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Effects of Near Natural Forest Management on Soil Greenhouse Gas Flux in *Pinus massoniana* (Lamb.) and *Cunninghamia lanceolata* (Lamb.) Hook. Plantations

Angang Ming [1,3], Yujing Yang [2,3], Shirong Liu [2,*], Hui Wang [2], Yuanfa Li [4], Hua Li [1,3], You Nong [1,3], Daoxiong Cai [1,3], Hongyan Jia [1,3], Yi Tao [1,3] and Dongjing Sun [1,3]

1 Experimental Center of Tropical Forestry, Chinese Academy of Forestry, Pingxiang 532600, China; mingangang0111@163.com (A.M.); lihua782003@163.com (H.L.); imnongyou@163.com (Y.N.); rlzxcdx@126.com (D.C.); rlzxjhy@163.com (H.J.); tyrzjl@126.com (Y.T.); happysdj@163.com (D.S.)
2 Key Laboratory of Forest Ecology and Environment, State Forestry Administration; Institute of Forest Ecology, Environment and Protection, Chinese Academy of Forestry, Beijing 100091, China; yangyujing8809@hotmail.com (Y.Y.); wanghui@caf.ac.cn (H.W.)
3 Guangxi Youyiguan Forest Ecosystem Research Station, Pingxiang 532600, China
4 College of Forestry, Guangxi University, Nanning 530004, China; xianggelilalyf@sina.com
* Correspondence: liusr@caf.ac.cn; Tel.: +86-10-6288-9311

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Abstract: Greenhouse gases are the main cause of global warming, and forest soil plays an important role in greenhouse gas flux. Near natural forest management is one of the most promising options for improving the function of forests as carbon sinks. However, its effects on greenhouse gas emissions are not yet clear. It is therefore necessary to characterise the effects of near natural forest management on greenhouse gas emissions and soil carbon management in plantation ecosystems. We analysed the influence of near natural management on the flux of three major greenhouse gases (carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)) in *Pinus massoniana* Lamb. and *Cunninghamia lanceolata* (Lamb.) Hook. plantations. The average emission rates of CO_2 and N_2O in the near natural plantations were higher than those in the corresponding unimproved pure plantations of *P. massoniana* and *C. lanceolata*, and the average absorption rate of CH_4 in the pure plantations was lower than that in the near natural plantations. The differences in the CO_2 emission rates between plantations could be explained by differences in the C:N ratio of the fine roots. The differences in the N_2O emission rates could be attributed to differences in soil available N content and the C:N ratio of leaf litter, while the differences in CH_4 uptake rate could be explained by differences in the C:N ratio of leaf litter only. Near natural forest management negatively affected the soil greenhouse gas emissions in *P. massoniana* and *C. lanceolata* plantations. The potential impact of greenhouse gas flux should be considered when selecting tree species for enrichment planting.

Keywords: near natural forest management; *Pinus massoniana* plantation; *Cunninghamia lanceolata* plantation; soil greenhouse gas flux

1. Introduction

Increased emissions of greenhouse gases, dominated by carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are the main cause of global climate change [1]. Most greenhouse gases in the atmosphere are produced and absorbed by soil [2]. Forest soils have the largest carbon pool in terrestrial ecosystems owing to soil respiration processes, mainly root respiration, microbial respiration, and soil animal respiration [3]. N_2O is released from the soil to the atmosphere through microbe-regulated nitrification and denitrification [4], while forest soil usually serves as the absorption sink for atmosphere CH_4 [5]. About 6% of global CH_4 is absorbed through soil processes by methanogenic bacteria [6,7]. The global warming potential of CH_4 and N_2O is 25 and 298 times larger than that of CO_2, respectively, although they are much less abundant than CO_2 in the atmosphere [8]. Therefore, a comprehensive understanding of the rates of greenhouse gas emissions and absorption and their key influencing factors in forest soils is critical to assessing the contribution of forest ecosystems to global climate change [9,10].

Near natural forest management, one of the most promising options for plantation silviculture, has received widespread attention in recent years [11]. Following the principle of near natural forest management, pure plantations are transformed into near natural forests through a series of management strategies, according to the structure and succession of natural forests. The strategies include species introduction, structural adjustment, natural regeneration promotion, and understory protection. Thus, the management of coniferous plantations has a significant impact on the structure, tree species composition, and regeneration of the forests [12,13]. Tree species are considered to alter the soil environment (including soil temperature and moisture), soil physical and chemical properties, and soil biological processes by influencing the composition and quality of the stand root system, canopy, litter, and fine roots [14,15]. As a result, soil greenhouse gas flux is greatly impacted by the composition of tree species. For example, the soil CH_4 flux of *Populus tremula* L., *Picea asperata* Mast. and pine forests in Europe differs significantly [16]. Menyailo and Hungate [17] observed higher CH_4 consumption in aspen, birch and spruce forest soils compared to Scots and Arolla pine forest soils in Siberia. However, average CH_4 uptake rates in mixed and pure beech plantations were about twice as large as that in pure spruce plantations [18]. Soil CO_2 efflux was accelerated after conversion from secondary oak forest to pine plantation in southeastern China [19]. Mature pine plantation soil emits 1.5 and 2.5 times more CO_2 than mature beech and Douglas fir [20]. Studies have also shown significant differences in soil respiration rates among 16 tree species in the tropics, with an emission flux from 2.8 to 6.8 μmol m^{-2} s^{-1} [21].

