Effects of Different Forest Gap Ages on Soil Physical Properties and Stoichiometric Characteristics in Cryptomeria japonica plantations (L.f.) D.Don, 1839

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Abstract: In this study, the evergreen plant Cryptomeria japonica (L.f.) D.Don, 1839 forest gap in the subtropical region of China were taken as the research object. The effects of different forest gap ages (<10 years, 10–20 years, >20 years) on soil physical properties and stoichiometric characteristics were analyzed in Lushan Mountain, China. With the increase of forest gap ages, the physical properties of soil surface layer in forest gap were improved, and the water holding capacity of soil was enhanced. The capillary porosity and total porosity of soil increased significantly, and the soil bulk density of 10–20 cm soil layer decreased. The increase of forest gap recovery years is beneficial to the increase of large particle size soil aggregates, and the increase of large particle size aggregates has a good effect on improving soil structure. The contents of carbon (C), nitrogen (N), and phosphorus (P) in soil showed an overall increasing trend with the increase of forest gap age and were significantly higher than those of Cryptomeria japonica pure forest (p < 0.05). The nutrient content of forest gap in 10–20 years was the highest, and the nutrient content of 0–10 cm soil layer was generally higher than that of 0–20 cm soil layer. The C:P and N:P in the soil showed an overall decreasing trend, while C:N was significantly smaller than other age gaps in 10–20 years. The results showed that soil physical properties and stoichiometric characteristics were improved with the increase of forest gap ages.

Keywords: forest gap ages; Cryptomeria japonica; soil; physical properties; stoichiometric characteristic

1. Introduction

Forest gap mainly refers to the death of old trees in the forest community or the death of dominant tree species in the mature stage due to accidental factors (such as drought, fire, etc.), thus causing gaps in the canopy [1]. As a medium- and small-scale disturbance, forest gap affects species composition, structure, and succession direction of forest [2]. As an important driving force for forest regeneration and environmental improvement, forest gap plays an important role in dynamic succession and ecological function optimization of forest ecosystem [3]. Forest gap is an important driving force for forest natural regeneration and an important channel for regulating vegetation recombination in plantations. It plays an important role in vegetation succession and nutrient cycling in forest ecosystems [4]. On the other hand, the formation of canopy gap can affect the microenvironment under canopy, the invasion and colonization of plants, and the regeneration of understory vegetation, and then change the stand structure, which may exert a strong effect on the ecological stoichiometric characteristics of canopy gap regeneration plants [5]. Compared with closed forest, the formation of forest gap changes the water and heat dynamics and decomposer community structure in the forest, which can affect the nutrient utilization and turnover efficiency of understory vegetation (such as litter decomposition), and then deeply affect the distribution pattern of soil nutrients [6].

Water conservation is an important part of forest ecosystem service function [7], mainly through the three levels of canopy, ground cover, and soil, in which forest soil is the main...
body of water conservation [8]. Soil water holding capacity is an important indicator of water conservation in terrestrial ecosystems and plays a key role in surface processes and water cycle [9]. Soil water holding capacity is mainly affected by soil physical and chemical properties, such as soil bulk density, porosity, soil aggregate size distribution, soil structure and organic matter, etc. [10]. Among them, soil organic matter and soil water holding capacity have a strong correlation [11]. Accumulation of soil organic matter can improve water binding and water retention capacity by changing soil structure, or by changing soil porosity, thereby increasing soil water holding capacity, especially in the surface soil [12–14].

Soil is an important part of terrestrial ecosystem and the main source of nutrients for the growth and development of forest vegetation [15]. Carbon (C), nitrogen (N), and phosphorus (P) in soil are essential nutrients for the growth of forest plants, which directly affect the growth and development of plants, the activity of soil microorganisms, and the nutrient cycle of soil [16]. Their ratios are considered to be important indicators of ecosystem structure and function [17]. Soil stoichiometry is a science that studies the balance and interaction of various chemical elements (mainly C, N, and P) in the soil [18]. It is believed that the ratio of element composition (C, N, and P) in the soil is stable, and the change of any element will change this ratio, which can be used to study the nutrient cycle in the soil ecosystem and determine its nutrient limiting factor [19,20]. At present, chemometrics theory has been widely used in plant tissues, forest communities, plant response to the environment, soil nutrient cycling, and dynamic changes of microbial elements [21,22]. Soil stoichiometry is often used to reflect the relationship between nutrients in the soil and the availability of nutrients, revealing soil nutrient limitation, nutrient cycling, and balance mechanisms [23,24]. Therefore, a comprehensive study of terrestrial soil nutrient content and its stoichiometric ratio can provide a theoretical basis for soil restoration of terrestrial ecosystems [25,26].

