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RESEARCH ARTICLE

Straw mulching has an enduring positive effect on soil CO_2 emissions in a humid plantation

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KEYWORDS

Soil carbon cycle, soil properties, soil respiration, straw mulching, temporal analysis

HIGHLIGHTS

- Straw mulching impacts on soil CO_2 flux in humid plantations were evaluated.
- Soil temperature and water content mainly regulated CO_2 emissions during mulching.
- Straw mulching had an enduring positive effect on soil CO_2 flux.
- Soil nutrients mainly influenced CO_2 emissions during the period of enduring mulch effect.

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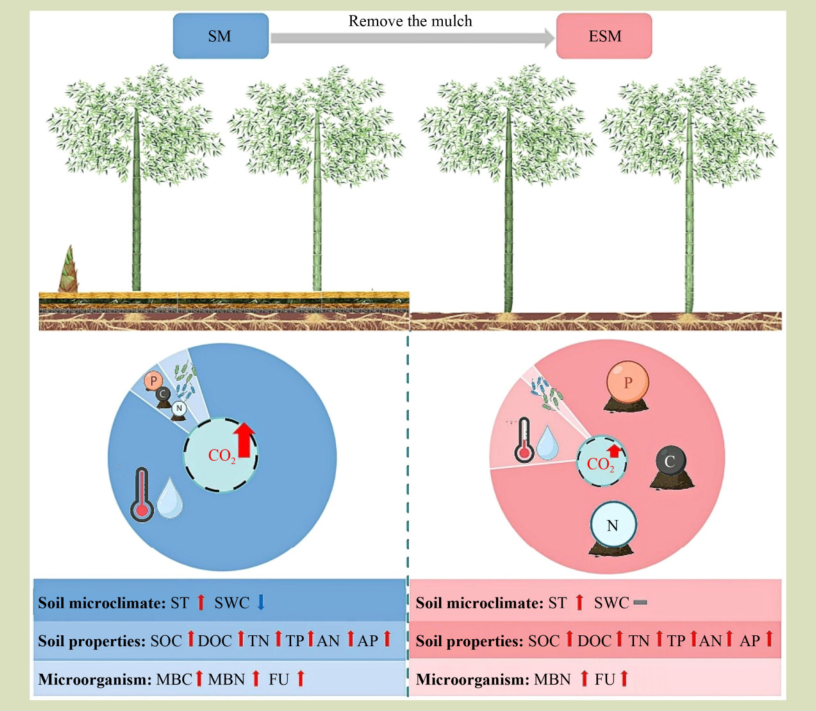
GRAPHICAL ABSTRACT



ABSTRACT

Mulching practices substantially affect soil CO_2 emissions from agricultural ecosystems. However, the impacts of mulching practices and their enduring effects on soil CO_2 fluxes in humid plantations have not been investigated. To address this research gap, a field experiment was conducted in a Moso bamboo (*Phyllostachys edulis*) plantation in a humid area of China to investigate the effects of various durations of straw mulching and its enduring effects on soil CO_2 fluxes and soil organic carbon (SOC). Straw mulching significantly increased the soil CO_2 flux by about 18 times relative to the control, mainly due to the increase in soil temperature during the mulching stage. During the period of enduing effect, straw mulching still significantly increased the soil CO_2 flux by 230%–270% relative to the control, primarily due to the enhancement of microbial activity resulting from improved soil nutrient contents, demonstrating that straw mulching had an enduring positive impact on soil CO_2 flux. Additionally, straw mulching significantly increased SOC by 27%–72% during the mulching and period of enduing effect. These results indicated that straw mulching in plantations in humid regions could be a potential carbon storage strategy by increasing soil carbon content.

1 Introduction

Forest soil respiration (Rs), that is soil CO_2 emissions, is a key pathway for the transfer of carbon between forest soils and the atmosphere, as it exerts a substantial influence on the global carbon balance and mitigates climate change[1–3]. Given the extensive diversity of forest ecosystems, there is an urgent need to enhance the research on Rs across different forest types. Currently, plantations are a vital component of global forest resources, encompassing a substantial area of 294 Mha, which is about 7.2% of the terrestrial forest area[4]. These plantations are under intensive management, including regular harvesting, fertilizer addition, mulching and pest control[5–7]. Consequently, understanding the effects of these management strategies on Rs in plantations is essential for precisely evaluating plantation soil carbon stocks and their contribution to the carbon cycle in forest ecosystems.

Straw mulching (SM) is a widely recognized sustainable management practice used to cover the soil surface, thereby preserving soil and water resources in dry and semidry areas[8–10]. Previous research has shown that SM alters Rs, including increases, decreases or no changes, mainly through regulating the functionality of soil microorganisms and plant growth[11–14]. SM can increase soil temperature (ST) and soil water content (SWC)[14–16], which directly influences microbial and plant activities. However, the decomposition of straw also contributes to soil fertility[9], supplying essential nutrients for microbes and plants and influencing soil CO_2 emissions. Most studies have concentrated on examining the impact of SM on Rs in agricultural ecosystems, particularly during intervals when mulching is applied[9,14,17]. Also, empirical research has consistently demonstrated that management practices (such as fertilizer addition) have an enduring impact on soil characteristics, which subsequently has a clear impact on Rs[18,19]. The impacts of SM on Rs and whether this mulching also has enduring effects on humid plantations remain unclear.

To fill this knowledge gap, we conducted a field study in a Moso bamboo plantation in southern China to examine the response of Rs to SM and its potential enduring effects. Moso bamboo (*Phyllostachys edulis*) is a globally important plantation species[20,21], with a cultivation area of 5.3 Mha that accounts for 70% of the total bamboo cultivation in China[7,22]. Winter straw mulching is a common practice in Moso bamboo plantations to advance the harvesting timeline of bamboo shoots and enhance their yield, thereby maximizing economic benefits[23,24]. Previous research has demonstrated that straw mulching improves soil nutrient concentrations, microbial activity, and Rs in Moso bamboo plantations[23–25]. However, these studies were not conducted at the same time in the same bamboo forest, which can have spatial heterogeneity. Based on these findings, we formulated two hypotheses: (1) straw mulching can increase soil CO_2 flux by enhancing soil nutrients, and (2) even after removing mulch materials, straw mulching can continue to increase the soil CO_2 flux.

2 Materials and methods

2.1 Site description

The study site is located in Wuxing District, Huzhou City, Zhejiang Province, China (30°37′ N, 119°51′ E). This area has a subtropical monsoon climate, with a mean yearly temperature of 16 °C and mean yearly rainfall of 1278 mm. The soil is classified as red soil.

