The Linkage of Soil CO₂ Emissions in a Moso Bamboo (Phyllostachys edulis (Carriere) J. Houzeau) Plantation with Aboveground and Belowground Stoichiometry

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Abstract: Understanding the effects of soil stoichiometry and nutrient resorption on soil CO₂ emissions is critical for predicting forest ecosystem nutritional demands and limitations to optimal forest growth. In this study, we examined the effects of above- and belowground stoichiometry on soil CO₂ emissions and their mediating effect on soil respiration in subtropical moso bamboo (Phyllostachys edulis) plantations. Our results showed that the soil respiration rate did not differ significantly among four bamboo stands. Nitrogen (N) and phosphorous (P) concentrations were higher in bamboo leaves than litter, whereas the C:N and C:P ratios showed the opposite trend. Significant positive correlations of soil cumulative CO₂ emission with litter C:P (p = 0.012) and N:P (p = 0.041) ratios indicated that litter stoichiometry was a better predictor of soil respiration than aboveground stoichiometry. Cumulative soil CO₂ emissions were significantly negatively correlated with soil microbe C:N (p = 0.021) and C:N (p = 0.036) ratios, and with soil respiratory quotients (p < 0.001). These results suggest that litter and soil stoichiometry are reliable indicators of the soil respiration rate. This study provides important information about the effects of ecosystem stoichiometry and soil microbial biomass on soil CO₂ emissions and highlights the editing role of soil nutritional demands and limitations in the association between soil respiration rates and aboveground plant tissues.

Keywords: ecological stoichiometry; moso bamboo; plant tissues; soil microbes; soil respiration

1. Introduction

Ecological stoichiometry has been used to investigate plant growth, nutrient conditions, and physiological characteristics [1]. Leaf nitrogen (N) and phosphorus (P) concentrations, as well as the N:P ratio, play important roles in controlling plant photosynthesis, metabolism, and growth [2]. The foliar N:P ratio is used to evaluate plant nutrient limitations [3], where N:P ratios of 14 and 16 typically indicate N and P limitations, respectively [4]. Changes in N or P levels in various plant parts indicate functional changes in nutrient uptake and allocation [5].

Plant foliage stoichiometry, which varies widely among plant organs, litter, soil microbes, and soil, plays an important role in soil nutrient status and aboveground–belowground soil nutrient linkage [6]. The relationships between soil and foliar carbon (C):N:P stoichiometry in ecosystems can be used to investigate the roles of available nutrients in plant growth under soil nutrient limitations [7]. Plant tissue stoichiometry is constrained by belowground stoichiometry [8]. Fan et al. [9] showed that plant N:P ratios were significantly related to soil N:P ratios in Eucalyptus urophylla × grandis, Pseudosasa amabilis, and Rubus swinhoei, indicating that soil nutrients are tightly coupled to plant nutrients. Bell et al. [8] showed that plant tissue stoichiometry was related to soil and...
microbial stoichiometry, and that the leaf C:N ratio was positively correlated with the soil C:N ratio and negatively correlated with the soil N:P ratio. Soil microbial communities are related to the N:P stoichiometry of the plant and soil system [10]. Further studies are needed to evaluate the stoichiometry of above- and belowground compartments, and their interactions [11].

Nutrient resorption between green leaves and litter affects litter decomposition, soil respiration, nutrient mineralization, and N fixation by regulating litter quality [12]. Zhao et al. [13] showed that soil respiration is strongly influenced by changes in plant and soil stoichiometry, as well as soil enzyme activity. Soil microbial respiration is related to soil and litter C [14], and microbial respiration is positively correlated with the soil C:P ratio and C concentration; thus, microbial nutritional demands depend on soil stoichiometry [15]. However, the effects on ecosystem functions and processes, such as soil C emission, of these plant and soil stoichiometric relationships remain poorly understood [9]. Shifts in microbial biomass C, N, and P concentrations, and their stoichiometry may impact soil respiration by increasing labile soil C and altering microbial communities [13]. Ferlian et al. [11] showed that soil stoichiometry plays a more important role in soil microbial biomass and respiration than plant stoichiometry. However, little is known about the potential effects of plant and soil stoichiometry on soil microbial activity and respiration, or soil CO₂ emissions [16].

