Research progress on the influence of forest fire on the eco-stoichiometric characteristics of carbon, nitrogen and phosphorus in forest ecosystem

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ABSTRACT

Forest fire can change the eco-stoichiometric characteristics of forest ecosystem elements, reflect the biogeochemical cycle change mode of forest ecosystem environment after fire, and clarify the eco-stoichiometric characteristics of carbon (C), nitrogen (N), phosphorus (P) in forest ecosystem under forest fire disturbance, which is very important for understanding the response mechanism of forest ecosystem to forest fire disturbance. By consulting a large number of relevant literatures, the author summarized and analyzed the impact mode of forest fire disturbance on the C–N–P eco-stoichiometric characteristics of forest ecosystem, as well as the impact of forest fire disturbance on the C–N–P eco-stoichiometric characteristics of plants, C–N–P eco-stoichiometric characteristics of litter, and C–N–P eco-stoichiometric characteristics of soil. It is considered that the C–N–P eco-stoichiometric characteristics of forest ecosystem are mainly affected by fire factors (fire intensity, fire frequency, recovery time after fire), vegetation types and soil properties. In view of the scientific problems that forest fire urgently needs to be solved in the study of forest ecosystem eco-stoichiometry, three aspects: the impact mechanism of forest fire disturbance on the homeostasis of plant eco-stoichiometry, the study of multi-element eco-stoichiometry under forest fire disturbance, the establishment of the eco-chemometrics relationship of the plant–litter–soil composite system under the interference of forest fire are proposed, in order to deeply understand the plant regulation strategy under the interference of forest fire, clarify the mutual coupling mechanism between multiple chemical elements after the interference of forest fire, and improve the relationship between the input and output of aboveground and underground nutrients with the plant–litter–soil as a composite whole, which is of great significance for a deep understanding of the nutrient cycle and balance of the forest ecosystem under the background of global climate change, and reasonable formulation of forest fire management measures.

Keywords: Forest Fire; Forest Ecosystem; Eco-stoichiometry; Litter; Soil Nutrient

1. Introduction

Forest fire disturbance is one of the internal ecological processes of forest ecosystem, which plays a vital role in maintaining the structure and function of forest ecosystem[1]. Plants and soil are important components of the ecosystem, and litter returns nutrients in plants to the soil, the three are closely related[2]. Forest fire, as an important factor of biogeochemical cycle, drives the redistribution of nutrient elements in forest ecosystem in time and space by directly applying different degrees of effects on soil carbon (C), nitrogen (N), phosphorus (P) pool and changing soil physical and chemical properties and biological properties[3], thereby breaking the nutrient proportion balance in plants and litter and affecting the nutrient cycle of forest ecosystem. In the context of global climate change, the increase in the frequency and intensity of forest fires has changed the nutrient balance among the components of
the forest ecosystem\textsuperscript{4}. Therefore, to explore the nutrient ratio and coupling mechanism between components of forest ecosystem under forest fire disturbance has become a hot spot in forest fire ecology. Understanding the regulation mechanism of forest fire disturbance on C, N, P cycle is also an important content of biogeochemical cycle research under the background of global change\textsuperscript{5}.

Eco-chemometrics explores its response mechanism to climate change through the relative content changes, balance relationships and biogeochemical cycle processes of multiple chemical elements at different levels and scales, so as to maintain the material cycle, energy balance and ecosystem stability of the ecosystem\textsuperscript{6}. Due to the special and complex effect of forest fire disturbance on forest ecosystem, its disturbance on the stability of nutrient supply in geochemical process\textsuperscript{7}, and the relationship between C–N–P eco-stoichiometric distribution and plant growth, litter decomposition, and soil nutrient environment in the process of post fire vegetation restoration still need to be further studied and clarified. Applying eco-stoichiometry theory to study the eco-stoichiometric characteristics of forest ecosystem under forest fire interference can not only improve the understanding of forest ecosystem response strategies, but also contribute to the development and improvement of forest fire ecology theory\textsuperscript{8}. At present, although some researchers have paid attention to the coupling effect between C–N–P eco-stoichiometry of post fire forest ecosystem\textsuperscript{9,10}, there is a lack of systematic summary of the stoichiometric characteristics of post fire forest ecosystem, especially the unified discussion of the impact of forest fire on the plant–litter–soil eco-stoichiometric characteristics of forest ecosystem as a whole is rarely reported.