The Moso bamboo plantation, with a density of 2100–2500 culms ha^{-1} and a diameter at breast height ranging from 7.2 to 10.3 cm, was mulched with straw during winter. The protocol for straw mulching was as follows: in December, 15 $t·ha^{-1}·yr^{-1}$ of pig manure was applied to about 1 cm deep, followed by 75 $t·ha^{-1}·yr^{-1}$ of rice straw to about 5 cm deed; then, covered with 30 $t·ha^{-1}·yr^{-1}$ of fresh bamboo leaves to 14 cm deep and topped with 105 $t·ha^{-1}·yr^{-1}$ of rice husk to a 20 cm deep; in late April of the following year, the rice husks where removed, leaving the other mulching materials (about 1–3 cm deep) on the soil (Fig. 1). The period from May to November, which did not include mulching, was designated as the period of enduring effect. The total carbon content of pig manure, rice straw, bamboo leaves and rice husk was 236, 315, 367, and 350 $g·kg^{-1}$, respectively; the total nitrogen content was 15.8, 3.4, 9.6, and 2.4 $g·kg^{-1}$, respectively; and the total phosphorus content was 19.0, 1.3, 2.7, and 1.3 $g·kg^{-1}$, respectively. Detailed information on the materials used and the timeline for straw mulching are shown in Fig. 1. The atmospheric temperature and precipitation levels throughout the sampling phase are depicted in Fig. S1. During the experimental period, the annual average temperature was 17.6 °C, and the annual rainfall was 1359 mm. The highest monthly average temperatures occurred in July (28.5 °C), and the lowest in January (5.6 °C), with rainfall primarily concentrated from May to August.

2.2 Experimental approach and soil collection process

In November 2020, nine experimental plots (20 m × 20 m) were set up in the selected Moso bamboo plantation, with a 20-m buffer zone separating each plot to minimize interference. The experimental design incorporated three treatments and used a completely randomized block design to evenly distribute the treatments across the study area (Fig. 1). The treatments were as follows: control, with no winter straw mulching; SM1, with the initial year of winter straw mulching starting from 2020; and SM3, with the third consecutive year of winter straw mulching starting from 2018. Each treatment was applied to three replicate plots (Fig. 1).

During the mulching periods, polyvinyl chloride (PVC) tubes (20 cm diameter, 50 cm long) were arbitrarily installed 5 cm beneath the soil surface in the SM1 and SM3 plots, which were filled with the respective mulching materials. In the control plots, shorter PVC tubes (20 cm diameter, 10 cm long) were installed 5 cm below the soil surface. Following the removal of mulch materials in April 2021, new PVC collars (20 cm diameter, 10 cm long) were arbitrarily positioned at a depth of 5 cm beneath the soil surface in the SM1 and SM3 plots (Fig. 1).

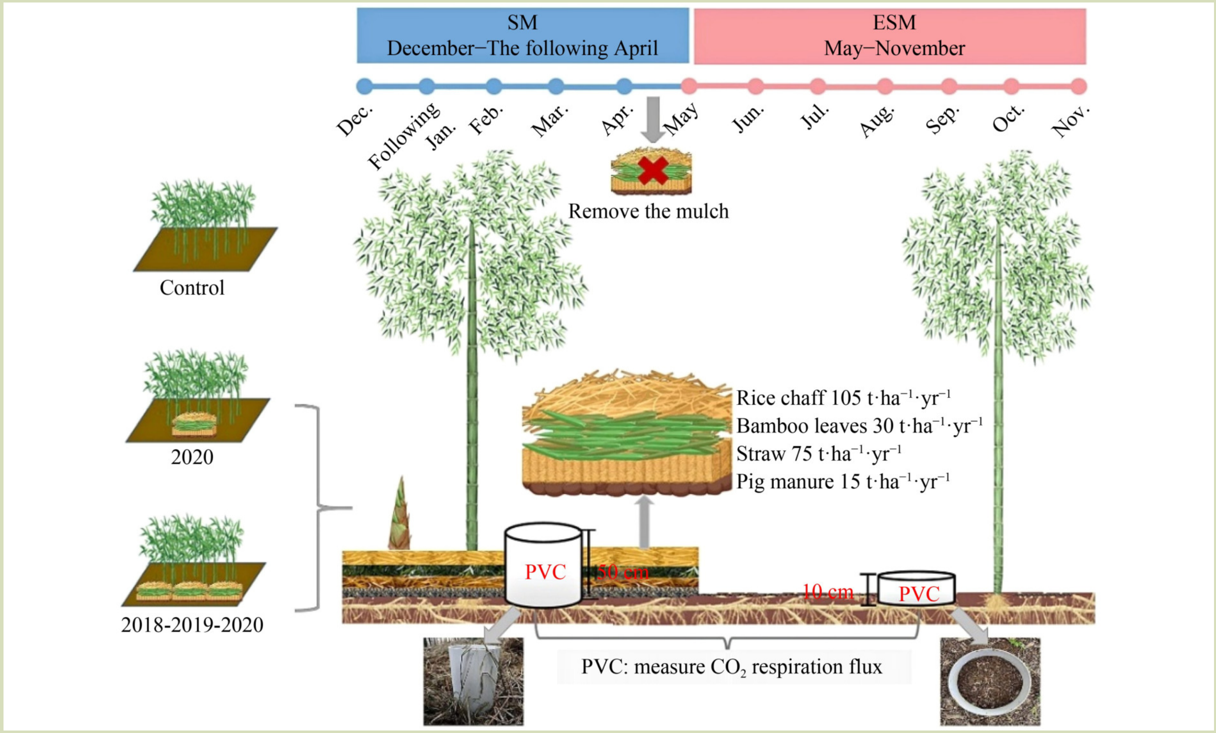


Fig. 1 Mulching materials, quality and time of straw mulching, as well as the placement of polyvinyl chloride (PVC) collars in a Moso bamboo plantation. SM, straw mulching period, ESM, period of enduring mulch effect.

Soil samples were taken in each plot in January and July 2021 to a depth of 20 cm, using a 3.5-cm diameter soil auger. The sampling sites within each plot were chosen arbitrarily to obtain a sample that accurately reflected the soil conditions. The collected soil samples were sieved (2-mm) to remove any roots and gravel. The sieved soil was divided into three subsamples for separate measurements and analyses. One subsample was stored at 4 °C and used for subsequent analyses of soil microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), dissolved organic carbon (DOC), available nitrogen (AN) and available phosphorus (AP). The subsample was stored at −80 °C for soil DNA extraction to study soil microbial gene copies. The remaining subsample was air-dried at a temperature of about 25 °C for determining soil properties such as soil pH, soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP).

2.3 Measurements of Rs and soil properties

From December 2020 to November 2021, the Rs rate was measured at least once every monthly between 9:00 and 11:00 under sunny conditions using an LI-8100 soil CO_2 flux system (LI-COR Inc., Lincoln, NE, USA). Concurrently, the ST and water content at a depth of 5 cm were recorded using portable temperature and humidity meters during Rs measurements.