Moso bamboo (Phyllostachys edulis (Carriere) J. Houzeau) is an important forest resource in southern China, occupying 3.87 × 10⁶ ha and accounting for 71.9% of the total bamboo area. Plant stoichiometry has been shown to be correlated with soil ecosystem functional characteristics, and to influence soil biogeochemical cycling processes [8]. In this study, we determined C, N, and P concentrations, and their stoichiometry, in various plant tissues and soil in a moso bamboo plantation. The main objectives of this study were to investigate the effects of C, N, and P stoichiometry of fresh leaves, litter, and soil on soil CO₂ emissions, assess the relationships between soil microbes and above-and belowground stoichiometry, and determine whether above-or belowground stoichiometry is better as an indicator of soil CO₂ emissions. Finally, we discussed the effects of above-and belowground stoichiometric changes on soil respiration and evaluated the influence of ecosystem stoichiometry on soil CO₂ emissions by the nutrient resorption function of moso bamboo.

2. Materials and Methods

2.1. Site Description

The study site is located within Maoshanwu Nature Reserve (119°56′–120°02′ E, 30°03′–30°06′ N), Zhejiang Province, China, which has an area of 536.7 ha, a core area of 348.8 ha, and an altitude of 10–536 m. The soil type belongs to Haplic Luvisol [17] and is mainly derived from granite. The study area has atypical subtropical monsoon climate with four distinct seasons, the mean annual precipitation is approximately 1513 mm, the annual mean sunshine duration is 1995 h, and the frost-free period is 237 days per year. The mean annual temperature is 16.9 °C, and maximum and minimum monthly temperatures are 25.4 and 4.5 °C, respectively.

The study area has historically consisted of forest; the native forest was destroyed for agricultural development, and to meet wood and charcoal demands. The vegetation includes moso bamboo, Cunninghamia lanceolata, Pinus massoniana, natural secondary forest, and shrub forest.

2.2. Experimental Design

Four stands with similar site conditions (elevation and slope etc.) were randomly selected within the study area in March 2014 (Table 1). Three 20 × 20 m standard plots were established in each stand. The diameter at breast height (DBH) of all trees was measured in each plot, and five sample bamboo plants were selected according to the average DBH. In March 2014 and April 2016, fresh leaves and litter were collected as the initial and
In July 2015 and December 2015, fresh leaves and litter were also collected as growing season and nongrowing season value. Fresh leaves of each selected sample tree were collected from four directions and then mixed into a sample with five repeated in each plot. Fresh litter samples were randomly collected by hand in each plot, divided into five parts with five repeated in each plot. Then C, N, and P concentrations were measured in the bamboo leaves and litter. Fresh leaf samples were dried for 30 min at 105 °C and litter samples were dried for 48 h at 70 °C until constant weights were attained.

Table 1. General information of the study moso bamboo stands (mean ± SD, n = 3).

| Stands | Elevation (m) | Height (m) | DBH (cm) | Slope (°) | Canopy Density | Litter Depth (cm) | 1-2 Year-Old (Plants/ha) | 3-4 Year-Old (Plants/ha) | 5-6 Year-Old (Plants/ha) | Above 7 Year-Old (Plants/ha) | Total (Plants/ha) |
|--------|---------------|------------|----------|-----------|----------------|-------------------|------------------------|------------------------|-----------------------|------------------------|-----------------|
| 1      | 141           | 12.8 ± 1.1 | 11.9 ± 1.8 | 10        | 0.8           | 2.04 ± 0.56       | 875 ± 50               | 1000 ± 175             | 725 ± 40              | 100 ± 15              | 2200 ± 150        |
| 2      | 115           | 13.0 ± 0.9 | 12.7 ± 2.2 | 15        | 0.95          | 2.22 ± 0.49       | 550 ± 85               | 800 ± 125              | 1025 ± 100            | 750 ± 75              | 3125 ± 385        |
| 3      | 86            | 13.3 ± 1.5 | 13.6 ± 2.6 | 20        | 0.9           | 2.47 ± 0.67       | 725 ± 170              | 1050 ± 75              | 1100 ± 125            | 975 ± 80              | 3850 ± 140        |
| 4      | 157           | 12.2 ± 1.8 | 12.1 ± 1.9 | 20        | 0.8           | 2.60 ± 0.71       | 900 ± 45               | 775 ± 120              | 625 ± 130             | 200 ± 15              | 2500 ± 190        |

Note: DBH: diameter at breast height.