Although forest soil–atmosphere greenhouse gas exchange in temperate and tropical regions has been studied in depth [5,22–24], little is known about this process in the southern subtropical forests. There is a growing need locally and abroad to reduce greenhouse gas emissions from forests through plantation management. However, few studies have examined the use of plantation management strategies for manipulating soil greenhouse gas flux. Near natural management of coniferous plantations involves the transformation of even-aged pure stands of coniferous species into uneven-aged mixed broad-leaved forests, but it is not well known how this strategy affects the emission and absorption of greenhouse gases. Therefore, a subtropical, near natural *Pinus massoniana* plantation (P(CN)) and an unimproved pure stand of *P. massoniana* (P(CK)), as well as a near natural *Cunninghamia lanceolata* plantation (C(CN)) and an unimproved pure *C. lanceolata* stand (C(CK)) were selected in southern China. The objective of this study was to examine the effects of near natural forest management on soil–atmosphere greenhouse gas exchange and the main factors influencing these processes. The present study provides a theoretical basis for the multi-objective and sustainable management of plantations in southern subtropical regions.

2. Materials and Methods

2.1. Study Site Description

The study site is located in the Experimental Center of Tropical Forestry, Chinese Academy of Forestry (Pingxiang, Guangxi, China). It is one of the forest ecology study stations under the jurisdiction of the State Forestry Administration (22°10′ N, 106°50′ E). The site is within the southwestern region, which has a subtropical monsoon climate, with a semi-humid climate and obvious dry and wet seasons. The annual duration of sunshine is 1200 to 1600 h. The precipitation is abundant, with an annual average precipitation of 1200 to 1500 mm, mainly from April to September each year. The annual evaporation is 1200–1400 mm, the relative humidity is 80–84%, and the average annual temperature is 20.5–21.7 °C. The main types of landforms are low hills and hills. The soil is mainly composed of laterite and red soil based on the Chinese soil classification; this is classified as ferralsols in the World Reference Base for Soil Resources. The soil thickness is generally higher than 80 cm. Subtropical evergreen broad-leaved forests comprise the local vegetation.

There are nearly 20,000 ha of various plantation types in the Experimental Center of Tropical Forestry. *P. massoniana* and *C. lanceolata* are the main coniferous tree species. Native broad-leaved tree species include *Quercus griffithii* (Hook.f. and Thomson ex Miq.), *Erythrophleum fordii* Oliver, *Castanopsis hystrix* Miq., *Mytilaria laosensis* Lecomte., *Betula alnoides* Buch.-Ham. ex D. Don, and *Dalbergia lanceolata* Zipp. ex Span. The main alien tree species are eucalyptus and *Tectona grandis* L.f. Among these species, *E. fordii* and *D. lanceolata* are nitrogen-fixing trees, and *Q. griffithii* is a fast-growing broad-leaved tree species with a strong natural regeneration ability. The near natural management of pure plantations of *P. massoniana* and *C. lanceolata* with *E. fordii* and *Q. griffithii* is widely applied at the center, as it not only meets the need for short-period timbers and precious large-diameter timbers, but also realises the natural regeneration of native broad-leaved species and achieves the goal of near natural management.

2.2. Experimental Design

A single-factor and two-level stochastic block design was used for the present experiment. There were four blocks representing four replicates. Four forest types were set up in each block: near natural *P. massoniana* plantation (P(CN)), unimproved *P. massoniana* plantation (P(CK)), near natural *C. lanceolata* plantation (C(CN)), and unimproved pure *C. lanceolata* plantation (C(CK)). There were thus a total of 16 experimental plots, and the area of each experimental plot was 0.5 ha.

The pure plantations of *P. massoniana* and *C. lanceolata* were established in 1993 after the clear-cutting of *C. lanceolata*, with an initial planting density of 2500 trees ha^{-1}. Felling and afforestation were repeated a total of six times within the first three years after initial afforestation. The release felling was carried out in the seventh year, and the first-increment felling was carried out in the 11th year, retaining a density of 1200 trees ha^{-1}. In 2007, near natural management was carried out, and the main management strategies included reducing the intensity of the intermediate felling of pure stands of *P. massoniana* and *C. lanceolata* forests, while simultaneously preserving natural regeneration (the retention density was 600 trees ha^{-1}). In early 2008, *Q. griffithii* and *E. fordii* were replanted after the intermediate felling of *P. massoniana* and *C. lanceolata*, and the density of the native replanted tree species was 600 trees ha^{-1} (the average density of *Q. griffithii* and *E. fordii* was 300 trees ha^{-1}, respectively). Unevenly-aged mixed broad-leaved forests with a total density of 1200 trees ha^{-1} was formed. During the whole process, pure plantations of *P. massoniana* and *C. lanceolata* were maintained as controls, whose total density was kept at 1200 trees ha^{-1}. At present, the improved plantations have become unevenly-aged mixed stands with multilayer structures. A survey carried out in 2016 showed that the average diameter at breast height (DBH) and average tree height of *Q. griffithii* were 14.7 cm and 15.4 m, respectively, and the average DBH and average tree height of *E. fordii* were 5.2 cm and 6.3 m, respectively. The management processes for the four forests are shown in Table 1.

Table 1. Basic information and management history of the four plantations.