Soil pH was quantified at a soil:water ratio of 1:2.5 (w/v) using a pH meter (FE20; Mettler Toledo, Zurich, Switzerland). Soil organic carbon and TN were determined using an elemental analyzer (Vario EL III; Elementar, Langenselbold, Germany) and TP using the Bray method[26]. Soil AN and AP were extracted using 0.1 $mol\cdot L^{-1}$ KCl and 0.5 $mol\cdot L^{-1}$ $NaHCO_3$, respectively, and subsequently analyzed with a continuous segmented flow analyzer (AA3 Auto Analyzer 3HR; Seal Analytical, Mequon, WI, USA). The soil DOC was measured using a total organic carbon analyzer (TOC-Vwp; Shimadzu, Kyoto, Japan).

2.4 Soil microbial biomass and gene copy assays

The soil MBC and MBN were determined using the chloroform fumigation extraction method[27]. Microbial DNA was extracted from each 0.5 g fresh soil sample using the Qiagen (Hilden, Germany) DNA Easy Kit for Soil. Functional genes pertinent to both bacterial and fungal communities were targeted and quantified using a Bio-Rad CFX96 (Bio-Rad Laboratories, Hercules, CA, USA). The amplification process was conducted in 20 μL reaction volumes, employing the SYBR Premix Ex Taq (Tli RNaseH Plus) qPCR kit (Takara Bio, Dalian, China). Comprehensive details of the primer sequences and thermal cycling conditions are presented in Table S1[28,29]. Each sample was assayed in triplicate, yielding high correlation coefficients (R^2 values ranging from 0.992 to 0.996) and robust amplification efficiencies between 91.4% and 103.3%, with the majority exceeding 90%. Standard curves were constructed using serial dilutions of plasmids having the target genes, demonstrating linearity across a broad range of gene copies from 10^7 to 10^{11}.

2.5 Data calculations and statistical analysis

An exponential model was used to delineate the relationship between Rs and ST[30], using the equation $F = \alpha e^{kt}$, where F is the soil CO_2 emission rate associated with Rs, t is the ST, and α and k are parameters determined through curve fitting.

The temperature sensitivity parameter of the soil CO_2 flux (Q_{10}) was calculated using the formula[30,31] $Q_{10} = e^{10k}$.

One-way analysis of variance (ANOVA), supplemented by the least significant difference test, was conducted to evaluate the statistical significance of the differences in soil respiration, soil properties, MBC, MBN, and fungal (FU) and bacterial (BA) gene copies across various treatments. An independent-samples t-test was used to compare the means of the measured variables during mulching and the period of enduing effect. A repeated two-way ANOVA was performed to examine the interactive effects of mulching and time on Rs, soil properties, and microbial variables. An exponential regression model was used to investigate the relationship between Rs and ST. A linear regression model was used to examine the relationships between Rs and soil microclimate, soil nutrients, and microbial properties. To further clarify the individual impact of each variable on Rs, the R package “RandomForest” was used to assess their specific contributions. The R package “PLS-PM” was used to examine the direct and indirect influences of control factors on Rs during mulching and period of enduing effect. All statistical computations were conducted using IBM SPSS Statistics 22 (IBM Corp., Armonk, NY, USA) and R v4.3.1 (R Core Team, 2018).

3 Results

3.1 Soil CO_2 flux and Q_{10}

SM altered the typical seasonal pattern of the soil CO_2 flux, which was characterized by lower levels in winter and higher levels in summer (Fig. 2(a)). Throughout both the initial mulching and subsequent period of enduring effect, the soil CO_2 flux was higher by 230%–1820% in the SM treatments (SM1 and SM3) than in the control treatment ($P < 0.05$, Fig. 2(a,b)). The average soil CO_2 fluxes in the SM treatments were higher by 73.8%–77.5% during the initial mulching period than during the period of enduing effect ($P < 0.05$, Fig. 2(b)). Q_{10} values were clearly elevated in the SM treatments during the period of enduing effect compared to that of the control ($P < 0.05$, Fig. S2). A repeated two-way ANOVA revealed that mulching practices, mulching duration, and their combined interactions had a significant impact on the soil CO_2 flux (Table S2).

3.2 Soil physicochemical properties

SM did not significantly affect seasonal patterns of ST or SWC (Fig. 2(c,e)). However, it increased the mean ST (4.3%–108%) in the two distinct periods and decreased the mean SWC (11.4%–33.9%) in the mulching period ($P < 0.05$, Fig. 2(d,f)). Soil temperature and SWC under SM treatments were lower during the mulching period than during the period of enduing effect ($P < 0.05$, Fig. 2(d,f)).

During the initial and the subsequent period of enduing effect, SOC (27.2%–71.7%), TN (13.6%–50.1%), TP (26.6%–67.5%), DOC (90.4%–278%), AN (21.7%–52.9%), AP (61.5%–235%) and C/N (11.4%–12.9%) were all increased by the SM treatments relative to the control treatment ($P < 0.05$, Fig. 3). Also, SM3 resulted in higher levels of TN, DOC, TP and AP than SM1 ($P < 0.05$, Fig. 3). In the SM treatments, SOC, TN, TP and AN were higher during the initial mulching than those observed during the period of enduing effect ($P < 0.05$), whereas DOC showed the opposite trend. Repeated two-way ANOVA showed that mulching practices, mulching times, and their interactions altered SOC, DOC and TN ($P < 0.001$, Table S1).

3.3 Soil microbial biomass and functional gene copies

Compared to the control, the SM treatments increased MBC by 20.3%–63.4%, in MBN by 82.1%–85.7%, and increased the fungal gene copies by 44.5%–47.5% during the initial mulching but resulted in a significant decrease in MBC/MBN by 11.5%–33.9% ($P < 0.05$, Fig. 4). During the period of enduing effect, soil MBN (72.9%–92.1%) and fungal gene copies (52.5%–70.9%) in the SM treatments remained greater than those in the control treatment (Fig. 4(b,c)). In all treatments, soil microbial biomass (MBC and MBN) was higher during the mulching period than during the period of enduing effect ($P < 0.05$). Repeated two-way ANOVA found that the mulching management technique, mulching period and their interactions altered MBC (Table S1).

3.4 Linkages of soil CO_2 flux with controlling factors

During the mulching period, soil CO_2 flux was positively associated with ST, SOC, TN, TP, C/N, DOC, AN, AP, MBC, MBN and FU, but negatively associated with SWC and MBC/MBN ($P < 0.05$, Fig. 5(a)). Random forest and PLS-PM analyses demonstrated that ST and SWC were the dominant factors influencing the effects of SM on Rs during the mulching period (Figs. 5(b) and 6(a,b)). During the period of enduing effect, the soil CO_2 flux also demonstrated positive correlations with SOC, TN, TP, C/N, DOC, AN, AP, MBN and FU (Fig. 5(c)). The long-term impacts of SM on Rs were predominantly determined by soil nutrients, including TN, TP, DOC, AN, AP and C/N (Fig. 5(d)). PLS-PM analysis further confirmed that Rs was primarily influenced by soil nutrients during the period of enduing effect (Fig. 6(c,d)).

