Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-14

DOI: *10.15244/pjoes/213857* ONLINE PUBLICATION DATE: 2026-02-09

Original Research

Soil Carbon Flux Characteristics in Tobacco Fields of Guizhou under Different Mulching Methods

Hongbing Chen[1#], Jianyun Zhou[2#], Songhai Shi[1#], Weichang Gao[3*], Chen Xu[4], Juncong Liu[1], Linjing Wu[1], Taoze Liu[1,5], Ke Jiang[1,5], Jiegang Liu[1,5], Zhanghong Wang[1,5]**

[1]College of Eco-Environmental Engineering, Guizhou Minzu University, Guiyang 550025, China
[2]Guiyang Company of Guizhou Tobacco Company, Guiyang 550000, China
[3]Guizhou Academy of Tobacco Science, Guiyang, 550081, China
[4]China National Tobacco Corporation Chongqing Company, Chongqing, 409100, China
[5]Engineering Research Center of Green and Low-Carbon Technology for Plastic Application, Guizhou Minzu University, Guiyang 550025, China

Received: 29 July 2025
Accepted: 02 November 2025

Abstract

To investigate the effect of different mulching cultivation methods on soil carbon flux, continuous monitoring of soil carbon flux was conducted in tobacco fields in Kaiyang County, Guizhou Province, using the static chamber-gas chromatography method under three cultivation modes: no mulching (CK), mulching during half of the growth period (T1), and mulching throughout the full growth period (T2). The characteristics of soil carbon flux (including CO_2 and CH_4) were analyzed in combination with various environmental conditions. Results showed that the peaks of CO_2 and CH_4 fluxes under different mulching methods occurred on the 35th and 56th days after transplanting, and the fluxes followed an "M-shaped" double-peak curve during the tobacco growth period, with similar trends. Compared with CK, T1 and T2 increased the cumulative CO_2 emissions by 16.49% and 48.75%, respectively, while T1 resulted in a 27.69% reduction in cumulative CO_2 emissions compared to T2. The cumulative CH_4 emissions under CK and T1 showed a net absorption effect, while T2 displayed a net CH_4 emission effect. The diurnal CO_2 flux maxima and minima occurred at 12:00-14:00 and 4:00-6:00, respectively, which corresponded closely to the variations in sampling temperature. The CH_4 flux under CK, T1, and T2 peaked during the high-temperature period of the day (12:00-14:00). In summary, mulching cultivation methods significantly affect soil carbon flux in tobacco fields. Among these methods, mulching during half of the growth period (T1) achieves better carbon sequestration and emission reduction, making it a recommended cultivation practice for tobacco production in this region.

Keywords: soil carbon flux, mulching cultivation, variation characteristics, tobacco, influencing factors

#equal contribution
*e-mail: gzyksg@outlook.com
**e-mail: liutaoze2025@163.com

Introduction

With the growing problem of global climate change, agroecosystems, as an important component of terrestrial ecosystems, play a key role in carbon emissions and carbon cycling. Atmospheric carbon dioxide (CO_2) is the most important greenhouse gas, contributing the most to the enhancement of the greenhouse effect, accounting for about 60%, and is also considered to be the most important greenhouse gas causing global warming [1, 2]. The next most important greenhouse gas is CH_4, which has 21-23 times the greenhouse effect potential of CO_2, and its contribution to the greenhouse effect reaches 15% [3]. It is estimated that 5%-20% of CO_2 and 15%-30% of CH_4 in the atmosphere originate from soil every year [3], and agricultural soils are an important source of greenhouse gas emissions [4]. Changes in soil carbon flux are not only influenced by biotic factors (soil organic matter and soil microorganisms) [5, 6], but also related to abiotic factors (mulching method, soil temperature, and soil moisture, etc.) [7-9]. It is of great significance to study the changing characteristics of soil carbon flux and its influencing factors, and to try to reduce soil carbon emissions in China.

As a widely used farm management practice, mulching cultivation improves the microclimate conditions of the soil by covering the soil surface with PE film. Rise-and-fall cultivation expands the soil-atmosphere contact area, significantly enhances solar radiation absorption efficiency and surface soil warming effect, and intensifies soil-atmosphere heat exchange processes. Most studies have shown that mulching cultivation can effectively reduce soil moisture evaporation, enhance soil temperature, and realize the effect of increasing temperature and preserving moisture, moisturizing and fertilizing, thus improving the growing environment of crops, increasing crop yield, and carbon sequestration [10-13], which plays an important role in mountain agriculture. However, the yield-increasing effect brought by mulching cultivation technology is accompanied by an increase in carbon emission, especially in the case of improper management, which can easily lead to the release of carbon in the soil exceeding the amount of carbon sequestration and exacerbate the formation of carbon sources [14]. Previous studies most often employed a simple binary comparison between "mulched" versus "unmulched" plots. The effect of the duration of film coverage has not been considered. At present, the study of soil carbon flux in farmlands mainly focuses on rice, wheat, and maize, and there are relatively few studies on roasted tobacco [15], and the study of soil carbon flux in tobacco fields in mountainous tobacco areas is rarely reported. China is the world's largest producer and consumer of tobacco [16]. Guizhou Province ranks as China's second-largest tobacco-producing region [17], where tobacco cultivation primarily employs plastic mulching techniques. As a potential carbon source in agriculture, studying the variation characteristics of soil carbon flux throughout its growth period under different mulching methods can help enrich the existing observation data of carbon flux in tobacco fields, and at the same time, it can provide a reference for the subsequent study of carbon flux in tobacco farmland.

In this context, this study took the roasted tobacco field in Kaiyang County, Guiyang City, as the research object, and used the static box-gas chromatography method to conduct continuous spot monitoring, to compare and analyze the emission characteristics of the soil carbon flux in the tobacco field under different mulching cultivation modes, and to explore the effects of environmental factors, such as the atmospheric temperature, soil temperature, and soil humidity, on soil carbon flux, so as to reveal the regulatory effects of the mulching film on the soil carbon flux and the sequestration effect in the tobacco field, and to provide a theoretical basis for the optimization of mulching cultivation modes and low-carbon management measures in the tobacco field. This will provide a theoretical basis for optimizing the cultivation method and low-carbon management measures of tobacco field mulching.

Materials and Methods

Study Sites

The field study site was located in Kaiyang County, Guizhou Province (107.17°E, 26.98°N, 1250 m altitude), which has a typical subtropical monsoon humid climate, with an average annual temperature of 18-23°C, a frost-free period of 300 days, and an annual precipitation of 1100 mm. The experimental field was flat, ventilated and well-drained. The soil was mostly slightly acidic yellow soil with pH value of 4.78, organic matter content of 17.3 $g\cdot kg^{-1}$, total nitrogen of 0.101 $g\cdot kg^{-1}$, total phosphorus of 0.41 $g\cdot kg^{-1}$, effective phosphorus of 2.9 $mg\cdot kg^{-1}$, and quick-acting potassium of 121 $mg\cdot kg^{-1}$.