Year	Management	Plantation Type			
		P(CK)	P(CN)	C(CK)	C(CN)
1993	Afforestation	2500 trees ha^{-1}	2500 trees ha^{-1}	2500 trees ha^{-1}	2500 trees ha^{-1}
1993–1995	Tending for new plantations	6 times	6 times	6 times	6 times
2000	Released thinning	1600 trees ha^{-1}	1600 trees ha^{-1}	1600 trees ha^{-1}	1600 trees ha^{-1}
2004	Increment felling	1200 trees ha^{-1}	1200 trees ha^{-1}	1200 trees ha^{-1}	1200 trees ha^{-1}

Table 1. *Cont.*

Year	Management	Plantation Type			
		P(CK)	P(CN)	C(CK)	C(CN)
2007	Intensity thinning	No 1200 trees ha^{-1}	Yes 600 trees ha^{-1}	No 1200 trees ha^{-1}	Yes 600 trees ha^{-1}
2008	Complementary planting	No	Planting *Q. griffithii* and *E. fordii* with 300 trees ha^{-1} respectively	No	Planting *Q. griffithii* and *E. fordii* with 300 trees ha^{-1} respectively
2009	Tending	No	2 times	No	2 times
2016	Average DBH	22.2 ± 1.3 cm for *P. massoniana*	32.2 ± 1.6 cm for *P. massoniana*	17.1 ± 2.1 cm for *C. lanceolata*	22.3 ± 0.8 cm for *C. lanceolata*
2016	Average height	16.7 ± 0.5 m for *P. massoniana*	17.3 ± 0.7 m for *P. massoniana*	17.1 ± 0.4 m for *C. lanceolata*	17.2 ± 0.4 m for *C. lanceolata*

2.3. Measurement and Statistical Analysis

2.3.1. Soil CO_2, N_2O, and CH_4 Measurement

The sampling and analysis of three main greenhouse gases (N_2O, CH_4, and CO_2) in the soils were performed using the static chamber method and gas chromatography [25]. Three static boxes were randomly set in each plot of P(CN), P(CK), C(CN), and C(CK). The static box was 25 cm in diameter and 30 cm in height. A gas extraction valve and a small fan (8 cm in diameter) were installed at the top of the box to facilitate uniform gas mixing during sampling. The bottom of the box was buried in the ground at a depth of 5 cm two or three months before initial sampling [21]. From October 2014 to September 2015, sampling in all four plantations (a total of 16 plots) was completed from 9:00 a.m. to 11:00 a.m. on one day at the end of each month, and the measured values were used to calculate the average daily gas exchange flux [2]. During each sampling period, 100 ml gas samples were taken from static boxes with a medical syringe and timed with a stopwatch. The gas was sampled at 0, 15 and 30 min intervals. Three gas samples at each chamber were collected. The sample was injected into a polyethylene polythene sampling bag, cryopreserved, and sent back to the laboratory for measurement. We analysed gas samples for their N_2O, CH_4, and CO_2 concentrations using a gas chromatograph (Agilent 4890D, Agilent, Santa Clara, CA, USA). The flux of N_2O, CH_4, and CO_2 was calculated using the following formula:

$$F = \rho \times \frac{V}{A} \times \frac{P}{P_0} \times \frac{T_0}{T} \times \frac{dC_1}{dt} \quad (1)$$

where F is the mass change of the gas in the observation box per area and per unit time, ρ is the density of the measured gas in the standard state, V is the gas volume in the box, A is the area covered by the box, P is the atmospheric pressure at the sampling point, T is the absolute temperature at the time of sampling, $dC1/dt$ is the linear slope of gas concentration over time during the sampling, and P_0 and T_0 are the atmospheric pressure and absolute temperature in the standard state, respectively.

2.3.2. Micro-Environmental Data Measurement

Temperature and atmospheric pressure were measured with a thermometer and a barometer at the same time as sampling. The temperature of the soil at a depth of 5 cm was measured with a portable digital thermometer. Soil moisture (volumetric water content) at a depth of 5 cm was measured with an HH2 moisture meter (Delta-T Devices Ltd., Cambridge, UK) and converted into water-filled pore space (*WFPS*) using the following formula:

$$WFPS\,(\%) = \frac{Vol}{1 - \frac{bd}{2.65}} \quad (2)$$

where *bd* is bulk density, *vol* is volumetric water content, and 2.65 is the density of quartz.

2.3.3. Soil and Litterfall Sampling and Measurements

After the fresh and semi-decomposed litter residue at the upper surface of soil was stripped from the woodland near each static box in the four plantations, twelve soil samples at a depth of 0 to 10 cm were randomly collected using a stainless steel soil auger with an inner diameter of 8.7 cm. These samples were placed in mixed sample bags for preservation. The soil samples were then taken back to the laboratory to remove coarse roots, rubble, and other impurities using a 2 mm aperture screen and air dried for physical and chemical analysis.

Six 1 × 1 m leaf litterfall collectors made of nylon gauze (1 mm aperture) were set up randomly in the woodland near each static box in the four plantations. Leaf litterfall was collected once a month, and the leaves, branches, skin, and fruits were picked and sorted by tree species and organ and dried at 65 °C to a constant weight. A total of 12 collections of litterfall samples were prepared over the course of a year.

2.3.4. Fine Root Sampling and Measurements

Fine root biomass was determined by the continuous soil drilling method. Fine roots (diameter < 2 mm) were sampled in the 0–10 cm soil layer using a stainless steel soil auger with a diameter of 8.7 cm for sorting and collection. Twelve soil drillings collected for fine root biomass determination were carefully sorted out at random at the end of each bimonthly period in a sample plot of the four different plantations. In each plantation, the fine root samples were collected six times each year during the experiment. The fine root samples were weighed after drying at 65 °C to a constant weight. The average fine root biomass of the six sampling periods was used as the average fine root biomass [26].

