sustainability

MDPI

Article

Responses of Soil CO_2 Emission and Tree Productivity to Nitrogen and Phosphorus Additions in a Nitrogen-Rich Subtropical Chinese Fir Plantation

Xiaochen Lu [1,2], Binjie Li [1,2,3] and Guangsheng Chen [1,2,*]

1 State Key Laboratory of Subtropical Silviculture, Zhejiang A&F University, Hangzhou 311300, China; 2020602041069@stu.zafu.edu.cn (X.L.); wzkjxy@wzvcst.edu.cn (B.L.)
2 College of Environmental and Resource Sciences, Zhejiang A&F University, Hangzhou 311300, China
3 Wenzhou Vocational College of Science and Technology, Wenzhou 325006, China
* Correspondence: chengu1@zafu.edu.cn

Abstract: Nitrogen (N) and phosphorus (P) nutrients have been regularly applied to improve productivity in intensively managed and short-rotation forest plantations in subtropical China. Under the constraint of the national policy of "carbon neutrality", it is necessary to determine the rational fertilization options by considering both forest productivity and soil CO_2 emissions. Past worldwide studies have shown varied responses of forest soil heterotrophic respiration and CO_2 emissions to N and P additions. This study designed six treatments with N additions (high level: 15 g N/m^2, HN), P (low: 5 g P/m^2, LP; high: 15 g P/m^2, HP), and their interactions (HNLP and HNHP) to explore the effects of N and P additions on soil CO_2 emissions in a P-limited and N-rich Chinese fir plantation (*Cunninghamia lanceolata*), and we identified the underlying controls using the structural equation model (SEM). The results indicated that LP, HNLP, and HNHP treatments significantly increased soil CO_2 emissions in the first four months after treatment and the effects leveled since then. The balance between N and P inputs affected the responses of soil CO_2 emissions to P additions. A low P addition significantly increased tree productivity, but the promoting effect gradually declined and was no longer significant after 3 years. Other treatments did not significantly affect tree productivity. The SEM analysis revealed that the promoting effects of P additions on CO_2 emission were mainly due to their effects on increasing soil water-soluble organic carbon content and reducing microbial biomass nitrogen content. Considering both soil respiration and tree productivity, this study suggested that LP treatment can effectively balance the N and P nutrients and, in the meantime, maintain relatively low greenhouse gas emissions; thus a low P application level is suggested for N-rich Chinese fir plantations.

Keywords: nitrogen addition; phosphorus addition; soil CO_2 emission; tree productivity; Chinese fir forest

check for updates

Citation: Lu, X.; Li, B.; Chen, G. Responses of Soil CO_2 Emission and Tree Productivity to Nitrogen and Phosphorus Additions in a Nitrogen-Rich Subtropical Chinese Fir Plantation. *Sustainability* **2023**, *15*, 9466. https://doi.org/10.3390/su15129466

Academic Editors: Teodor Rusu and Marco Antonio Jiménez-González

Received: 15 March 2023
Revised: 29 May 2023
Accepted: 8 June 2023
Published: 13 June 2023

1. Introduction

In recent years, global warming has become an indisputable fact, leading to more frequent extreme climate events and other natural disasters. Carbon dioxide (CO_2), methane, and nitrous oxide are the three most important greenhouse gases (GHGs) that contribute to global warming. Among them, carbon dioxide is the most important greenhouse gas in the atmosphere [1], with a contribution rate of over 60%, while the atmospheric CO_2 concentration is still increasing at a rate of 0.4% per year. About 5–20% of the CO_2 in the atmosphere comes from soil [2]. The global soil carbon storage exceeds 1500 Pg C, and the global soil releases 75–100 Pg C per year into the atmosphere in the form of CO_2 through respiration. Therefore, any small changes in soils could cause changes in the atmospheric CO_2 concentration.

Soil CO_2 emissions are affected by many factors, including soil root respiration, soil microbial processes, organic matter content, soil permeability, soil microbial carbon substrates, soil microbial population levels, pH, and anthropogenic activities. Anthropogenic additions of nitrogen (N) and phosphorus (P) have been reported to significantly influence soil CO_2 emission [3]. N and/or P nutrients are the major limiting elements for most forest ecosystems, and their additions can affect soil nutrient cycles and further affect the soil and root respiration [4]. The previous reports indicated different responses of soil CO_2 emissions to N addition, showing either promoting, prohibitive, or non-significant effects [5–7], which are primarily due to the differences in forest types, soil conditions, fertilizer types and quantity, and duration. In a meta-analysis based on 410 field observational data, Liu et al. [8] synthesized the effects of N treatments on soil CO_2 emissions and also concluded that the effects could be promoting, prohibitive, and non-significant. In contrast, the effects of P addition on soil CO_2 emissions have been less reported. The existing few studies also indicated varied responses of soil CO_2 emission to P addition due to the same reasons as with N addition [9,10]. In addition, the interactive effects between N and P could also significantly affect the responses of N or P additions alone on soil CO_2 emission. P addition can redirect the N processes by increasing N uptake and N use efficiency, reducing the substrates of soil nitrification and denitrification processes, and stimulating plant–soil interactions [11]. However, the experiments with combined additions of N and P were even less. The interactive effects also varied, showing stimulating [12,13], prohibitive [14,15], or non-significant [16] effects on soil CO_2 emission, which depend on the stoichiometric balance between soil-available N and P nutrients [17]. Most of these studies for N, P, and NP additions were located in tropical and temperate regions; more studies are needed to enlarge the database and clarify the impact directions and extent.

In China, most of the studies for N and P addition effects on soil CO_2 emissions have focused on agricultural land. Few studies have focused on forest ecosystems, and the results varied significantly. For example, Yu et al. [18] found that N addition significantly increased soil CO_2 emission in the typical temperate forests in China. N addition provided N nutrients for the growth of trees and microbes, and enhanced N uptakes due to increased root biomass and N availability in these N-poor forest ecosystems. These further increased the microbial biomass and soil organic matter (SOM) content and thus stimulated the litter and SOM decomposition rates. On the contrary, Yuan et al. [19] found that N addition prohibited soil CO_2 emission in the N-saturated subtropical forests in China. This is because about 70–84% of the added N was retained in the soil organic matter in a short period under the N-saturated condition, which cannot be utilized by plants and microbes [20]. There are fewer studies on the N and P co-addition effects on soil CO_2 emission in China. In a long-term experiment with N and P co-addition in a Chinese fir forest in subtropical China, Wang et al. [21] found that N and P co-addition promoted soil CO_2 emission compared with the N-alone addition treatment, but the effect was significantly lower than the low P addition treatment. This is because N and P co-addition promoted plant N uptake, reduced the soil NH_4^+-N contents, and increased the soil pH value, thus reducing the promoting effects of N availability on soil respiration. In a 9-year experiment, Zhang et al. [22] found that the plots with N and P co-addition had the highest soil CO_2 emissions compared with the control and single N and P treatments. Most of these studies were conducted in an area with a N limitation, and it is still unclear how N and P addition affect soil CO_2 emissions under N-rich or saturated soil conditions.

Subtropical forest soil has the second highest soil respiration rate after tropical forest soil [23]. Chinese fir (*Cunninghamia lanceolata)* plantation is the main timber land in subtropical China, and it accounts for about 13% of China's plantation area [24]. Chinese fir has the advantages of fast growth and good quality. It not only has many economic benefits but also fixes a large amount of carbon and exerts huge ecological benefits [25,26]. The Chinese fir forests in the subtropical region generally rotate every 15–30 years, and many reports have indicated that the continuous planting of Chinese fir trees in the same site could significantly reduce the soil quality and thus the productivity [27,28]. To increase tree productivity, many secondary Chinese fir plantations are fertilized with N, P, and K fertilizers, generally either at the planting time or at the mid-rotation age [21,29,30]. These fertilizer applications could significantly affect soil nutrient and carbon cycling processes, and thus influence soil CO_2 emission patterns. At present, most studies have focused on the fertilization effects on tree growth, and few studies have addressed its effects on soil CO_2 emissions [22]. To achieve the carbon neutrality target in China, it is necessary to reduce the soil CO_2 emissions from the Chinese fir plantation. Therefore, how to increase tree productivity and in the meantime maintain low soil CO_2 emissions becomes a vital scientific and practical question. A guideline is also needed for forest managers to choose rational fertilizer types and application quantities in the fir forests of subtropical China.

