different correlations with calcium content (*Fig. 2*) and calcium accumulation (*Fig. 3*) in different vegetative organs. In the $P = 0.05$ level test, there was a significant positive correlation between CaUE of whole tree and stem. There was a significant negative correlation between CaUE and calcium content and calcium accumulation in needles, living branches, and barks of vegetative organs. The CaUE of the stem was significantly negatively correlated with the calcium content of needles and barks and the calcium accumulation of needles, living branches, and bark. The CaUE of the whole tree and stem was positively correlated with the calcium content and calcium accumulation of stems and negatively correlated with the calcium content of needles, living branches, dead branches, barks, and roots. The CaUE of whole tree and stem was positively correlated with the calcium content and calcium accumulation in the stem and negatively correlated with the calcium content of needles, living branches, dead branches, barks, and roots. Except for the significant positive correlation between the calcium content of needles and dead branches, the correlation between the calcium content of different vegetative organs did not reach a significant level (*Fig. 2*). In contrast, there was a significant positive correlation between the calcium accumulation of needles and living branches and barks, and between roots and living branches and barks. In addition, the correlation between calcium accumulation in other vegetative organs did not reach a significant level (*Fig. 3*).

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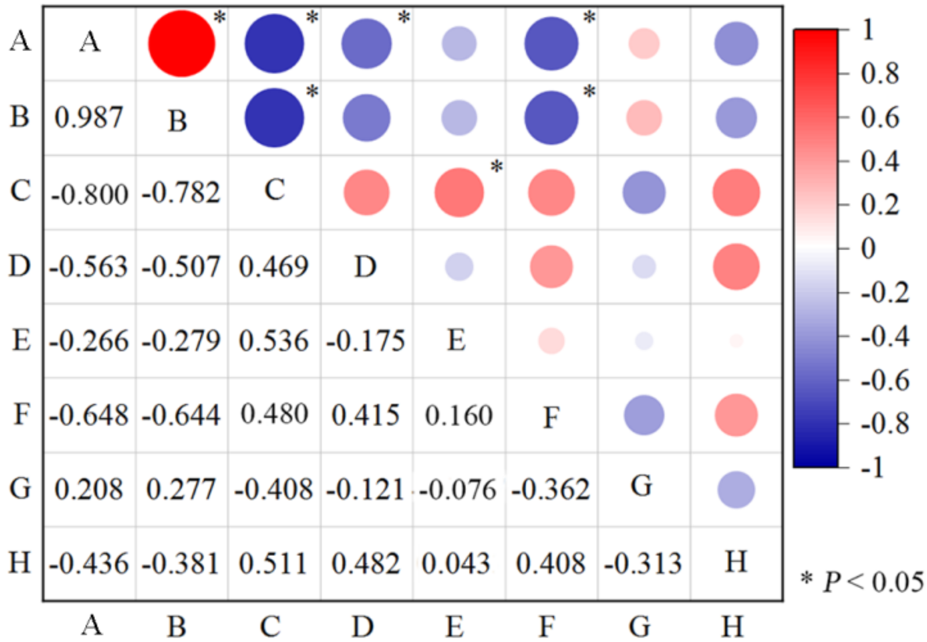

Figure 2. *Correlation between CaUE and calcium content in different organs. A: The whole tree CaUE; B: The stem CaUE; C, D, E, F, G, and H are Ca contents of needles, living branches, dead branches, barks, stems and roots, respectively*