Cryptomeria japonica (L.f.) D.Don, 1839 is an evergreen coniferous tree species of Cupressaceae [27]. It is an important part of different forest types in Lushan Mountain and one of the main afforestation tree species with high ecological and economic value [28]. At the beginning of the 20th century, Lushan Mountain in Jiangxi Province, China, was successfully introduced from Japan and subsequently planted in various parts of China [29]. Cryptomeria japonica is mainly distributed in the area above the altitude of 700 m in Lushan Mountain. It is the main afforestation tree species in the area and plays an important role in water conservation, atmospheric environment purification, forest recreation, and other ecological functions [30]. As Cryptomeria japonica tree age is generally larger, stand resistance decreased over the years often due to freezing rain and snow, whilst typhoons and other natural disasters led to tree tipping or even lodging phenomenon, and formed a forest gap. At present, the research on forest gap mainly focuses on the characteristics of forest gap and its environmental factors. The research on the spatial heterogeneity of forest gap mainly focuses on light, temperature, air relative humidity, and soil nutrients [31,32]. However, there are few studies on the physical properties and stoichiometric characteristics of soil caused by the interference gradient of forest gap formation at different ages, which limits the understanding of the mechanism of forest gap soil change to a certain extent. Ecological stoichiometric study provides an important indicator for forest soil nutrient limitation or nutrient cycling. At present, there are few reports on soil stoichiometric characteristics of forest gap. In particular, the relationship between soil physical properties and soil nutrient stoichiometric ratio of forest gaps with different ages is not clear. This study can help to understand the soil nutrient limitation of different forest gap ages. The significance of this study is to reveal the effects of different forest gap ages on soil physical and chemical properties and stoichiometric characteristics.
2. Materials and Methods

2.1. Research Area

This experiment was conducted in Lushan National Nature Reserve, Jiujiang City, Jiangxi Province, China (Figure 1) (115°52′–116°06′ E, 29°25′–29°41′ N), with an area of about 30.2 km². It belongs to a typical subtropical monsoon climate with an average annual temperature of 11.6 °C and an average annual precipitation of 2070 mm. Lushan Mountain has frost up to 150 days, and has foggy days 191 days, a year. Lushan Mountain is adjacent to the Yangtze River to the north and the Poyang Lake to the east. The complex topography and special climatic characteristics form a variety of habitats and have rich biodiversity. Among them, the plantation is dominated by coniferous forests. The most representative tree species are Cryptomeria japonica, Pinus taiwanensis, Cunninghamia lanceolata, etc. The soil types of Lushan Mountain are various, which are mountain brown soil, yellow soil, or red soil. The soil layer is barren, and the soil is rocky. Lushan Mountain’s highest altitude is 1446 m, with a unique geographical location and climatic conditions. Early-November to March is the snowfall period. Cryptomeria japonica often suffered snow and ice damage. When damaged after interference, Cryptomeria japonica forest progresses into a natural regeneration recovery.

![Figure 1. Location of the study site.](image_url)

2.2. Experimental Design

According to the previous survey results, through field investigation, three types of forest gaps of different ages were selected: <10 years, 10–20 years, and >20 years. Three plots were selected as replicates for each gap type, and Cryptomeria japonica pure forest with the same stand age and similar site conditions outside the gap was selected as the control (CK). According to the diagonal line of the plot, three points (upper slope, middle slope, and lower slope) were selected and divided into 0–10 cm and 10–20 cm depths to collect soil. The collected soil samples are divided into two parts: one part is to collect undisturbed soil by ring knife method to determine soil physical properties; the other part collected scattered soil and measured the soil particle size distribution and soil nutrients after drying. Gravel, litter, and other debris was removed from soil samples. The soil’s natural water content was measured by drying method, and the soil bulk density, porosity characteristics (total porosity, capillary porosity, and non-capillary porosity), and water holding capacity characteristics (maximum water holding capacity, capillary water holding capacity, and field water holding capacity) were measured by cutting ring method. The collected bulk soil was divided into six fractions by soil aggregate analyzer after natural drying, namely >2 mm, 1–2 mm, 0.5–1 mm, 0.25–0.5 mm, 0.106–0.25 mm, and <0.106 mm. The contents
of total nitrogen (TN) and total phosphorus (TP) in soil were determined by Smartchem Discrete Auto Analyzer, and the content of soil organic carbon (SOC) was determined by potassium dichromate oxidation-external heating method.

