

## Article

# Stoichiometric Characteristics of K, N, and P in the Shelter Forest Soils Across a Tropical Coastal Region of China

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## Abstract

Ecological stoichiometric ratios of soil provide insights into the interactions and limitations among elements. This study examined the nutrient characteristics K, N, and P stoichiometric ratios in the soils collected from three distinct shelter forests (*Casuarina equisetifolia*, secondary forest, and *Cocos nucifera*) in a tropical coastal region of Hainan Province, China. Significant differences were observed among forest types in terms of stoichiometric ratios and nutrient levels in soil ( $p < 0.05$ ). This may be related to the high species diversity in secondary forests and the complex composition of litter. Soil nutrient levels in the secondary forest were higher than those in *C. equisetifolia* and *C. nucifera*. The effects of soil nutrient factors on soil ecological stoichiometric ratios differed across shelterbelt types. Soil organic matter, total potassium, available potassium, and ammonium nitrogen content substantially influenced the N:P, K:P, and N:K ratios ( $Q^2 > 0.5$ ). Soil TN content was highly significantly positively correlated with N:P, N:K, in *C. equisetifolia* and *C. nucifera* ( $p < 0.01$ ), whereas in the secondary forest, it was highly significantly positively correlated with SOM and  $\text{NH}_4^+\text{-N}$  ( $p < 0.01$ ). These results reflecting the complexity of nutrient cycling as well as the interdependence and mutual regulation between vegetation and soil in coastal shelter forest ecosystems.

**Keywords:** tropical coastal area; stoichiometric ratio; shelter forest; soil nutrients; nutrient cycling



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## 1. Introduction

Soil nutrient recycling is an interconnected process in which changes in elemental composition drive soil nutrient recycling in ecosystems [1]. K, P, and N are essential elements supporting plant growth. Among these, N and P govern primary productivity in forest ecosystems, whereas K facilitates plant uptake of N and P [2,3]. The ecological stoichiometric ratio in soil reflects the variability in ecosystem function and characterizes soil nutrient recycling processes, thereby serving as an important indicator of material and energy balance within ecosystems [4].

Litter volume and composition vary among forest types, as do decomposition rates and nutrient cycling [5]. Furthermore, variations in root distribution and nutrient uptake rates among plants can contribute to heterogeneity in soil nutrient content and ecological

stoichiometric characteristics across forest types [3,6–10]. Coastal protection forests help regulate the local microclimate, protect against wind, prevent soil erosion, mitigate wave damage, reduce the occurrence of natural disasters, and ensure the safety of the coastal population [11,12]. Unlike inland forests [13–16], coastal windbreak forests are constantly exposed to strong winds and high-salinity environments, and the coastal soil is relatively nutrient-poor [17]. In recent years, several studies have investigated soil nutrients in coastal protective forests. Ai et al. [18] studied the physicochemical properties of the soil in five types of coastal protection forests along the sandy coast of Lianyungang; they found that forests improve soil structure, increase soil organic matter and readily available nutrients, and lower the pH. Zhang et al. [19] compared soil samples collected from coastal forests and exposed beaches on Hainan Island. Their results indicated that the protection forests can noticeably enhance P, C, and N levels and increase C pool in the coastal areas. Gao et al. [17] studied five types of shelterbelts on the sandy coast of Fujian and found that the inorganic N content and N transformation rate in secondary forests were higher than those in the other four types of planted forests. However, existing research mainly investigated the strategies to improve soil nutrients by coastal protection forests and compared different forest types. Few studies have investigated the stoichiometric properties of nutrients and nutrient-limiting factors in the soil of different types of coastal protection forests. Ecological stoichiometric ratios can reveal the limiting elements for plant growth and the synergistic and antagonistic interactions among nutrients, thereby providing critical scientific evidence for species selection and soil fertility management in coastal shelterbelts.

*C. equisetifolia* is the primary tree species in Hainan's coastal shelterbelts [20]. Wenchang City, located on Hainan Island, also contains well-preserved primary coastal shelter forests dominated by *C. nucifera* [21]. Secondary forests are predominantly composed of shrubs that grow naturally around villages in tropical coastal regions [22]. In this study, the understory soils of *C. equisetifolia*, *C. nucifera*, and secondary forests were investigated to determine whether the growth of these three shelter forests was limited by soil nutrients, and to identify the specific limiting nutrients. Accordingly, the following hypotheses were proposed for this study: (1) There are certain differences in the soil nutrient content and ecological stoichiometric ratios of soil N, P, and K among the three types of shelterbelts. (2) The correlations between soil N, P, and K stoichiometric ratios and soil nutrient contents varied among different shelterbelt types. (3) N, K, and P are the key indicators influencing the ecological stoichiometric ratios. This findings of this study are expected to provide a scientific foundation for the sustainable development of coastal shelter forests, contribute data to ecological stoichiometry research, and significantly advance our understanding of material and energy recycling in coastal forests.