This study assumed that N and P fertilization could significantly promote soil CO_2 emissions, and the effect could increase with the fertilization rates. Based on these assumptions, our specific objectives were to (1) uncover the relationship between soil CO_2 emission and environmental factors; (2) reveal the effects of N and P additions on soil CO_2 emission and monthly variation patterns; (3) explore the short-term response of tree productivity to N and P addition; and (4) identify the main controlling mechanisms of N and P additions on soil CO_2 emission. The study results could help provide guides for sustainable carbon and productivity management for Chinese fir plantations in the subtropical region.

2. Materials and Methods

2.1. Site Description

The study site is located at Wulitou forest station (119.67° E and 30.21° N), Lin'An District, Hangzhou City, Zhejiang Province, China (Figure 1) [31]. This site has a subtropical monsoon climate. The mean annual temperature and precipitation are 16.4 °C and 1613.9 mm, respectively. The altitude is 175 m, and the annual sunshine hours are 1847.3 h [32]. The study plots were 10 years old (mid-rotation age) and planted with pure Chinese fir forests. The detailed study site conditions, stand characteristics, and plot soil physical and chemical properties have been presented in detail in our previous study [32]. Our previous study [31] also proved that this study site is an N-rich and P-limited ecosystem.

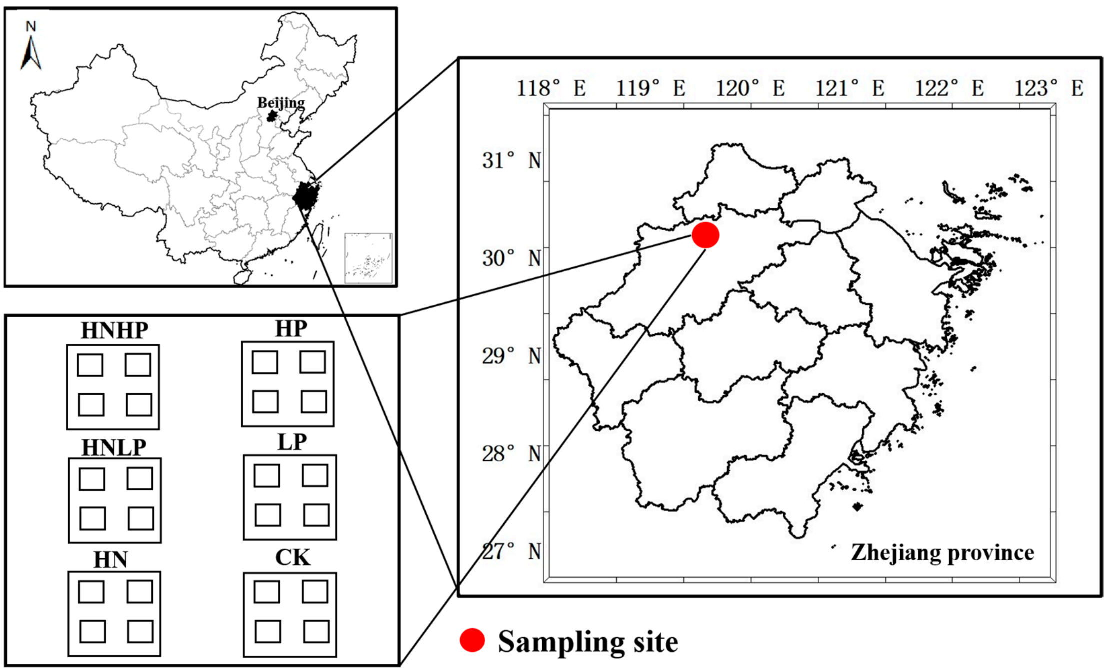

Figure 1. The study area and the designed experiments [31].

2.2. Experimental Design

In a 10-year-old Chinese fir forest, we set up six 20 m × 20 m plots on 15 February 2019 (Figure 1). These plots were over 10 m away from the major roads and other ecosystems. A 5 m buffer zone was set among plots to isolate the interactive impacts among adjacent treatments. The static chamber method was applied to soil CO_2 flux sampling. The experimental design for chamber deployment has been described in our previous paper [31].

The six treatments were (1) control (CK; no treatment), (2) adding 15 g N/m^2 (HN treatment), (2) adding 5 g P/m^2 (LP), (3) adding 15 g P/m^2 (HP), (4) adding 15 g N/m^2 and 5 g P/m^2 (HNLP), and (5) adding 15 g N/m^2 and 15 g P/m^2 (HNHP).

Urea ($CO(NH_2)_2$) and sodium hydrogen phosphate (NaH_2PO_4) were used as N or P fertilizers, respectively. Four 5 m × 5 m grids within each plot were isolated. The fertilizer amount was weighed and applied evenly into each grid. Within each chamber, the fertilizer amount was specifically weighed and applied according to the actual area of each chamber. On 20 March 2019, the fertilizer was applied. The observational period was from March 2019 to July 2020; when the soil CO_2 emissions were observed, no significant differences among different treatments were found.

2.3. Methods for Soil and Leaf Sampling and Chemical Analyses

The soil samplings were conducted five times on 19 March (before treatment); 20 April; 20 June; 20 September 2019; and 20 May 2020. The leaf sampling was conducted two times (before and after experiments). In our previous study [31], we described the sampling methods for soil, green leaf, and litter. In addition, the detailed descriptions for the chemical analysis and environmental factors have been described in detail. These chemical analyses include water-soluble organic C (WSOC), microbial biomass C (MBC), microbial biomass N (MBN), leaf C and N concentrations, pH value, soil available, and total P, NO_3^--N, and NH_4^+-N. The environmental factors include soil temperature (ST) and soil moisture (SM) (Table 1), which have been analyzed in [31].

Table 1. The soil and leaf chemical properties under different nutrient addition treatments in the studied Chinese fir plantation. Note: the numbers in the parentheses are standard deviations; different letters indicate statistically significant differences ($p < 0.05$) [31].

Variables	CK	LP	HP	HN	HNLP	HNHP
NH_4^+ (mg/kg)	12.62 (0.76) b	11.61 (0.86) b	12.80 (1.17) b	14.22 (1.97) a	14.87 (2.08) a	12.88 (1.36) b
NO_3^- (mg/kg)	3.71 (0.076) b	4.78 (0.42) ab	3.86 (0.18) b	4.46 (0.36) b	4.80 (0.33) ab	5.89 (0.30) a
MBN (mg/kg)	54.21 (9.5) a	22.23 (1.4) b	24.08 (1.2) b	54.53 (9.3) a	32.39 (4.4) b	28.55 (4.2) b
MBC (mg/kg)	137.55 (9.1) b	173.94 (18.9) a	206.76 (15.6) a	158.65 (11.4) ab	159.07 (7.7) ab	198.59 (12.7) a
WSOC (mg/kg)	46.93 (2.9) c	80.20 (3.5) ab	96.48 (5.8) a	62.69 (5.2) c	63.37 (2.0) bc	91.50 (3.8) a
Leaf N (g/kg)	7.55 (0.11) a	8.00 (0.27) a	7.05 (0.30) a	7.96 (0.81) a	8.75 (0.99) a	9.22 (0.86) a
Soil TN (g/kg)	0.86 (0.036) a	0.90 (0.04) a	0.91 (0.043) a	1.04 (0.095) a	1.00 (0.097) a	1.00 (0.082) a
SOC (%)	1.55 (0.031) ab	1.67 (0.10) ab	1.86 (0.12) a	1.47 (0.06) b	1.81 (0.11) ab	1.57 (0.048) ab
Soil TP (g/kg)	0.13 (0.014) b	0.14 (0.01) b	0.23 (0.024) a	0.13 (0.011) b	0.13 (0.008) b	0.15 (0.025) ab

2.4. Tree Growth Measurements

We measured the diameter at breast height (DBH) and height (H) of all standing living trees three times on 15 February 2019 (before fertilization treatment); 8 December 2020; and 3 October 2022. The position for measuring DBH was recorded in 2019 and measured again at the same position in 2020 and 2022. A diameter tape was used to measure DBH, and ultrasonic altimeter (Vertex III) was used to measure tree height. The difference of tree DBH and height between the two measurement times was calculated and compared. There are many suitable biometric equations to calculate biomass of Chinese fir stands in the study area [33]; however, due to the larger measurement errors for tree height and canopy extent, this study chose the biomass equation only using DBH as the independent variable. The selected equation is [33]

$$W = 0.1657D^{2.1456} \quad (1)$$

where W is the mean biomass of individual trees within a plot (kg) and D is the mean DBH (cm). In this study, we used the increment of biomass (ΔW) after treatment as the representation of tree productivity.