4 Discussion

4.1 Impact of straw mulching on soil CO_2 emissions

SM increased the soil CO_2 flux in the humid Moso bamboo plantation (Fig. 2), confirming our initial hypothesis and aligning with Jiang et al.[23] and Liu et al.[9], who also reported increased soil CO_2 flux after SM in both *Phyllostachys praecox* plantations and rainfed farmland. In the present study, ST and SWC were pivotal in mediating the soil CO_2 flux under the straw mulching treatment during the mulching period (Figs. 5 and 6). Previous studies have reported similar results[32–35]. The observed effects were likely due to high ST creating favorable conditions for microbial activity[36] and the growth of bamboo shoots[37] in winter; these advantageous conditions subsequently accelerate the mineralization of soil organic matter and autotrophic respiration[38,39], thereby accounting for the observed increases in soil CO_2 fluxes. In the present present study, SM increased ST and microbial biomass during the winter mulching period (Figs. 2(d) and 3(a,b)). Also, positive correlations were detected between soil CO_2 flux and ST, MBC, MBN and FU during the mulching period (Fig. 5(a), which verified the above conclusion. Additionally, SM increased rhizome growth and bamboo shoot yields in Moso bamboo plantations, indicating that root respiration was increased[17], thereby increasing soil CO_2 emissions.

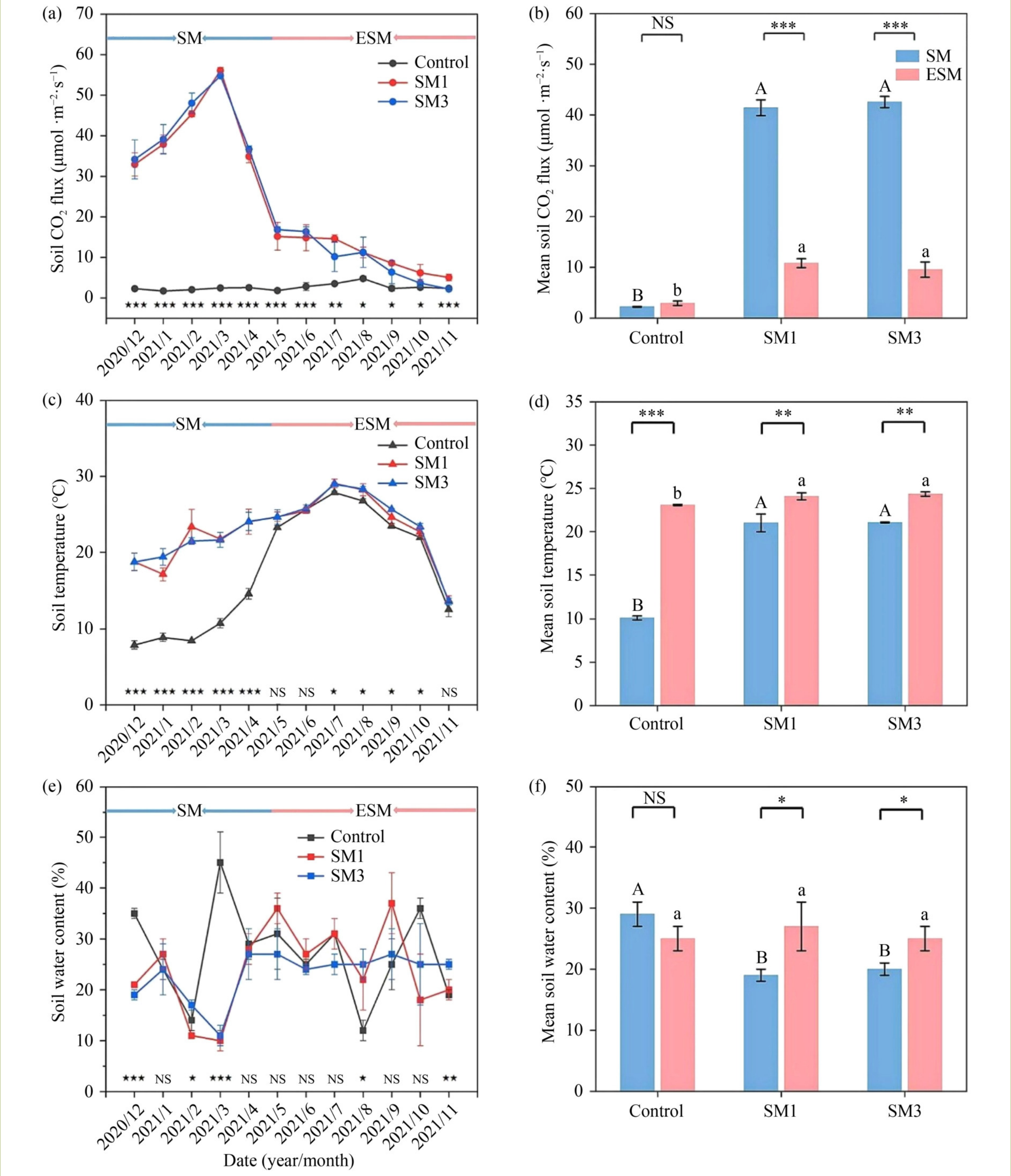


Fig. 2 Effect of straw mulching (SM) on the monthly variations (a, c, e) and mean (b, d, f) of the soil CO_2 flux, soil temperature, and soil water content during the initial mulching and period of enduing effect (ESM) periods in a Moso bamboo plantation. Control, no straw mulching; SM1, the initial year of straw mulching (from 2020); and SM3, the third consecutive year of straw mulching (from 2018 to 2020). Five-pointed stars indicate significant differences between various SM treatments from December 2020 to November 2021 (NS, not significant; ★, $P < 0.05$; ★★, $P < 0.01$; and ★★★, $P < 0.001$). Capital letters indicate significant differences between various SM treatments during the initial mulching period ($P < 0.05$). Lowercase letters indicate significant differences between various SM treatments during the period of enduing effect ($P < 0.05$). Asterisks indicate significant differences between the initial SM and ESM periods under the same SM treatment (NS, not significant; *, $P < 0.05$; **, $P < 0.01$; and ***, $P < 0.001$).