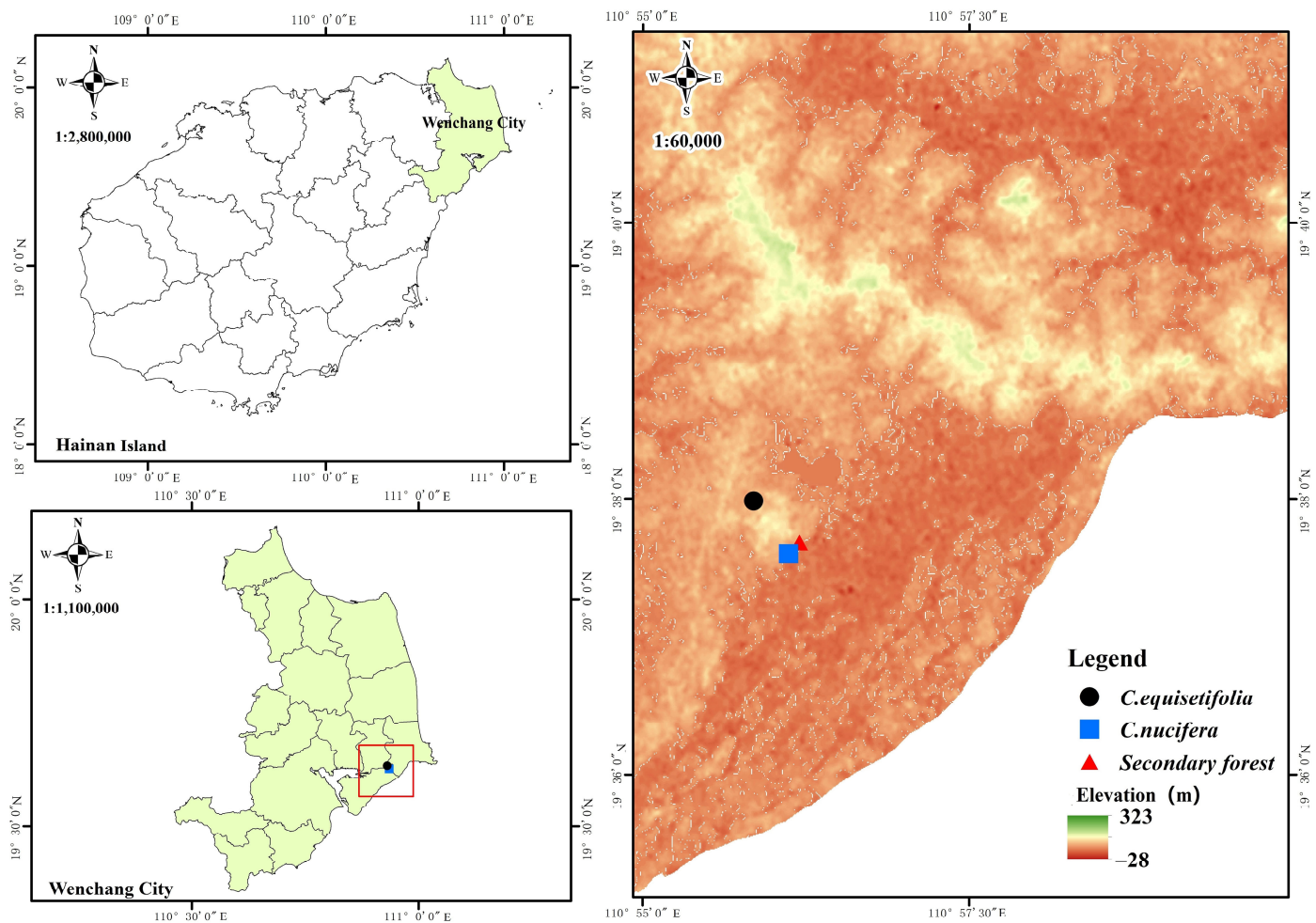
## 2. Materials and Methods

### 2.1. Study Area

The research site was in Wenchang, Hainan Province, China (19°20' N–20°10' N 108°21' E–111°03' E). The area lies within a plain with low hills, with the terrain sloping from the inland southwest toward the northeastern coast. Located in the northern tropical coastal region, it experiences a tropical monsoon maritime climate and is frequently affected by typhoons. The region is characterized by abundant light, water, humidity and heat, with an annual mean air temperature of 23.9 °C and a mean yearly sunshine duration of 1953.8 h. The mean yearly annual precipitation is 1721.6 mm, with distinct dry and wet seasons. Approximately 80% of the annual precipitation occurs during the wet season, which spans from May to October. While the dry season extends from November to April.

2.2. Soil Sampling

The soil data was obtained from the Wenchang Forest Ecosystems Positioning Observation Research Station in Hainan. Soil samples were collected monthly from March 2021 to March 2022, yielding 13 sampling events. Permanent plots were established by selecting three stand types with similar site conditions. Figure 1 shows the forest sites, while Table 1 presents an overview of the sample plots.



**Figure 1.** Plot locations. Note: Forests of *Casuarina equisetifolia* and *Cocos nucifera*, denoted as *C. equisetifolia* and *C. nucifera*, respectively.