Study Design

The tobacco variety was "Yunyan 87", and a randomized block experimental design was adopted, with three treatments: no mulching (CK), mulching during half of the growth period (T1), and mulching throughout the full growth period (T2), among which T1 and T2 used transparent PE film with a thickness of 0.01 mm. T1 will be uncovered 45 days after transplantation. Three replications were set up for each treatment, and each plot was planted in an area of 40.8 m^2 (17×2.4 m). A 0.5 m wide protection row was provided around the experimental area. The plant spacing was 60 cm, the row spacing was 120 cm, and 3 rows were planted in each plot, and the specific baked tobacco field layout was shown in Fig. 1.

Except for the experimental factors, other cultivation measures were carried out in accordance with the

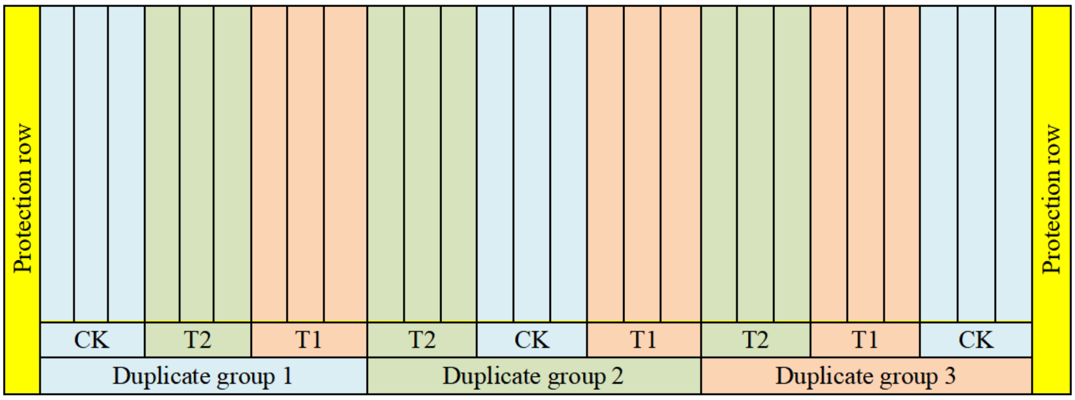

Fig. 1. Layout of the field plots of the baked tobacco trial.

local management standard for high-quality tobacco production, including the application of basal fertilizer before transplanting, regular follow-up fertilizer, and manual weeding. In this experiment, transplanting was carried out on April 23, and the tobacco seedlings lasted 35 days from transplanting to vigorous growth (Root stretching stage), 35 days from vigorous growth to maturity (Vigorous growth stage), and 35 days from maturity to the end of harvesting and roasting (Maturity stage). The whole reproductive period is 105 days.

Measurement Items and Methods

Soil Carbon Flux Measurement

In the field experiment, soil carbon fluxes (CO_2 and CH_4) from the tobacco field were monitored by static box-gas chromatography [18-20]. The gas box includes two parts: the box and the base. The static box is a circular dark box with a diameter of 31 cm and a height of 60 cm, with a small fan installed inside to mix the gases, and the gas collection interface is connected through a rubber tube and a three-way valve. The base is 20 cm high, slightly larger in diameter than the box, and has a 5 cm groove in it. Before the start of the study, the base was placed into the soil for 15 cm and remained fixed throughout the test, and no crops were planted inside the base. Before gas collection, the water-seal tank was filled with clean tap water. This ensured an airtight seal at the junction between the collection box and its base, preventing the exchange of internal and external gases. It should be noted that the static chamber method may underestimate total soil respiration by weakening plant root respiration and may be influenced by chamber-induced microclimatic changes. However, the method remains widely used for its practicality and reliability in field-based GHG flux measurements [18-20].

The gas collection time was from 8:00 to 12:00, because this period is considered to be a good representative of the average daily emission. At 0, 15, and 30 min after the static box is closed, use a 50 mL syringe to extract 30 mL of gas from the box, inject it into a 50 mL gas sampling bag for storage, and conduct a total of three acquisitions. At the same time, record the temperature in each gas flow node box. After flue-cured tobacco transplanting, the test site conducted gas collection once a week. In case of special weather, the collection time can be adjusted appropriately. At the same time, a 24-hour average daily emission flux monitoring was conducted during the vigorous growth stage of tobacco, and the sampling interval was 2 h. After gas collection, the concentrations of CO_2 and CH_4 in the gas samples were determined with a gas chromatograph (Agilnet Technologies GC9790 Plus) within 24 h. The detector of CO_2 and CH_4 concentrations adopts flame ionization detection (FID), and the column temperature is set at 120°C, and the detector temperature is 300°C. Nitrogen was used as the carrier gas at a flow rate of 50 mL·min-1. Hydrogen gas was used as fuel gas at a flow rate of 30 mL·min-1. Air is used as the auxiliary gas, and the flow rate is 300 mL·min-1. CH_4 and CO_2 standard gases are provided by Mianyang Changjun Gas Co., Ltd.

Environmental Impact Factors Measurement

Each time the gas was collected at 0 min, soil temperature and moisture were measured using a portable sensor (LY-201, Guangzhou Xinglianying Instrument Co., Ltd). The sensor was inserted into the soil on the base ridge at depths of 0-5 cm and 5-15 cm. Measurements for each stratified depth were recorded immediately after the sensor was placed. Concurrently, the atmospheric temperature inside the static chamber was also recorded at each gas sampling node. A digital thermometer was used to measure the atmospheric temperature between the tobacco canopy height and the tobacco rows.

Data Processing and Analysis

The calculation formula of carbon flux is as follows [21, 22]:

$$F = \rho \times h \times (dc/dt) \times 273/(273 + T)$$

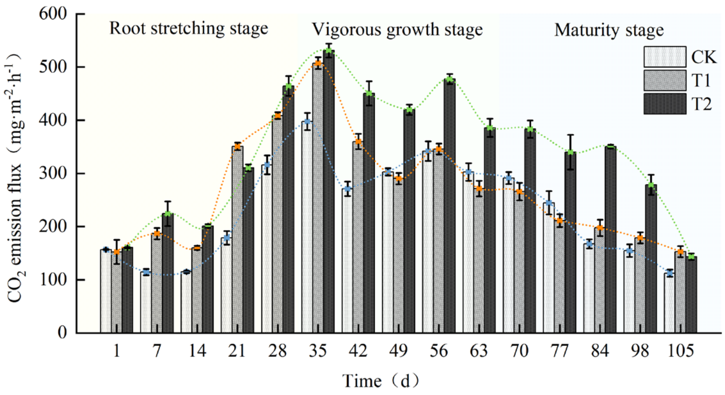

Fig. 2. Characteristics of CO_2 emission flux during the reproductive period of roasted tobacco under different film-covering cultivation methods.