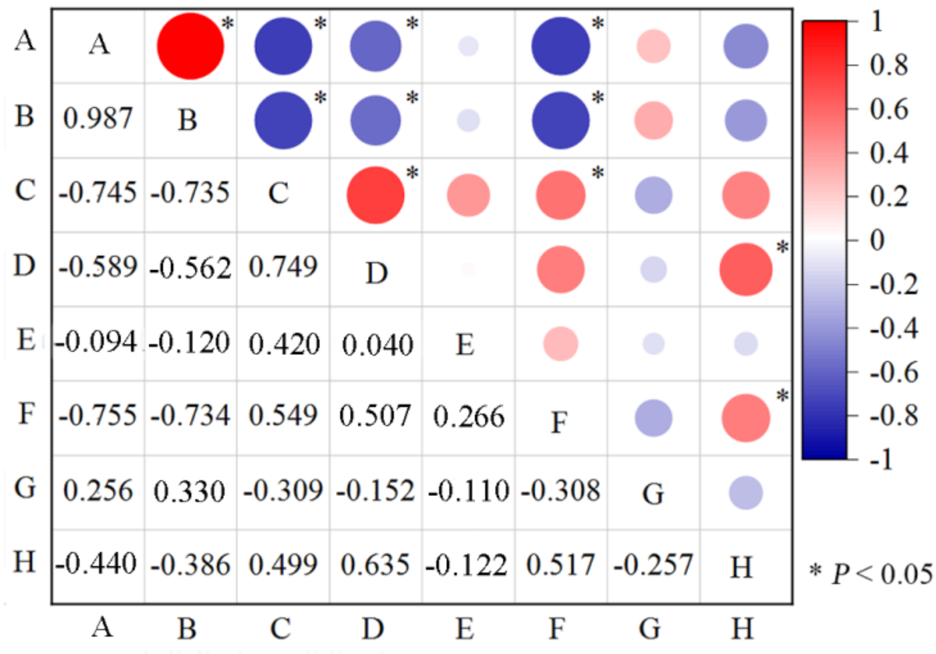

Figure 3. *Correlation between CaUE and calcium accumulation in different organs. A: The whole tree CaUE; B: The stem CaUE; C, D, E, F, G, and H are Ca accumulation in needles, living branches, dead branches, barks, stems and roots, respectively*

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Discussion

The nutrient element content in plants reflects the ability of plants to absorb and accumulate mineral nutrients from soil under certain habitat conditions. Because of the different components of organic matter in different organs, their physiological functions are different. Furthermore, the functions of different nutrient elements in plants are also different, resulting in differential distributions of nutrient elements in the same organ and the same nutrient element in different organs. For example, the content of nutrient elements in living tissues is higher than that in aging tissues, usually in needles, branchlets, and other organs, which have the highest nutrient input, whereas only low nutrient content is found in dry organs, which indicates an effective utilization of nutrients by plants (Zhao et al., 2016; Zhang et al., 2018). According to our results, the calcium content in the needles of the tested Chinese fir clones was the highest, and the stems calcium content was the lowest. This is mainly because the needles are assimilation organs, which are important for photosynthesis and organic matter synthesis; their growth cycle is short, and their metabolic activities are the most vigorous, so their nutritional content is generally the highest. The stem mainly comprises wood, supports the plant body and has the weakest physiological function. Most nutrients contained are utilized or transferred, and thus their nutrient element content is the lowest. In addition, the function, transport, and distribution of calcium in plants are also important reasons for this phenomenon. Generally, the calcium content in the apical meristem is high because this is where vigorous plant metabolism occurs. This is also because long-distance transportation of calcium in the plant mainly depends on the xylem, and the transportation power of the xylem is in transpiration. Calcium first reaches the vigorous growth parts, such as treetops and needles, through the xylem due to transpiration. After calcium reaches these tissues and organs, it generally becomes relatively stable because there is no re transportation and distribution, there is poor mobility of calcium in the phloem, and transportation volume is small. This characteristic also indicates that more calcium is present in the aboveground organs and less in the underground roots.

Plant nutrient accumulation is an indispensable link in the material cycle of ecosystems and the basis for studying the logistics and energy flow of forest ecosystems. It is important to maintain the structure and function of forest ecosystems. The accumulation of plant nutrient elements depends on the size of the biomass and the content of nutrient elements. Zhou et al. (2019) showed that the calcium accumulation in a 16-year-old Chinese fir forest was 376.64 $kg \cdot hm^{-2}$. However, the calcium accumulation of Chinese fir clones in this study was not high (between 46.91 and 189.47 $kg \cdot hm^{-2}$), which may have been caused by many factors, such as low wood density, slow growth, and low calcium concentration in tissues (mainly roots and stems). The accumulation and distribution of biomass in different organs of Chinese fir clones were different. Wu et al. (2012) reported that the proportion of stem biomass in stand biomass was the greatest, ranging from 53.37% to 65.48%, and the average biomass value of each organ was stem > root > living branch > bark > needle > dead branch. Chen et al. (2019) identified that the characteristics of Chinese fir as a timber (stem utilization) species, indicating that its stem biomass is the main component of stand biomass. In this study, the average calcium content of roots and stems was low, and the difference between the average values was only 0.03 $g\ kg^{-1}$. Therefore, although the nutrient content of the stem was the lowest among all organs, its nutrient accumulation was higher than the roots. Zhou et al. (2019) studied nutrient accumulation and distribution characteristics in the tree layer of Chinese fir forests of different forest ages. The results showed that in the same Chinese fir forest, the contents

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of five nutrient elements (N, P, K, Ca, and Mg) in each organ were needle > branch > bark > root > stem, and the distribution law of nutrient accumulation in each organ was needle > branch > bark > stem > root, which differs slightly from the results, but the accumulation in the needles was the highest. It also shows that stand biomass and its distribution in different organs and nutrient content in Chinese fir are the main factors affecting nutrient accumulation and distribution in Chinese fir forests. Research has shown that plant tissues or organs maintain the relative balance of nutrient absorption and transfer during growth (Guyonnet et al., 2018). Therefore, the growth of Chinese fir and its nutrient demand at different growth stages also affect nutrient accumulation and distribution.