**Table 1.** Overview of Sample Plots.

| Serial Number | Forest Type             | Soil Type | Dominant Species                                                                                                                                        |
|---------------|-------------------------|-----------|---------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1             | <i>C. equisetifolia</i> | Laterite  | <i>Casuarina equisetifolia</i>                                                                                                                          |
| 2             | Secondary forest        | Laterite  | <i>Castanopsis wenchangensis</i> , <i>Calophyllum inophyllum</i> , <i>Litsea pseudoelongata</i> , <i>Heteropanax fragrans</i> , <i>Psychotria rubra</i> |
| 3             | <i>C. nucifera</i>      | Laterite  | <i>Cocos nucifera</i>                                                                                                                                   |

Three 20 m × 20 m fixed plots were set up for each forest type, with each fixed plot spaced at least 10 m apart. In each plot, five 5 m × 5 m subplots were positioned, one at each of the four corners and one at the center. A 5-point sampling method was used for each subplot. After surface litter was removed, a 5 cm diameter soil auger was used to collect 100 g of topsoil from the 0–20 cm layer. The five soil samples from a subplot were mixed and placed into a self-sealing bag to form one homogenous soil sample, after which

it was labeled and transported to the laboratory. A total, of 15 soil samples were collected monthly for each forest type, yielding 45 samples per month and 585 samples over the entire study period.

### 2.3. Soil Nutrient Analysis

Soil samples were spread out in a well-ventilated area and air-dried naturally. That were weighed periodically until constant mass was achieved (with a mass difference of  $\leq 0.1\%$  between two consecutive weighings). The dried samples were then ground and passed through a 2 mm nylon sieve. Soil nutrients were evaluated in accordance with the relevant methods described in the literature [23]. pH was determined using the potentiometric method. Potassium dichromate oxidation method was employed to determine the soil organic matter (SOM) [24]. Total nitrogen (TN) was analyzed by the semi-micro Kelvin process. Total phosphorus (TP) was quantified by acid dissolution and molybdenum–antimony colorimetry [25]. Total potassium (TK) was assessed via alkali dissolution followed by flame photometry. Available phosphorus (AP) was measured through Bray I extraction followed by colorimetric analysis with molybdenum–antimony reagent. Available potassium (AK) was quantified by ammonium acetate extraction and flame photometry. Nitrate nitrogen ( $\text{NO}_3^-$ -N) and ammonium nitrogen ( $\text{NH}_4^+$ -N) [26] were obtained from soil using 1 mol/L KCl and analyzed using a continuous flow analyzer.

### 2.4. Data Processing

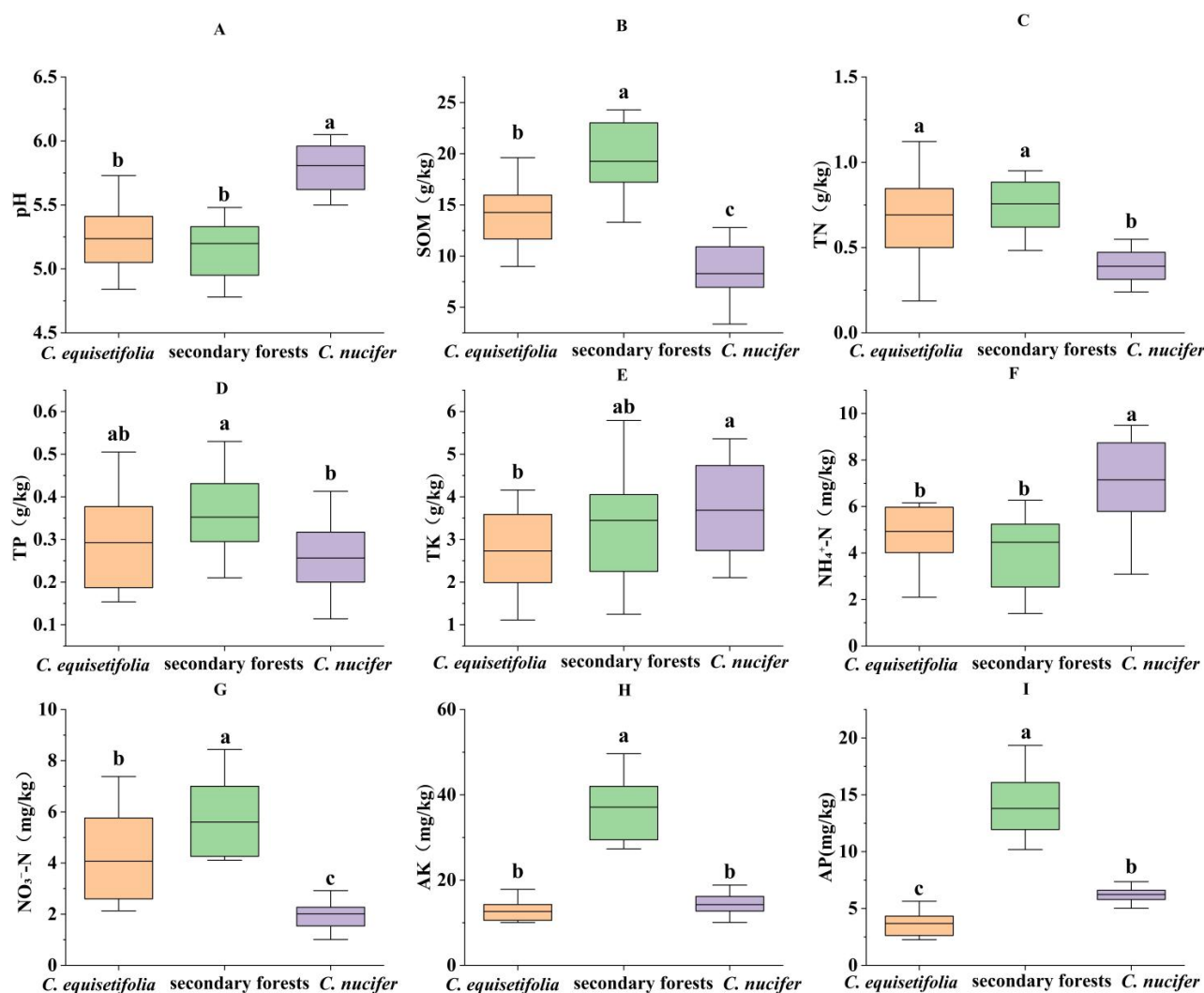
In this study, the arithmetic mean of the observations from each plot over a 13-month period was calculated, and an analytical dataset was constructed using the plots as independent statistical units ( $n = 3$ ). Microsoft Excel 2019 and Origin 2024 were employed for data assessment and visualization. Differences in soil nutrients and stoichiometric ratios among forest types were detected by one-way ANOVA ( $\alpha = 0.05$ ) and the least significant difference (LSD) test. Pearson correlation analysis was employed to examine the associations between soil nutrients and stoichiometric ratios.