2.3.5. Biogeochemical Properties Analysis of Plant and Soil Samples

Soil bulk density was measured using the volumetric ring during field sampling. Soil pH value was measured using glass electrodes after leaching the soil with 1 mol L^{-1} KCl solution. The organic C contents of the soil, litterfall, and fine root samples were determined by the potassium dichromate external heating method, and total N was determined by the Kjeldahl method. Soil ammonium and nitrate N contents were determined by spectrophotometry. Soil available N was analyzed through quantification of alkali-hydrolysable N in a Conway diffusion unit with Devarda's alloy in the outer chamber and boric acid-indicator solution in the inner chamber [27]. Soil total P was measured by inductively-coupled plasma optical-emission spectrometry (ICP-OES). Soil microbial biomass C and N were determined by the fumigation-extraction method [28].

2.3.6. Statistical Analysis

A one-way analysis of variance (ANOVA) was employed to determine the differences among the annual mean fluxes of soil greenhouse gases, as well as the biogeochemical properties of soil and plant samples in different plantations. Regression models were used to analyse the correlation between soil greenhouse gas flux and soil temperature and soil moisture in the four plantations. Multiple linear regression analyses were used to determine the main factors influencing differences in soil greenhouse gas flux among the four plantations. All of the data in the study followed a normal distribution and satisfied the test of homogeneity of variance. We performed statistical analyses using Windows SPSS 19.0. Statistical significance was determined at a threshold of $p < 0.05$.

3. Results

3.1. Soil Temperature and Moisture

Soil temperature and *WFPS* in the four plantations varied seasonally. The soil was cooler and drier during November 2014 and February 2015, whereas the soil was warmer and more humid from March 2015 to August 2015 (Figure 1). The sampling period in December 2014 was unusual in that it was a short wet period within the cool–dry season. January 2015 and July 2015 could be classified as within the cool–dry season and warm–humid season, respectively.

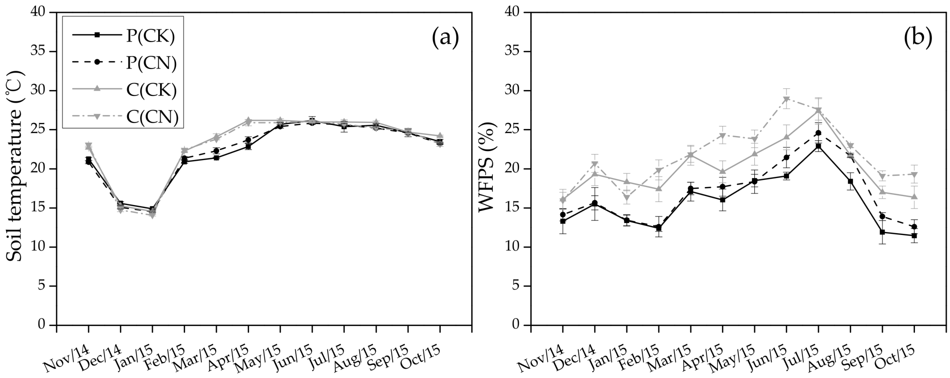

Figure 1. Seasonal patterns of soil temperature (**a**) and soil water-filled pore space (WFPS) (**b**) in the four plantations.

3.2. Seasonal Variation in Soil Greenhouse Gas Flux

The soil CO_2 and N_2O emission rates in the four plantations showed significant seasonal variations. The CO_2 emission rate was highest in July, when it was hot and humid, but lowest in January, during the dry season. All plantations had similar seasonal patterns for N_2O emission and CH_4 uptake (Figure 2).

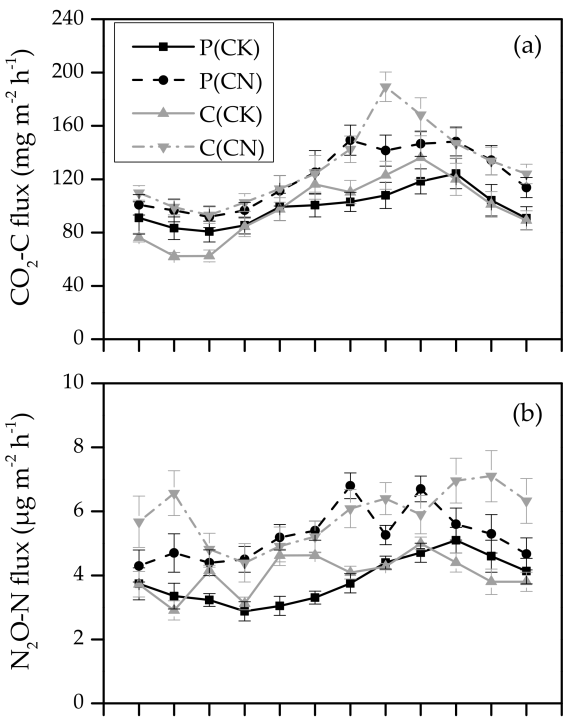

Figure 2. *Cont.*

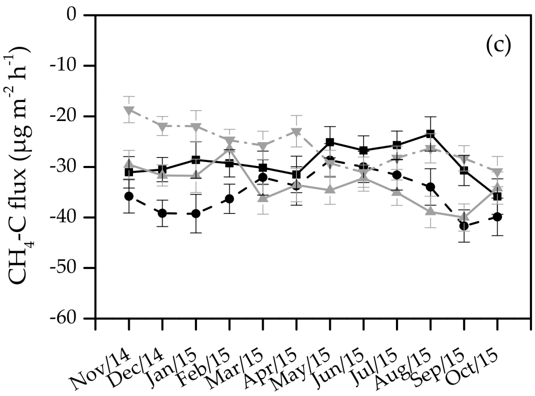

Figure 2. Seasonal patterns of soil CO_2, N_2O, and CH_4 flux in the four plantations.