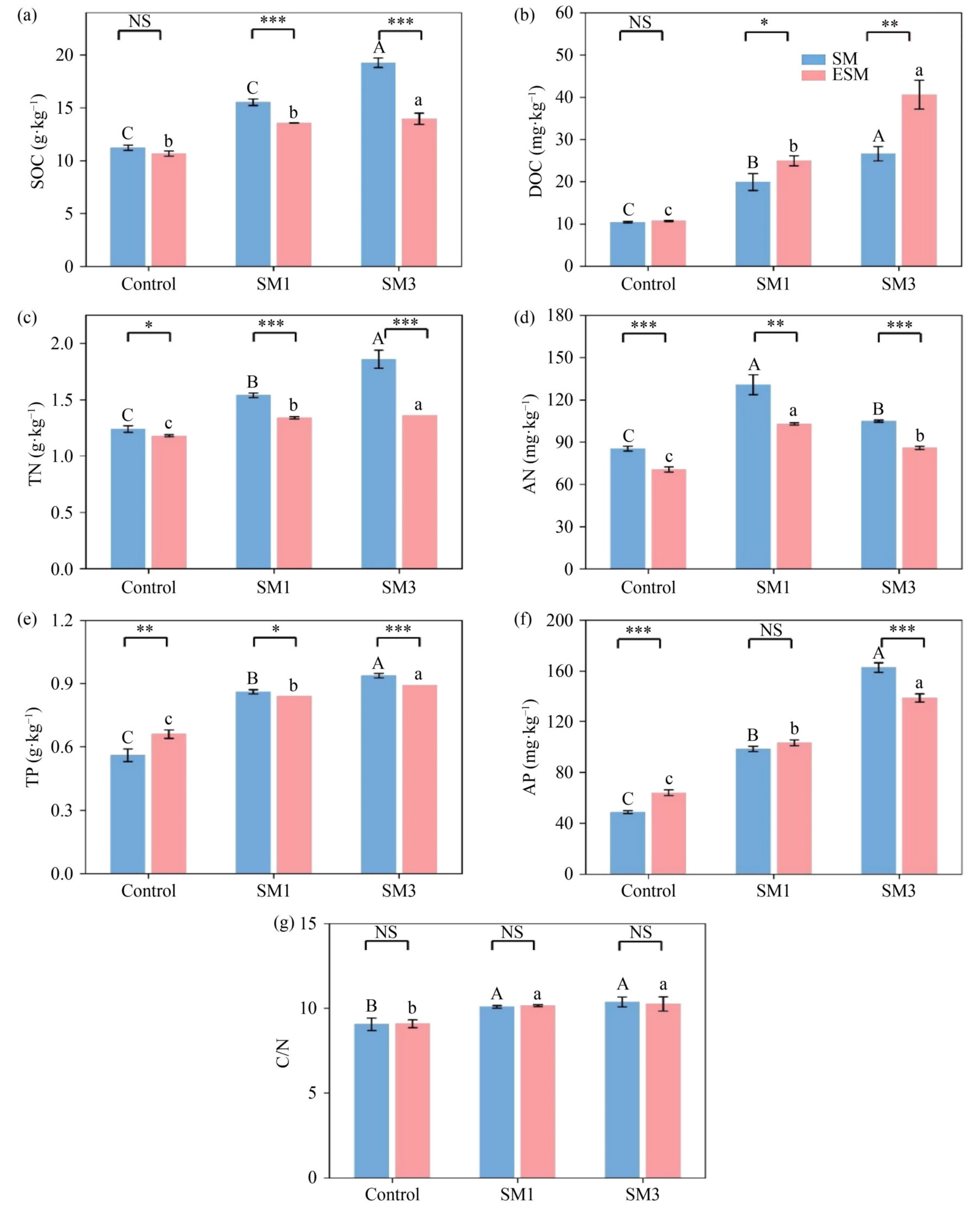


Fig. 3 Effect of straw mulching on soil properties during the initial straw mulching and period of enduing effect in a Moso bamboo plantation. (a) SOC, soil organic carbon; (b) DOC, dissolved organic carbon; (c) TN, total nitrogen; (d) AN, available nitrogen; (e) TP, total phosphorus; (f) AP, available phosphorus; and (g) C/N, SOC to TN ratio. Control, no straw mulching; SM1, the initial year of straw mulching (from 2020); and SM3, the third consecutive year of straw mulching (from 2018 to 2020). Capital letters indicate significant differences between various SM treatments during the initial mulching period ($P < 0.05$). Lowercase letters indicate significant differences between various SM treatments during the period of enduing effect ($P < 0.05$). Asterisks indicate significant differences between the initial SM and ESM periods under the same SM treatment (NS, not significant; *, $P < 0.05$; **, $P < 0.01$; and ***, $P < 0.001$).