Partial least squares (PLS) regression is suitable for scenarios with numerous independent variables and small sample sizes. It effectively addresses the issue of multicollinearity among independent variables that ordinary multiple regression cannot resolve, ensuring model stability [27]. Therefore, this study employed the pls package in R 4.5.1 to perform PLS regression analysis, examining the influence of soil nutrients on eco-chemometric ratios.

## 3. Results

### 3.1. Soil Nutrients in the Three Shelter Forests

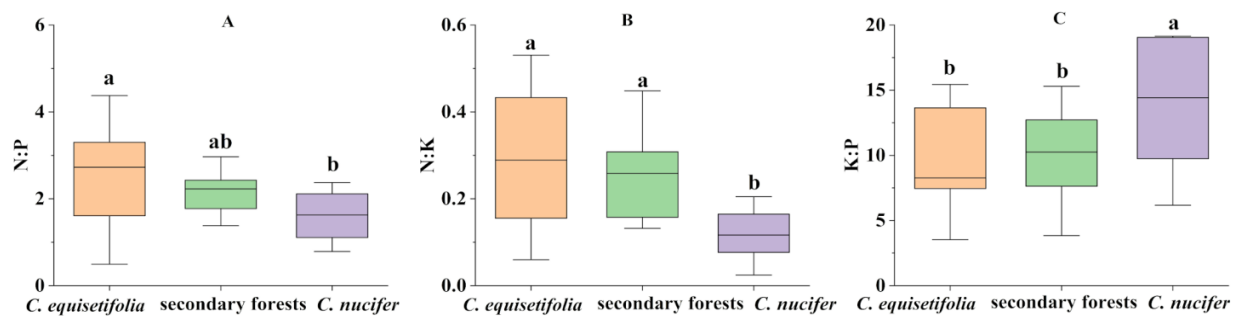
Soil nutrient concentrations varied considerably across the three shelter forests (Figure 2). The soil pH of *C. nucifera* was the highest, and it showed a significant difference compared to that of *C. equisetifolia* and secondary forests ( $p < 0.05$ ). Soil SOM, TN, TP,  $\text{NO}_3^-$ -N, AK, and AP concentrations were all highest in the secondary forest, with substantial variations ( $p < 0.05$ ) in SOM and  $\text{NO}_3^-$ -N between different forest soils. The secondary forest exhibited significantly different TN levels compared with the other two forest types ( $p < 0.05$ ). TP showed significant differences between the secondary forest and *C. nucifera* ( $p < 0.05$ ). AK and AP showed significant differences between *C. nucifera* and both other forest types ( $p < 0.05$ ). Soil TK and  $\text{NH}_4^+$ -N concentrations were highest in *C. nucifera*, with TK showing significant differences between *C. equisetifolia* and *C. nucifera* ( $p < 0.05$ ).  $\text{NH}_4^+$ -N showed significant differences between *C. nucifera* and both other forest types ( $p < 0.05$ ). Overall, the soil nutrient content was greater in the secondary forest than in the *C. nucifera* and *C. equisetifolia* forests.



**Figure 2.** Soil factors in the three shelter forests: (A–I) pH, SOM, TN, TP, TK,  $\text{NH}_4^+\text{-N}$ ,  $\text{NO}_3^-\text{-N}$ , AK, and AP contents. Note: Distinct letters show significant variations ( $p < 0.05$ ) in soil nutrients. Forests of *Casuarina equisetifolia* and *Cocos nucifera*, denoted as *C. equisetifolia* and *C. nucifera*, respectively.