Soil CO_2 emission rates were positively correlated with soil temperature and soil moisture (Figure 3a,b), but the correlation between CO_2 flux and soil moisture was significant in P(CN) only (Table 2). The N_2O emission was significantly and positively correlated with soil temperature in both P(CK) and C(CK) (Figure 3c). However, no significant correlation was found between soil N_2O flux and soil moisture (Figure 3d and Table 2).

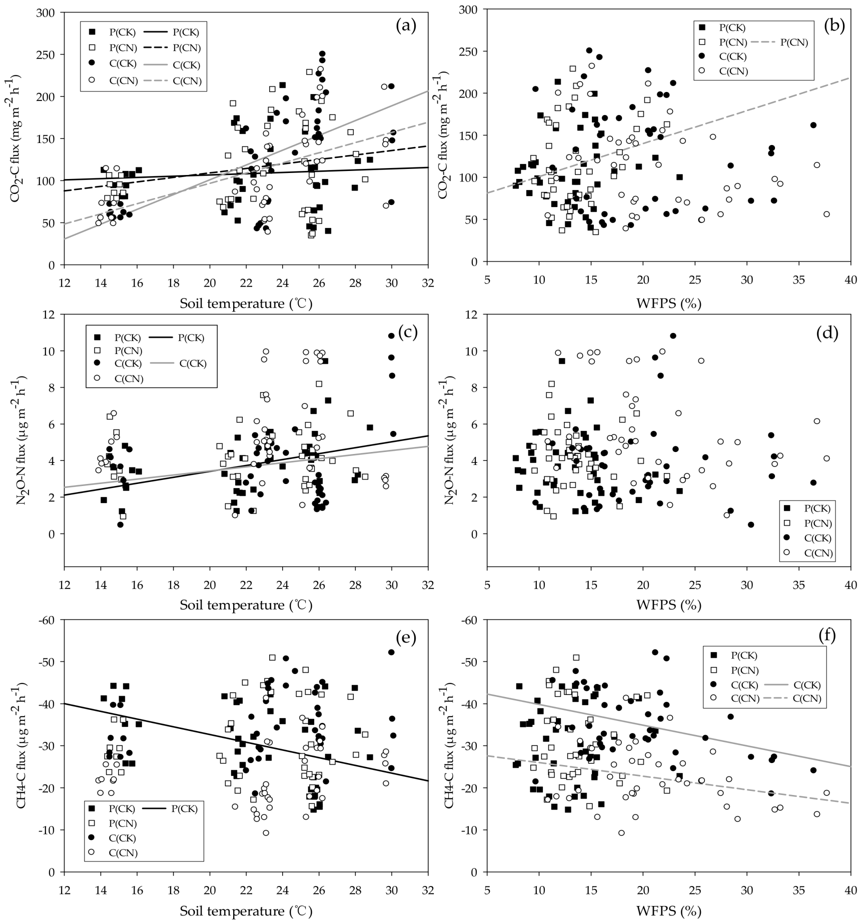

Figure 3. Relationships between soil CO_2 flux and temperature (**a**), CO_2 flux and water-filled pore space (WFPS) (**b**), N_2O flux and temperature (**c**), N_2O flux and WFPS (**d**), CH_4 flux and temperature (**e**), and CH_4 flux and WFPS (**f**) in the four plantations. Significant correlations were shown in solid and dashed lines ($p < 0.05$).

Table 2. Models, coefficients of determination (R^2) and *p*-values of regressions between soil greenhouse gas flux and soil temperature (T) and WFPS (W) in the four plantations. The rows of "T + W" represent the models considering both T and W, while others are those using T and W separately.

Plantation Type	P(CK)	P(CN)	C(CK)	C(CN)
		CO_2-C flux (mg m^{-2} h^{-1})		
T(°C)	CO_2 = 0.71T + 92.31 R^2 = 0.11, $p < 0.05$	CO_2 = 2.67T + 55.83 R^2 = 0.15, $p < 0.05$	CO_2 = 9.14T + 80.44 R^2 = 0.37, $p < 0.001$	CO_2 = 6.05T + 24.15 R^2 = 0.30, $p < 0.001$
W(%)	R^2 = 0.01, p = 0.47	CO_2 = 3.92W + 61.71 R^2 = 0.13, $p < 0.05$	R^2 = 0.06, p = 0.61	R^2 = 0.04, p = 0.28
T(°C) + W(%)	R^2 = 0.01, p = 0.80	R^2 = 0.09, p = 0.17	CO_2 = 9.19T + 0.98W − 103.51 R^2 = 0.41, $p < 0.001$	CO_2 = 5.34T − 1.28W + 19.03 R^2 = 0.33, $p < 0.01$
		N_2O-N flux (μg m^{-2} h^{-1})		
T(°C)	N_2O = 0.16T + 0.17 R^2 = 0.16, $p < 0.01$	R^2 = 0.02, p = 0.43	N_2O = 0.11T + 1.19 R^2 = 0.16, $p < 0.05$	R^2 = 0.00, p = 0.77
W(%)	R^2 = 0.03, p = 0.297	R^2 = 0.01, p = 0.54	R^2 = 0.01, p = 0.90	R^2 = 0.00, p = 0.77
T(°C) + W(%)	N_2O = 0.19T − 0.13W + 1.32 R^2 = 0.22, $p < 0.01$	R^2 = 0.03, p = 0.54	R^2 = 0.06, p = 0.30	R^2 = 0.15, p = 0.05
		CH_4-C flux (μg m^{-2} h^{-1})		
T(°C)	CH_4 = 0.92T − 51.07 R^2 = 0.17, $p < 0.01$	R^2 = 0.01, p = 0.13	R^2 = 0.05, p = 0.15	R^2 = 0.04, p = 0.25
W(%)	R^2 = 0.00, p = 0.998	R^2 = 0.01, p = 0.454	CH_4 = 0.49W − 44.75 R^2 = 0.15, $p < 0.01$	CH_4 = 0.24W − 29.21 R^2 = 0.10, $p < 0.05$
T(°C) + W(%)	CH_4 = 0.96T − 0.23W − 48.95 R^2 = 0.18, $p < 0.05$	R^2 = 0.03, p = 0.56	CH_4 = −0.23T + 0.44W − 38.50 R^2 = 0.16, $p < 0.05$	R^2 = 0.09, p = 0.16