Under specific nutrient supply conditions, nutrient efficiency can be divided into nutrient absorption efficiency and NUE. The factors affecting plant NUE include soil nutrient content and effectiveness (such as soil quality and nutrient management) and differences in plant strains. Efficient nutrient absorption and utilization are two important characteristics of nutrient-efficient strains. Nutrient efficiency is not only related to plant root morphology and configuration, rhizosphere processes, and nutrient transmembrane transport; it is also closely related to the behavior of nutrients in plants, especially how they affect the synthesis, transport, distribution, transformation, and transport of photosynthetic substances and their storage in yield organs (Mi, 2017). Our results indicated that the CaUE of different Chinese fir clones was significantly different, and the CaUE was significantly related to the calcium content and calcium accumulation in needles, living branches, and barks organs of Chinese fir. Clones with high CaUE can carry out normal growth and metabolism with low nutrient concentrations in their bodies and produce a certain biomass. Considering the CaUE and biological accumulation of whole trees and stems of different Chinese fir clones, M23, M25, and M10 were preliminarily selected as clones with high CaUE. Plant lines with high nutrient utilization have ideal root morphology and reasonable root distribution, strong adaptive response in the rhizosphere under nutrient stress, high specific absorption rate for low concentration nutrients, strong ability for nutrient transportation and reuse in plants, and high nutrient utilization rate or low metabolic demand (Wu and Ma, 2009; Wu et al., 2011; Zou et al., 2018). In addition, Hawkesford et al. (2014) pointed out that the difference in plant genetic characteristics significantly affects the NUE, which can be improved through improved seed cultivation. The functions of different nutrients in plants vary because of the differences in physical and chemical properties between different soil nutrients and the complex interactions between them. For example, the phosphorus content in soil affects the absorption and utilization of calcium by plants (Ding et al., 2018; Suo et al., 2021). Soil nutrient conditions are also an important factor affecting the utilization efficiency of plant nutrients. Therefore, nutrient absorption and utilization efficiency reflect the relationship between nutrient processes and plant growth processes and directly reflects nutrient acquisition and utilization of different plant lines.

The purpose of studying plant nutrient efficiency is to improve the genetic characteristics of plant nutrition and improve the yield and quality of crops. Notably, the NUE in plants is a complex dynamic process involving multiple physiological processes such as transportation, distribution, utilization, and reuse of nutrients in plants, which needs to be analyzed from the whole growth period of plants. Calcium is a nutrient element not easy to move in plants, and calcium ions have formed a more rigorous and complex signal regulation mechanism after hundreds of millions of years of evolution. At present, research regarding calcium signaling has entered the molecular level, and

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calcium signal elements in some plant cells have been identified and analyzed. However, the operation mechanism of calcium signaling in plants is not very clear, and still many aspects need to be further studied. Therefore, the selected calcium-efficient Chinese fir clones should be monitored, and their nutrient efficiency during the entire growth period should be dynamically tracked. Furthermore, emerging technologies such as bioinformatics, genomics, proteomics, and metabolomics should be applied to study the physiological processes of calcium transport, distribution, utilization, and reuse in Chinese fir through pot control experiments. In addition, the calcium metabolism, transmission, perception response, and expression of stress signals, especially the response mechanism of calcium messengers in Chinese fir toward stressors, should be explored. Such extensive studies can help us utilize the potential of Chinese fir for calcium absorption and can provide a reference for maximizing the yield from Chinese fir plantations.

Conclusion

Among the vegetative organs of different Chinese fir clones, the calcium content and accumulation were the highest in the needles and the lowest in the stem and dead branches. There were significant differences in calcium content and accumulation among different Chinese fir clones, and there were also significant differences in the CaUE of whole tree and stem. There was a significant negative correlation among CaUE, calcium content, and calcium accumulation in Chinese fir needles, living branches, and barks. Clones with high CaUE can normally grow and metabolize with low nutrient concentrations in their bodies and produce a certain biomass. The calcium content and accumulation in the vegetative organs of Chinese fir are important factors affecting the CaUE of whole tree and stem among different Chinese fir clones. Considering the CaUE and biological accumulation of whole tree, M23, M25, and M10 were preliminarily selected as clones with high CaUE. It is an effective way to maintain the productivity of Chinese fir plantations in subtropical red soil forest areas to improve their productivity. Furthermore, it is an important strategy to enhance the adaptation of Chinese fir to nutrient-stressed habitats. This experiment only studied 17-year-old Chinese fir, which could not reveal the CaUE of Chinese fir forests at different growth stages and its impact on productivity. In the future, we should strengthen the research on the production, calcium utilization, and utilization efficiency of Chinese fir forests at different growth stages.

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