### 3.2. Stoichiometric Ratios of K, N, P in Different Shelter Forest Soils

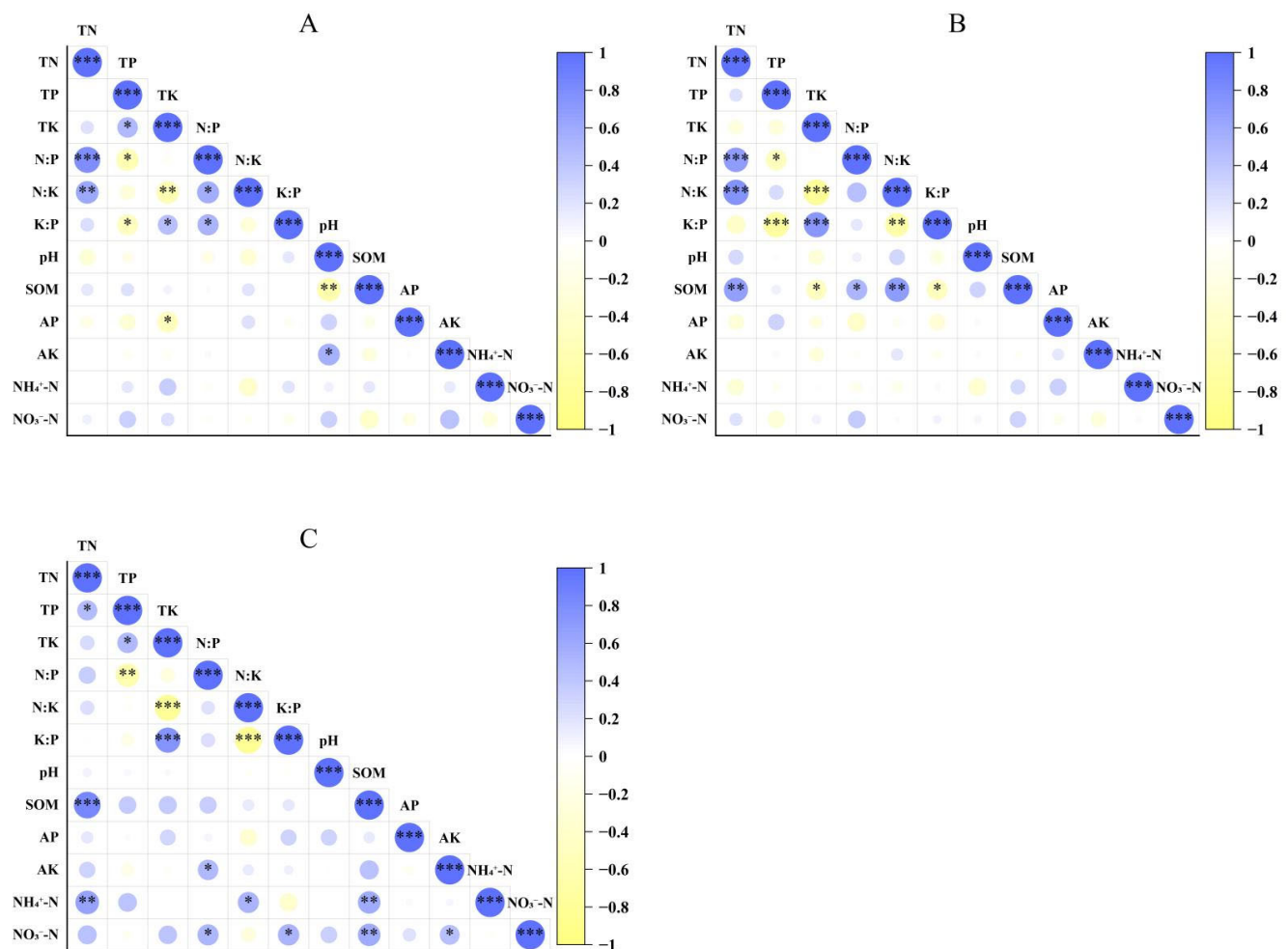
Figure 3 illustrates the elemental ratios of K, N, and P in different forest soils. The mean N:P ratio of *C. equisetifolia* was substantially greater compared to that of *C. nucifera* ( $p < 0.05$ ), while the mean N:P ratio of the secondary forest was not significantly different from that of the two. The mean N:K ratios of *C. equisetifolia* and secondary forest were relatively high and showed no significant differences, although both were noticeably greater than that of *C. nucifera* ( $p < 0.05$ ). The mean K:P ratio of *C. nucifera* was substantially greater than those of *C. equisetifolia* and secondary forest ( $p < 0.05$ ), with secondary forest and *C. equisetifolia* forest showing no noteworthy difference. Overall, the N:K and N:P ratios of secondary forest and *C. equisetifolia* were both significantly higher than that of *C. nucifera*, with the N:K ratio being twice as high, while the K:P ratio for *C. nucifera* was much higher than those for the *C. equisetifolia* and secondary forests.



**Figure 3.** N:P (A), N:K (B), and K:P (C) ratios in different forest soils. Note: Distinct letters show significant variations ( $p < 0.05$ ) in soil nutrients. Forests of *Casuarina equisetifolia* and *Cocos nucifera*, denoted as *C. equisetifolia* and *C. nucifera*, respectively.