The response of elements required by plants to ecological patterns and processes has a specific proportion\textsuperscript{11}, and forest fire interference may break and change the C–N–P ecological stoichiometric balance in the ecosystem\textsuperscript{12}. By consulting a large number of relevant literatures, the author summarizes and analyzes the influence mode of forest fire on the stoichiometric characteristics of forest ecosystems, the response of the stoichiometric characteristics of forest ecosystems to forest fire, and the influencing factors of the stoichiometric characteristics of post fire ecosystems. Finally, by analyzing the shortcomings of current research, the author puts forward the scientific issues that need urgent attention in this field, and discusses the latest research progress of forest fire interference on the stoichiometry of forest ecosystems. It is expected to provide reference for further exploring the mechanism of plant growth, litter decomposition and soil nutrient supply in China’s forest ecosystem after forest fire disturbance, and promote the development of this field.

\section*{2. Influence mode of forest fire on C–N–P eco-stoichiometric characteristics of forest ecosystem}

The influence mode of forest fire on the C–N–P eco-stoichiometric characteristics of forest ecosystem is mainly related to fire factors (fire intensity, fire frequency and recovery time after fire), vegetation types and soil properties (Figure 1). Because different elements (such as C, N, P) have different volatilization temperatures, forest fire has different effects on the content of each element. For example, the volatilization loss of C and N elements occurs at 200–500 °C, while P is above 774 °C\textsuperscript{13}. Research shows that frequent forest fire interference will deplete soil C and N pools\textsuperscript{14} and reduce the content ratio of soil C and P (recorded as C/P) and the content ratio of N and P (recorded as N/P). The change of soil C, N and P content ratio in forest ecosystem caused by forest fire reflects the different changes of C, N and P cycle in the post fire environment, and destroys the ongoing biogeochemical processes, such as the absorption of nutrients by plants and the decomposition of litter\textsuperscript{15}. Due to the intrinsic stability of plants, plants cannot flexibly adjust their own ecological stoichiometric ratio, but some studies have found that forest fire reduces C/P and N/P in plant tissues\textsuperscript{16}. Litter is the link between plants and soil. Most of the nutrients absorbed by plants come from the recycling of nutrients decomposed by litter into soil\textsuperscript{17}. Forest fire disturbance further affects the quality and decomposition rate of litter by changing vegetation types and soil proper-
ties, and changes the nutrient status and chemical characteristics of litter after fire\[^{18}\].

In the process of forest fire combustion, the volatilization of a large number of nutrients causes soil stoichiometric imbalance\[^{19}\]. However, the deposition of ash, mineralization of organic matter and the increase of pH in the soil will increase the availability of resources, such as increasing the utilization rate of basic nutrient elements of N and P, etc.\[^{20}\], which is conducive to seed germination.

With the restoration of vegetation in the post fire ecosystem, the ecological processes such as soil temperature change, topographic wind erosion, and the flushing and leaching of rainfall on the soil surface jointly participate in changing the soil nutrient environment, thus affecting the C–N–P stoichiometric ratio in the post fire vegetation organization, and having a long-term impact on the nutrient cycle of the whole forest ecosystem\[^{21,22}\].

![Figure 1](image.png)