In March, 2014, July 2015, December 2015 and April 2016, six soil samples in each plot were collected at depths of at 0–10 and 10–20 cm, respectively, by "S" type using an auger (diameter, 3 cm), and then, randomly, two soil samples were mixed together to create three samples from each soil layer. All fresh soil samples were sieved through a 2 mm mesh to remove roots and visible debris, and each mixed sample was air-dried and sieved through a 0.25 mm mesh before soil nutrient analysis.

Soil respiration rates were measured using a Li-8100 soil CO$_2$ flux system (LI-COR Inc., Lincoln, NE, USA). We randomly installed five polyvinyl chloride (PVC) collars (height, 10 cm; diameter, 20 cm) 2–3 cm above the soil surface in each subplot with as little interference as possible. The first measurements were performed 1 week after the collars had been installed to allow recovery from disturbance. All installed PVC collar remained intact throughout the experimental period, i.e., from May 2014 to April 2016. All measurements were performed on sunny days without strong wind, at 9:00–16:00 local time in all months. Each collar measurement typically lasted 6–7 min with 2 repeated, and then averaged the results. Generally, each collar was measured twice a month in the growing season and once a time in the nongrowing season.

2.3. Plant and Soil Chemical Analyses

Leaf and litter C concentrations were measured using an H$_2$SO$_4$-HClO$_4$ digestion method. N concentrations were estimated using the Kjeldahl method with a UDK 152 distillation and titration unit, and a DK20 digestion unit (VELP Scientifica, Usmate, Italy). P concentrations were determined using a standard ammonium molybdate method [18]. Soil organic C (SOC) and soil total N (STN) were measured using an elemental analyzer (Elementar, Langenselbold, Germany), and soil total P (STP) was measured by wet digestion with HClO$_4$-H$_2$SO$_4$, and then colorimetrically [19]. Soil microbial biomass C (SMC) and N (SMN, respectively) were measured using chloroform fumigation-extraction method [20], which is described in detail elsewhere [21].

2.4. Data Analysis

Nutrient resorption efficiency (NRE) was estimated as follows [22]:

$$\text{NRE} = (1 - \frac{X_{\text{litter}}}{X_{\text{leaf}}}) \times 100\%$$  \hspace{2cm} (1)

where NRE is N or P resorption efficiency and X$_{\text{leaf}}$ and X$_{\text{litter}}$ are leaf and litter N and P concentrations, respectively.

The respiration quotient (RQ) was estimated as follows [21]:

$$\text{RQ} = \frac{\text{SOC}}{(\text{CO}_2 - C)}$$  \hspace{2cm} (2)
Cumulative soil CO₂ emissions (Rₑ, kg CO₂ m⁻²) were estimated using the following exponential equation [23]:

\[
R_c = \sum_{i=1}^{24} R_{si} \times t_i \times 10^{-9} \times 44
\]

where \(R_{si}\) is the mean monthly soil respiration rate, \(t_i\) is the time within each month (s), and 44 is the CO₂ molecular mass (g mol⁻¹).

All statistical analyses were performed using Sigma Plot (ver.12.5; SYSTAT Software Inc., San Jose, CA, USA) and SPSS software (ver.22.0; SPSS Inc., Chicago, IL, USA). One-way analysis of variance (ANOVA) was conducted to compare plant and soil nutrient and stoichiometry values among four stands. A regression analysis was used to describe the relationships between annual soil cumulative respiration, fresh leaves, and litter as well as soil stoichiometry. The significance level for all statistical tests was \(p \leq 0.05\). A structural equation model (SEM) was devised using the SPSSAMOS program (ver. 26.0) to estimate changes in NRE that sequentially affect soil nutrient stoichiometry, microbial activity, and soil cumulative CO₂ emission.

3. Results
3.1. Plant Nutrient Content and Stoichiometry in Leaves and Litter

We detected no significant difference in C concentrations between leaves and litter (Figure 1a). N and P concentrations were higher in leaves than litter (Figure 1b,c). The opposite trend was observed in the C:N and C:P ratios, which were lower in leaves than in litter (Figure 1d,e). The litter C:N ratio was significantly higher in Stand 2 than in Stand 3 (Figure 1d). The leaf C:P ratio was significantly higher in Stand 3 than in Stands 1 and 2, and the litter C:P ratio was higher in Stands 2 and 4 than in Stand 1. Leaf and litter N:P ratios were higher in Stands 3 and 4 than that in Stand 1 (Figure 1f). P and N resorption efficiency were significantly higher in Stand 2 than in Stands 1 and 3 (Figure 2).