Where F is the CO_2 emission flux (mg·m^{-2}·h^{-1}) and the CH_4 emission flux (μg·m^{-2}·h^{-1}), ρ is the density of CO_2 gas (1.977 g·L^{-1}) and the density of CH_4 gas (0.713 g·L^{-1}) under standard conditions, h is the height of the box (m), dc/dt is the rate of change of greenhouse gas concentration in the sampling box, the rate of change of CO_2 concentration is in mg·h^{-1} and the rate of change of CH_4 concentration is in μg·h^{-1}, T is the average temperature (°C) in the static chamber.

The calculation formula of cumulative emissions is as follows [23]:

$$M = \sum((F_{i+1} + F_i)/2) \times (t_{i+1} - t_i) \times 24 \times 10^{-2} (\times 10^{-5})$$

Where M is the cumulative soil CO_2 emission (t·hm^{-2}) and the CH_4 emission (kg·hm^{-2}), F is the CO_2 emission flux (mg·m^{-2}·h^{-1}) and the CH_4 emission flux (μg·m^{-2}·h^{-1}), i is the number of samples, $t_{i+1} - t_i$ is the number of days between samples, 10^{-2} is the unit conversion for cumulative CO_2 emissions, and 10^{-5} is the unit conversion for cumulative CH_4 emissions.

The data in this study are expressed as the mean of multiple repetitions. Excel 2016 was used to calculate and sort out the original data. Origin 2024 software was used to plot images of related data, such as dynamic changes in soil carbon flux and cumulative emissions of CO_2 and CH_4. SPSS 27.0 was used for effect sizes, correlation analysis, and one-way ANOVA. Effect sizes (Cohen's d) and 95% confidence intervals were used to test the difference between soil carbon flux and influencing factors ($p<0.05$).

Results

Characterization of Soil Carbon Flux During the Fertility Period in Tobacco Fields

As shown in Fig. 2, the CO_2 emission flux under various film-mulched cultivation methods exhibited a bimodal distribution, characterized by an "M"-shaped pattern of rapid increase followed by decrease. The peaks were mainly concentrated in the vigorous growth stage of flue-cured tobacco, which varied according to the filming methods. During the root stretching stage, soil carbon flux increased rapidly, and the rates of T1 and T2 were comparable and greater than that of CK, showing significant differences ($p<0.05$). In the vigorous growth stage of tobacco, soil carbon flux under different mulching methods showed two distinct CO_2 emission peaks, which appeared at 35 and 56 days after transplanting. At 35 days after transplanting, the peaks of CK, T1, and T2 were 397.56, 507.34, and 531.19 mg·m^{-2}·h^{-1}, respectively. After a rapid "falling-rising" change, the second peak appeared at 56 d after transplanting, and the peak values of CK, T1, and T2 were 341.83, 345.91, and 477.47 mg·m^{-2}·h^{-1}, respectively. The overall trend of carbon flux at the maturity stage was decreasing, and the rates of CK and T1 were comparable and smaller than those of T2, showing significant differences ($p<0.05$). In addition, after uncovering the film at the 45th day of T1, the soil carbon flux showed an overall downward trend, from 290.22 mg·m^{-2}·h^{-1} at the 49th day after transplanting to 152.89 mg·m^{-2}·h^{-1} at the end of harvest, with a decrease of 47.32%, which was consistent with that of CK. Through the overall comparison, the CO_2 emission flux of T1 before film uncovering had the same trend as that of T2, with a correlation of 96.09%. The CO_2 emission flux of T1 after film uncovering was similar to that of CK, with a correlation of 95.58%.

From Fig. 3, it can be seen that different mulching cultivation methods have significant effects on the CH_4 emission flux ($p<0.05$). Similar to the CO_2 emission flux, the CH_4 emission flux showed an "M"-shaped pattern of rapid increase followed by a decrease. Peak fluxes for both gases occurred primarily during the vigorous growth stage of flue-cured tobacco. Negative values indicate CH_4 uptake (sink), and positive values indicate CH_4 emission (source). Soil temperature and humidity varied significantly under different plastic film mulching methods. At the root stretching stage of flue-cured tobacco, the soil CH_4 flux showed an overall upward trend, and T2 changed from CH_4 uptake (sink)

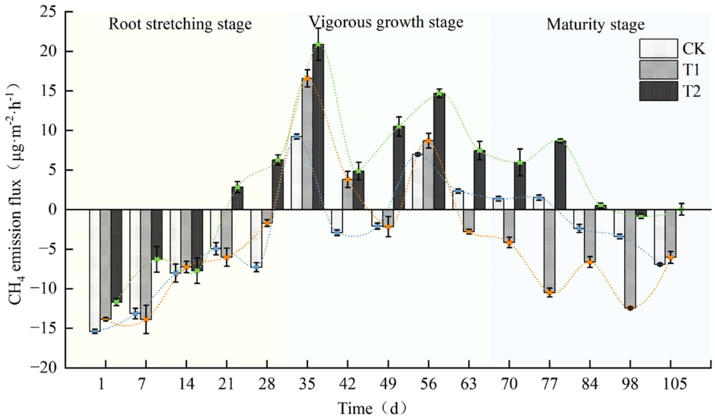

Fig. 3. Characteristics of CH_4 emission flux during the reproductive period of roasted tobacco under different film-covering cultivation methods.

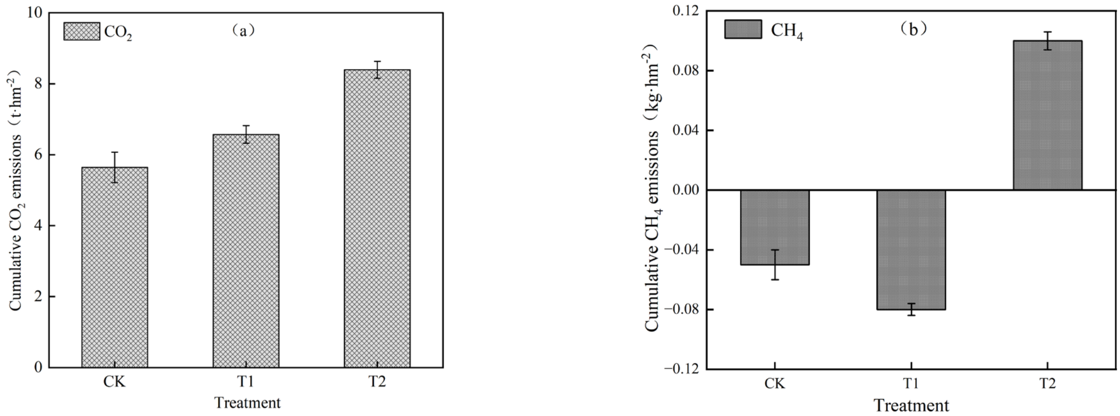

Fig. 4. Accumulated soil carbon emissions in tobacco fields under different mulching cultivation methods. a) Accumulated CO_2 emissions; b) Accumulated CH_4 emissions.

to CH_4 emission (source) for the first time at 21 days after transplanting, with a value of 2.86 μg·m^{-2}·h^{-1}. After that, the flue-cured tobacco entered the vigorous growth stage. CK, T1, and T2 reached the peak at 35 days after transplanting, and realized the transformation of CH_4 source and sink, with 9.24, 16.59, and 20.91 μg·m^{-2}·h^{-1}, respectively. The second CH_4 emission peak appeared in CK, T1, and T2 in the third week (56 days after transplantation), with 6.99, 8.71, and 14.70 μg·m^{-2}·h^{-1}, respectively. The CH_4 flux in soil decreased from 3.83 μg·m^{-2}·h^{-1} at 42 days after transplanting to -2.15 μg·m^{-2}·h^{-1} at 49 days after transplanting at T1 after film uncovering at 45 days, which once again became the role of the soil CH_4 sink. After flue-cured tobacco entered the maturity stage, the CH_4 flux of CK and T1 gradually changed from emission source to an absorption sink and lasted until -6.92 μg·m^{-2}·h^{-1} and -6.03 μg·m^{-2}·h^{-1}, respectively, at 105 days after transplanting. However, the flue-cured tobacco under the T2 film mulching method played the role of soil CH_4 emission source for most of the time, and the CH_4 flux after harvesting was 0.05 μg·m^{-2}·h^{-1}.