**Figure 1.** Impact pattern of forest fire on C–N–P ecological stoichiometry characteristics of forest ecosystem.

### 3. Effect of forest fire on C–N–P eco-stoichiometric characteristics of forest ecosystem

#### 3.1 Effect of forest fire on C–N–P eco-stoichiometric characteristics of plants

The fluctuation of C, N and P elements in time and space after fire has a far-reaching impact on plant nutrient absorption. Butler *et al.*\[^{9}\] found that in Austrianian *Eucalyptus crebra* forests with poor soil nutrients, microorganisms with low nutrient demand or fixable nutrients can indicate the nutrient status of plant leaves. The content of Acinetobacter Johnson in the soil after planned fire is 27% higher than that in the control area, demonstrating that fire significantly reduces the C/N of plant leaves; in addition, C/P and N/P of plant leaves after fire were significantly higher than C/N. Ti\[^{23}\] studied the impact of forest fire on the eco-stoichiometric characteristics of forest ecosystems in the northern subtropical and warm temperate transition zone and found that one year after the fire, the C/N of shrub and tree leaves increased by 18.09% and 10.02%, respectively; C/P of shrub leaves increased by 6.67%, and N/P decreased by 13.5%; the N/P of tree leaves decreased by 15.45%. At the global scale, Dijkstra *et al.*\[^{8}\] collected the N and P contents of plants under wildfire, planned fire and slash-and-burn, and pointed out that when N and P were limited, respectively, the N and P contents in the leaves of woody plants increased after fire, so fire was helpful to alleviate the imbalance of N and P contents in vegetation\[^{9}\]. Cui *et al.*\[^{24}\] and Britton *et al.*\[^{25}\] took temperate grassland and wasteland ecosystems as research objects, respectively, and found that fire did not change the N/P of plant leaves. They believed that this was due to the simultaneous increase of plant N and P content after
fire. Forest fire causes the value of N/P of one-year plants in California grassland to decrease\textsuperscript{[26]}, but in savanna, fire interference has no significant impact on the ecological stoichiometric characteristics of plants\textsuperscript{[10]}. In China, C/N of plant leaves increased significantly after burning in plateau meadows, but burning did not change the original state of soil N limitation\textsuperscript{[27]}.

3.2 Effect of forest fire on C–N–P eco-stoichiometric characteristics of litter

Forest fire further changes the decomposition rate of litter by changing the ecological stoichiometry of litter: when C/N is low, decomposition is faster; on the contrary, the decomposition is slow. Huang \textit{et al.}\textsuperscript{[28]} found that the C/N of the litter of \textit{Pinus armandii} forest after fire was 9.79\% lower than that of the litter of \textit{Pinus armandii} without fire; the C/N of litter in \textit{Cupressus funebris} forest was not significantly different before and after fire. Yang, \textit{et al.}\textsuperscript{[29]} studied the eco-stoichiometric characteristics of litter in \textit{Larix gmelinii} forest with different burning years in the northern forest ecosystem and found that after fire, the content of plant N and P increased, the values of litter C/N and C/P decreased, and the decomposition rate of litter accelerated. Toberman \textit{et al.}\textsuperscript{[30]} found that in the Australian \textit{Eucalyptus} forest, the N/P of the forest burned once every 4 years is larger than that of the forest burned once every 2 years, and the decomposition rate of forest litter is also the fastest (32\%), which may be that the mitigation of N limitation after fire plays a key role in the process of litter decomposition. In the Alpine sclerophyte shrub communities of African, the C/N and C/P values of litter decrease with the recovery time after fire\textsuperscript{[31]}, but this study questioned that forest fire interference is an important factor affecting litter decomposition, and believed that the decomposition rate of litter after fire should fully consider the effects of fire frequency, soil quality and seasonal or 1-year-old plants on litter decomposition.

3.3 Effect of forest fire on soil C–N–P eco-stoichiometric characteristics

There are differences in the response of soil Eco-stoichiometric characteristics to forest fire in different forest ecosystems (Table 1). The consumption of a large amount of organic C and the increase of N mineralization during forest fire combustion have significantly reduced the value of soil C/N\textsuperscript{[32]}. With the passage of time after fire, the value of soil C/N increases (such as the frozen soil area of northern forest)\textsuperscript{[33]}. The consumption of a large amount of organic C and the increase of N mineralization during forest fire combustion have significantly reduced the value of soil C/N\textsuperscript{[32]}. With the passage of time after fire, the value of soil C/N increases (such as the frozen soil area of northern forest)\textsuperscript{[33]}. In the forest ecosystem of northern China, the value of soil C/N decreased by 13\% after 1 year of fire, and the effective N/P decreased by 6.9\%. The value of soil N/P after 11 years of fire was significantly higher than that of the control, indicating that forest fire has a long-term impact on the balance between soil N and P\textsuperscript{[21]}. In the savanna of South Africa, hundreds of years of frequent forest fires have exhausted N in the soil, so that even the sample plots that have not been burned for 58 years have not recovered from the condition of N limitation\textsuperscript{[10]}. Due to the slow weathering speed of rocks, the fixation of P on the soil surface, and the gradual consumption of soluble organic P, the value of C/P in soil in low latitude areas is high\textsuperscript{[34]}. With the regeneration of trees after the fire, the demand of plants for P exceeded the supply, resulting in the increase of C/P and N/P values, exacerbating the P limitation\textsuperscript{[35]}. In some tropical rainforests, frequent felling and burning have exhausted C, N and P in the soil, and the forest land status has changed from the initial P enrichment to P limitation\textsuperscript{[36]}. 
Table 1. Fire disturbance on soil ecological stoichiometry characteristics of different forest ecosystem