![Figure 1](image_url)

**Figure 1.** Carbon (C), nitrogen (N), and phosphorous (P) concentrations, and stoichiometry, in litter and leaves of moso bamboo (**Phyllostachys edulis**). The error bar was the mean value of four samplings (mean ± SD, \(n = 4\)), and different lowercase letters indicate significant differences between groups (\(p \leq 0.05\)). (a–c), is the concentration of C, N, P of leaves and litter; (d–f), is the stoichiometry of C:N ratio, C:P ratio and N:P ratio in leaves and litter.
Soil organic carbon (g kg\(^{-1}\))

![Figure 2. N and P resorption efficiency in four moso bamboo stands. The error bar is the mean value of four samplings (mean ± SD, n = 4), and different lowercase letters indicate significant differences between groups (p ≤ 0.05).](image)

**3.2. Soil Stoichiometry Differences among Bamboo Plantations**

At soil depths of 0–10 and 10–20 cm, the mean SOC values were 48.85 ± 2.78 and 44.22 ± 2.34 g kg\(^{-1}\), respectively. The STN values were 2.31 ± 0.11 and 2.05 ± 0.10 g kg\(^{-1}\), the STP values were 0.43 ± 0.09 and 0.42 ± 0.08 g kg\(^{-1}\), the soil C:N ratios were 12.28 ± 0.21 and 12.57 ± 0.38, the soil C:P ratios were 118.31 ± 30.20 and 110.01 ± 27.82, and the soil N:P ratios were 5.57 ± 1.33 and 5.09 ± 1.25, respectively (Figure 3).

![Figure 3. Soil organic C, soil total N and soil total P concentration, as well as their stoichiometry, in moso bamboo stands. The error bar was the mean value of four samplings (mean ± SD, n = 4), and different lowercase letters indicate significant differences between groups (p ≤ 0.05). (a–c), is the concentration of soil organic carbon, soil total nitrogen, soil total phosphorus; (d–f), is the stoichiometry of C:N ratio, C:P ratio and N:P ratio in soil.](image)

At a soil depth of 0–10 cm, the SOC concentration was significantly lower in Stand 1 than in Stands 2-4. STN was lower in Stand 1 than in all other stands. STP was similar at soil depths of 0–10 and 10–20 cm, with the highest value occurring in Stand 1 and the lowest
in Stand 4. C:P and N:P ratios were similar between soil depths of 0–10 and 10–20 cm, with the highest value being in Stand 4 and the lowest in Stand 1.

3.3. Differences in Soil Microbial Biomass C and N among Bamboo Stands

At soil depths of 0–10 and 10–20 cm, soil microbial biomass carbon (MBC) values were 933.89 ± 108.22 and 564.48 ± 40.75 mg kg⁻¹, respectively, soil microbial biomass nitrogen (MBN) values were 26.23 ± 4.14 and 17.47 ± 2.00 mg kg⁻¹, soil MBC:MBN ratios were 36.18 ± 4.50 and 32.58 ± 3.62, and soil respiratory quotients were 3.15 ± 0.47 and 2.30 ± 0.16 (Figure 4).

![Figure 4](image_url)

**Figure 4.** Soil microbial biomass C and N, and the respiratory quotient in four moso bamboo stands. The error bar was the mean value of four samplings (mean ± SD, n = 4), different lowercase letters indicate significant differences between groups (p ≤ 0.05). (a–d), is the concentration of soil microbial biomass carbon (MBC), soil microbial biomass nitrogen (MBN), the ratio of soil microbial biomass carbon to soil microbial biomass nitrogen, respiratory quotient in soil 0–10 cm and 10–20 cm.

3.4. Soil Respiration Rates in Different Moso Bamboo Stands

We detected no significant differences in mean annual soil respiration rates among four bamboo stands (3.21, 3.51, 3.17, and 3.40 µmol m⁻² s⁻¹ in Stands 1–4, respectively; Figure 5). There was a clearly seasonal dynamic, with maximum values occurring in June or July, and minimum values occurring in January or February. The cumulative soil CO₂ emission rates were 4.47 ± 0.48, 4.89 ± 0.31, 4.42 ± 0.54, and 4.75 ± 0.68 kg CO₂ m⁻² for Stands 1–4, respectively (Figure 6).
Figure 5. Soil respiration rates monthly dynamic between May 2014 and April 2016 in four moso bamboo stands. The error bar was the mean value of three plots in each stand (mean ± SD, n = 3).