2.5. Soil CO_2 Emission Sample Collection and Measurements

On 20 March 2019 (before treatments), the first sampling for soil CO_2 efflux was implemented, and regular sampling of CO_2 gas was implemented since then at the end of each month. The sampling methods have been described in [31]. The CO_2 flux (F) is calculated as [34]

$$F = \rho \cdot \frac{V}{A} \cdot \frac{P}{P_o} \cdot \frac{T_o}{T} \cdot \frac{dCt}{dt} \quad (2)$$

where F is the net CO_2 exchange (mg/m^2/h), ρ is the gas density under standard conditions, A is the chamber (m^2), V is the volume of each chamber (m^3), and T_o and T are the standard state and chamber (°C) during gas sampling. P_o and P are the standard and actual atmospheric pressure (kPa), respectively, during gas sampling. $\frac{dCt}{dt}$ is CO_2 concentration change rates between two gas sampling times (10-min gap between two sampling times in this study) [35].

2.6. Statistical and Analysis Methods

The R4.0.2 software (R Core Team, 2016) was used for processing the data and statistical tests. All data were tested for normality (Kolmogorov–Smirnov's test) and homoscedasticity (Levene's test) before conducting any statistical analyses. The treatment effects were tested using ANOVA analysis [36] and Tukey's *HSD* tests on soil properties, productivity increment, and CO_2 emission.

The direct and indirect effects of treatments on CO_2 emissions were explained by Structural equation model (SEM) based on different hypothetical approaches. The independent explanatory variables included ST, SM, WSOC, NO_3^--N, NH_4^+-N, MBN, and MBC. The maximum likelihood estimation method was applied to fit the SEM model. The model adequacy was evaluated using X^2 and root square mean errors of approximation (RMSEA). The lower RMSEA and non-significant X^2 indicated that the fitted model was adequate. The basic steps of SEM model analysis were mentioned in Li et al. [31]. Statistical significance was determined by $p < 0.05$.

3. Results

3.1. Effects of Soil Temperature and Moisture on Soil CO_2 Emission

N and P additions and other climatic factors could interactively affect the change in soil CO_2 efflux. The correlation analyses indicated a significant positive correlation between soil temperature and CO_2 efflux under all treatments, showing an increasing trend with increasing soil temperature (Figure 2). Soil temperature explained 76–82% of the variations in soil CO_2 emissions, among which the HN treatment had the highest correlation, and the HNHP treatment had the lowest interpretation rate. However, all treatments had higher correlation coefficients than the control (69%), indicating that N and P addition increased the sensitivity of soil CO_2 emission to soil temperature. Soil CO_2 emissions showed a significant positive correlation with soil moisture under the control and all treatment plots (Figure 3). The interpretation rates of soil moisture ranged from 63% to 74%, with the highest interpretation rate in the HP treatment and the lowest in the HNLP treatment, but all treatments were higher than the control.

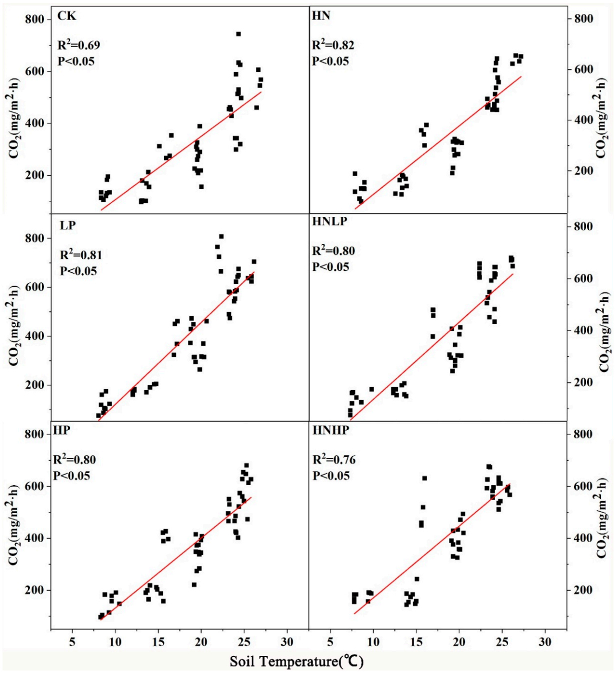

Figure 2. Correlations between soil temperature (°C) and CO_2 flux (mg/m^2/h) under different treatments. R^2 is the coefficient of determination, p is the significance level for the slope of the fitted line, with $p < 0.05$ denoting a significant correlation.

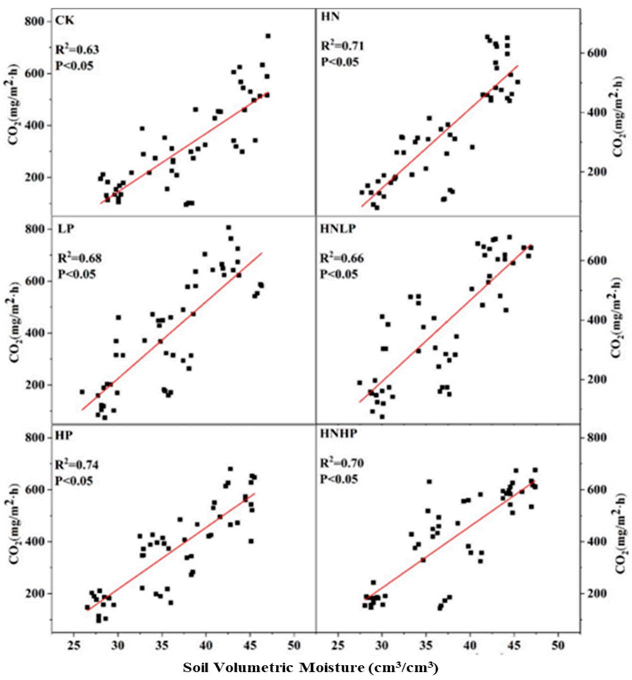

Figure 3. Correlations between soil volumetric moisture (cm^3/cm^3) and CO_2 flux (mg/m^2/h) under different treatments.

3.2. Monthly Dynamic of Soil CO_2 Flux

The soil CO_2 effluxes under all treatments showed similar monthly variation patterns (Figure 4). The soil CO_2 emission in the growing season is higher than that in the non-growing season. The highest emissions occurred in July, ranging from 629.4 ± 80.4 mg/m^2/h to 740.1 ± 52.3 mg/m^2/h under all treatments. During the first four months after N and P additions, soil CO_2 emission increased under all treatments compared with the control. The soil CO_2 emissions under HNLP, LP, HNHP and HP treatments were significantly ($p < 0.05$) higher than the CK, while the difference was not significant ($p > 0.05$) under HN treatment. This implied that the N-alone treatment had no significant impacts on the seasonal change in soil CO_2 flux, while P-related treatments significantly promoted the monthly soil CO_2 emission budgets. The monthly CO_2 emissions among HNLP, LP, HNHP, and HP were not significantly different. After the first four months, soil CO_2 emissions were not significantly different among all treatments, indicating that N and P addition effects can only maintain for about four months in the study region.