2.3. Statistical Analyses

We calculated the soil bulk density, porosity, water holding capacity, and nutrient content (C, N, and P) of each forest gap age. IBM SPSS 25.0 software was used to analyze the data. One-way ANOVA and Tukey multiple comparison (α = 0.05) were used to analyze the effects of different forest gap ages on soil bulk density, porosity characteristics (total porosity, capillary porosity, and non-capillary porosity), water holding capacity characteristics (maximum water holding capacity, capillary water holding capacity, and field water holding capacity), nutrient content (C, N, and P), and stoichiometric characteristics.

3. Results

3.1. Soil Water Holding Capacity Characteristics in Forest Gap of Different Ages

The soil maximum water holding capacity, field water holding capacity, and capillary water holding capacity of *Cryptomeria japonica* pure forest after the formation of forest gap decreased significantly in <10 years (p < 0.05) (Table 1) but increased significantly with the increase of forest gap ages (p < 0.05). In the 0–10 cm soil layer, the maximum water holding capacity, field water holding capacity, and capillary water holding capacity of >20 years forest gap soil increased by 36.0%, 24.3%, and 28.2% compared with <10 years, respectively. In 10–20 cm soil layer, the maximum water holding capacity, field water holding capacity, and capillary water holding capacity of <10 years forest gap soil decreased by 17.8%, 16.5%, and 20.4% compared with >20 years, respectively. The results showed that the increase of *Cryptomeria japonica* forest gap ages could improve the physical properties of surface soil moisture and enhance soil water holding capacity.

<table>
<thead>
<tr>
<th>Different Forest Gap Ages</th>
<th>Soil Depth/cm</th>
<th>Maximum Water Holding Capacity/g·kg⁻¹</th>
<th>Field Water Holding Capacity/g·kg⁻¹</th>
<th>Capillary Water Holding Capacity/g·kg⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure forest (CK)</td>
<td>0–10</td>
<td>882.88 ± 44.91 ab</td>
<td>709.84 ± 36.44 a</td>
<td>778.77 ± 39.11 a</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>793.24 ± 54.29 a</td>
<td>623.14 ± 42.02 a</td>
<td>684.85 ± 48.26 a</td>
</tr>
<tr>
<td>&lt;10 years</td>
<td>0–10</td>
<td>687.90 ± 51.97 b</td>
<td>494.70 ± 48.02 b</td>
<td>566.95 ± 48.29 b</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>818.27 ± 25.10 b</td>
<td>578.15 ± 20.17 b</td>
<td>696.88 ± 22.14 b</td>
</tr>
<tr>
<td>10–20 years</td>
<td>0–10</td>
<td>817.64 ± 34.95 a</td>
<td>587.87 ± 28.45 a</td>
<td>692.87 ± 34.14 a</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>960.96 ± 60.15 a</td>
<td>658.58 ± 39.22 a</td>
<td>775.67 ± 40.26 a</td>
</tr>
<tr>
<td>&gt;20 years</td>
<td>0–10</td>
<td>837.31 ± 37.58 a</td>
<td>592.19 ± 42.89 a</td>
<td>712.31 ± 38.29 a</td>
</tr>
</tbody>
</table>

Note: The values in the table are mean ± standard error. Different letters indicate significant differences between different forest gap ages in the same soil layer (p < 0.05).