<table>
<thead>
<tr>
<th>Climate type</th>
<th>Vegetation type, distribution area</th>
<th>Fire intensity</th>
<th>Time after fire</th>
<th>c(C)/%</th>
<th>c(N)/(mg·kg⁻¹)</th>
<th>c(P)/(mg·kg⁻¹)</th>
<th>N/P</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold temperate zone</td>
<td><em>L. gmelinii</em>, Great Khing’an Mountains</td>
<td>Control</td>
<td>1</td>
<td>10.100 ± 2.000a</td>
<td>4,000 ± 700a</td>
<td>—</td>
<td>—</td>
<td>[37]</td>
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<tr>
<td></td>
<td></td>
<td>Low</td>
<td>6.800 ± 0.800a</td>
<td>3,700 ± 300a</td>
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<tr>
<td></td>
<td></td>
<td>High</td>
<td>7.300 ± 1.200a</td>
<td>3,100 ± 200a</td>
<td>—</td>
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<tr>
<td></td>
<td><em>P. pumila–L. Gmelinii</em>, Great Khing’an Mountains</td>
<td>Control</td>
<td>5</td>
<td>12.683 ± 0.332a</td>
<td>5,460 ± 430a</td>
<td>960 ± 270</td>
<td>5.69 ± 1.15</td>
<td>[38]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td>11.945 ± 0.918a</td>
<td>5,230 ± 280a</td>
<td>870 ± 340</td>
<td>6.01 ± 2.02</td>
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<tr>
<td></td>
<td></td>
<td>Medium</td>
<td>8.793 ± 0.401b</td>
<td>4,200 ± 230b</td>
<td>530 ± 21</td>
<td>7.92 ± 2.70</td>
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<td></td>
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<td>High</td>
<td>7.255 ± 0.392c</td>
<td>4,410 ± 370c</td>
<td>440 ± 37</td>
<td>10.02 ± 7.58</td>
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<td></td>
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<td>Low</td>
<td>19</td>
<td>12.174 ± 0.187a</td>
<td>5,280 ± 630a</td>
<td>930 ± 520</td>
<td>5.68 ± 2.49</td>
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<td></td>
<td></td>
<td>Medium</td>
<td>8.916 ± 0.411b</td>
<td>4,490 ± 470b</td>
<td>620 ± 230</td>
<td>7.24 ± 1.92</td>
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<tr>
<td></td>
<td></td>
<td>High</td>
<td>7.934 ± 0.362a</td>
<td>4,490 ± 170b</td>
<td>460 ± 230</td>
<td>9.56 ± 4.41</td>
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<tr>
<td></td>
<td><em>L. gmelinii</em>, Great Khing’an Mountains</td>
<td>Control</td>
<td>5</td>
<td>—</td>
<td>—</td>
<td>597 ± 68</td>
<td>—</td>
<td>[39]</td>
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<td></td>
<td></td>
<td>High</td>
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<td>833 ± 160</td>
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<td>Temperate zone</td>
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<td></td>
<td><em>P. tabuliformis</em> (0–10 cm soil layer), Pingqu, Hebei</td>
<td>Control</td>
<td>1</td>
<td>2.960 ± 0.060</td>
<td>1850 ± 930a</td>
<td>380 ± 190a</td>
<td>4.87 ± 0.01</td>
<td>[40]</td>
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<tr>
<td></td>
<td></td>
<td>Low</td>
<td>2.340 ± 0.030</td>
<td>1340 ± 90a</td>
<td>240 ± 10a</td>
<td>5.58 ± 0.14</td>
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<td></td>
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<td>Medium</td>
<td>2.430 ± 0.030</td>
<td>860 ± 240a</td>
<td>110 ± 40a</td>
<td>7.81 ± 0.66</td>
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<td></td>
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<td>High</td>
<td>2.970 ± 0.410</td>
<td>2170 ± 130a</td>
<td>290 ± 30a</td>
<td>7.48 ± 0.33</td>
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<td></td>
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<td>Control</td>
<td>1</td>
<td>1.560 ± 0.060</td>
<td>1260 ± 810a</td>
<td>330 ± 190a</td>
<td>3.81 ± 0.26</td>
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<td></td>
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<td>Low</td>
<td>1.300 ± 0.060</td>
<td>790 ± 140a</td>
<td>190 ± 20a</td>
<td>4.15 ± 0.30</td>
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<td></td>
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<td>Medium</td>
<td>1.270 ± 0.060</td>
<td>470 ± 90a</td>
<td>60 ± 20a</td>
<td>7.83 ± 1.11</td>
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<td></td>
<td></td>
<td>High</td>
<td>1.680 ± 0.220</td>
<td>1110 ± 140a</td>
<td>170 ± 0a</td>
<td>6.52 ± 0.82</td>
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<td>Control</td>
<td>1</td>
<td>0.740 ± 0.080</td>
<td>910 ± 730a</td>
<td>300 ± 160a</td>
<td>3.03 ± 0.82</td>
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<tr>
<td></td>
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<td>0.950 ± 0.050</td>
<td>620 ± 90a</td>
<td>170 ± 20a</td>
<td>3.65 ± 0.10</td>
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<td></td>