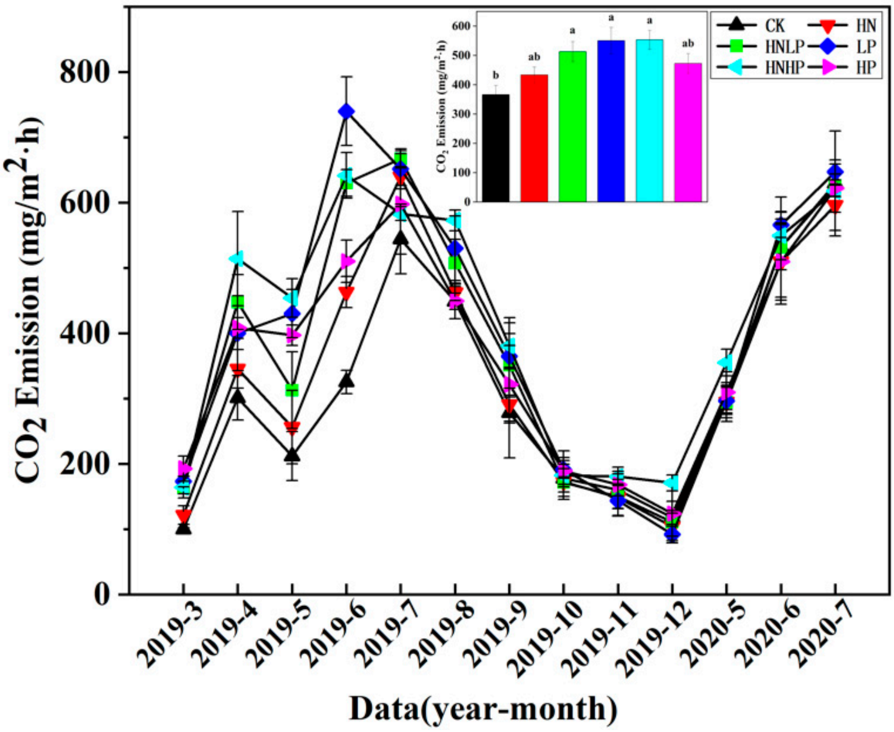

Figure 4. Monthly dynamics of soil CO_2 emission (mg/(m^2·h)) under different treatments. Error bars denote standard deviation (n = 4). The inserted small bar graph on the top depicts the mean emission rate of CO_2 in the first four months (from April to July 2019). Each bar represents mean value of all four months under each treatment. The different letters above bars indicate significant differences among months, and the bar colors denote different treatments.

3.3. Effects of N and P Additions on Soil CO_2 Emissions

The above analysis indicated that the four-month soil CO_2 emission patterns were different from other periods, so we further analyzed the impacts of N and P additions on the overall soil CO_2 budgets from the basis of four-month and entire study periods. The effects of N and P additions showed great difference in the first four months and the entire period (Table 2). For the first four months, the mean soil CO_2 emissions under all treatments except HN and HP significantly increased compared with the CK. The LP treatment increased the most (61%), and the HN treatment increased the least (23%). We noticed that the low P addition (LP) had a greater promotion effect on soil CO_2 emission than that of the high P addition (HP). When P addition was combined with N, the higher P addition (HNHP) could slightly promote soil CO_2 emission, compared with the lower P addition (HNLP). This implied that the N and P interaction may greatly affect the soil carbon dynamics. On the annual time scale, the HN, HNLP, HNHP, and HP treatments increased soil CO_2 emission by 7%, 20%, 27%, 30%, and 16%, respectively, compared with the CK. However, the difference was not significant ($p > 0.05$; Table 2), which is because of the high internal variations of CO_2 emissions among all replicates under each treatment. The differences in soil CO_2 emissions among treatments were not significant either. This indicated that the

N and P additions can only stimulate the soil decomposition processes at a short period (i.e., four months), while their effects cannot sustain for a longer period (i.e., a year). The N and P effects were further differentiated based on the ANOVA analysis. The results showed that N addition had no significant ($p > 0.05$) impact on soil CO_2 emissions in both cases, while P addition could significantly promote soil CO_2 emissions. This further proved that the study region is more P-limited. The N and P interactive effect did not significantly change the soil CO_2 emissions ($p = 0.13$).

Table 2. Average CO_2 emissions (mg/m^2/h) in the first 4 months and throughout the study period in a subtropical Chinese fir plantation. Note: Different lowercase letters indicate significant differences among treatments; the values within the parentheses are standard errors; *F* is the F-statistic and *p* is the *p*-value in ANOVA.

Treatment	CO_2 (mg/m^2/h)		Treatment		4 Months	All Months
	4 Months	All Months				
CK	346 (33.0) b	318 (23.9) a	N application	*F*	1.82	0.51
HN	426 (38.1) ab	339 (24.8) a		*p*	0.18	0.48
HNLP	514 (38.2) a	382 (27.4) a	P application	*F*	11.87	4.03
LP	555 (39.1) a	402 (29.3) a		*p*	<0.05	<0.05
HNHP	548 (21.4) a	413 (25.3) a	N*P Interaction	*F*	2.07	0.79
HP	478 (23.9) ab	369 (23.2) a		*p*	0.13	0.45

3.4. Structural Equation Modeling of CO_2 Emissions under N and P Additions

SEM analysis can be used to determine the indirect and direct effects of different factors on the soil CO_2 flux; therefore, it can help identify the controlling mechanisms of N and P additions on soil CO_2 emissions. The results of SEM analysis showed that about 73% of soil CO_2 changes under nitrogen and phosphorus addition treatments were explained by soil nutrients and environmental factors (including ST, SM, NO_3^--N, NH_4^+-N, MBC, MBN, and WSOC), indicating that other factors not included in this study contributed to the remaining 27% of the change (Figure 5). Nitrogen addition significantly and positively affected NO_3^--N, while NO_3^--N indirectly promoted CO_2 emissions by increasing NH_4^+-N. The addition of P significantly increased WSOC and further increased MBC, resulting in a significant increase in CO_2 emissions (please see the attachment). Phosphorus addition suppressed CO_2 emissions by reducing MBN. Overall, P addition promoted soil CO_2 emission due to a greater positive effect than negative effect. Soil temperature and humidity promoted CO_2 emission by increasing soil NH_4^+-N.

3.5. Effects on Tree Productivity

We further analyzed the effects of N and P addition on the tree productivity represented by the changes in biomass. After the growing season of the experiments, the biomass of the Chinese fir forest under all treatments increased (Figure 6a). Under the control (CK), the biomass increment rate was 25.5%, while increment rates under LP, HP, HNLP, and HNHP were 31%, 25%, 23%, and 24%, respectively. Among these, the increment rate under LP treatment was significantly higher than those of under other treatments and the CK, while the increment rates under other treatments were not significantly different from the CK. After three growing seasons (Figure 6b), under the control (CK), the biomass increment rate was 53%, while the increment rates under HN, LP, HP, HNLP, and HNHP were 45%, 58%, 52%, 45%, and 52%, respectively. The increment rate under LP was still greater than the CK, but the difference was no longer significant, indicating an abating effect of LP on tree growth after the end of LP addition. By comparing the shorter and longer effects (Figure 6a,b), we found that LP treatment can exert a long-term promoting effect on the biomass increment due to legacy effects. This suggests that only a lower P addition level can maintain tree N and P nutrient balances in the N-saturated Chinese fir plantation of the study region. Either high P-alone or high N addition could suppress tree growth by causing the imbalance between N and P availability.