3.2. Soil Bulk Density and Porosity Characteristics in Forest Gap of Different Ages

In the 0–10 cm soil layer, the soil bulk density of 10–20 years forest gap increased by 12.0% compared with pure forests (Table 2), and the soil bulk density of >20 years forest gap was 9.5% lower than 10–20 years. In the 10–20 cm soil layer, the soil bulk density of >20 years forest gap decreased by 8.2% compared with pure forest. In the 0–10 cm soil layer, the capillary porosity, non-capillary porosity, and total porosity of >20 years forest gap increased by 7.8%, 41.2%, and 11.7% compared with the pure forest, respectively. This study showed that the capillary porosity and total porosity of soil increased significantly with the increase of forest gap restoration years, the soil bulk density of 10–20 cm soil layer showed a decreasing trend, and the soil of >20 years forest gap showed a looser structure, which improved the soil structure compared with *Cryptomeria japonica* pure forest.
3.3. Soil Aggregate Particle Size Distribution in Forest Gap of Different Ages

Aggregates of >2 mm and 1–2 mm were dominant in 0–10 cm and 10–20 cm soil layers in Cryptomeria japonica pure forest and forest gap of different ages (Table 3). Soil aggregates of 1–2 mm, 0.5–1 mm, and 0.25–0.5 mm in 0–10 cm and 10–20 cm soil layers showed an overall increasing trend with the increase of forest gap restoration years (p < 0.05), and in 10–20 cm soil layer, aggregates of 1–2 mm and 0.5–1 mm had significant differences in different restoration ages (p < 0.05), which showed that >20 years forest gap was significantly larger than <10 years forest gap and Cryptomeria japonica pure forest (p < 0.05). The results of this study showed that the increase of forest gap restoration years was beneficial to the increase of the content of large particle soil aggregates.

<table>
<thead>
<tr>
<th>Different Forest Gap Ages</th>
<th>Soil Depth/cm</th>
<th>Bulk Density/g cm(^{-3})</th>
<th>Capillary Porosity/%</th>
<th>Non-Capillary Porosity/%</th>
<th>Total Porosity/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure forest (CK)</td>
<td>0–10</td>
<td>0.75 ± 0.03 c</td>
<td>55.18 ± 1.01 b</td>
<td>7.23 ± 0.61 c</td>
<td>62.41 ± 0.97 b</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>0.85 ± 0.04 a</td>
<td>53.80 ± 1.88 b</td>
<td>8.58 ± 1.49 b</td>
<td>62.37 ± 1.77 c</td>
</tr>
<tr>
<td>&lt;10 years</td>
<td>0–10</td>
<td>0.72 ± 0.04 c</td>
<td>58.70 ± 2.01 a</td>
<td>9.15 ± 1.06 b</td>
<td>67.85 ± 2.54 a</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>0.79 ± 0.05 b</td>
<td>60.92 ± 1.82 b</td>
<td>9.80 ± 1.15 a</td>
<td>70.73 ± 2.13 a</td>
</tr>
<tr>
<td>10–20 years</td>
<td>0–10</td>
<td>0.84 ± 0.03 a</td>
<td>56.64 ± 2.33 a</td>
<td>8.54 ± 0.83 b</td>
<td>67.18 ± 2.45 a</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>0.86 ± 0.04 a</td>
<td>59.53 ± 2.83 a</td>
<td>7.41 ± 0.79 c</td>
<td>66.94 ± 3.10 b</td>
</tr>
<tr>
<td>&gt;20 years</td>
<td>0–10</td>
<td>0.76 ± 0.04 b</td>
<td>59.50 ± 1.92 a</td>
<td>10.21 ± 0.83 a</td>
<td>69.71 ± 2.15 a</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>0.78 ± 0.03 b</td>
<td>56.98 ± 2.19 b</td>
<td>8.87 ± 0.99 b</td>
<td>65.85 ± 2.45 b</td>
</tr>
</tbody>
</table>

Note: The values in the table are mean ± standard error. Different letters indicate significant differences between different forest gap ages in the same soil layer (p < 0.05).