Figure 6. Soil annual cumulative CO$_2$ emissions in four moso bamboo stands. Different lowercase letters indicate significant differences between groups (p ≤ 0.05), and the error bars mean the average of 2 years data (mean ± SD, n = 6).

3.5. Relationships between Soil CO$_2$ Emission and Plant as Well as Soil Stoichiometry

Significant relationships were found between soil cumulative CO$_2$ emissions and leaf, litter, and soil stoichiometry (Figures 7 and 8). Cumulative soil CO$_2$ emissions were significantly negatively correlated with the C:N ratio ($R^2 = 0.39$, $p = 0.01$) in leaves, and positively correlated with the C:P ($R^2 = 0.38$, $p = 0.012$) and N:P ratios ($R^2 = 0.27$, $p = 0.041$) in litter (Figure 7). Cumulative soil CO$_2$ emissions had significant quadratic function relationships with the C:N ratio ($R^2 = 0.42$, $p = 0.028$), C:P ratio ($R^2 = 0.49$, $p = 0.012$) and N:P ratio ($R^2 = 0.38$, $p = 0.045$) in the 0–10 cm soil layer, and negatively correlated only with the C:N ratio ($R^2 = 0.36$, $p = 0.015$) in the 10–20 cm soil layer (Figure 8).

The structural equation model showed the interaction effect relationship of above- and belowground stoichiometry on soil cumulative CO$_2$ emission. Cumulative soil CO$_2$ emissions were positively correlated with N and P resorption efficiency and significantly negatively correlated SMC:SMN ratios ($p = 0.036$) and soil respiratory quotients ($p < 0.001$) (Figure 9).
Figure 7. Relationships between the annual mean cumulative soil respiration rate and stoichiometry in leaves and litter on moso bamboo. The data means three plots in each stand and the total mean value of each stand (n = 16). (a, c, e), is the relationships between annual mean cumulative respiration and leaves C:N ratio, C:P ratio and N:P ratio; (b, d, f), is the relationships between annual mean cumulative respiration and litter C:N ratio, C:P ratio and N:P.
Figure 8. Relationships between the annual mean cumulative soil respiration rate and stoichiometry in soil (0–20 cm) on moso bamboo. The data means three plots in each stand and the total mean value of each stand (n = 16). (a,c,e), is the relationships between annual mean cumulative respiration and soil C:N ratio, C:P ratio and N:P ratio in 0–10 cm; (b,d,f), is the relationships between annual mean cumulative respiration and soil C:N ratio, C:P ratio and N:P in 10–20 cm.
4. Discussion

4.1. Effects of Leaf and Litter Stoichiometry, and NRE, on Soil CO2 Emissions

Plant and soil stoichiometry have interactive effects on nutrient cycling [24]. Nutrient return from leaves plays a major role in decomposition by soil organisms and the processes driving soil nutrient cycling [11]. In this study, soil cumulative CO2 emissions were negatively correlated with leaf C:N ratios ($p < 0.05$, Figure 7a), which may therefore indirectly influence soil respiration by litter decomposition rate. These results are inconsistent with the report by Ferlian et al. [11], where soil C:N ratios were not significantly correlated with C and N concentrations in aboveground tissues or their stoichiometry, and leaf C:N ratios were therefore poor predictors of soil respiration rates. In this study, soil cumulative CO2 emissions were not significantly correlated with leaf C:P ratios, indicating that leaves were poor indicators of soil respiration rates due to large differences in nutrient content between leaves and litter (Figure 1c). Thus, leaf C:P ratios may also be poor indicators of soil respiration rates.

Litter carries nutrients between leaves and soil; this dynamic nutrient exchange maintains the balance of soil nutrients and elements needed for plant growth [25]. In this study, soil cumulative CO2 emissions were significantly related to litter N:P and C:P ratios, indicating that soil respiration rates are better reflected by litter than living foliage. More importantly, P concentrations have a greater influence than N concentrations on C:P ratios [4]. In contrast, Fanin et al. [26] showed that soil respiration rate was not related to litter stoichiometry and does not accurately reflect changes in substrate respiration. Fan et al. [9] demonstrated that soil N:P ratios were significantly correlated with plant N:P ratios in Eucalyptus urophylla × grandis, Pseudosasa amabilis, and Rubus swinhoei plantations.
indicating tight coupling between soil and plant nutrients. In this study, soil cumulative CO$_2$ emissions were not significantly related to litter C:N ratios, suggesting that soil C:N ratios are not significantly correlated with leaf litter C:N ratios due to their limited contribution to soil heterogeneity [27,28].