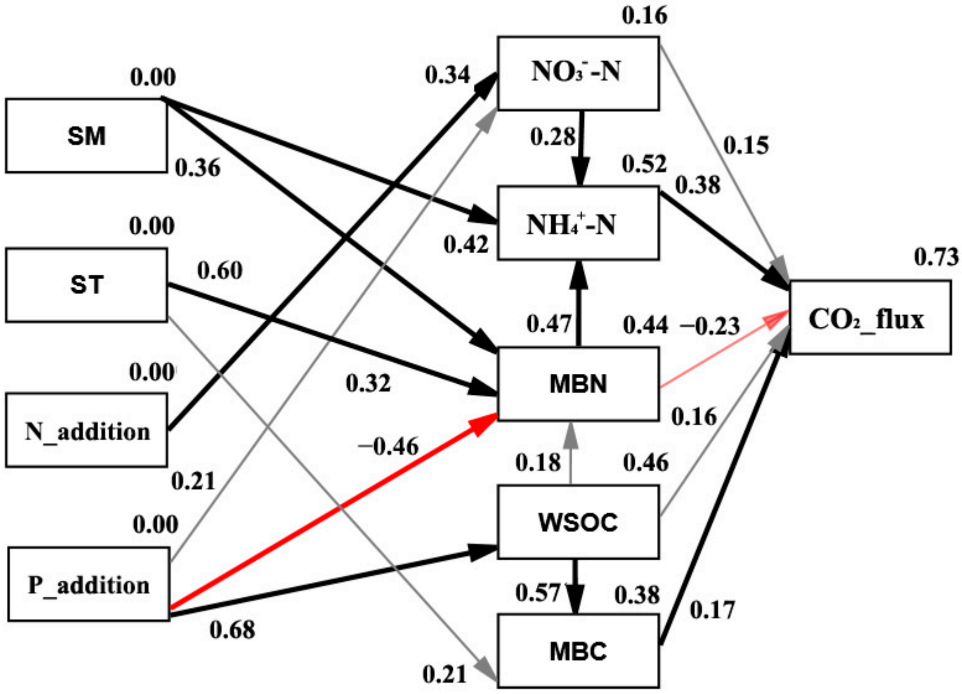

Figure 5. Structural equation modeling results for the effect of N and P additions on soil CO_2 emissions based on all observational data. SEM model parameters: $X^2 = 25.46$, $df = 24$, $RMSEA = 0.025$, and $GFI = 0.95$. Black arrows indicate significant positive correlations, and red arrows indicate significant negative correlations ($p < 0.05$), while gray arrows indicate no significant correlations. The numbers on the arrows are normalized path coefficients (similar to correlation coefficients). The width of the arrows indicates the strength of the causal influence.

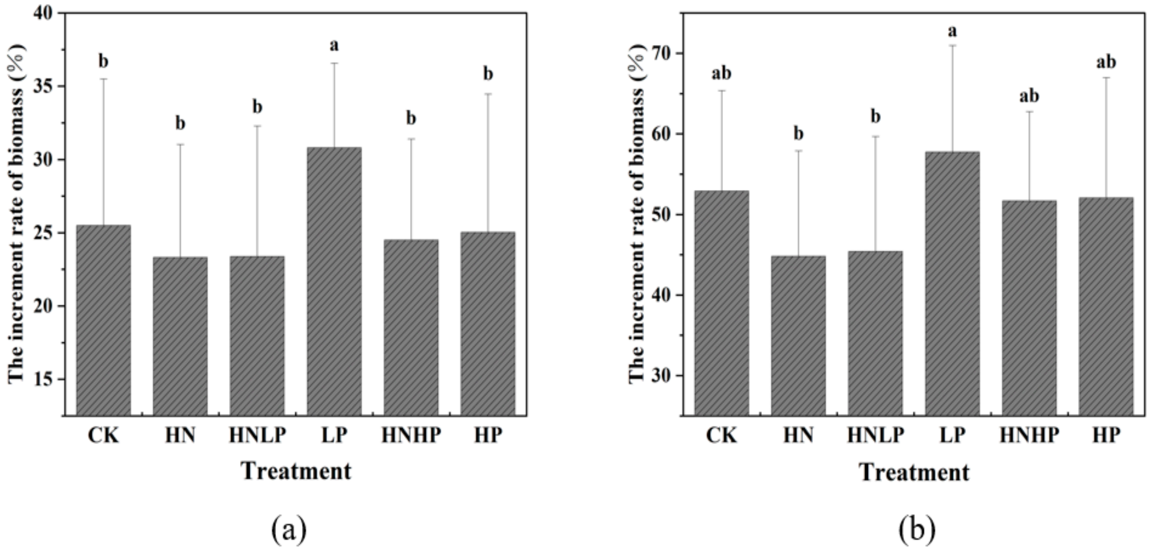

Figure 6. The changes in tree productivity, represented by biomass increment rates (%) of the Chinese fir after treatments of a growing season. (**a**) (2020) and three growing seasons; (**b**) (2022) as compared with the pre-treatment (March 2019). Error bars represent standard deviation (n = 36–45). Different lowercase letters indicate significant differences among treatments.

4. Discussion

4.1. Effects of N and P Addition on Soil CO_2 Flux

4.1.1. Effect of N-Alone Addition

Our results indicated that N addition only slightly (not significant) increased soil CO_2 emission. This may be because the study site is N-saturated due to long-term high N deposition. The same phenomenon was observed in many previous studies (e.g., [8,37,38]). In addition, Gao et al. [39] also found that the stimulation effects of a low-level N addition rate (5 g $N/m^2/yr$) on soil respiration were significantly higher than those of a high-level N addition rate (10 g $N/m^2/yr$) in a naturally-regenerated subtropical forest. In our study, a higher N addition level was applied (15 g $N/m^2/yr$), which may have caused the non-significant responses to N addition. After N addition, most of the added N leaves the ecosystem soon or remains in the soil in the form of inorganic N and cannot be absorbed and utilized by plants and microorganisms, which causes non-significant effects on CO_2 emission [20]. In our study, we also found that NH_4^+-N and NO_3^--N contents under HN treatment were significantly higher than those of the CK in the first three months, but MBN and MBC were not significantly different (Table 1). This implied that the added N was mostly unused by the microbes. Some previous studies have also found that N addition alone has no significant effect [40–42] on MBC and MBN. We also found that the increased WSOC after HN treatment was the main cause of the slightly increased soil CO_2 emissions.

4.1.2. Effect of P-Alone Addition

Our study found that the P-alone treatment significantly promoted soil CO_2 emission, especially in the first four months after treatment. LP and HP treatments increased soil CO_2 emission by 61% and 38%, respectively. This is consistent with the report of Lin et al. [43], who found that soil CO_2 emissions significantly increased with LP addition in a Chinese fir forest. Some previous studies have explained that the increase in CO_2 emission after P addition is associated with increased heterotrophic microbial biomass and activity, thereby promoting respiration [5,44,45]. Our study also proved that MBC significantly increased by 26% and 50% after LP and HP treatments, respectively (Table 1). The increased MBC has also been found by Allison et al. [46] in Alaska and Liu et al. [44] in tropical China. In addition, we observed that MBN had been significantly reduced by 83% and 80%, respectively, implying an enhancing N limitation for microbial activities. This is also the reason why significant simulative effects on soil CO_2 emissions only last for four months. From the SEM analysis, we found the enhanced MBC occurred through the increased WSOC, which provides substrates for the growth of microbes. P addition also enhanced plant root respiration and increased root exudates, which in turn leads to an increase in WSOC [47] and ultimately promotes soil CO_2 emissions [48]. Our study also found that soil CO_2 emission under HP was greatly lower (14%) than that of under LP, suggesting that overdose P addition may suppress microbial activities or root respiration.

4.1.3. Effects of N and P Interaction

Our study found that soil CO_2 emissions under N and P co-treatments were 49% higher than those of the control in the first four months, which may be because P addition promoted N absorption by plants [49] or the changed soil N:P ratio stimulated soil microbial activity [50]. Deng et al. [50] found that N addition can change the ratio of *ectomycorrhizal* to *arbuscular mycorrhizal* fungi, thus promoting the absorption of P elements to maintain a stable N:P ratio in temperate coniferous forests. Their study further implied that N:P balance is important for controlling soil CO_2 emission rates, which is consistent with our conclusion that LP addition had higher (8%), but not significant, soil CO_2 emissions than HNLP in the N-saturated soil condition. In a 9-year experiment on a Chinese fir plantation, Zhang et al. [22] found that N and P co-addition had the highest soil CO_2 emissions compared with single N and P treatments, while the CK had the lowest CO_2 emissions. They argued that N and P co-addition significantly altered the soil microbial community structure and favored more active soil microbial metabolisms. Our study also observed that the N and P co-addition greatly (not significant) increased soil CO_2 emissions compared with the CK and single N and P additions. Our study also found that increased MBC was the main cause for the slightly increased CO_2 emission, which is consistent with their study.