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<td>Medium</td>
<td>0.650 ± 0.030</td>
<td>320 ± 90a</td>
<td>50 ± 0a</td>
<td>6.4 ± 1.80</td>
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<td>High</td>
<td>1.000 ± 0.080</td>
<td>740 ± 230a</td>
<td>160 ± 60a</td>
<td>4.63 ± 0.30</td>
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<td></td>
<td>Subtropical Zone</td>
<td><em>E. crebrea</em>, Queensland</td>
<td>Control</td>
<td>5</td>
<td>2.300 ± 0.200</td>
<td>3750 ± 530</td>
<td>347 ± 26</td>
<td>10.81 ± 0.72</td>
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<td></td>
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<td>Low</td>
<td>1.900 ± 0.200</td>
<td>5700 ± 590</td>
<td>635 ± 50</td>
<td>8.98 ± 0.22</td>
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<td>Control</td>
<td>—</td>
<td>3.390 ± 0.900a</td>
<td>2000 ± 600ab</td>
<td>260 ± 30ab</td>
<td>7.69 ± 1.42</td>
<td>[41]</td>
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<td>Low</td>
<td>3.080 ± 0.360a</td>
<td>2100 ± 600a</td>
<td>260 ± 20b</td>
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<td>2.870 ± 0.340</td>
<td>1900 ± 400b</td>
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<td>2.530 ± 0.480</td>
<td>1800 ± 500b</td>
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<td>7.83 ± 1.15</td>
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<td>Control</td>
<td>—</td>
<td>1.530 ± 0.660a</td>
<td>1200 ± 300ab</td>
<td>220 ± 40ab</td>
<td>5.45 ± 0.37</td>
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<td>Low</td>
<td>1.400 ± 0.380a</td>
<td>1200 ± 300a</td>
<td>220 ± 30a</td>
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<td>1.310 ± 0.350a</td>
<td>1100 ± 200b</td>
<td>210 ± 30b</td>
<td>5.24 ± 0.20</td>
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<td>1.130 ± 0.320</td>
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<td>190 ± 40</td>
<td>5.26 ± 0.06</td>
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<td>Control</td>
<td>—</td>
<td>2.090 ± 1.060a</td>
<td>2500 ± 400abc</td>
<td>320 ± 40abc</td>
<td>7.81 ± 0.27</td>
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<td>Low</td>
<td>1.830 ± 0.530a</td>
<td>2600 ± 500a</td>
<td>320 ± 40a</td>
<td>8.13 ± 0.55</td>
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<td>Medium</td>
<td>1.680 ± 0.420a</td>
<td>2400 ± 300b</td>
<td>310 ± 30b</td>
<td>7.74 ± 0.22</td>
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<td>1.470 ± 0.300</td>
<td>2200 ± 400b</td>
<td>290 ± 40</td>
<td>7.59 ± 0.33</td>
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<td>Control</td>
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<td>1.440 ± 1.060ab</td>
<td>900 ± 30a</td>
<td>100 ± 10a</td>
<td>9.00 ± 0.60</td>
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<td>1.290 ± 0.700a</td>
<td>900 ± 30a</td>
<td>90 ± 20a</td>
<td>10.00 ± 1.33</td>
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<td>Medium</td>
<td>1.200 ± 0.590a</td>
<td>800 ± 30a</td>
<td>90 ± 10a</td>
<td>8.89 ± 0.65</td>
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<td>High</td>
<td>1.040 ± 0.500a</td>
<td>900 ± 80a</td>
<td>90 ± 20a</td>
<td>10.00 ± 1.89</td>
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<td>Control</td>
<td>—</td>
<td>0.046 ± 0.004a</td>
<td>2890 ± 220a</td>
<td>1540 ± 150</td>
<td>1.88 ± 0.04</td>
<td>[10]</td>
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<tr>
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<td></td>
<td>Low</td>
<td>0.037 ± 0.003b</td>
<td>1790 ± 70b</td>
<td>1740 ± 230</td>
<td>1.03 ± 0.10</td>
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<tr>
<td></td>
<td></td>
<td>High</td>
<td>0.039 ± 0.005b</td>
<td>2040 ± 150b</td>
<td>1660 ± 320</td>
<td>1.23 ± 0.15</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>1</td>
<td>5.460 ± 0.500</td>
<td>5400 ± 40</td>
<td>2.89 ± 0.14</td>
<td>1868.51 ± 76.68</td>
<td>[42]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td>4.270 ± 0.700</td>
<td>4200 ± 100</td>
<td>4.53 ± 0.18</td>
<td>927.15 ± 14.77</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>1</td>
<td>6.980 ± 2.300</td>
<td>5700 ± 100</td>
<td>3.54 ± 0.21</td>
<td>1610.17 ± 67.27</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td>10.480 ± 1.700</td>
<td>9100 ± 100</td>
<td>7.60 ± 0.18</td>
<td>1197.37 ± 15.20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: *: Savanna; the unit of soil c(C), c(N) and c(P) is kg·hm⁻²; —: not reflected in the article; different lowercase letters in the table indicate that the difference has reached a significant level (P < 0.05).
4. Influencing factors of C–N–P eco-stoichiometric characteristics of post fire forest ecosystem