NRE may depend on the ratio of leaf soluble to structural nutrients [29]. Stoichiometric differences among plant tissues are attributable to N and P allocation and use efficiencies during the growing season [5]. In this study, N and P resorption efficiency were significantly related to C:N ($p < 0.001$) and C:P ($p < 0.001$) ratios in litter, but not to N:P in litter (Figure 9), suggesting that NRE values are influenced by underestimated litter N content prior to leaf senescence [29], or that P resorption efficiency is similar to that of N. Lu et al. [30] showed that N and P resorption efficiency are negatively related to N:P ratios in leaves, but positively related to N:P ratios in litter. This inconsistency may be caused by differences in NRE or soil nutrient conditions [31]. In this study, soil cumulative CO$_2$ emissions were positively correlated with N ($p < 0.001$) and P resorption efficiency ($p = 0.019$), indicating that N and P recycling is important for soil respiration rates; plants gradually reach stoichiometric equilibrium within the leaf-litter-soil system by adjusting nutrient reabsorption capacity and soil respiration rates [25]. Future studies should explore how nutrient availability regulates litter N content through the allocation of soluble and structural leaf nutrients. Xu et al. [32] showed that resorption efficiency was significantly correlated with soil available P, indicating that plant and soil N and P content regulate nutrient resorption.

4.2. Effect of Belowground Stoichiometry on Soil CO$_2$ Emission

A previous study showed that soil microorganisms generally have better C:N ratio homeostasis than plants [33], because the former are generally more competitive for N [34]. In this study, soil cumulative CO$_2$ emissions showed a quadratic function with soil C:N ratios in 0–10 cm (Figure 8a, $p = 0.028$) and a negative correlation with soil C:N ratios in 10–20 cm (Figure 8b, $p = 0.015$). This result indicated that there may be a more complicated interaction effect between them for the rhizome root system of bamboo just as structural equation analysis (Figure 9). Wu et al. [35] and He et al. [36] both showed that soil respiration rates were positively correlated with soil C:N ratios ($p < 0.01$). Shi et al. [37] also showed that annual total CO$_2$ emissions were positively correlated with soil C:N ratios ($p < 0.05$), and that the C:N ratio explained 86.5% of the variance in soil respiration. In contrast, Nguyen et al. [38] showed that soil CO$_2$ emissions (mineralization rates) were negatively correlated with soil C:N ratios due to the higher concentration of available mineralized C. These inconsistent results show that soil cumulative CO$_2$ emissions are directly and indirectly controlled by the amount of soil C stored, and the factors that influence this amount, such as soil moisture and temperature [37]. The relationship between soil respiration and the soil C:N ratio has also been found to depend on the C:N ratio, with a positive correlation observed at C:N ratios of 12.2–19.7 in one study [39].

Generally, soil cumulative CO$_2$ emissions are controlled by factors that influence soil nutrients and their stoichiometry [37]. In this study, soil cumulative CO$_2$ emissions had quadratic function relationships with soil C:P ratio ($p = 0.012$) and N:P ratios ($p = 0.045$) in 0–10 cm (Figure 8a,b), consistent with the finding that P resorption efficiency indirectly affects soil respiration rates under limited soil P conditions at soil C:N ratios $< 25$ [15]. Spohn and Chodak [15] showed that soil respiration rates increase with soil C:P ratios in *Fagus sylvatica* L., *Picea abies* L. Karst., and mixed forests dominated by both species, and with C:N ratios only in forest dominated by *P. abies*. He et al. [36] showed that soil respiration rates were negatively correlated with soil C:P and N:P ratios ($p < 0.01$). Spohn and Chodak [15] showed that soil microbial respiration was positively correlated with soil C:P ratios in *Fagus sylvatica* L. ($R^2 = 0.93$) and *P. abies* L. Karst. ($R^2 = 0.80$) forest soils. Nguyen and Marschner [40] showed that soil cumulative respiration rates were not influenced by changes in C:P ratios. Wei et al. [41] showed that soil cumulative CO$_2$ emissions were negatively correlated to NH$_4^+$--N: available P ratios. Collectively, these
inconsistent relationships between soil respiration and C:P ratios appear to depend on the balance between the contributions of C fluxes and soil available P, which ultimately enhances plant nutrient uptake from soil, leading to microbial decomposition of SOC [40].