CH_4 flux had a significant correlation with soil temperature in P(CK) only (Figure 3e). In the near natural and pure *C. lanceolata* plantations, soil CH_4 uptake rates decreased with seasonal increases in soil moisture (Figure 3f and Table 2).

When combining soil temperature and moisture in a regression model, significant relations were detected for the CO_2 flux in C(CK) and C(CN), N_2O flux in P(CK), and CH_4 flux in each pure forest (Table 2).

3.3. The Effects of Plantation Type on Soil Greenhouse Gas Flux

Near natural management had significant effects on the annual average emission rate of soil CO_2 and N_2O, and the uptake rate of soil CH_4 (Table 3). The soil CO_2 emission rate in the near natural *P. massoniana* plantation was 17.7% higher than that in the control forest, and the soil CO_2 emission rate of the near natural *C. lanceolata* plantation was 14.5% higher than control. This indicates that the soil CO_2 emission rates for *P. massoniana* and *C. lanceolata* plantations were accelerated by near natural management. Compared with the control forests, the near natural management enhanced the annual average soil N_2O emission rate by 19.4% and 47.4% in the *P. massoniana* and *C. lanceolata* plantation, respectively. Therefore, the soil N_2O emission rates for *P. massoniana* and *C. lanceolata* plantations increased as a result of near natural management.

Table 3. Annual average flux of soil greenhouse gas in the four plantations. Data are shown as means ± standard errors (n = 4). Values designated by the different letters within each variable are significant at $p < 0.05$.

Plantation Type	P(CK)	P(CN)	C(CK)	C(CN)
CO_2-C flux (mg m^{-2} h^{-1})	103.3 ± 9.7cd	121.6 ± 4.8ab	112.4 ± 8.9bc	128.7 ± 5.0a
N_2O-N flux (μg m^{-2} h^{-1})	3.6 ± 0.1cd	4.3 ± 0.5b	3.8 ± 0.2bc	5.6 ± 1.1a
CH_4-C flux (μg m^{-2} h^{-1})	−34.7 ± 1.7c	−27.2 ± 1.6b	−34.9 ± 2.8c	−22.4 ± 1.8a

The average soil CH_4 flux was negative for all the four plantations, which indicates that all the forest soils were functioning as CH_4 sinks. The annual average soil CH_4 uptake rate for the near natural plantations was 21.6% and 55.8% lower than the corresponding controls, as for *P. massoniana* and *C. lanceolata*, respectively (Table 3). Therefore, near natural management reduces the soil CH_4 uptake rate of *P. massoniana* and *C. lanceolata* plantations.

3.4. Main Influencing Factors on Soil Greenhouse Gas Flux

Compared with the control, the near natural management of each plantation increased the fine root biomass, soil temperature, pH, and the contents of soil organic C, available N, NH_4^+-N, NO_3^--N, microbial biomass C, and microbial biomass N, while it reduced the C:N of leaf litter and fine roots, as well as soil total P and C:N ($p < 0.05$, Table 4).

Table 4. The biogeochemical properties in the four plantations. Data are shown as means ± standard errors ($n = 4$). Values designated by the different letters within each variable are significant at $p < 0.05$.