4.2. Effects of N and P Addition on Tree Growth

Our study indicated that the mean biomass increment under HN treatment was slightly lower than that of the CK, which is consistent with the results from Alvarez-Clare et al. [15]. Their study found that N addition could reduce the relative growth rate of N-fixing tree species in Costa Rica. Some studies indicated that the higher soil-available N caused by N addition could stimulate plant N uptake and accumulation but could decrease the absorption of P, which might result in nutrient imbalances between N and P and consequently reduce dry matter production [51,52]. In addition, the excessive amount of N could temporarily exceed the microbial demand for N, leading to enhanced nitrification and soil acidification, and thus toxic effects on plant roots and reduced plant photosynthesis. However, more studies have also shown that N addition can promote tree growth [53] or has no impact [14,54]. A possible reason for the different responses may be because of the different soil N conditions. Another possible reason may be because N addition can influence plant growth indirectly by increasing N mineralization and availability, soil acidification, nutritional imbalances, and the leaching of nutrients [51,55]; thus, the overall effects depend on which function is dominant. In addition, tree growth is not only affected by nutrient availability but also by factors such as climate, tree size, forest age, and other soil properties [56]. Subtropical forests are generally considered to be N-rich ecosystems, typically have older and more weathered soils, have a lower total soil P value and a higher percentage of sequestered P, higher plant N:P, higher plant P use efficiency, and lower plant and soil P concentrations; thus, the subtropical forests in China are mainly P-limited [57].

Our study found that LP addition significantly promoted tree productivity compared with the control and other treatments, proving this forest plantation is P-limited. However, we also observed that HP treatment had no significant effect on the growth of Chinese fir. This may be because the low P addition can neutralize the excessive N nutrient and thus maintain the soil N and P balance, while the excessive P addition broke the stoichiometric balance between N and P nutrients and thus inhibited the growth of Chinese fir [58,59]. Therefore, we suggest that a low P addition level (<5 g P/m^2/yr) is more suitable for increasing tree productivity in N-saturated subtropical forests.

Many previous studies have indicated that N and P co-addition can significantly increase tree growth rate [60,61]. This is because N and P co-addition can relieve the N or P limitation conditions [14]. However, our results indicated that N and P co-addition did not significantly affect tree growth, which is also consistent with some studies in the temperate and tropical regions [12,62]. This is also partly due to either N-saturated conditions or an imbalance between N and P nutrients. In addition, some studies have found that N and P co-addition can result in reduced soil pH value, leading to toxic effects on soil microbial communities [63].

4.3. Management Implications and Limitations

Generally, one or two instances of fertilization, either at the planting time or/and at the mid-rotation age are implemented in most of China's managed forests. This is why our study adopted a one-time fertilization experiment at the mid-rotation age: to mimic the reality of fertilization management. Our study indicated that N-alone addition did not significantly change the soil respiration and tree productivity in the study area, suggesting that the Chinese fir plantation is N-saturated and no more N fertilizer is needed. LP and combined N and P additions could significantly increase soil respiration in the short term, while the HP treatment did not significantly affect soil respiration. This suggests there should be a balance point between N and P nutrients, and imbalanced P and N nutrients are not conducive to soil microbial activities and organic matter decomposition. We further observed that only LP treatment can significantly increase tree productivity within 3 years, which further proved that N and P balance is more important for tree growth and soil microbes. Although soil CO_2 emission increased in the short term, considering its significant effects on promoting productivity and CH_4 uptake and non-significant effects on N_2O emission [31], we suggest that an LP amount (i.e., <5 g P/m^2/yr) should be applied in the study area to maintain the balance of N and P nutrients.

We stopped further observations after one half year since we did not observe significant differences from treatments in the soil's chemical and physical properties, especially for the greenhouse gas (CO_2, CH_4, and N_2O) fluxes. However, many previous studies have implied that the effects of N and P fertilization (especially P) will last a longer period since the tree and litter N and P contents have been modified and need long-term observation for their recycling and feedback effects [41]. Therefore, our short-term experiment may underestimate the impacts of N and P addition on soil CO_2 emissions. In addition, we did not separate the soil CO_2 emissions from the soil and roots, so our observed changes in soil CO_2 emissions were actually a combined emission, which limits our deep analysis from identifying the contributions from these two sources.

5. Conclusions

To determine the best fertilization option for the Chinese fir plantation under N-saturated conditions, this study designed six N and P addition experiments. The results indicated that LP and combined N and P treatments can significantly increase soil CO_2 emission in the first four months after treatment, while HP and HN treatments do not significantly affect soil CO_2 emission. LP treatment can significantly promote tree growth, and the effects decline with time, while other treatments do not significantly affect tree productivity. Our study further proved that the study site is N-saturated. How to maintain the balance between N and P availability is the key question for forest productivity and greenhouse gas management in the study area. Considering the overall effects on soil CO_2 emission, CH_4 uptake, N_2O emission, and productivity, we recommend that a low-level P addition (<5 g P/m^2/yr) could be more suitable for the N-saturated Chinese fir plantations in the study region.

Author Contributions: Conceptualization: X.L., B.L. and G.C.; methodology: B.L. and G.C.; investigation: X.L. and B.L.; validation: X.L. and B.L.; formal analysis: X.L. and B.L.; data curation: B.L. and X.L.; writing—original draft: X.L. and G.C.; writing—review and editing: X.L., B.L. and G.C.; visualization: X.L. and B.L.; supervision: G.C.; project administration: G.C.; funding acquisition: G.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Natural Science Foundation of Zhejiang Province (Grant number LY20C030001), the Scientific Research Foundation of Zhejiang A&F University (Grant number 2034020080), and the Overseas Expertise Introduction Project for Discipline Innovation (111 Project; Grant number D18008).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available on request from the authors.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Jassal, R.S.; Black, T.A.; Trofymow, J.A.; Roy, R.; Nesic, Z. Soil CO_2 and N_2O flux dynamics in a nitrogen-fertilized Pacific Northwest Douglas-fir stand. *Geoderma* **2010**, *157*, 118–125. [CrossRef]
2. IPCC. *Climate Change 2001: The Scientific Basis, Intergovernmental Panel on Climate Change, Working Group 3, Third Assessment Report*; Cambridge University Press: Cambridge, UK, 2001.
3. Jenssen, M.; Butterbach-Bahl, K.; Hofmann, G.; Papen, H. Exchange of trace gases between soils and the atmosphere in Scots pine forest ecosystems of the northeastern German lowlands: 1. Fluxes of N_2O, NO/NO_2 and CH_4 at forest sites with different N-deposition. *For. Ecol. Manag.* **2002**, *167*, 135–147. [CrossRef]
4. Gruber, N.; Galloway, J.N. An Earth-system perspective of the global nitrogen cycle. *Nature* **2008**, *451*, 293–296. [CrossRef]