### 3.3. Relationships Between Stoichiometric Characteristics of Soil Nutrients and Influencing Factors in Different Shelter Forests

Figure 4 shows heat maps of soil chemical characteristics and the correlations among nutrient parameters *C. equisetifolia* forest, *C. nucifera* forest, and secondary forests, respectively. In the *C. equisetifolia* forest, soil TN content showed a highly significant positive correlation with N:P and N:K, whereas TK and pH were both negatively correlated with N:K and SOM, respectively (all  $p < 0.01$ ).



**Figure 4.** Correlations between the stoichiometric ratios of N, P, and K and other soil nutrient concentrations in coastal shelter forests. (A–C) stands of *Casuarina equisetifolia*, *Cocos nucifera* and secondary forest, respectively. Note: \*, \*\*, and \*\*\* represent the significance levels at 0.05, 0.01, and 0.001, respectively.

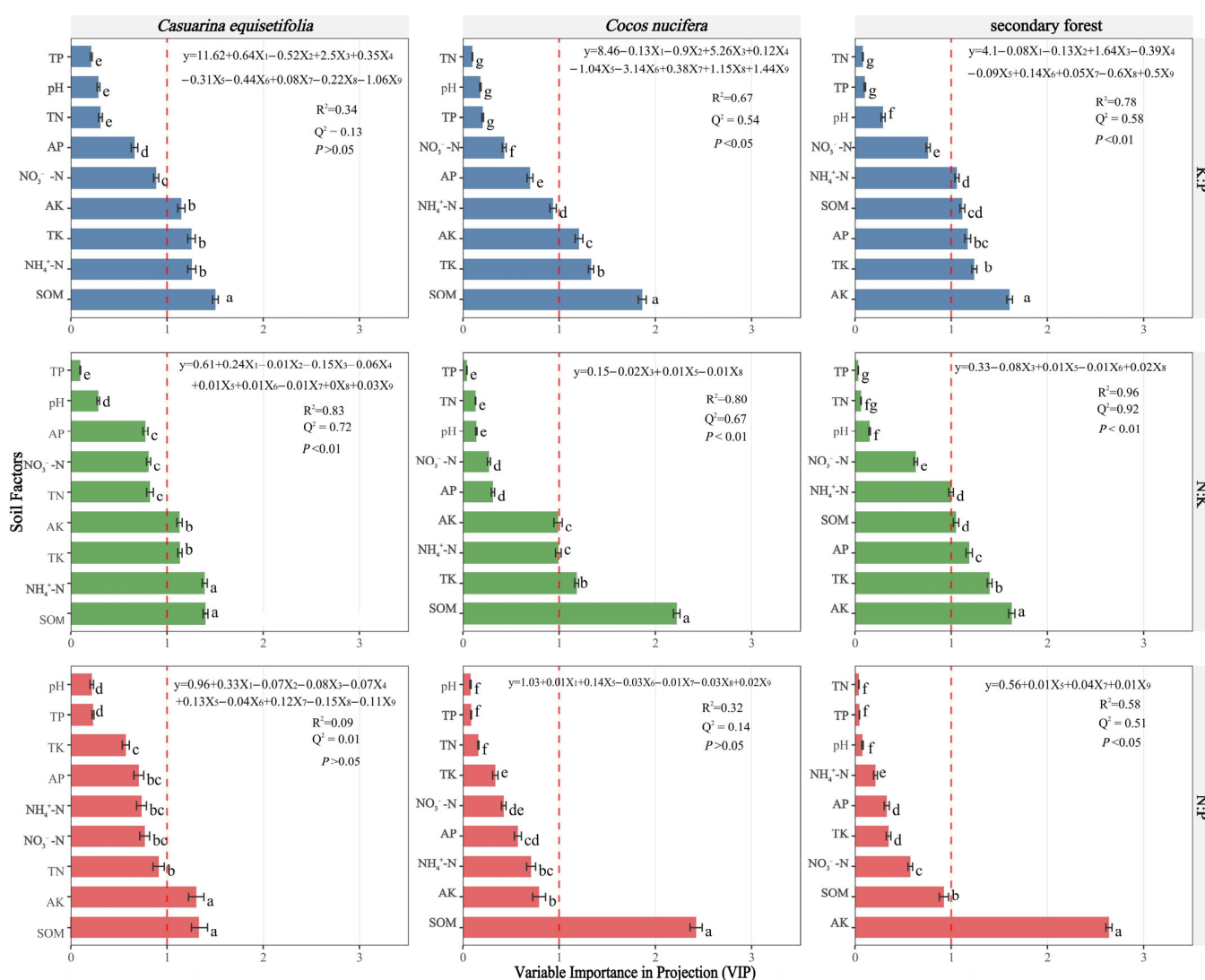
In the *C. nucifera* forest, soil TN exhibited significant positive associations with N:P, N:K, and SOM ( $p < 0.01$ ). TP showed a significant negative association with K:P ( $p < 0.001$ ). TK displayed a negative relationship with N:K and positive one with K:P ( $p < 0.001$ ). N:K demonstrated a negative correlation with K:P and positive correlation with SOM ( $p < 0.01$ ).

In the secondary forest, the significant correlations were as follows: TN positively with SOM and  $\text{NH}_4^+\text{-N}$  ( $p < 0.01$ ). TP negatively with N:P ( $p < 0.01$ ). TK positively with N:K and negatively with K:P ( $p < 0.01$ ) and N:K negatively with K:P ( $p < 0.001$ ). SOM positively with  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_3^-\text{-N}$  ( $p < 0.01$ ).