In the long-term succession process of forest ecosystems, the eco-stoichiometry of different forest ecosystems is relatively stable, but due to the different responses of biogeochemical cycles to nutrient supply, interference will affect nutrient stability\cite{14}. Forest fire, as an important interference factor in the ecosystem, has a profound impact on the nutrient balance and circulation of the ecosystem\cite{13}. A large number of studies have confirmed that fire factors (including fire intensity, fire frequency, post fire recovery years), vegetation types and soil properties are closely related to the eco-stoichiometric characteristics of post fire forest ecosystems\cite{21,29,30,43}.

4.1 Fire factor

(1) **Fire intensity.** The heat release rate of fire when forest combustibles are burning is called fire intensity\cite{44}. Fire intensity is one of the main interference factors driving vegetation change, and plays an important role in shaping soil nutrient composition and eco-stoichiometry. High intensity forest fires can burn the forest canopy, fully burn organic matter, and cause the volatilization loss of C and N elements\cite{45}. Nave, et al.\cite{46} conducted an integrated analysis of the impact of forest fires on temperate forest ecosystems and found that the ground carbon reserves decreased by 67% after high-intensity fires. In addition, high-intensity forest fires will release elements with higher volatilization temperature, such as P, calcium (CA), magnesium (Mg), and increase the available nutrients in the forest land. However, the open forest land after the fire, surface runoff and erosion will redistribute nutrients, and have a long-term impact on the vegetation community and nutrient composition of the forest ecosystem\cite{19}. In contrast, moderate fire will not change the vegetation type, and the nutrient deposition after forest fire increases the productivity of the ecosystem, but the duration of nutrient increase is short and quickly tends to stabilize\cite{45}.