Cumulative Emissions of CO_2 and CH_4 During the Reproductive Period of Tobacco Fields

According to Fig. 4, the cumulative emissions of soil carbon during the growth period of flue-cured tobacco vary greatly under different film mulching cultivation methods. In the whole growth period of flue-cured tobacco, the cumulative emissions of soil CO_2 and CH_4 under different film mulching cultivation methods were significantly different ($p<0.05$), indicating that film mulching cultivation had a greater impact on soil CO_2 and CH_4 emissions. Compared with CK, the cumulative CO_2 emissions of T1 and T2 increased by 16.49% and 48.75%, respectively. Compared with T1, the cumulative CO_2 emissions of T2 decreased by 27.69%. The cumulative emissions of CH_4 under CK and T1 were negative, which showed carbon absorption (sink), and were -0.06 kg·hm^{-2} and -0.08 kg·hm^{-2}, respectively. The cumulative emission of CH_4 under T2 was carbon emission (source), which was 0.10 kg·hm^{-2}.

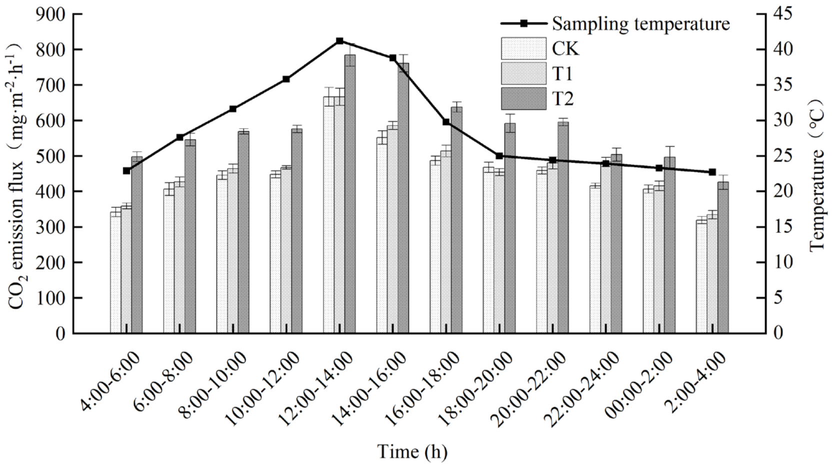

Fig. 5. Daily variation of soil CO_2 emission flux in tobacco fields under different mulching cultivation methods.

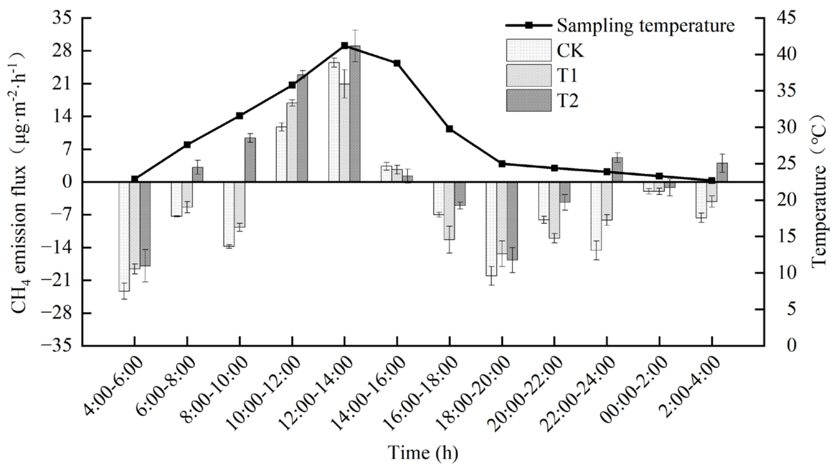

Fig. 6. Daily variation of soil CH_4 flux in a tobacco field under different mulching cultivation methods.

Study on the Daily Variation of Soil Carbon Flux in Tobacco Fields

Daily Dynamics of Soil CO_2 Flux in Tobacco Fields

As shown in Fig. 5, the daily variation in soil CO_2 flux under different film mulching methods exhibited a single peak curve, with higher values during the day and lower values at night. This trend was consistent with the changes in sampling temperature. The peak and valley values of soil CO_2 flux appeared at 12:00-14:00 p.m. and 4:00-6:00 a.m., respectively. The diurnal variation ranges of soil CO_2 flux of CK, T1, and T2 were 341.62-666.34, 358.58-666.36, and 497.80-784.22 mg·m^{-2}·h^{-1}, respectively. Under different film mulching cultivation modes, the soil CO_2 daily emission flux of CK was the smallest (4:00-6:00), and that of T2 was the largest (12:00-14:00). This indicates that the soil CO_2 flux was affected by the film mulching cultivation method, and the warming effect will increase soil CO_2 release.

Daily Dynamics of Soil CH_4 Flux in Tobacco Fields

Fig. 6 demonstrates that the daily CH_4 emission flux of tobacco field soil exhibited significant diurnal dynamic characteristics, showing the characteristics of source-sink function conversion. The methane emissions of CK, T1, and T2 peaked during the daytime high-temperature period (12:00-14:00), and were 25.48, 20.92, and 29.03 μg·m^{-2}·h^{-1}, respectively. From 14:00 to 16:00, the CH_4 emission flux of each film mulching method decreased the most, with 86.84%, 88.74%, and 95.69% respectively. Thereafter, CH_4 absorption occurred in the afternoon and at nighttime low-temperature period (16:00-6:00 the next day) as a whole. The CH_4 absorption rates of CK, T1, and T2 were 23.31, 18.59, and 17.93 μg·m^{-2}·h^{-1} at 4:00-6:00, respectively.

Table 1. Daily variation of 24 h CO_2 flux in tobacco field soil at different time periods.