Overall, the correlations between the soil ecochemical ratios and soil nutrient concentrations differed among the three types of shelterbelts, illustrating the complex interactions between different forest types and soil physicochemical properties.

### 3.4. Effects of Soil Nutrients in Different Shelterbelts on N, P, K Stoichiometric Ratios

PLS regression indicated that soil nutrients significantly influence the N:P ratio in secondary forests ( $Q^2 > 0.5$ ) (Figure 5 blue). The SOM, AK, TK, and AP content in secondary forest soils are key indicators that significantly affect the N:P ratio (VIP > 1).



**Figure 5.** Influence of soil factors on K:P (blue), N:K (green), and N:P (red) revealed by partial least squares regression. Note:  $R^2$ : Measure of model fit.  $Q^2$ : Percentage of variation explained by cross-validated predictions ( $Q^2 > 0.5$  indicates good fit.  $Q^2 < 0.5$  depicts poor fit). VIP: Variable Importance

for the Projection (VIP > 1 indicates significant influence of the independent variable on the dependent variable, given a good model fit). Significant differences exist between the nutrients denoted by different letters. The red dashed line represents the variable importance in projection (VIP) threshold used to select significant predictors.

Soil nutrients in all three coastal shelter forests significantly influenced the N:K ratio ( $Q^2 > 0.5$ ) (Figure 5 green). For *C. equisetifolia*, soil SOM, AK,  $\text{NH}_4^+\text{-N}$ , TK, and TN content significantly affected N:K (VIP > 1). For *C. nucifera*, soil SOM,  $\text{NH}_4^+\text{-N}$ , and TK content significantly affected N:K (VIP > 1). For secondary forests, soil AK, TK, and AP content significantly affected N:K (VIP > 1).

Soil nutrients significantly influence the K:P ratio in *C. nucifera* and secondary forests ( $Q^2 > 0.5$ ) (Figure 5 red). Specifically, soil parameters including SOM,  $\text{NH}_4^+\text{-N}$ , and TK content were indicators that strongly influenced K:P ratios in *C. nucifera* (VIP > 1). Similarly, soil parameters including SOM, AK,  $\text{NH}_4^+\text{-N}$ , TK, and AP content were indicators that strongly influenced K:P ratios in the secondary forest (VIP > 1).

In summary, the key soil nutrient indicators influencing soil stoichiometric ratios vary among different forest stands. Soil SOM, AK,  $\text{NH}_4^+\text{-N}$  and TK contents in the three coastal shelter forests are significant indicators that substantially influence the nutrient ratios in soil.

## 4. Discussion

### 4.1. Soil Nutrient Content of Different Shelter Forests

Soil nutrient content reflects organic matter composition and soil fertility, serving as an effective indicator of soil K, N, and P cycling [28,29]. Coastal sandy areas are transitional zones where the land meets the sea. Influenced by atmospheric activity, tides, and sea fog, these areas are characterized by high wind speeds, high salinity, and high humidity [30–33]. The coastal areas selected for this study have sandy soil. The soil matrix consists of loose, unstructured sand particles, which have low cohesion and high permeability, resulting in relatively poor soil fertility [2,34,35]. Soil N content in the study area was significantly lesser compared to the Chinese standard (1.5 g/kg) and the standard for Chinese tropical rainforests (2.75 g/kg) [36,37]. Soil P content was lower than both the Chinese average (0.65 g/kg) and the global average value (2.8 g/kg) [38]. Soil K content in this study ranged from 2.73 to 3.68 g/kg (Figure 2). According to the “National Second Soil Survey Nutrient Classification Standards”, the K levels in the soil samples were within Level 6, indicating extremely K-deficient soil.

Dominant tree species in different forest types influence soil nutrient cycling processes and spatial distribution patterns by regulating the amount of litterfall and the microenvironment [39]; a potential explanation for the considerable differences in soil nutrient content between forest stands lies in this aspect. The findings suggest that soil nutrient levels in secondary forests are generally higher than those in *C. equisetifolia* and *C. nucifera*. This may be related to the high species diversity in secondary forests and the complex composition of litter. The decomposition rates and cycles of different plant litter types complement one another, providing a continuous and stable supply of substrate for soil microorganisms. This optimizes the composition of microbial populations and enhances their activities, thereby significantly promoting SOM mineralization and nutrient cycles [40–42]. In contrast, *C. equisetifolia* and *C. nucifera* possess low species diversity, with low understory biodiversity. Their litter composition is simple, and *C. nucifera* litter is rich in substances that do not easily decompose, such as phenols and tannins [43–45]. This is likely the main factor contributing to lower rates of nutrient return to the soil and reduced nutrient cycling efficiency. The aforementioned mechanisms may be key reasons why secondary forests had substantially greater nutrient levels in soil than the other two forests.