5. Cleveland, C.C.; Townsend, A.R. Nutrient additions to a tropical rain forest drive substantial soil carbon dioxide losses to the atmosphere. *Proc. Natl. Acad. Sci. USA* **2006**, *103*, 10316–10321. [CrossRef] [PubMed]
6. Mo, J.; Zhang, W.; Zhu, W.; Gundersen, P.; Fang, Y.T.; Li, D.J.; Wang, H. Nitrogen addition reduces soil respiration in a mature tropical forest in southern China. *Glob. Chang. Biol.* **2008**, *14*, 403–412. [CrossRef]
7. Janssens, I.A.; Dieleman, W.; Luyssaert, S.; Subke, J.A.; Reichstein, M.; Ceulemans, R.; Ciais, P.; Dolman, A.J.; Grace, J.; Matteucci, G. Reduction of forest soil respiration in response to nitrogen deposition. *Nat. Geosci.* **2010**, *3*, 315–322. [CrossRef]
8. Liu, L.; Greaver, T.L. A global perspective on belowground carbon dynamics under nitrogen enrichment. *Ecol. Lett.* **2010**, *13*, 819–828. [CrossRef]
9. Keith, H.; Jacobsen, K.L.; Raison, R.J. Effects of soil phosphorus availability, temperature and moisture on soil respiration in Eucalyptus pauciflora forest. *Plant Soil* **1997**, *190*, 127–141. [CrossRef]
10. Steudler, P.; Garcia-Montiel, D.; Piccolo, M.; Neill, C.; Melillo, J.; Feigl, B.; Cerri, C. Trace gas responses of tropical forest and pasture soils to N and P fertilization. *Glob. Biogeochem. Cycles* **2002**, *16*, 1023. [CrossRef]
11. Homeier, J.; Hertel, D.; Camenzind, T.; Cumbicus, N.L.; Maraun, M.; Martinson, G.O.; Poma, L.N.; Rillig, M.C.; Sandmann, D.; Scheu, S.; et al. Tropical Andean forests are highly susceptible to nutrient inputs--rapid effects of experimental N and P addition to an Ecuadorian montane forest. *PLoS ONE* **2012**, *7*, e47128. [CrossRef]
12. Goswami, S.; Fisk, M.C.; Vadeboncoeur, M.A.; Garrison-Johnston, M.; Yanai, R.D.; Fahey, T.J. Phosphorus limitation of above-ground production in northern hardwood forests. *Ecology* **2018**, *99*, 438–449. [CrossRef] [PubMed]
13. Rappe-George, M.O.; Gärdenäs, A.I.; Kleja, D.B. The impact of four decades of annual nitrogen addition on dissolved organic matter in a boreal forest soil. *Biogeosciences* **2013**, *10*, 1365–1377. [CrossRef]
14. DeForest, J.L.; Snell, R.S. Tree growth response to shifting soil nutrient economy depends on mycorrhizal associations. *New Phytol.* **2020**, *225*, 2557–2566. [CrossRef] [PubMed]
15. Alvarez-Clare, S.; Mack, M.C.; Brooks, M. A direct test of nitrogen and phosphorus limitation to net primary productivity in a lowland tropical wet forest. *Ecology* **2013**, *94*, 1540–1551. [CrossRef]
16. Tian, D.; Li, P.; Fang, W.; Xu, J.; Luo, Y.; Yan, Z.; Zhu, B.; Wang, J.; Xu, X.; Fang, J. Growth responses of trees and understory plants to nitrogen fertilization in a subtropical forest in China. *Biogeosciences* **2017**, *14*, 3461–3469. [CrossRef]
17. Elser, J.J.; Bracken, M.E.S.; Cleland, E.E.; Gruner, D.S.; Harpole, W.S.; Hillebrand, H.; Ngai, J.T.; Seabloom, E.W.; Shurin, J.B.; Smith, J.E. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. *Ecol. Lett.* **2007**, *10*, 1135–1142. [CrossRef]
18. Yu, H.; Chen, Y.; Zhang, H.; Zhou, Z. The effect of inorganic nitrogen addition on soil nitrogen and greenhouse gas flux for the *Pinus tabulaeformis* forest in Taiyue Mountain, Shanxi Province. *J. Nanjing For. Univ. (Nat. Sci.)* **2019**, *43*, 85–91.
19. Yuan, L.; Li, W.; Chen, W.; Zhang, J.; Cai, Z. Characteristics of nitrogen deposition in Daiyun Mountain National Nature Reserve. *Environ. Sci.* **2016**, *37*, 4142–4146.
20. Nadelhoffer, K.J.; Emmett, B.A.; Gundersen, P.; Kjønaas, O.J.; Koopmans, C.J.; Schleppi, P.; Tietema, A.; Wright, R.F. Nitrogen deposition makes a minor contribution to carbon sequestration in temperate forests. *Nat. Int. Wkly. J. Sci.* **1999**, *398*, 145–148. [CrossRef]
21. Wang, J.; Li, Q.; Fu, X.; Dai, X.; Kou, L.; Xu, M.; Chen, S.; Chen, F.; Wang, H. Mechanisms driving ecosystem carbon sequestration in a Chinese fir plantation: Nitrogen versus phosphorus fertilization. *Eur. J. For. Res.* **2019**, *138*, 863–873. [CrossRef]
22. Zhang, M.; Niu, Y.; Wang, W.; Bai, S.; Luo, H.; Tang, L.; Chen, F.; Xu, Z.; Guo, X. Responses of microbial function, biomass and heterotrophic respiration, and organic carbon in fir plantation soil to successive nitrogen and phosphorus fertilization. *Appl. Microbiol. Biotechnol.* **2021**, *105*, 8907–8920. [CrossRef] [PubMed]
23. Liu, S.; Zhou, T.; Wei, L.; Shu, Y. The spatial distribution of forest carbon sinks and sources in China. *Chin. Sci. Bull.* **2012**, *57*, 1699–1707. [CrossRef]
24. Xu, J. The 8th Forest Resources Inventory Results and Analysis in China. *For. Econ.* **2014**, *37*, 6–8.
25. Li, J.; Bai, Y.F.; Peng, Y.; Jiang, C.Q.; Wang, S.L.; Sun, R.; Xu, R. Research on Carbon Sequestration of Chinese Fir Plantation Management in Huitong County, Hunan. *For. Sci. Res.* **2017**, *30*, 436–443.
26. Shi, Z.J.; Bai, Y.F.; Sun, R.; Peng, Y.; Jiang, C.Q.; Wang, S.L. Comparison of carbon storage of two restoration models after cutting Chinese fir plantation. *For. Sci. Res.* **2017**, *30*, 214–221.
27. Selvaraj, S.; Duraisamy, V.; Huang, Z.; Guo, F.; Ma, X.J.G. Influence of long-term successive rotations and stand age of Chinese fir (*Cunninghamia lanceolata*) plantations on soil properties. *Geoderma* **2017**, *306*, 127–134. [CrossRef]
28. Farooq, T.H.; Yan, W.; Rashid, M.; Tigabu, M.; Wu, P. Chinese fir (*Cunninghamia lanceolata*) a green gold of China with continues decline in its productivity over the successive rotations: A review. *Appl. Ecol. Environ. Res.* **2019**, *17*, 11055–11067. [CrossRef]
29. Li, R.; Yu, D.; Zhang, Y.; Han, J.; Zhang, W.; Yang, Q.; Gessler, A.; Li, M.-H.; Xu, M.; Guan, X.; et al. Investment of needle nitrogen to photosynthesis controls the nonlinear productivity response of young Chinese fir trees to nitrogen deposition. *Sci. Total Environ.* **2022**, *840*, 156537. [CrossRef]
30. Chen, J.; Zhao, G.; Wei, Y.; Dong, Y.; Jiao, R. Isolation and screening of multifunctional phosphate solubilizing bacteria and its growth-promoting effect on Chinese fir seedlings. *Sci. Rep.* **2021**, *11*, 9081. [CrossRef] [PubMed]
31. Li, B.J.; Chen, G.S.; Lu, X.C.; Jiao, H.B. Effects of Nitrogen and Phosphorus Additions on Soil N_2O Emissions and CH_4 Uptake in a Phosphorus-Limited Subtropical Chinese Fir Plantation. *Forests* **2022**, *13*, 772. [CrossRef]