(2) **Fire frequency.** Fire frequency is an important factor to change vegetation communities and soil properties. Frequent forest fire disturbance exposes the forest land by reducing and temporarily removing the vegetation cover, accelerates the erosion of water and wind, and increases the risk of soil degradation\cite{1}. Pellegrini et al.\cite{14} explored the driving effect of fire frequency on soil on a global scale and found that the higher the fire frequency, the lower the content of soil TC and TN, especially in broad-leaved forests and savanna, the higher fire frequency reduced the content of soil TC and TN by 12.1% and 10.4%, respectively. However, in some forest ecosystems, long-term and large-scale planned fires are needed for forest fuel management\cite{4}. This forest fire management system can change the nutrient status by consuming biomass, depositing ash and accumulating nutrients, so that the organic form of nutrient mineralization can be changed\cite{47}. In Australia, long-term high-frequency planned burning can alleviate the P limitation, and even make the soil nutrient content tend to the N limitation\cite{30}. Vitousek et al.\cite{36} believe that the frequency of fire may be a key factor in determining the response of tropical rain forests to forest fires limited by P. In the *Pinus palustris* Mill forest of South Africa and the southeastern United States, because of the germination and growth of seeds after fire accelerates the recovery rate of N content, the plant community changes significantly with the frequency of fire\cite{48,49}.

(3) **Recovery period after fire.** The impact of forest fire on forest ecosystem is long-term, and the eco-stoichiometric characteristics are different in different periods. In the early stage after the fire, nutrients surged, which was conducive to vegetation restoration\cite{50}. With forest succession and plant growth, due to different sources of nutrient acquisition, the change of C, N and P content in soil will also affect the coupling of C, N and P in plants. Butler et al.\cite{9} studied the ecological stoichiometry of the lower leaves of Australian *Eucalyptus* forest after the planned fire and found that although the planned fire will not burn the trees, the increase of soil nutrients caused by ash deposition has a long-term (>4 a) impact on the ecological stoichiometry characteristics and nutrient absorption mode.
of the leaves of plants. In the northern forest ecosystem, C/N and C/P of litter decreased with the increase of recovery time after fire, while N/P showed an upward trend, indicating that plant growth was continuously restricted by P during vegetation recovery after fire\cite{28}. In the heavily burned area, although the amount of litter is still small and the bed structure of combustible is still thin with the recovery and renewal of vegetation, forest fire still has a long-term and lasting (>16 a) impact on the ecological stoichiometric characteristics of litter and soil\cite{2}.

### 4.2 Vegetation type

Vegetation type is one of the main factors affecting the succession of post fire communities. The obvious differences in chemical characteristics, productivity, litter decomposition rate and fine root turnover between different vegetation types cause different feedback effects on C, N and P of soil after fire\cite{51}. Compared with coniferous trees, deciduous broad-leaved trees grow faster, have higher litter and root regeneration rates, and higher N and P contents in leaves and roots\cite{52}. Hume et al.\cite{43} studied the soil of broad-leaved forest and coniferous forest after fire and found that the soil C/N of coniferous forest is greater than that of broad-leaved forest and mixed forest. The C/N of coniferous forest litter is high, and its tree species and litter contain flammable oil organic compounds\cite{53}, which increases the intensity of fire. In contrast, hard broad-leaved forests produce less flammable litter and wood debris, and are not prone to forest fires or have low fire intensity\cite{54}.