<table>
<thead>
<tr>
<th>Different Forest Gap Ages</th>
<th>Soil Depth/cm</th>
<th>&gt;2 mm</th>
<th>1–2 mm</th>
<th>0.5–1 mm</th>
<th>0.25–0.5 mm</th>
<th>0.106–0.25 mm</th>
<th>&lt;0.106 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure forest (CK)</td>
<td>0–10</td>
<td>48.03 ± 1.95 a</td>
<td>18.04 ± 0.68 b</td>
<td>14.72 ± 0.86 b</td>
<td>9.02 ± 0.44 b</td>
<td>5.79 ± 0.62 a</td>
<td>4.40 ± 0.25 b</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>45.87 ± 1.84 a</td>
<td>18.48 ± 0.97 c</td>
<td>13.92 ± 0.72 b</td>
<td>9.37 ± 0.47 b</td>
<td>6.81 ± 0.79 a</td>
<td>5.55 ± 0.41 a</td>
</tr>
<tr>
<td>&lt;10 years</td>
<td>0–10</td>
<td>43.57 ± 2.81 b</td>
<td>21.23 ± 1.48 a</td>
<td>15.15 ± 1.04 ab</td>
<td>10.08 ± 0.77 a</td>
<td>5.32 ± 0.43 a</td>
<td>4.65 ± 0.35 b</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>42.32 ± 2.04 a</td>
<td>21.94 ± 0.71 b</td>
<td>14.28 ± 0.74 b</td>
<td>11.45 ± 0.52 a</td>
<td>5.49 ± 0.52 b</td>
<td>4.52 ± 0.33 b</td>
</tr>
<tr>
<td>10–20 years</td>
<td>0–10</td>
<td>40.94 ± 4.28 c</td>
<td>22.15 ± 2.67 a</td>
<td>15.86 ± 1.31 ab</td>
<td>9.18 ± 0.80 a</td>
<td>5.81 ± 0.98 a</td>
<td>6.06 ± 0.69 a</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>44.49 ± 4.18 a</td>
<td>22.04 ± 1.61 ab</td>
<td>14.11 ± 1.38 b</td>
<td>8.56 ± 1.07 b</td>
<td>4.75 ± 0.30 c</td>
<td>6.05 ± 1.20 a</td>
</tr>
<tr>
<td>&gt;20 years</td>
<td>0–10</td>
<td>40.23 ± 2.40 c</td>
<td>23.08 ± 1.08 a</td>
<td>17.08 ± 1.04 a</td>
<td>10.14 ± 1.34 a</td>
<td>5.28 ± 0.52 a</td>
<td>4.19 ± 0.44 b</td>
</tr>
<tr>
<td></td>
<td>10–20</td>
<td>34.34 ± 3.22 b</td>
<td>24.82 ± 1.10 a</td>
<td>17.53 ± 1.61 a</td>
<td>12.03 ± 1.51 a</td>
<td>6.92 ± 0.47 a</td>
<td>4.36 ± 0.43 b</td>
</tr>
</tbody>
</table>

Note: The values in the table are mean ± standard error. Different letters indicate significant differences between different forest gap ages in the same soil layer (p < 0.05).

3.4. Soil Nutrient Characteristics in Forest Gap of Different Ages

With the increase of forest gap ages, the content of C in 0–10 cm and 10–20 cm soil layers increased gradually (Figure 2). In the 0–10 cm soil layer, the C content in the 10–20 years forest gap soil increased by 28.6% compared with pure forest. In the 0–10 cm soil layer and the 10–20 cm soil layer, the N content in 10–20 years forest gap soil increased by 52.5% and 21.8% compared with pure forest, respectively. In the 0–10 cm soil layer and the 10–20 cm soil layer, the P content in the soil of >20 years forest gap increased by 54.9% and 43.2% compared with pure forest, respectively. The results showed that the contents of C, N, and P in soil increased with the increase of forest gap ages and were significantly higher than those in Cryptomeria japonica pure forest (p < 0.05). The nutrient contents in 10–20 years were the highest, and the nutrient contents in 0–10 cm soil layer were higher than those in 0–20 cm soil layer.
3.4. Soil Nutrient Characteristics in Forest Gap of Different Ages

With the increase of forest gap ages, the content of C in 0–10 cm and 10–20 cm soil layers increased gradually (Figure 2). In the 0–10 cm soil layer, the C content in the 10–20 years forest gap soil increased by 28.6% compared with pure forest. In the 0–10 cm soil layer and the 10–20 cm soil layer, the N content in 10–20 years forest gap soil increased by 52.5% and 21.8% compared with pure forest, respectively. In the 0–10 cm soil layer and the 10–20 cm soil layer, the P content in the soil of >20 years forest gap increased by 54.9% and 43.2% compared with pure forest, respectively. The results showed that the contents of C, N, and P in soil increased with the increase of forest gap ages and were significantly higher than those in *Cryptomeria japonica* pure forest (*p* < 0.05). The nutrient contents in 10–20 years were the highest, and the nutrient contents in 0–10 cm soil layer were higher than those in 0–20 cm soil layer.