4.3. Drivers of Soil Microbial Biomass and Soil CO₂ Emission

Soil microorganisms play an important role in soil respiration (CO₂ emission) by improving available nutrients, such that soil microbial biomass is a significant driver of soil CO₂ emission [42]. He et al. [34] showed that the MBC concentration was positively related to the SOC concentration, and directly and negatively influenced fine root N concentration. Fujita et al. [43] showed that soil respiration (i.e., C flux) depends on microbial C:N stoichiometry and a high microbial C:N ratio. In this study, soil cumulative CO₂ emissions were negatively correlated with the MBC:MBN ratio (Figure 9), which supports the use of this ratio as an indicator of soil respiration [13]. This result indicates tight stoichiometric coupling between soil microbial biomass and SOC, such that soil microorganisms attain low microbial C:N stoichiometry by acquiring more N [44]. Moreover, soil properties, especially MBC and MBN, regulate variation in the C:N:P stoichiometry of leaves and litter [45]. Sushko et al. [42] reported that soil respiration rates were strongly positively correlated with MBC. Yuan et al. [46] showed that soil CO₂ emissions were significantly correlated with microbial biomass under N addition, indicating that soil microbial biomass is influenced by the response of microbial respiration to N addition. Microbial nutrient demand is affected by microbial biomass and nutrient stoichiometry [16].

The respiratory quotient is an important indicator of substrate quality and its influence on respiration [47,48], and reflects the relationship between the biotic and abiotic fractions of SOC [49]. In this study, soil cumulative CO₂ emissions were negatively related to the respiratory quotient at a soil depth of 0–10 cm (p < 0.001, Figure 9), due to the energy required by microorganisms for the metabolic activity driving biomass synthesis [50]. Similarly, Rui et al. [51] showed that the respiratory quotient was positively correlated with soil cumulative CO₂ production under light-fraction organic matter addition. In contrast, Spohn [52] showed that soil respiration was indirectly positively correlated with the respiratory quotient via the litter C:N ratio. These inconsistent results may be attributed to variation in the respiratory quotient and composition of SOC [49], reflecting changes in the labile utilization of microbial communities [53]. In this study, differences in the respiratory quotient among stands suggested differences in nutrient mineralization and the storage of potentially available nutrients, as well as microbial C use efficiency and the stability of SOC [21].

In this study, the structural equation analysis showed the effect of aboveground stoichiometry on soil CO₂ emission by nutrient resorption as well as the soil microbial properties (Figure 9). Ferlian et al. [11] showed that soil C:N ratios were significantly related to soil microbial properties, but were not significantly correlated with C and N concentrations in aboveground tissues or their stoichiometry. Rivas-Ubach et al. [54] suggested that leaf-level changes in stoichiometry (e.g., the C:nutrient ratio) decreased with growth stimulated by environmental changes, whereas Ferlian et al. [11] showed that plant above- and belowground C:N ratios were weakly correlated. Therefore, these complex relationships may help to understand bamboo plantation function (e.g., rapid expansion) by above-and belowground nutrients integration and CO₂ emission linkage under nutrients limitation [55,56].

5. Conclusions

In this study, soil CO₂ emissions were significantly correlated with litter and soil stoichiometry rather than leaf stoichiometry, except for the C:N ratio, indicating that soil CO₂ emission does not depend on aboveground plant tissue stoichiometry. Positive significant relationships between soil cumulative CO₂ emissions and N (p < 0.001) and P resorption efficiency (p = 0.019) indicated a strong indirect link between aboveground (leaf) stoichiometry and soil nutrient demand. Thus, differences in soil cumulative CO₂
emissions and NRE are likely to be accompanied by changes in litter and soil stoichiometry, although this requires further investigation. Together, our results indicate that aboveground stoichiometry indirectly affects soil CO₂ emission through nutrient resorption efficiency, which also helps us to understand the nutrient utilization function of moso bamboo plantations in expansion and rapid integration mechanism.

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