Sampling period	CK ($mg·m^{-2}·h^{-1}$)	CK time period Mean Ratio	T1 ($mg·m^{-2}·h^{-1}$)	T1 time period Mean Ratio	T2 ($mg·m^{-2}·h^{-1}$)	T2 time period Mean Ratio
4:00~6:00	341.62±13.14	0.757	358.58±8.32	0.762	497.8±13.9	0.856
6:00~8:00	406.32±18.29	0.901	426.5±13.79	0.906	545.73±17.51	0.938
8:00~10:00	445.76±11.92	0.988	463.98±12.49	0.986	568.56±7.47	0.977
10:00~12:00	447.91±9.48	0.993	466.9±4.96	0.992	575.52±10.46	0.989
12:00~14:00	666.34±26.64	1.477	666.36±23.98	1.416	784.22±31.99	1.348
14:00~16:00	551.46±18.58	1.223	585.26±11.3	1.243	760.73±24.05	1.307
16:00~18:00	486.35±12.8	1.078	513.74±16.84	1.092	637.53±14.57	1.096
18:00~20:00	467.68±14.14	1.037	453.86±9.89	0.964	591.6±25.56	1.017
20:00~22:00	458.55±9.79	1.017	480.28±17.13	1.020	595.21±10.82	1.023
22:00~24:00	415.67±7.42	0.921	482.59±12.86	1.025	503.56±18.58	0.865
00:00~2:00	406.3±11.33	0.901	415.48±13.3	0.883	496.2±30.51	0.853
2:00~4:00	319.03±10.04	0.707	334.37±11.56	0.710	425.69±19.87	0.732
Average carbon flux	451.08±13.63	/	470.66±13.04	/	581.86±18.77	/

Comparison of 4 h (8:00-12:00) and 24 h CO_2 Flux Daily Means

In order to further explore the variation characteristics of soil CO_2 flux, the CO_2 flux of tobacco field soil in different film mulching cultivation methods was compared with the average soil CO_2 flux of the tobacco fields at different periods (see Table 1). The results showed that in the three time periods of 8:00-10:00, 10:00-12:00, and 20:00-22:00, the ratio of CO_2 flux to average CO_2 flux of different film mulching cultivation methods was the closest, which were 0.984, 0.991, and 1.020, respectively. This suggested that measurements taken during 8:00-12:00 (including 8:00-10:00 and 10:00-12:00) can better reflect the daily average CO_2 emission flux of soil. That is, the average flux measured in the 4 h (8:00-12:00) can be used to estimate the daily average carbon emission flux over the 24 h of the day, which is consistent with the results of previous studies [24, 25]. Therefore, the daily average soil carbon flux can be estimated by the flux value measured from 8:00 to 12:00, which is important for predicting the soil carbon flux in the whole growth period or even the whole year.

Analysis of Factors Affecting Soil Carbon Flux in Tobacco Fields

Human Factors Analysis

Throughout the growth period of flue-cured tobacco, the soil CO_2 emission flux differed significantly ($p<0.05$) among the various film mulching cultivation methods. Under the condition of film mulching, the CO_2 emission flux of T1 and T2 was significantly higher than that of CK. The sustained, stable microclimate of elevated temperature and humidity under the plastic film mulch promoted robust soil microbial activity and accelerated organic matter decomposition. Consequently, a high rate of CO_2 emission flux was maintained throughout the experimental period. The topdressing treatment of flue-cured tobacco at the root stretching stage was carried out 30 days after transplanting. The fertilizer promoted an increase in soil biomass and an enhancement of soil respiration, and the soil carbon flux of each treatment reached the first peak at 35 days after transplanting. With the passage of time, the fertilizer was gradually absorbed by the soil, the growth of flue-cured tobacco also entered a vigorous growth stage, and the respiration of plant roots gradually enhanced, so that the carbon flux 56 days after transplanting entered the second small peak. After that, the flue-cured tobacco entered the maturity stage, the growth gradually stopped, the root activity weakened, the soil carbon source decreased, and the organic matter was depleted. In addition, the late human factors led to serious damage to the PE film, while also increasing its impact on soil temperature and moisture, which further changed the soil environmental conditions, making the activities of soil microorganisms in tobacco fields weaken as they needed to adapt to the new environmental conditions. Therefore, the CO_2 emission flux of the film mulching cultivation methods gradually decreased and tended to be stable, and finally fell to the valley value at the end of harvesting (105 days).

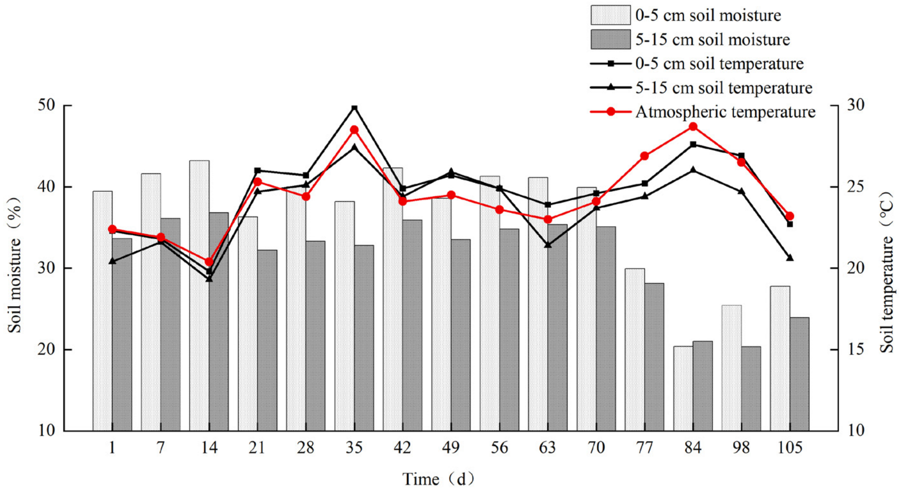

Fig. 7. Dynamics of soil impact factors in tobacco fields.

Hydro-Thermal Factor Analysis

According to Fig. 7, during the whole growth period of flue-cured tobacco, the variation trends of atmospheric temperature, 0-5 cm soil temperature, and 5-15 cm soil temperature are basically the same. Film mulching effectively prevented the loss of soil heat, making the layered soil temperature close to the atmospheric temperature, and even 0-5 cm soil temperature slightly higher than the atmospheric temperature. After July 2 (70 days after transplanting), the variation ranges of soil temperature at 0-5 cm and 5-15 cm were 22.7-27.6 and 20.7-27.4℃, respectively, which was lower than the atmospheric temperature in the same period (23.2-28.7℃). With the passage of time, the atmospheric temperature reached the maximum value of 28.6℃ on July 16 (84 days after transplanting). During the whole growth period, the soil temperature at 0-5 cm was slightly higher than that at 5-15 cm, which was consistent with the direction of heat transfer. Soil temperatures at 0-5 cm and 5-15 cm were closely related to CO_2 emission flux, with the highest correlation of 0.692 and 0.793 ($p<0.01$), respectively.