### 4.3 Soil properties

The redistribution of nutrients varies with elements and soil properties. Generally, soil aggregates with small particle size have better protective effects on soil C and N elements\cite{55}. High intensity forest fires cause the disintegration of soil aggregates, and the exposed soil after the fire undergoes rain erosion and wind transport erosion\cite{56}, resulting in the increase of large-size aggregates and the decrease of small-size aggregates of soil, thus affecting the soil C–N–P eco-stoichiometric characteristics\cite{57}. Forest fire can also reduce soil water holding capacity by promoting the formation of aquifers and the deposition of ash, resulting in increased surface runoff and soil surface erosion\cite{56}, intensifying nutrient loss and the redistribution of eco-stoichiometry. In the Great Khing’an Mountains of China, high-intensity forest fires reduce soil water capacity and soil moisture content\cite{58}, leading to a reduction in plant biomass, thereby reducing the content of soil organic carbon and TN\cite{59}. In contrast, the impact of low-intensity fire on soil properties is not significant\cite{60}. Therefore, soil properties after fire may no longer be the main factor driving the change of eco-stoichiometric characteristics of forest ecosystems.

### 5. Outlook

Nowadays, eco-chemometrics theory has made great progress in exploring the C–N–P eco-stoichiometric characteristics of forest ecosystems after fire. However, the heterogeneity and complexity of forest ecosystems lead to more complex effects of forest fire disturbance on their biogeochemical cycle. Therefore, an in-depth understanding of plant regulation strategies under forest fire disturbance, a clear understanding of the mutual coupling mechanism between multiple chemical elements after forest fire disturbance, and improving the relationship between aboveground and underground nutrient input and output with plant–litter–soil as a composite whole are of great significance in deeply understanding the nutrient cycle and balance of forest ecosystem under the background of global climate change and reasonably formulating forest fire management measures. The author believes that in the future, the research on the impact of forest fire on the C–N–P eco-stoichiometric characteristics of forest ecosystem should be further carried out from the following three aspects.

To explore the influence mechanism of forest fire disturbance on the homeostasis of plant eco-stoichiometry. Eco-chemometrics believes that organisms have the ability to maintain the relative stability of their own C, N and P elements, that is, homeostasis\cite{11}. At present, the study of homeostasis of plant eco-stoichiometric homeostasis at home and
abroad still belongs to a new research field, and there is little research on higher plants. The research area is also mostly concentrated on the grassland ecosystem[61,62]. The strength of plant homeostasis and its response mechanism and ecological strategy to external factors such as global climate change and human disturbance are not clear[62]. In the future, it is necessary to strengthen the characteristics and change rules of plant homeostasis in different ecosystems under forest fire interference, explore the impact of forest fire interference on plant ecological stoichiometric homeostasis, and verify the universality of plant ecological stoichiometric homeostasis theory, which is of great significance for the study of climate change and plant evolution[63].

Comprehensively expound the ecological chemometrics research of multiple elements under forest fire interference. The elements in plants interact with each other. Any change in the content of elements after forest fire interference may cause changes in the content of C, N and P[64]. Exchangeable base ions (Ca²⁺, Mg²⁺, K⁺, Na⁺) are important components of soil acid buffer capacity[5], and different combustion methods have different effects on the stoichiometric characteristics of these elements. Some studies believe that exchangeable base ions may play an important role in the effectiveness of N and P after fire[65], but the regulation mechanism of these elements on the main elements of plants after fire is still unclear[4]. In the future, we should strengthen the research on the role of these factors in regulating the time feedback of ecosystems to environmental changes, and improve the prediction of ecosystem response to future global changes.

Establish the eco-chemometrics relationship of plant–litter–soil complex system under forest fire disturbance. As the main link and repository of material circulation and energy flow in the ecosystem, plant–litter–soil is closely related to each other in structure and function[66]. The effect of forest fire on forest ecosystem is very complex. Although plant leaf eco-stoichiometry is often associated with soil eco-stoichiometry and provides an effective diagnostic method for evaluating nutrient limitation[67], the mechanism of plant–litter–soil nutrient element interaction and nutrient limitation on forest fire response is not clear[15]. For example, how the species and composition of vegetation after fire affect the redistribution of C and nutrients (N and P) among plants, litter and soil, and the change of the limiting effect of N and P on different tree species after fire. A comprehensive study on the coupling of C, N and P in plant–litter–soil and the nutrient flow and circulation mechanism under the interference of forest fire are conducive to reasonably formulating the post fire vegetation restoration mode or the frequency of planned fire, and reducing the potential risk of soil degradation and retrograde succession of vegetation communities[68].

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Conflict of interest

The authors declare that they have no conflict of interest.

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