Properties	P(CK)	P(CN)	C(CK)	C(CN)
Litterfall quantity (t hm^{-2} r^{-1})	10.23 ± 0.94a	10.84 ± 0.49a	9.02 ± 0.19b	9.54 ± 0.34b
Fine root biomass (t hm^{-2})	0.81 ± 0.07b	1.36 ± 0.22a	0.64 ± 0.26b	1.33 ± 0.28a
C:N of leaf litter	48.07 ± 4.82c	37.49 ± 4.77d	68.13 ± 8.12a	52.70 ± 6.92b
C:N of fine root	57.53 ± 10.7a	39.70 ± 5.70c	55.38 ± 3.30a	45.70 ± 4.40b
Soil porosity (%)	56.80 ± 2.83a	56.04 ± 2.58a	49.05 ± 4.99b	45.17 ± 4.86b
Soil temperature (°C)	22.15 ± 0.12d	22.47 ± 0.17c	22.73 ± 0.04b	23.04 ± 0.03a
Soil WFPS (%)	13.06 ± 0.56b	13.67 ± 0.49b	19.91 ± 1.00a	21.28 ± 1.06a
Soil pH	4.18 ± 0.04d	4.31 ± 0.08c	4.67 ± 0.07b	4.91 ± 0.20a
Soil organic C(g kg^{-1})	25.99 ± 1.32b	29.15 ± 2.42a	17.24 ± 1.85d	21.61 ± 2.58c
Soil total N(g kg^{-1})	2.58 ± 0.04	3.28 ± 0.12	2.29 ± 0.15	3.32 ± 0.13
Soil available N (mg kg^{-1})	94.37 ± 3.94b	103.32 ± 5.62a	77.0 ± 9.07c	96.25 ± 7.27ab
Soil total P (g kg^{-1})	0.28 ± 0.01a	0.25 ± 0.02b	0.24 ± 0.03b	0.21 ± 0.01c
Soil C:N	17.06 ± 0.50a	15.34 ± 0.72c	16.42 ± 0.14b	15.16 ± 0.46c
Soil NH_4^+-N content (mg kg^{-1})	20.30 ± 2.07 b	26.67 ± 3.35a	18.44 ± 2.17b	24.56 ± 4.02a
Soil NO_3^--N content (mg kg^{-1})	21.97 ± 1.83b	25.00 ± 2.21a	18.36 ± 2.28b	24.65 ± 4.19a
Soil microbial biomass C (mg kg^{-1})	301.12 ± 24.54b	388.12 ± 11.76a	234.44 ± 29.49c	312.50 ± 32.51b
Soil microbial biomass N (mg kg^{-1})	39.07 ± 6.59bc	53.30 ± 8.11a	36.40 ± 6.45c	46.51 ± 4.21ab

To explain the observed variations in annual average soil greenhouse gas flux among the plantations, the first "stepwise" multiple linear regression model was performed using all the tested biogeochemical properties in the plantations. The model performed on CO_2 emissions indicated that the soil temperature and C:N ratio of the fine roots explained 77.4% of the variation in the soil CO_2 emission rate among the plantations ($R^2 = 0.774$, $p < 0.001$; Table 5). Other independent variables, such as the C:N ratio of leaf litter, soil organic C, soil pH, and soil nitrogen content, were excluded in the model owing to their non-significance or evidence of multicollinearity. The C:N ratio of the fine roots was negatively correlated with the annual average soil CO_2 emission rate, whereas the soil temperature was positively correlated with the annual average soil CO_2 emission rate (Table 5). This indicates that the annual average CO_2 uptake rate increases with an increasing soil temperature and decreasing C:N ratio of the fine roots.

Another multiple linear regression model that examined the variation in the average soil N_2O flux among the four plantations showed that the C:N ratio of leaf litter and soil available N explained 69.3% of the variation in the annual average soil N_2O emission rate ($R^2 = 0.693$, $p < 0.001$; Table 5). The annual average soil N_2O emission rate was negatively correlated with the C:N ratio of leaf litter but positively correlated with soil available N content. This indicates that the annual average N_2O emission rate increases with decreasing C:N ratio in leaf litter and increasing soil available N content.

A final multiple linear regression model showed that the C:N ratio of leaf litter was the only variable that explained a significant proportion (62.4%) of the variation in the annual average soil CH_4 uptake rate among the plantations ($R^2 = 0.624$, $p < 0.001$; Table 5). The annual average soil CH_4 flux was positively correlated with the C:N ratio of leaf litter.

Table 5. Results of multiple linear regression analysis of biogeochemical parameters and annual average soil greenhouse gas flux in the four plantations.

Parameters	Models
CO_2-C flux (mg m^{-2} h^{-1}) (Y_1)	
C:N ratio of fine root (X_1) Soil temperature (°C) (X_2)	$Y_1 = -0.707X_1 + 16.2X_2 - 217.0$, $R^2 = 0.774$, $p < 0.001$
N_2O-N flux (μg m^{-2} h^{-1}) (Y_2)	
C:N ratio of leaf litter (X_3) Soil available N (mg kg^{-1}) (X_4)	$Y_2 = -0.044X_3 + 0.16X_4 + 5.886$, $R^2 = 0.693$, $p < 0.001$
CH_4-C flux (μg m^{-2} h^{-1}) (Y_3)	
C:N ratio of leaf litter (X_5)	$Y_3 = 0.343X_5 - 6.026$, $R^2 = 0.624$, $p < 0.001$

4. Discussion

4.1. CO_2 Flux and Main Influencing Factors

The present study showed that the seasonal variation in the soil CO_2 emission rate in most cases can be attributed to soil temperature rather than soil moisture (Figure 3 and Table 2). Conversely, previous studies have found that soil CO_2 emission rates increase with increasing soil moisture and temperature in subtropical forests [2,25]. Therefore, there is no unified understanding of the soil moisture effects on the seasonal variation in soil CO_2 flux among different plantations.