![Figure 2](image-url)

**Figure 2.** Variations of C content (a), N content (b), and P content (c) in different forest gap ages. Note: Different letters indicate significant differences between different forest gap ages in the same soil layer (*p* < 0.05). Error bars represent ±standard errors.

3.5. Soil Stoichiometric Characteristics in Forest Gap of Different Ages

In the 0–10 cm soil layer, the C:N in the soil of 10–20 years forest gap was 15.7% and 18.7% lower than pure forest and <10 years, respectively (Figure 3). The C:P in soil showed a decreasing trend with the increase of forest gap ages. In the 0–10 cm soil layer, the forest gap of >20 years was 31.6% and 44.5% lower than pure forest and <10 years, respectively. The N:P in the soil showed a decreasing trend with the increase of forest gap ages. In the soil layers of 0–10 cm and 10–20 cm, the N:P in the soil of >20 years forest gap decreased by 27.6% and 43.8% compared with pure forest, respectively. The C:N ratio of soil is an indicator to measure the mineralization rate of organic matter. The lower C:N ratio can indicate faster nutrient cycling, whilst C:N stoichiometric ratio is best used to measure the rate of nutrient cycling. The results showed that with the increase of *Cryptomeria japonica* forest gap ages, the C:P and N:P in the soil showed an overall decreasing trend, while the C:N of 10–20 years forest gap soil was significantly smaller than other forest gap ages (*p* < 0.05) which indicated that nutrient cycling in 10–20 years forest gap was the fastest.
4. Discussion

4.1. Effects of Different Forest Gap Ages on Soil Water Holding Capacity, Bulk Density, and Porosity

In this experiment, by studying the age of natural forest gap formation and succession of Cryptomeria japonica in Lushan Mountain, the dynamic process of soil water holding capacity, bulk density, and porosity with different forest gap ages was discussed. Soil water holding capacity, one of the most important physical properties of soil, is an important factor determining the water conservation capacity of an ecosystem [33]. Soil water holding capacity is an important index to evaluate soil water conservation function, which has an extremely important impact on the restoration and reconstruction of ecological communities [34]. The maximum water holding capacity, capillary water holding capacity, and field water holding capacity of soil can directly reflect the water holding capacity of soil, and indirectly reflect the redistribution ability of water [35]. The soil maximum water holding capacity, field water holding capacity, and capillary water holding capacity increased significantly with the increase of forest gap ages after 10 years (Table 1). In the 0–10 cm soil layer, the maximum water holding capacity, field water holding capacity, and capillary water holding capacity of the soil in the gap of >20 years were significantly higher than those in the gap of <10 years and the gap of 10–20 years (p < 0.05). The results showed that the restoration of Cryptomeria japonica forest gap could improve the physical properties of surface soil moisture and enhance soil water retention capacity. This may be because the pure Cryptomeria japonica forest generally has high density, small coverage of undergrowth vegetation, few species, and low biodiversity. In the early stage after the formation of forest gap, the undergrowth vegetation is in the growth and development stage because of the change of surface cover, and the soil water holding capacity and water holding capacity will decrease. However, with the increase of restoration years, the composition
and structure of vegetation are optimized, and the soil water holding capacity is gradually restored and enhanced.

Soil bulk density and porosity are important physical properties of soil, reflecting the compactness of soil structure, and can affect soil water permeability and root extension [36]. There are many large and small pores in the soil, which can reflect the size of the total pore volume in the soil and the distribution and matching of the pores, that is, the structure of the soil [37]. Soil pores are occupied by water and gas, and the size of total soil porosity is mainly determined by the arrangement of soil particles [38]. The pores that can be occupied by capillary water are capillary pores, while those that cannot be occupied by capillary water are non-capillary pores [39]. Through the study of total soil porosity, capillary porosity, and non-capillary porosity, we can understand the structural state of soil and further determine the existence state of water in soil [40]. With the increase of forest gap ages, soil capillary porosity and total porosity increased significantly compared with pure forest \( (p < 0.05) \) (Table 2). In the 0–10 cm soil layer, the soil bulk density of >20 years forest gap was significantly lower than that of forest gap restored to 10–20 years \( (p < 0.05) \). In the 10–20 cm soil layer, the soil bulk density of >20 years forest gap was significantly lower than that of pure forest \( (p < 0.05) \).