Overall, from Fig. 8, CO_2 emission flux also tends to increase with the increase in layered soil temperature. Especially at 35 days after transplanting, the soil temperature at 0-5 cm reached the peak (29.9℃), and the CO_2 emission flux also reached a significant peak, which verified the driving mechanism of soil temperature on soil CO_2 emission. The change between CH_4 emission flux and temperature showed a stage characteristic: from 14 to 49 days after transplanting, CH_4 emission flux also changed with the change of atmospheric temperature and soil temperature, but the synchronization between soil temperature and CH_4 emission flux was more significant. At 56 days after transplanting, flue-cured tobacco entered the maturity stage, CH_4 emission flux decreased and became relatively stable, and the flue-cured tobacco field showed a state of CH_4 absorption.

This study evaluated the strength of correlations between environmental factors and soil carbon dioxide emission fluxes based on Cohen's J [26] classification criteria ($0\leq|d|<0.2$ indicates no significant correlation, $0.2\leq|d|<0.5$ indicates weak correlation, $0.5\leq|d|<0.8$ indicates moderate correlation, $0.8\leq|d|$ indicates strong correlation). Table 2 shows that temperature (r = 0.723, r = 0.707, r = 0.403) and stratified soil moisture (r = 0.317, r = 0.323) exhibit significant positive correlations with CO_2 emission flux. Among these, 0-5 cm soil temperature (d = 5.173), 5-15 cm soil temperature (d = 5.198), and atmospheric temperature (d = 5.179) exerted a greater influence on CO_2 emission flux than soil moisture (d = 4.011). As shown in Table 3, stratified soil moisture had negligible effects on CH_4 emission flux, whereas temperature exhibited significant correlations with CH_4 emission fluxes. Specifically, 0-5 cm soil temperature (d = -4.813), 5-15 cm soil temperature (d = -4.617), and air temperature (d = -4.789) exerted significantly stronger effects on CO_2 emission flux than stratified soil moisture (d = -0.276).

During the growth period of flue-cured tobacco, the soil moisture of 0-5 cm and 5-15 cm maintained a high level of more than 35% for most of the time, but gradually decreased in the vigorous growth stage of flue-cured tobacco. The variation range of soil moisture at 0-5 cm was 20.4% - 43.2%, and that at 5-15 cm was 22.9% - 43.5%. The soil moisture at 5-15 cm was higher than that at 0-5 cm, but the variation range was smaller. Stratified soil moisture was significantly negatively correlated with atmospheric temperature ($p<0.05$). From the perspective of correlation, CO_2 emission flux did not show a strict linear correlation with stratified soil moisture, and the highest correlation was only 0.357 (see Fig. 9). At the same time, there was a complex relationship between soil moisture and CH_4 emission flux. Stratified soil moisture did not significantly affect soil CH_4 emission flux, and there was no obvious correlation between the two trends (see Fig. 10).

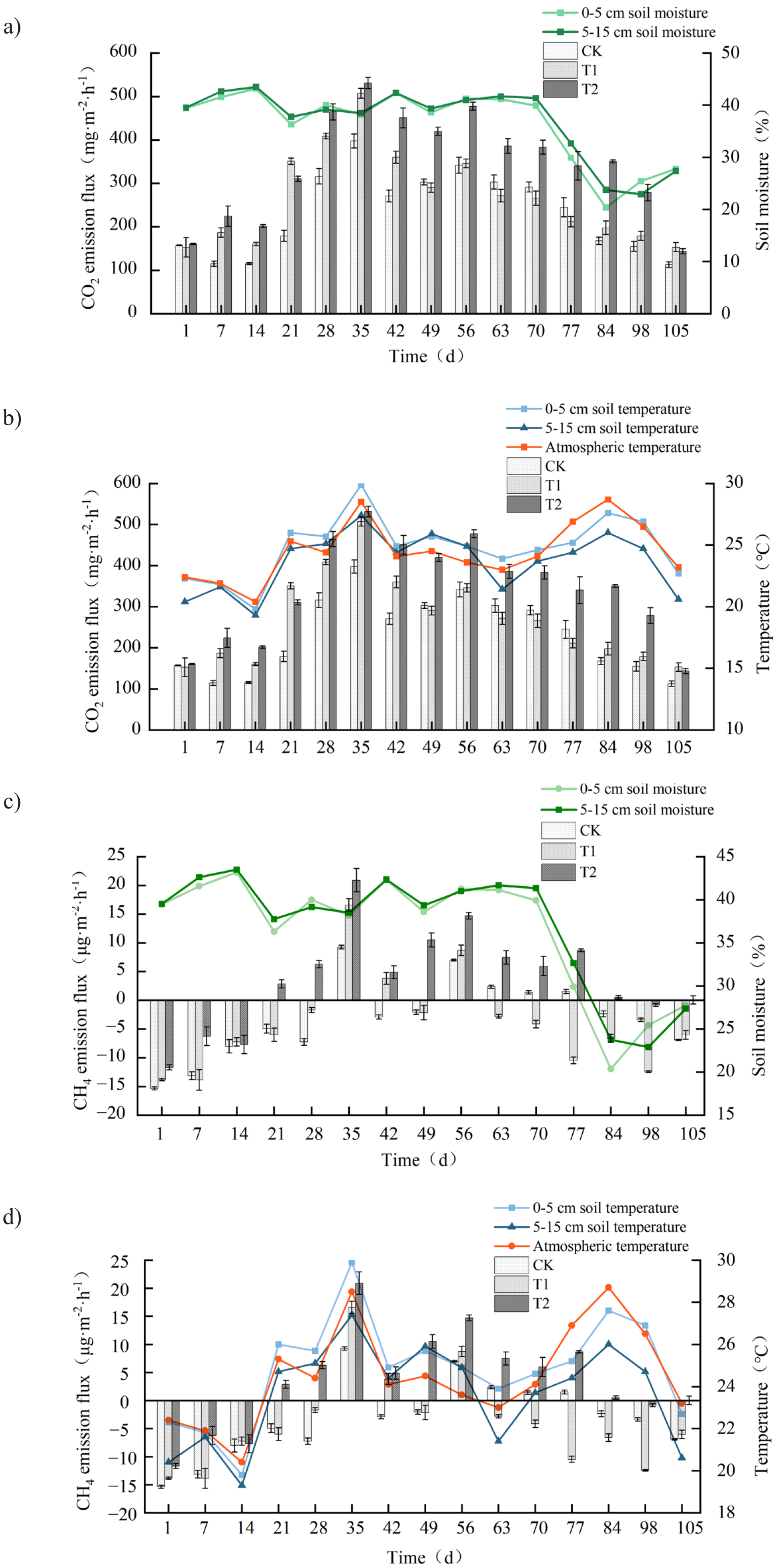

Fig. 8. Dynamics of soil carbon flux and environmental factors in tobacco fields. a) CO_2 flux and soil moisture; b) CO_2 flux and temperature; c) CH_4 flux and soil moisture; d) CH_4 flux and temperature.

Table 2. Effect size analysis results of influencing factors on CO_2 emission flux.