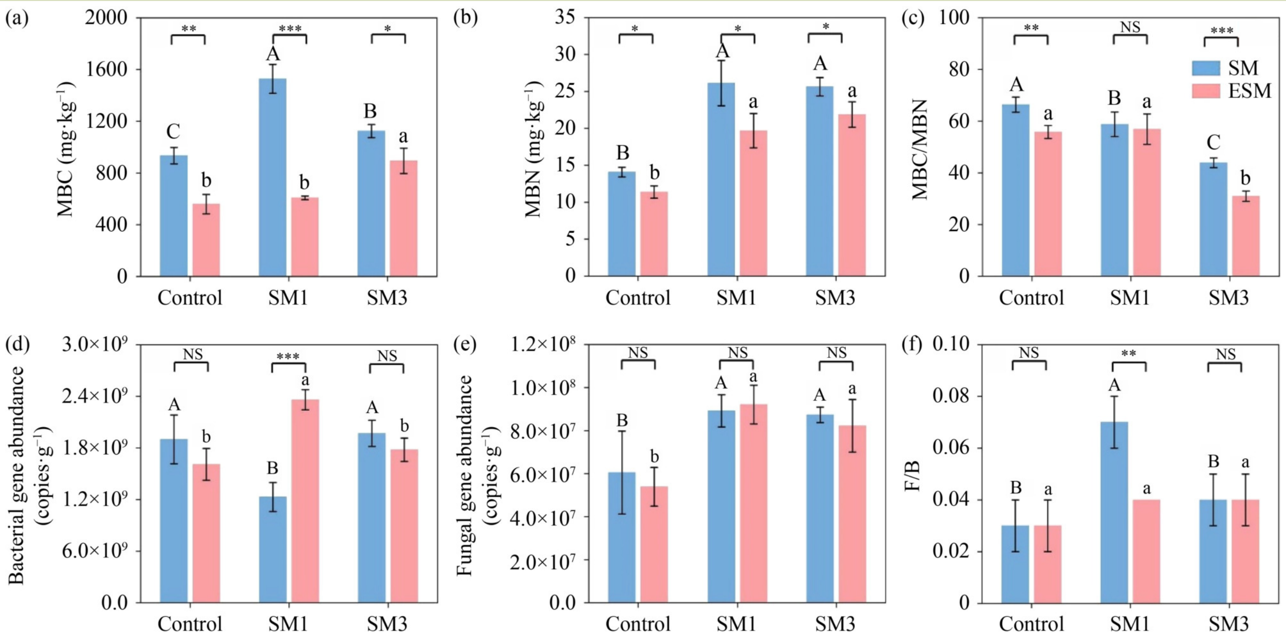


Fig. 4 Effect of straw mulching on soil microbial properties during the initial straw mulching and period of enduing effect in a Moso bamboo plantation. (a) MBC, microbial biomass carbon; (b) MBN, microbial biomass nitrogen; (c) MBC/MBN, MBC to MBN ratio; (d) bacterial gene abundance; (e) fungal gene abundance; and (f) F/B, fungal gene abundance to bacterial gene abundance ratio. Control, no straw mulching; SM1, the initial year of straw mulching (from 2020); and SM3, the third consecutive year of straw mulching (from 2018 to 2020). Capital letters indicate significant differences between various SM treatments during the initial mulching period ($P < 0.05$). Lowercase letters indicate significant differences between various SM treatments during the period of enduing effect ($P < 0.05$). Asterisks indicate significant differences between the initial SM and ESM periods under the same SM treatment (NS, not significant; *, $P < 0.05$; **, $P < 0.01$; and ***, $P < 0.001$).

Previous studies have demonstrated that SM increases ST[9] and soil moisture when the surface soil is wet[40,41]. However, our study observed that the mean SWC was lower in the SM treatments during the mulching period (Fig. 2(f)) and showed a significant negative correlation with the soil CO_2 flux (Fig. 5(a)). The reason for this result may be that most of the subjects of previous studies were farmland ecosystems in arid and semiarid areas, whereas this research focused on plantation ecosystems in a humid area. Also, our study found that the soil CO_2 flux under the SM3 treatment was similar to that under the SM1 treatment, suggesting that the increased impact of SM on soil CO_2 flux did not depend on the duration of mulching management (Fig. 2). This could be due to the relatively short duration of the mulching period.

4.2 Enduring impact of straw mulching on soil CO_2 emissions

Previous studies have found that maize stover retention or organic matter addition alters the soil carbon cycle by changing microorganisms and plant activities[42–44]. To our knowledge, the present study represents the first to document soil CO_2 flux responses to the prolonged impact of SM in a humid Moso bamboo plantation. Our results illustrate that SM increased soil CO_2 emissions during the period of enduing mulch effect (Fig. 2(b)), which supported the second hypothesis and demonstrated that the increased impact of SM on Rs would continue for at least 3 years after removing mulch materials. Despite the increase in ST under SM treatments during the period of enduing mulch effect (Fig. 2(d)), ST was not significantly correlated with soil CO_2 flux (Figs. 5 and 6), which indicated that ST became less important in the period of enduing effect compared to soil nutrients. Also, soil nutrients are integral in regulating the soil CO_2 flux by modulating soil microbial and plant activities under SM conditions[9,45–47].

Previous studies have demonstrated that the addition of nitrogen and phosphorus enriches microorganisms with essential nutrients, which can increase microbial populations, enzyme activities and alter microbial community structures, consequently enhancing soil microbial respiration in nitrogen- or phosphorus-limited systems[48–50]. Moso bamboo plantations are generally limited by nitrogen and phosphorus[51,52]. The present study found that SM treatments