This study showed that with the increase of forest gap age, the capillary porosity and total porosity of soil increased significantly, and the soil bulk density of 10–20 cm soil layer showed a decreasing trend, indicating that the soil of >20 years forest gap showed a looser structure, which improved the soil structure compared with Cryptomeria japonica pure forest. This may be due to the formation of forest gaps which can increase the light intensity in the forest to a certain extent, which is conducive to the development of undergrowth vegetation, and in addition the root system increases accordingly. The roots of undergrowth grass and shrub are mainly concentrated in the 0–10 cm soil layer, and the roots are interspersed and squeezed in the soil. With the increase of forest gap age, the bulk density of soil surface layer decreases and the porosity of soil increases.

4.2. Effects of Different Forest Gap Ages on Particle Size Distribution of Soil Aggregates

Aggregate is the basic unit of various types of soil structure, which is an important material basis for people to study and improve various types of soil structure. It can comprehensively reflect the soil structure integrity and soil fertility status of various types of soil [41]. The formation of soil aggregates is a complex physical, chemical, biological, and biochemical process. Soil aggregate status is the central regulator of soil fertility, which greatly affects soil aeration and erosion resistance [42]. The degradation of soil first shows the disappearance of soil aggregate structure, and different particle size aggregates play a crucial role in the storage, transport, and transformation of nutrient substances [43]. In this study, the aggregates of >2 mm and 1–2 mm were dominant in the 0–10 cm and 10–20 cm soil layers of Cryptomeria japonica pure forest and forest gap of different ages (Table 3), and the aggregates of 1–2 mm, 0.5–1 mm, and 0.25–0.5 mm showed an overall increasing trend with the increase of forest gap recovery years in 0–10 cm and 10–20 cm soil layers \( (p < 0.05) \). The formation of forest gap changed the distribution of soil aggregates, and the proportion of large particle aggregates increased with the increase of gap ages. Large particle aggregates are formed by cementation of organic matter and microaggregates, and the organic carbon content is high [44]. Large particle aggregates are the basis of soil structure stability and the main part of organic carbon storage. The increase of large particle aggregates content has a good effect on improving soil structure [45].

4.3. Effects of Different Forest Gap Ages on Soil Nutrient Characteristics

Soil is an important component of terrestrial ecosystems and the main source of nutrients for plant growth and development [46]. Carbon (C), nitrogen (N), and phosphorus (P) in soil are essential nutrients for plant growth. As a stable and long-lasting carbon source, soil organic carbon plays an important role in maintaining soil fertility. Its quality (the activity level of organic carbon) and the content affects the potential productivity of
After the *Cryptomeria japonica* forest gap was formed, the C content in the soil showed a gradually increasing trend with the increase of the restoration period, and the C content in the 0–10 cm soil layer was generally higher than that in the 10–20 cm soil layer (Figure 2). In the 10–20 cm soil layer, the N content in the soil of 10–20 years forest gap was significantly higher than pure forest and <10 years forest gap ($p < 0.05$). And in the 0–10 cm soil layer, the soil P content of >20 years forest gap was significantly higher than <10 years forest gap and pure forest ($p < 0.05$). The results showed that with the increase of forest gap ages, the contents of C, N, and P in soil showed an overall increasing trend and were significantly higher than those in pure forest ($p < 0.05$). The nutrient content of forest gap with 10–20 years was the highest, and the nutrient content of the 0–10 cm soil layer is generally greater than that of the 0–20 cm soil layer. This may be because *Cryptomeria japonica* forest gap changed the light conditions and rainfall conditions in the forest, and the temperature and humidity in the forest gap changed accordingly, which affected the activity of soil microorganisms, thus causing changes in soil nutrient element content. With the increase of forest gap ages, the plant species in the forest gap became more abundant, and the decomposition of litter increased the C, N, and P contents in the soil.