32. Zhang, Q.X.; Chen, J.; Wang, X.T.; Wang, N.; Bai, S.B. Short-term response of Chinese fir plantation soil greenhouse gas emissions to *Phyllostachys edulis* invasion and logging. *J. Zhejiang A F Univ.* **2021**, *38*, 703–711.
33. Sun, Y.; Wang, G.; Hou, J.; Mo, L. Biomass estimation model and its universality of *Cunninghamia lanceolata* in Lin'an. *J. Zhejiang For. Sci. Technol.* **2018**, *38*, 50–56.
34. Wang, Z.; Ineson, P. Methane oxidation in a temperate coniferous forest soil: Effects of inorganic N. *Soil Biol. Biochem.* **2003**, *35*, 427–433. [CrossRef]
35. Liu, L.; Liu, Y.; Wen, X.; Wang, Y. CH_4 emission flux from soil of pine plantations in the qianyanzhou red earth hill region of China. *Chin. J. Plant Ecol.* **2008**, *32*, 431–439.
36. Hansen, M.C.; Potapov, P.V.; Moore, R.; Hancher, M.; Turubanova, S.A.; Tyukavina, A.; Thau, D.; Stehman, S.V.; Goetz, S.J.; Loveland, T.R. High-resolution global maps of 21st-century forest cover change. *Science* **2013**, *342*, 850–853. [CrossRef] [PubMed]
37. Chen, X.; Liu, J.; Jiang, P.; Wu, J.; Zhou, G.; Li, Y. Effects of Nitrogen Deposition on Soil Biochemical Properties and Enzymes Activities in Moso Bamboo (*Phyllostachys edulis*) Forest. *J. Soil Water Conserv.* **2020**, *34*, 277–284.
38. Gao, W.; Yang, H.; Li, S.; Kou, L. Responses of soil CO_2, CH_4 and N_2O fluxes to N, P, and acid additions in mixed forest in subtropical China. *J. Resour. Ecol.* **2017**, *8*, 154–164.
39. Gao, Q.; Hasselquist, N.J.; Palmroth, S.; Zheng, Z.; You, W. Short-term response of soil respiration to nitrogen fertilization in a subtropical evergreen forest. *Soil Biol. Biochem.* **2014**, *76*, 297–300. [CrossRef]
40. Liu, C.; Dong, Y.; Sun, Q.; Jiao, R. Soil bacterial community response to short-term manipulation of the nitrogen deposition form and dose in a Chinese fir plantation in Southern China. *Water Air Soil Pollut.* **2016**, *227*, 447. [CrossRef]
41. Zhao, B.; Geng, Y.; Cao, J.; Yang, L.; Zhao, X. Contrasting responses of soil respiration components in response to five-year nitrogen addition in a *Pinus tabulaeformis* forest in northern China. *Forests* **2018**, *9*, 544. [CrossRef]
42. Zhang, T.; Chen, H.Y.H.; Ruan, H. Global negative effects of nitrogen deposition on soil microbes. *Int. Soc. Microb. Ecol.* **2018**, *12*, 1817–1825. [CrossRef] [PubMed]
43. Lin, Y.; Ai, J.; Song, X.; Li, Q.; Zhang, J. Effects of simulated nitrogen deposition and phosphorus addition on soil respiration in Chinese fir forest. *J. Zhejiang A F Univ.* **2021**, *38*, 494–501.
44. Liu, L.; Gundersen, P.; Zhang, T.; Mo, J. Effects of phosphorus addition on soil microbial biomass and community composition in three forest types in tropical China. *Soil Biol. Biochem.* **2012**, *44*, 31–38. [CrossRef]
45. Feng, J.; Zhu, B. A global meta-analysis of soil respiration and its components in response to phosphorus addition. *Soil Biol. Biochem.* **2019**, *135*, 38–47. [CrossRef]
46. Allison, S.D.; Czimczik, C.I.; Treseder, K.K. Microbial activity and soil respiration under nitrogen addition in Alaskan boreal forest. *Glob. Chang. Biol.* **2008**, *14*, 1156–1168. [CrossRef]
47. Zhang, J.; Li, Y.; Jiang, P.; Zhou, G.; Shen, Z.; Liu, J.; Wang, Z. Effects of fertilization on soil CO_2 flux in *Castanea mollissima* stand. *Chin. J. Appl. Ecol.* **2013**, *24*, 2431–2439.
48. Shi, L.; Dech, J.P.; Yao, H.; Zhao, P. The effects of nitrogen addition on dissolved carbon in boreal forest soils of northeastern China. *Sci. Rep.* **2019**, *9*, 8274. [CrossRef]
49. Long, M.; Wu, H.; Smith, M.D.; La Pierre, K.J.; Lü, X.; Zhang, H.; Han, X.; Yu, Q. Nitrogen deposition promotes phosphorus uptake of plants in a semi-arid temperate grassland. *Plant Soil* **2016**, *408*, 475–484. [CrossRef]
50. Deng, M.; Liu, L.; Sun, Z.; Piao, S.; Ma, Y.; Chen, Y.; Wang, J.; Qiao, C.; Wang, X.; Li, P. Increased phosphate uptake but not resorption alleviates phosphorus deficiency induced by nitrogen deposition in temperate *Larix principis-rupprechtii* plantations. *New Phytol.* **2016**, *212*, 1019–1029. [CrossRef]
51. Sager, E.P.S.; Hutchinson, T.C. The effects of UV-B, nitrogen fertilization, and springtime warming on sugar maple seedlings and the soil chemistry of two central Ontario forests. *Can. J. For. Res.* **2005**, *35*, 2432–2446. [CrossRef]
52. Nakaji, T.; Fukami, M.; Dokiya, Y.; Izuta, T. Effects of high nitrogen load on growth, photosynthesis and nutrient status of *Cryptomeria japonica* and *Pinus densiflora* seedlings. *Trees* **2001**, *15*, 453–461. [CrossRef]
53. Fownes, J.H.; Harrington, R.A. Seedling response to gaps: Separating effects of light and nitrogen. *For. Ecol. Manag.* **2004**, *203*, 297–310. [CrossRef]
54. Nasto, M.K.; Winter, K.; Turner, B.L.; Cleveland, C.C. Nutrient acquisition strategies augment growth in tropical N_2-fixing trees in nutrient-poor soil and under elevated CO_2. *Ecology* **2019**, *100*, e02646. [CrossRef]
55. Wan, S.; Hui, D.; Wallace, L.; Luo, Y. Direct and indirect effects of experimental warming on ecosystem carbon processes in a tallgrass prairie. *Glob. Biogeochem. Cycles* **2005**, *19*, GB2014. [CrossRef]
56. Feng, J.; Zhu, B. A review on the effects of nitrogen and phosphorus addition on tree growth and productivity in forest ecosystems. *Chin. J. Plant Ecol.* **2020**, *44*, 583–597. [CrossRef]
57. Vitousek, P.M.; Porder, S.; Chadwick, H. Terrestrial phosphorus limitation: Mechanisms, implications, and nitrogen—Phosphorus interactions. *Ecol. Appl.* **2010**, *20*, 5–15. [CrossRef]
58. Báez, S.; Homeier, J. Functional traits determine tree growth and ecosystem productivity of a tropical montane forest: Insights from a long-term nutrient manipulation experiment. *Glob. Chang. Biol.* **2018**, *24*, 399–409. [CrossRef]
59. Zheng, M.; Zhou, Z.; Luo, Y.; Zhao, P.; Mo, J. Global pattern and controls of biological nitrogen fixation under nutrient enrichment: A meta-analysis. *Glob. Chang. Biol.* **2019**, *25*, 3018–3030. [CrossRef]
60. Li, Y.; Tian, D.; Yang, H.; Niu, S. Size-dependent nutrient limitation of tree growth from subtropical to cold temperate forests. *Funct. Ecol.* **2018**, *32*, 95–105. [CrossRef]

61. Jiang, J.; Wang, Y.P.; Yang, Y.; Yu, M.; Yan, J. Interactive effects of nitrogen and phosphorus additions on plant growth vary with ecosystem type. *Plant Soil* **2019**, *440*, 523–537. [CrossRef]
62. Wright, S.J. Plant responses to nutrient addition experiments conducted in tropical forests. *Ecol. Monogr.* **2019**, *89*, e01382. [CrossRef]
63. Čapek, P.; Manzoni, S.; Kaštovská, E.; Wild, B.; Diáková, K.; Bárta, J.; Schnecker, J.; Biasi, C.; Martikainen, P.J.; Alves, R.J.E.; et al. A plant-microbe interaction framework explaining nutrient effects on primary production. *Nat. Ecol. Evol.* **2018**, *2*, 1588–1596. [CrossRef] [PubMed]