Treatment	k	N	SD	Cohen's d	r	95% confidence interval	
						lower limit	upper limit
0-5 sm %	15	45	1.473	4.011	0.317	35.617	37.117
5-15 sm %	15	45	1.092	4.011	0.323	36.355	37.455
0-5 st °C	15	45	0.606	5.173	0.723	24.486	25.106
5-15 st °C	15	45	0.805	5.198	0.707	23.212	24.032
at °C	15	45	0.718	5.179	0.403	24.144	24.864

Note: k = number of studies with effect sizes, N = cumulative sample size across k studies, SD = pooled standard deviation, Cohen's d = mean comparison, r = average correlation coefficient after effect size analysis, sm = soil moisture, st = soil temperature, at = atmospheric temperature.

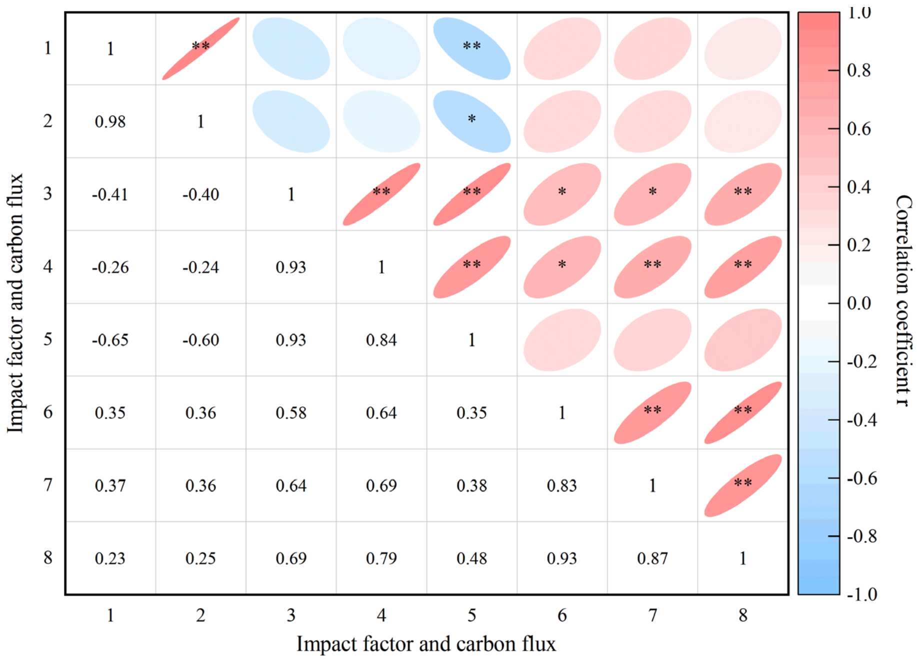

Fig. 9. Heat map of the correlation between CO_2 emission flux and impact factors.
1. 0-5 cm soil moisture %, 2. 5-15 cm soil moisture %, 3. 0-5 cm soil temperature °C, 4. 5-15 cm soil temperature °C, 5. Atmospheric temperature °C, 6. CO2 emission flux from CK, 7. CO2 emission flux from T1, and 8. CO2 emission flux from T2. * p<0.05, and ** p<0.01. An ellipse sloping to the right (red) inclination indicates a positive correlation, while an ellipse inclined to the left (blue) indicates a negative correlation. The correlation coefficient is proportional to the eccentricity of the ellipse and inversely proportional to the area of the ellipse.

There was a positive correlation between soil carbon flux and water and heat factors under different film mulching cultivation methods ($p<0.05$). Among them, the carbon flux showed a highly significant positive correlation with the soil temperature of 0-5 cm and 5-15 cm in general ($p<0.01$), while the stratified soil temperature was mainly affected by the atmospheric temperature, and the correlations were as high as 0.927 and 0.835, respectively (see Fig. 9 and Fig. 10). In conclusion, there is a clear synergy between soil temperature and atmospheric temperature, and it also shows that stratified soil temperature plays a leading role in soil carbon flux.

Discussion

Soil Carbon Flux Analysis

During the growth period of flue-cured tobacco, the change in soil carbon flux under different film mulching methods showed an "M"-type bimodal curve of rapid increase followed by a decrease. Li et al. [27] showed a single peak curve in the study of soil CO_2 emissions from flue-cured tobacco in Weining, Guizhou, which differed from the pattern observed in this study, but both of them peaked on the 56th day (vigorous growth stage) after tobacco transplanting. The reason for the different trends may be the topdressing treatment of flue-cured

Table 3. Effect size analysis results of influencing factors on CH4 emission flux.

Treatment	k	N	SD	Cohen's d	r	95% confidence interval	
						lower limit	upper limit
0-5 sm %	15	45	1.473	-0.276	0.117	35.617	37.117
5-15 sm %	15	45	1.092	-0.277	0.120	36.355	37.455
0-5 st °C	15	45	0.606	-4.813	0.620	24.486	25.106
5-15 st °C	15	45	0.805	-4.617	0.637	23.212	24.032
at °C	15	45	0.718	-4.789	0.457	24.144	24.864

Note: k = number of studies with effect sizes, N = cumulative sample size across k studies, SD = pooled standard deviation, Cohen's d = mean comparison, r = average correlation coefficient after effect size analysis, sm = soil moisture, st = soil temperature, at = atmospheric temperature.

tobacco at the root stretching stage, which was carried out on the 30th day after transplanting in this study. The addition of fertilizer significantly promoted the increase of plant root activity and biomass, and also enhanced soil respiration, resulting in the emergence of a bimodal curve [28]. In addition, the peak value showed that soil microbial activity, soil root respiration and carbon metabolism were the most vigorous during this period [29].

The seasonal dynamics of methane flux we observed result from the equilibrium between two opposing processes: methane production and methane oxidation, both regulated by soil environmental factors [30]. Before plastic mulch removal at T1, the high-temperature, high-humidity soil environment jointly promoted methanogenic activity, while anaerobic conditions simultaneously inhibited methanotrophic bacteria, leading to elevated CH_4 flux levels during this period [31]. After the cover was removed on day 45, the tobacco plants had fully entered their vigorous growth stage. Methanogenesis was inhibited due to reduced substrate availability and improved soil aeration [32], while increased oxygen enhanced methane oxidation potential, thereby maintaining net fluxes at lower levels.