#### 4.2. N:K, K:P, and N:P Ratios in Coastal Shelter Forests

The ratios of K:P, N:K, and N:P in soil reflect the adaptive responses of vegetation to external environmental drives [46]. N:P serves as an indicator of the relative availability of N and P for vegetation and is widely used to diagnose nutrient limitation in soils [47,48]. The N:P ratio in Chinese soils averages approximately 3.9 [31]. In the present study, the average N:P ratios for *C. equisetifolia*, secondary forest, and *C. nucifera* were 2.73, 2.23, and 1.63, respectively, all below the national mean. These findings are similar to those reported for understory soils in 12 coastal cities and counties on Hainan Island [19] and for coastal sandy soils under the canopy of the Dahe State Protective Forest Farm in Changle, Fujian [49].

N:K and P:K ratios serve as important reference points for soil nutrient management and plant growth [50]. According to a previous research [51], K becomes the primary limiting factor for plant growth when  $K:P < 3.4$  and  $N:K > 2.1$ . The N:K ratios for *C. equisetifolia*, secondary forest, and *C. nucifera* were 0.29, 0.26, and 0.12, respectively, while their corresponding K:P ratios were 10.13, 9.94, and 16.57. None of the forests in this study met these criteria, suggesting that K availability may not be a primary limiting factor for vegetation growth.

#### 4.3. Relationship Between Stoichiometric Characteristics of Soil Nutrients and Influencing Factors of Different Shelter Forests

According to the correlation analysis, significant correlations were observed among soil nutrient contents as well as between these nutrient contents and the stoichiometric ratios of N, P, and K. However, some differences were noted across forest types. Studies have demonstrated that SOM content is closely related to soil quality [52]. In this study, SOM contents in the secondary forest and *C. nucifera* plantation demonstrated significant positive dependences on ( $p < 0.01$ ) with TN,  $NH_4^+-N$ ,  $NO_3^--N$ , and N:K. This is consistent with the findings of previous studies [53–55] that the decomposition of SOM in the topsoil promotes nitrogen release and that increased SOM content may also lead to higher nitrogen levels.

Based on the results of the partial least squares regression model, soil SOM, AK,  $NH_4^+-N$ , and TK content were identified as indicators substantially influencing the ecological stoichiometric ratios of K, P, and N in the shelter forest soils. SOM serves as the core reservoir for forest soil nutrients, and SOM content directly influences the mineralization rates and supply capacity of N and P. Higher SOM levels typically indicate stronger nutrient retention and transformation capabilities, enabling regulation of N and P availability [56,57]. K, as an essential macronutrient for plants, plays a crucial role in regulating plant–water relations, enzyme activity, and photosynthesis, thereby indirectly influencing the absorption and utilization efficiency of N and P [58]. Soil AK is the most readily available form of potassium for plant uptake, and its concentration directly reflects the level of plant-available potassium in the soil [59–63]. TK and AK were identified as a key indicator, highlighting the potentially underestimated role of K in regulating the nutrient balance of various shelter forests. Soil nitrogen pools consist of organic and inorganic nitrogen, with 95%–99% of the nitrogen present in the latter form. Plants can directly absorb and utilize inorganic nitrogen, and  $NH_4^+-N$  is one of the key components of inorganic nitrogen. Therefore,  $NH_4^+-N$  indirectly influences soil nitrogen availability through processes such as mineralization and nitrification [64–68]. This study still has the following limitations. First, the number of spatially independent samples was limited, the seasonal dynamics and interannual variations in soil nutrients were not examined. Secondly, the potential driving mechanisms behind soil nutrient differences, such as litter decomposition rates and microbial community structure, that were not directly measured. Building on this

foundation, next research should be further deepened to more comprehensively elucidate the regulatory mechanisms of soil ecochemical ratios.

## 5. Conclusions

This research examined three coastal shelter forests, namely *Casuarina equisetifolia*, secondary forest, *Cocos nucifera*, in a tropical coastal area region to analyze variations in soil nutrient characteristics, stoichiometric nutrient ratios, and the controlling factors. The results confirmed the first and second hypotheses proposed above, but did not support the third hypothesis. Significant differences in soil nutrient content and ecochemical ratios were noted among the three types of shelterbelts. The soil nutrient levels in the secondary forest were higher than those in *C. equisetifolia* and *C. nucifera* forests. Soil SOM, AK,  $\text{NH}_4^+\text{-N}$ , and TK content were significant indicators that substantially influenced the eco-stoichiometric nutrient ratios in shelter forests. Significant correlations were observed both among soil nutrients and between soil nutrients and ecological stoichiometric ratios in different forest types. However, though the magnitudes of these correlations vary, illustrating the complex interactions between forests and soil.

These findings implicate a complex network of interactions and restrictions between soil nutrients and the ecological stoichiometric ratios of N, K, and P in three typical tropical coastal shelter forests. Due to limited spatial samples and the lack of data on seasonal dynamics and driving mechanisms (e.g., litter decomposition and microbes), future research should further investigate the regulatory mechanisms of soil ecological stoichiometric ratios.

**Author Contributions:** Conceptualization, Y.C., Z.C. and J.L.; methodology, S.N. and Y.C.; investigation, Z.L., S.S., J.J., L.L., H.C. and X.L.; data curation, X.L. and H.C.; writing—original draft preparation, X.L.; writing—review and editing, Y.C. and Z.C.; visualization, X.L.; project administration, S.N. and Y.C.; funding acquisition, Y.C. All authors have read and agreed to the published version of the manuscript.

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