Soil CO_2 is mainly produced through autotrophic respiration by plant roots and heterotrophic respiration by microorganisms [29]. The spatial variability in soil respiration is due to the differences in soil moisture, bulk density, root biomass, and soil organic matter [30]. The results of the present study indicated that the differences in soil CO_2 emission rates among the plantations were caused mainly by the C:N ratio of the fine roots (Table 5). The soil CO_2 emission rates of the near natural *P. massoniana* and *C. lanceolata* plantations were significantly higher than those of the control plantations (Table 3). Near natural management alters the composition of tree species, thus influencing the composition and quality of roots and litter, which in turn leads to the differences in CO_2 emission rates between the near natural and control forests. This is consistent with the results of previous comparative studies on soil CO_2 flux in coniferous pure forests and coniferous and broad-leaved mixed forests [25,31]. The C:N ratio of fine roots plays an important role in regulating microbial activity as an indicator of underground substrate quality, which affects the decomposition of fine roots [32]. The near natural management reduced the C:N ratios of fine root in *P. massoniana* and *C. lanceolata* plantations (Table 4). Therefore, the decomposition rates of fine roots in the near natural plantations can be higher than control, leading to higher soil CO_2 emission rates. These results indicate that the higher CO_2 emission rates observed in the near natural forest soil can be attributed mainly to the lower C:N ratio and higher decomposition rate. Some studies have also suggested that differences in fine root biomass or the composition and quality of leaf litter due to land use may affect soil respiration [33,34], or that different tree species affect soil respiration through associated differences in leaf litter quantity, chemical properties, and soil environmental conditions [18,21]. However, we found that fine root biomass, litterfall quantity, C:N ratio of leaf litter, and soil environmental conditions were the non-significant variables in our regression model. This indicates that they are not key factors influencing the soil CO_2 emission rate in our study area.

4.2. N_2O Flux and Main Influencing Factors

The average soil N_2O emission rate in our study was 4.3 μg N m^{-2} h^{-1}, which is similar to some other forests [31,35]. However, this is lower than that in tropical rainforests, forests in the northern hemisphere, and those seriously affected by nitrogen deposition [2,36]. This may be attributed to different soil properties. We found no seasonal changes in the N_2O emission rates in the plantations (Figure 2), while soil N_2O emission rates in the near natural *P. massoniana* and *C. lanceolata* plantations were higher than those of control (Table 3). This is in line with previous studies [18,37], and essentially consistent with a study on soil N_2O flux in mixed forests of *C. hystrix* and *P. massoniana* and pure forests of *P. massoniana* in the same study site [25]. The soil N_2O emission rate also differs significantly among vegetation types across Japan [38]. Our present result confirms that tree species composition has significant effects on the soil N_2O emission rate in coniferous plantations.

Soil N_2O emission rates are affected primarily by soil pH [39], soil moisture [40,41], soil carbon and nitrogen pools [41,42], and the C:N ratio of leaf litter [43]. Our present results show that the C:N ratio of leaf litter and soil available N content had the strongest effect on soil N_2O emission rates in the four plantations (Table 5). The N_2O emission rate decreased with increased leaf litter C:N ratio but increased with increased soil available N content. Near natural management enhanced the soil available N content and reduced the C:N ratio of leaf litter (Table 4), thus increasing the soil N_2O emission rates. The increased soil available N content could be largely explained by the introduction of *E. fordii*, which is an N-fixing species. These results were in line with a previous study indicating that the C:N ratio of leaf litter significantly affects the soil nitrification process and nitrogen-containing greenhouse gas flux [43]. The differences in soil N_2O emission rates between near natural and control plantations were therefore due mainly to differences in the C:N ratio of leaf litter and soil available N content. Similarly, the relatively low soil N_2O emissions in the present study compared to other studies may be attributed to low soil N content at the study site.

4.3. CH_4 Flux and Main Influencing Factors

The soil CH_4 flux in the study plantations varied from −22.4 to −34.9, which indicates that the soils are sinks for atmospheric CH_4. This is consistent with previous studies [5,41]. According to the present study, the tree species affects the CH_4 uptake rate (Table 3). The soil CH_4 uptake rate can be higher in broad-leaved forests than in coniferous forests [17,18,20]. However, so far little is known about the soil CH_4 flux in coniferous and broad-leaved mixed forests, particularly in near natural plantations. In this study, the soil CH_4 uptake rate was lower in the near natural plantations than in the control forests (Table 3). This indicates that near natural management reduces the soil CH_4 uptake rate in *P. massoniana* and *C. lanceolata* plantations.

The exchange of CH_4 between the soil and atmosphere is determined by the CH_4 production and consumption processes in the soil. The soil CH_4 production requires a suboxic environment for methanogenic bacteria, whereas CH_4 consumption requires aerobic conditions. Thus, soil aeration and oxygen content are important factors that regulate CH_4 production and consumption [41]. Soil temperature, moisture, pH, substrate availability, and aeration affect the activity and quantity of methanogenic bacteria [44,45], and thus regulate the soil CH_4 flux. However, the near natural management did not affect soil porosity and moisture (Table 4). These were thus not the reason for the differences in CH_4 uptake rates between the forests. Instead, the C:N ratio of the litter can explain the differences in soil CH_4 flux (Table 5). Near natural management significantly reduced the C:N ratio of leaf litter (Table 4), which consumes more oxygen during soil respiration. The hypoxic condition then leads to a production of soil CH_4 that is further released into the atmosphere [44]. Therefore, the net CH_4 absorption in soil decreases at a high rate of soil microbial respiration.

5. Conclusions

Near natural management increased the average soil CO_2 and N_2O emission rates in *P. massoniana* and *C. lanceolata* plantations and reduced the average soil CH_4 absorption rates. The differences in the CO_2 emission rate among plantations can be attributed mainly to the C:N ratio of fine roots, whereas the differences in the N_2O emission rate can be attributed to soil available N content and the C:N ratio of leaf litter. The variation in the CH_4 uptake rate can be attributed only to the C:N ratio of leaf litter. The results of the present study show that near natural management of *P. massoniana* and *C. lanceolata* plantations may increase the emission of greenhouse gases in subtropical China. Therefore, plantation enrichment strategies should take into account potential impacts on greenhouse gas flux. Other research is needed to evaluate the effects of near natural forest management on global climate change.

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