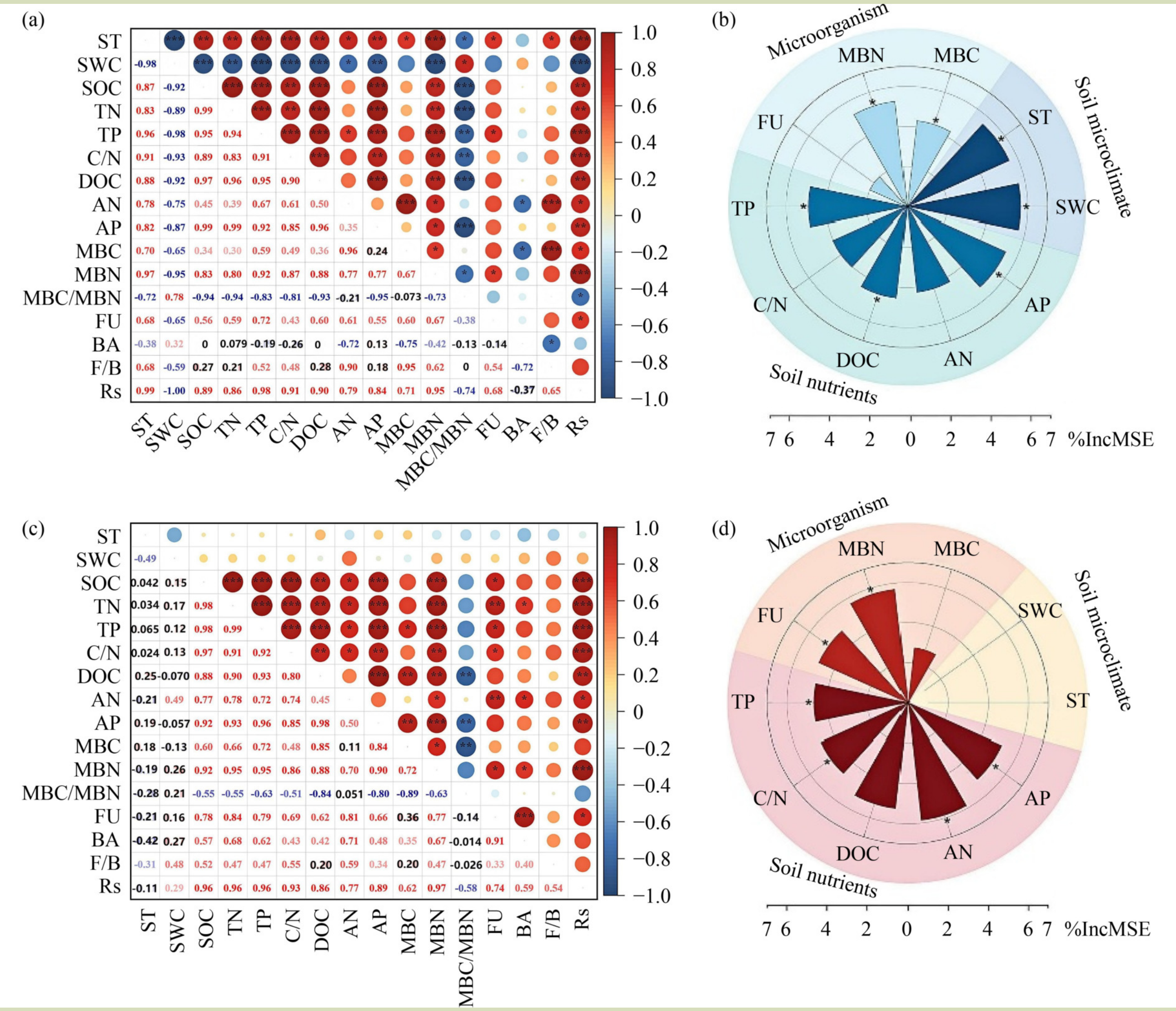


Fig. 5 Relationship between soil respiration (Rs) and abiotic and biotic soil factors in the initial straw mulching (a) and period of enduing effect (c). A random forest analysis was used to identify the relative importance of soil microclimates (ST and SWC), soil properties (TP, DOC, AN, AP and C/N), and microbial factors (MBC, MBN and FU) to Rs in the initial mulching (b) and period of enduing effect (d). ST, soil temperature; SWC, soil water content; DOC, dissolved organic carbon; AN, available nitrogen; TP, total phosphorus; AP, available phosphorus; C/N, SOC to TN ratio; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; MBC/MBN, MBC to MBN ratio; FU, fungal gene abundance; BA, bacterial gene abundance, and F/B, fungal gene abundance to bacterial gene abundance ratio. *, $P < 0.05$; **, $P < 0.01$; and ***, $P < 0.001$.

increased soil carbon, nitrogen and phosphorus contents in the period of enduing mulch effect (Fig. 3). The increase in these nutrients provided sufficient substrate for the growth and activity of microbes, accelerated the microbial decomposition rate[38], and increased soil CO_2 emissions. This point was partly supported by the soil MBN and fungal gene abundance increasing under SM treatments during the period of enduing mulch effect, which has a clear positive association with the soil CO_2 fluxes. The increased soil nutrients (N and P) also facilitated root growth[53,54], and increased soil CO_2 emissions. This result was supported by the positive correlations between the soil CO_2 fluxes and SOC, TN, TP, DOC, AN and AP during the period of mulch enduing effect (Fig. 5). Additionally, no significant variation was found in soil CO_2 flux among various mulching times during the period of enduing mulch effect, indicating that the enduing effect of SM on soil CO_2 flux was independent of mulching duration. We found that SM increased Q_{10} values during the period of enduing mulch effect, contrasting with previous studies by Li et al.[55] and Tu et al.[56], which found that nitrogen addition decreased Q_{10} values. This implies that SM could enhance the priming effects of future climate warming on soil CO_2 emissions from Moso

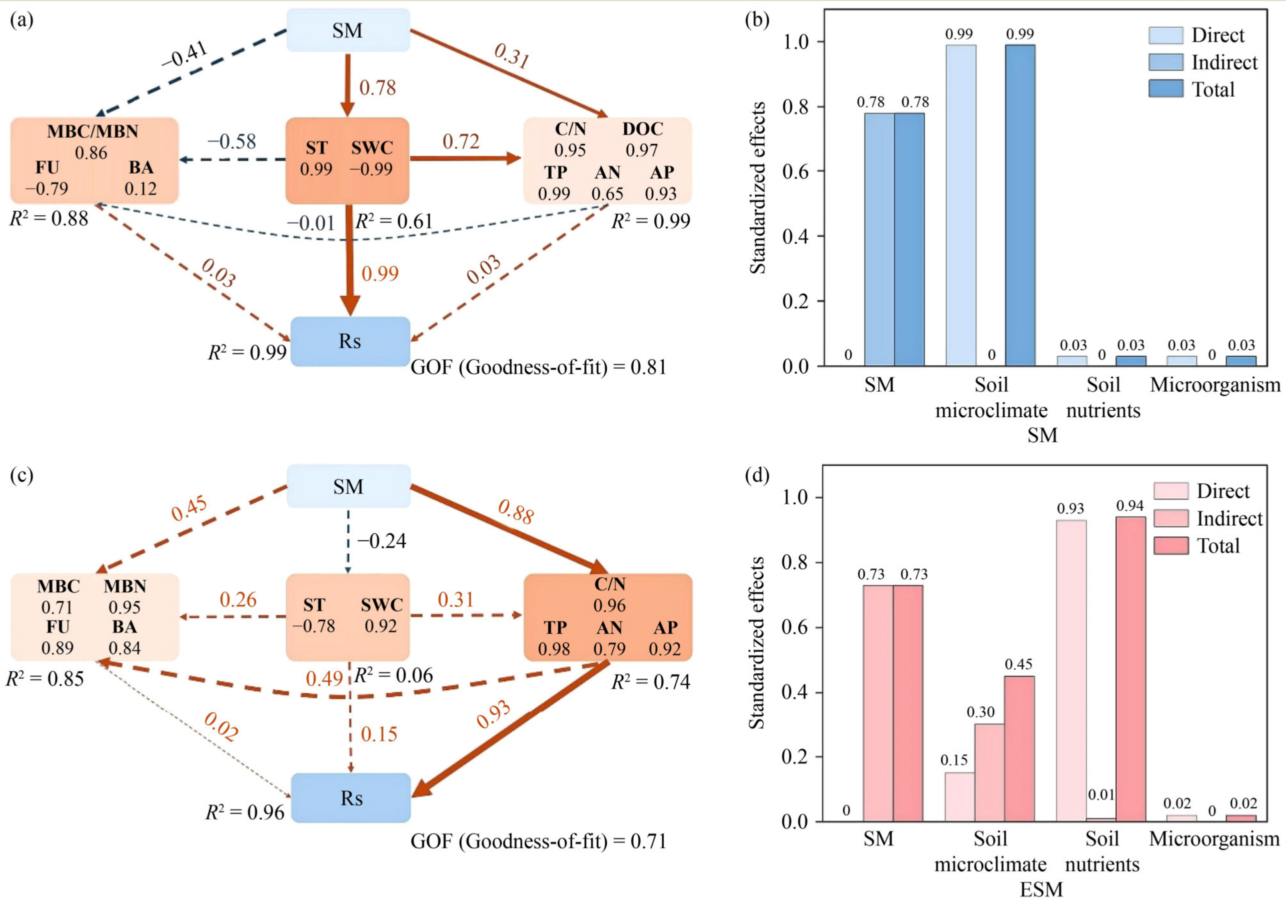


Fig. 6 Partial least squares-path model revealing the direct and indirect effects of biotic and abiotic factors on Rs during the initial straw mulching (a) and period of enduing effect (c). The standardized effects of variables from PLS-PM in the initial mulching (b) and period of enduing effect (d). Red and blue indicate positive and negative correlations, respectively. Solid and dashed lines indicate significant and insignificant pathways, respectively. The numbers next to the arrows indicate important standardized path coefficients. The width of the arrows is proportional to the strength of the association.

bamboo plantations. These differing outcomes are attributed to the varying amounts of nutrient addition.