Analysis of Daily Changes in Soil CO_2 Emission Flux

The soil CO_2 emission flux peaked at 12:00-14:00. This trend was consistent with the changes in sampling

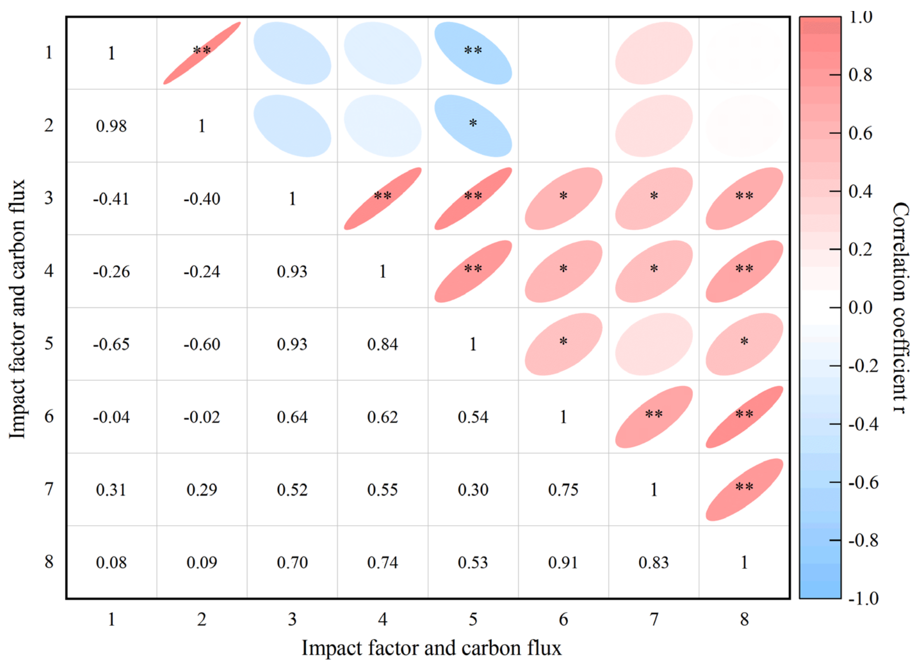

Fig. 10. Heat map of the correlation between CH_4 emission flux and impact factors.
0-5 cm soil moisture %, 2. 5-15 cm soil moisture %, 3. 0-5 cm soil temperature °C, 4. 5-15 cm soil temperature °C, 5. Atmospheric temperature °C, 6. CH_4 emission flux from CK, 7. CH_4 emission flux from T1, and 8. CH_4 emission flux from T2. * $p<0.05$, and ** $p<0.01$. An ellipse sloping to the right (red) indicates a positive correlation, while an ellipse inclined to the left (blue) indicates a negative correlation. The correlation coefficient is proportional to the eccentricity of the ellipse and inversely proportional to the area of the ellipse.

temperature. The sampling temperature was mainly affected by atmospheric temperature, which indicated that the daily emission of soil CO_2 was greatly affected by temperature. After sunrise, the solar radiation drove the soil temperature to rise, which in turn increased the soil microbial activity and the enzymatic reaction rate of tobacco root respiration. At the same time, photosynthesis provided fresh organic carbon substrate for the soil, which further stimulated soil respiration and therefore led to higher carbon flux. After sunset, temperature and light intensity gradually decrease, photosynthesis stops, substrate supply decreases, and soil respiration rate decreases, thus reducing carbon flux.

Previous studies have shown that in the daily dynamics of soil carbon flux, the all-day CO_2 emission flux showed a single-peak, single-valley pattern, with a maximum around 12:00 noon and a minimum around 4:00 a.m. [24], and the daily trend of carbon flux was similar to that of temperature, which was basically in agreement with the results of this experiment. However, Shi [33] found that soil CO_2 emissions reached a maximum at 13:00 to 15:00 and a minimum at 5:00 to 7:00 in a study of northeastern black soils, and Dong et al. [34] showed that the minimum value of soil CO_2 appeared at 23:00. The reasons for the different results may be as follows: (1) There are great differences in the test locations. The present study was in the mountainous area of Kaiyang, Guizhou, while the latter was in the mountainous area of Northeast China's Black Soil Zone and Ningxia's Pengyang County, respectively, with different climatic, soil, and other conditions. (2) The crops studied were different, with the former being tobacco and the latter winter wheat. (3) The time of study was different, with the present study being in spring and summer, while the latter was in winter. (4) The methods of study were different, with the present study using the static box method, while the latter used the alkali uptake method.

In order to understand the relationship between soil CO_2 emission flux and average daily soil CO_2 emission flux at different time periods, by calculating the ratio of CO_2 emission flux to average carbon flux at different time periods for different mulching cultivation methods, it was concluded that the carbon flux measurements from 8:00 a.m. to 12:00 noon can better represent the average daily soil CO_2 emission flux, which is in line with the results of a previous study [25].

Analysis of Factors Influencing Soil Carbon Flux

Temperature is a key factor in regulating and controlling many ecological processes, and is also one of the determinants of soil carbon flux [35]. Changes in atmospheric temperature cause changes in surface and soil temperatures, which have an impact on plant root growth, soil microbial activity, and decomposition of apoplastic and soil organic matter [36]. The correlation coefficients were, in descending order, 5-15 cm soil temperature, 0-5 cm soil temperature, atmospheric temperature, 5-15 cm soil moisture, and 0-5 cm soil moisture, which were similar to the results of Xiong [37]. Comparative analysis of Cohen's effect sizes across different environmental factors revealed that soil temperature exerts the strongest and most significant influence on soil carbon flux. In addition to hydrothermal conditions, other biotic and management factors significantly influence soil respiration. These include the practice of plastic film mulching in flue-cured tobacco cultivation, as well as soil litter and root biomass [38]. Related studies have found a positive correlation between soil carbon flux and root biomass [39]. There are many factors affecting soil carbon flux, such as vegetation type, fertilization method, and irrigation method [38, 40].

Environmental and Management Implications

Although plastic mulch can improve soil microclimate, it may also increase soil microplastic pollution due to incomplete recovery [41]. Residual films and microplastics alter soil physical structure and chemical microenvironments, negatively impacting the diversity, abundance, and activity of soil organisms [42]. Mulching during half of the growth period (T1) method effectively reduces material degradation and damage caused by environmental weathering (such as sunlight and wind) by shortening the exposure time of agricultural film in the field, thereby significantly enhancing the integrity and recyclability of the film. Furthermore, since the mulching material used in this study was PE film, future research could explore biodegradable materials as novel alternatives. This approach aims to safeguard agricultural production while minimizing potential threats to farmland environments.

Conclusions

From 8:00 a.m. to 12:00 p.m., soil CO_2 and CH_4 fluxes in tobacco fields under three mulching cultivation methods better reflect the daily average rate of soil carbon flux. The sensitivity of tobacco field soil carbon flux to stratified soil temperature was the highest, with a highly significant positive correlation overall ($P<0.01$, $|d|\geq0.8$), indicating that stratified soil temperature played a dominant role in soil carbon flux. T1 reduced the soil CO_2 emission flux and cumulative emissions relative to T2, and can also better maintain the state of soil CH_4 absorption. From the perspective of carbon sequestration and emission reduction, T2 may be a more suitable mulching cultivation method for flue-cured tobacco planting in Kaiyang County.

Acknowledgments

This work was supported through financial support from the National Natural Science Foundation of China (Grant Nos. 42167067, 42263007, and 52260018), the Department of Education of Guizhou Province (No. QianJiaoJi [2023] 034), the Scientific Research Fund of Guizhou Minzu University (GZMUZK [2023] CXTD03), the Key Program for Science and Technology of CNTC (Nos. 110202202030 and 110202402016), and the Science and Technology Project of Guiyang Branch of Guizhou Tobacco Company (No. Qianyanzhuke [2023] 4).

Conflict of Interest

The authors declare no conflict of interest.

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