### 4.4. Effects of Different Forest Gap Ages on Soil Stoichiometric Characteristics

Ecological stoichiometry is a theoretical science that uses the coupling relationship of various chemical elements in the ecological process to analyze the interaction of various chemical elements on the ecosystem. It integrates the basic principles of biology, physics, and chemistry [49]. Due to the regulation of natural conditions such as soil parent material, climate, landform, and vegetation cover, as well as the interference of human activities and differences in soil hydrothermal conditions and pedogenesis, soil stoichiometric characteristics have great spatial variability [50]. Carbon is the most important element that constitutes dry matter in plants. Nitrogen (N) and phosphorus (P) are essential and limiting elements for plant growth and are closely related to plant growth, development, and reproduction. Changes in nutrient distribution patterns (such as C:N, N:P, C:P) affect community structure, nutrient use efficiency, and productivity [51]. Gap is an important driving force for natural regeneration of forests, an important channel for regulating the reorganization of plantation vegetation and plays an important role in vegetation succession and nutrient cycling in forest ecosystems [52]. On the one hand, the formation of gaps can affect the microenvironment below the canopy, the invasion and settlement of plants, and the regeneration of understory vegetation, thereby changing the stand structure, which may exert a strong effect on the soil stoichiometric characteristics of gaps [53]. On the other hand, compared with the canopy forest, the formation of gaps changes the water and heat dynamics and the community structure of decomposers in the forest, which can affect the nutrient utilization and turnover efficiency (such as litter decomposition) of the understory vegetation, and then profoundly affects the soil nutrients’ distribution pattern [54]. Soil C:N is a sensitive indicator reflecting soil quality and an important factor affecting the carbon and nitrogen cycle in soil. The evolution trend of C:N has an important impact on soil C and N cycles [55]. Soil C:N can indicate the C decomposition rate, and a lower C:N ratio indicates a faster C decomposition rate [56].

In this experiment, the soil C:N in 10–20 years *Cryptomeria japonica* forest gap was significantly smaller than other forest gap ages and pure forest ($p < 0.05$), indicating that in the 10–20 years *Cryptomeria japonica* forest gap, the soil C decomposition rate was faster than other ages, and the nutrient cycling period was the shortest. The C:P in soil can be used as an indicator to measure the availability of soil P, which is an important indicator to measure the potential of soil organic matter mineralization to release phosphorus or absorb and retain phosphorus. A lower C:P indicates a higher availability of soil P in the study area [57]. In this experiment, with the increase of *Cryptomeria japonica* forest gap ages, the C:P in the soil showed an overall decreasing trend, indicating that the effectiveness of soil P in the gaps gradually increased. This may be due to the better nutrient release by microorganisms in the process of organic matter decomposition, which promotes the
increase of soil available phosphorus. N and P elements in soil are common and important elements required for plant growth, and N:P in soil can be used as an indicator of plant nutrient limitation and is often used for the diagnosis of soil nutrient limiting factors and the determination of nutrient limitation thresholds [58]. In this experiment, soil N:P showed a decreasing trend with the increase of Cryptomeria japonica forest gap ages, especially >20 years forest gap which were significantly smaller than other forest gap ages and pure forests (p < 0.05). Combined with the gradual increase in soil P content, this may be due to the fact that soil N content is the main nutrient limiting factor [59].

5. Conclusions

In this study, the effects of different Cryptomeria japonica forest gap ages (<10 years, 10–20 years, >20 years) on soil physical properties and stoichiometric characteristics were analyzed. With the increase of forest gap ages, the water physical properties of soil surface were improved and the soil water holding capacity was enhanced. The capillary porosity and total porosity of soil increased significantly, and the soil bulk density of 10–20 cm soil layer showed a decreasing trend, indicating that the soil of >20 years forest gap showed a looser structure, which improved the soil structure compared with Cryptomeria japonica pure forest. The increase of forest gap restoration years is conducive to the increase of the content of large particle soil aggregates. The large particle aggregates are formed by the cementation of organic matter and microaggregates, and the organic carbon content is higher. Large particle aggregates are the basis of soil structure stability and the main part of organic carbon storage. The increase of large particle aggregates content has a good effect on improving soil structure. The contents of C, N, and P in soil showed an overall increasing trend with the increase of gap age and were significantly higher than those in pure forest (p < 0.05). The nutrient content of forest gap in 10–20 years was the highest, and the nutrient content of 0–10 cm soil layer was generally higher than that of 0–20 cm soil layer. The C:P and N:P in soil showed an overall decreasing trend, while the C:N in 10–20 years gaps was significantly lower than other forest gap ages (p < 0.05). The results showed that with the increase of forest gap ages, the soil physical properties and stoichiometric characteristics in the forest gap were improved, which was more conducive to the growth of vegetation in the forest gap.

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