In the context of the SM treatments, the soil CO_2 flux observed during the initial mulching period was elevated compared to those recorded during the subsequent period of enduing mulch effect (Fig. 2(b)). Several factors contributed to this observation. First, the proliferation of bamboo shoots during the mulching period will substantively stimulate autotrophic respiration[53]. Conversely, the period of enduing mulch effect was characterized by an absence of bamboo shoot growth, which corresponds to a diminished rate of autotrophic respiration. However, the decomposition of the mulch material itself is a source of substantial CO_2 emissions during the mulching period. However, the interpretations given here are largely based on the findings of prior research. To validate these conclusions, it is necessary to improve the methodologies for the precise measurement and quantification of autotrophic respiration within the soil and heterotrophic respiration linked to the decomposition of the mulch material. This approach will provide a robust empirical foundation for comprehending the complex dynamics of soil CO_2 emissions to straw mulching practices.

4.3 Limitations and implications for future research

Although we have elucidated the impact of SM on Rs in Moso bamboo plantations[57], there are still shortcomings in the present study. First, Rs includes both autotrophic and heterotrophic respiration, and it is unclear what proportion each contributes to total soil respiration and whether their responses to SM are consistent. Therefore, it is recommended that future studies use a trenching method to measure heterotrophic respiration[58,59]. Second, we have shown that ST

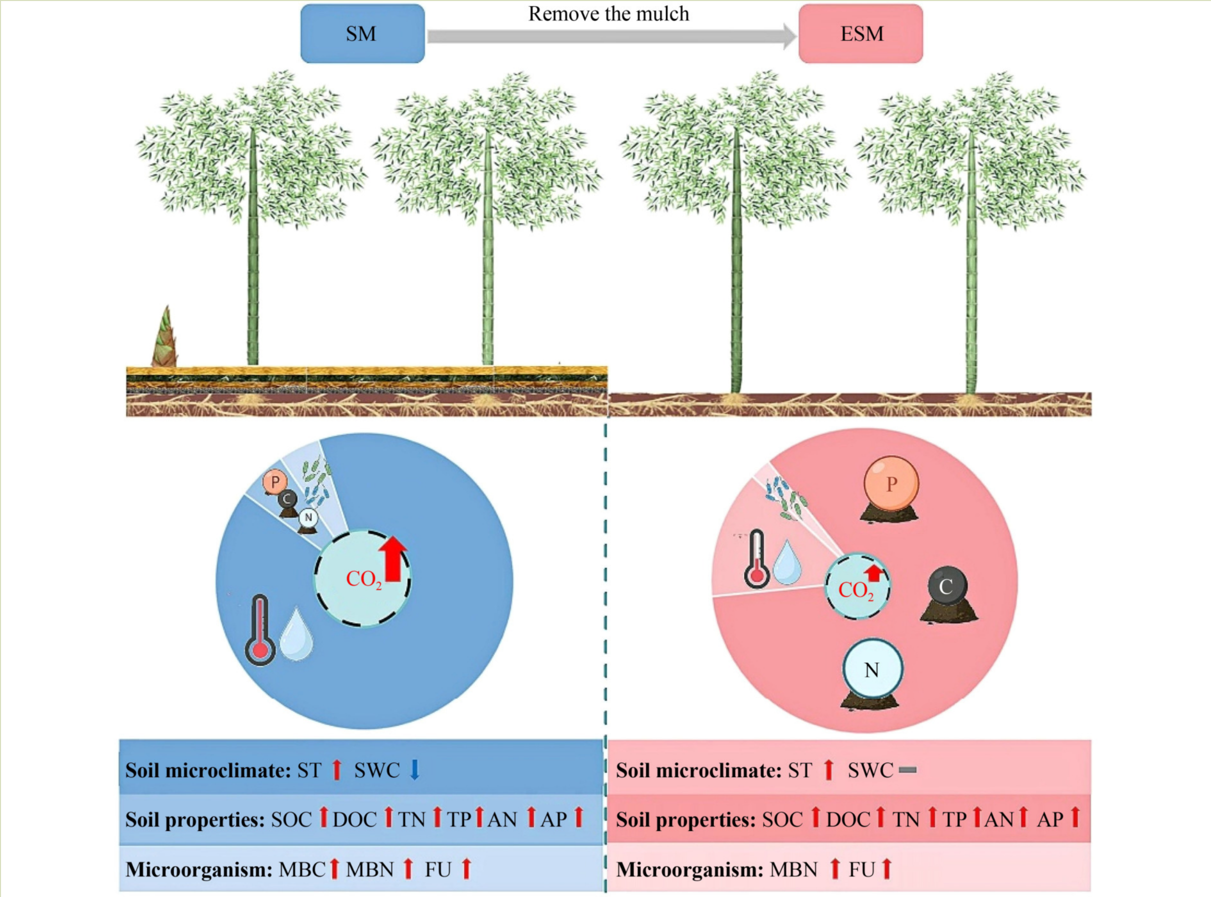


Fig. 7 Conceptual diagram illustrating soil respiration during the straw mulching period (SM) and the period of enduring effect (ESM). Specifically, this diagram shows how soil microclimate (ST and SWC), soil properties (SOC, TN, TP, DOC, AN, AP and C/N) and microbial factors affect the soil CO_2 flux. The red and blue arrows and yellow boxes indicate an increase, decrease and no effect, respectively.

significantly influenced Rs during the mulching period, and soil nutrients are crucial for Rs during the period of enduring mulch effect, using random forest and PLS-PM models; these approaches lack the interpretability of linear models. Hence, we should undertake further experiments to confirm the mechanisms we have proposed.

5 Conclusions

This research examined the effect of SM on soil CO_2 emissions and the underlying factors during the mulching period and the subsequent period of enduring mulch effect in a humid bamboo plantation (Fig. 7). During the mulching period, SM significantly elevated soil CO_2 fluxes, primarily attributed to the rise in ST. Also, SM increased soil CO_2 fluxes by increasing the availability of soil nutrients during the period of enduring mulch effect. The mulching duration did not alter the positive influence of SM on soil respiration during the two periods. Considering the impact of SM on increasing Rs, we recommend decreasing the quantity and thickness of the mulching materials to reduce soil CO_2 emissions without compromising productivity. This approach could lead to a dual benefit of improving the economic returns and carbon sequestration potential. Also, the impact of SM on Rs in other ecosystems, especially crops, in humid or semihumid regions should be considered to enhance the adaptability of SM techniques.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2025607 contains supplementary materials (Figs. S1–S2; Tables S1–S2).

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Compliance with ethics guidelines

Quan Li, Jiarui Fu, Jiahui Zeng, Chao Zhang, Changhui Peng, Lei Deng, Tingting Cao, Man Shi, Zhikang Wang, Junbo Zhang, Weifeng Zhang, Yi Zhang, and Xinzhang Song declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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