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Intercropping Peanut under Forests Can Reduce Soil N_2O Emissions in Karst Desertification Control

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Abstract: In the process of vegetation restoration for karst desertification management, the lack of scientific and rational intercropping technology and the blind application of large amounts of nitrogen fertilizer have made the soil the main source of atmospheric N_2O in this region. How soil N_2O emissions vary under different intercropping modes is a scientific question worthy of study. This study took a three-year-old loquat (*Eribotrya japonica* L.) artificial forest in the karst plateau canyon as the experimental site and designed loquat intercropping with peanut, corn, and sweet potato (*Ipomoeabatatas* (L.) Lam.) as well as non-intercropping to analyze the differences in soil physicochemical properties and greenhouse gas emissions under different intercropping patterns. The results showed that intercropping with peanut significantly increased loquat yield, soil moisture, temperature, SOC, MBC, TN, and MBN content. The emissions of N_2O and CO_2were mainly positively correlated with soil moisture and temperature, while CH_4 showed a negative correlation with soil moisture and soil temperature. The soil absorbed CH_4 in the control of karst desertification. Karst area soils exhibited higher N_2O emissions. Intercropping patterns significantly influenced soil N_2O emissions, with N_2O-N cumulative emissions ranging from 5.28 to 8.13 $kg \cdot hm^{-2}$ under different intercropping conditions. The lowest N_2O-N cumulative emissions were observed for peanut intercropped under the forest. The peak N_2O emission occurred in April 2022, which may be attributed to the higher rainfall and soil moisture during that month. Intercropping peanut with loquat significantly reduced the global warming potential. Therefore, intercropping peanut in young forests can improve soil water and fertilizer conditions, reduce soil N_2O emissions and global warming potential, and serve as a nitrogen fixation and emission reduction technique suitable for karst desertification areas.

Keywords: karst desertification control; loquat; vegetation restoration; intercropping peanut; N_2O emission

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1. Introduction

The continuous increase in greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4), is a major driving factor for global climate change [1]. Although the emissions of CH_4 and N_2O are much lower than those of CO_2, their global warming potential (GWP) is 25 times and 298 times greater than CO_2, respectively (over a 100-year horizon) [2]. Nitrous oxide (N_2O) is one of the main greenhouse gases, which can participate in photochemical reactions in the atmosphere to destroy the ozone layer in the stratosphere, thereby exacerbating the greenhouse effect [3]. N_2O has a long residence time in the atmosphere, and its continuous increase in concentration will further contribute to the greenhouse effect. Soil is the main source of N_2O emissions [4], and denitrification is the main process of N_2O production [5,6]. The main reason for this is the unreasonable use of synthetic fertilizers in agricultural production [7,8], especially in the karst areas of southern China centered around the Guizhou Plateau, where the soil is thin and the ecosystem is fragile [9,10]. In order to increase yields, farmers blindly apply a large amount of nitrogen fertilizer, increasing the mineral nitrogen content in the soil nitrogen transformation process [11,12], causing the soil to become one of the main sources of atmospheric N_2O production in the karst area. Therefore, changes in N_2O concentration will have a significant impact on future climate change. Reducing or controlling N_2O emissions to improve the ecological environment and mitigate global change is of great significance.

Loquat (*Eriobotrya japonica* L.) is a subtropical evergreen fruit tree with rich nutrition and high economic value. Loquat has the characteristics of drought resistance, barrenness resistance, and wide adaptability, and it plays an important role in the control of karst desertification. By planting loquat in this area, the vegetation in the rocky desertification area can be effectively restored, and it has become an important source of income for local farmers [13,14]. However, during the vegetation restoration process, due to the lack of scientific and reasonable intercropping patterns, most farmers are accustomed to intercropping with crops such as corn and sweet potato (*Ipomoeabatatas* (L.) Lam.) and using a large amount of chemical fertilizers, which not only restrict the growth of loquat but also increase greenhouse gas emissions. Therefore, selecting suitable intercropping crops is of great significance for increasing farmers' income and promoting sustainable environmental development.

Afforestation is a major and long-term control method in karst desertification but does not meet the income needs of farmers for life within a year. Intercropping peanut under forests provides a good idea for a solution to this problem. Peanut (*Arachishypogaea* L.) is an important oil and economic crop worldwide, with China having the highest total peanut production in the world. It is one of the main export agricultural products and plays an important role in national economic development and food security. Due to its characteristics of dwarf stature, nitrogen fixation, low input, and high output, it has gradually become an ideal pioneer crop for intercropping with young tea gardens, orchards, medicinal gardens, and other economic forests [15–18]. Especially in karst areas, intercropping peanut under forests can not only increase the income of farmers in remote and poor areas and prevent water and soil loss on rocky desertification farmland but also effectively alleviate the conflict between food and oil land, playing an important role in ensuring China's food and oil security. Research has found that under conditions of no or low nitrogen application, the selection of crop varieties (such as peanut) can slow down global warming [19], and the N_2O emissions from peanut soil are significantly lower than those from nitrogen-fixing tree species [20]. Therefore, can intercropping loquat with peanut reduce greenhouse gas emissions in vegetation restoration and karst desertification control?

To this end, this study selected a loquat (*Eribotrya japonica* L.) site that had undergone karst canyon desertification control and restoration for three years as the experimental site and conducted intercropping patterns of loquat with peanut, corn, sweet potato, and other crops to study changes in soil temperature, moisture content, and greenhouse gas emission flux under different intercropping patterns. This study focused on analyzing changes in warming potential under different intercropping patterns to clarify the soil water–nutrient–gas cycle characteristics of the vegetation restoration system in ecologically fragile areas of karst desertification, and to provide technological support for the sustainable restoration of vegetation in karst desertification control areas.

2. Materials and Methods

2.1. Overview of the Experimental Site

The experiment was conducted in Guanling County, Anshun City, Guizhou Province, China, which represents the karst landscape of southern China. The site is located in Bangui Township, Huajiang Town, with coordinates of 25°41′33″ N and 105°37′32″ E. The area belongs to the medium- to high-intensity karst canyon desertification zone, with high rock exposure, scarce soil resources, rare surface runoff, and severe human–land conflicts. In order to control desertification, loquat, Sichuan pepper, dragon fruit, honeysuckle, and other crops have been widely promoted for planting. Currently, loquat has become one of the dominant industries in the area. This experiment selected a loquat forest as the sample site for the restoration of karst desertification for three years. The soil is mainly yellow soil and yellow calcareous soil. The organic matter content in the 0–20 cm soil layer was 42.80 ± 1.25 g·kg^{-1}, the total nitrogen content was 2.61 ± 0.13 g·kg^{-1}, the total phosphorus content was 1.32 ± 0.22 g·kg^{-1}, the bulk density was 1.24 ± 0.10 g·cm^{-3}, and the pH was 7.64 ± 0.16. The average height of the loquat trees was 1.57 ± 0.12 m, the crown width was 1.52 ± 0.14 m (east–west) × 1.60 ± 0.17 m (north–south), and the ground diameter was 4.81 ± 0.37 cm.

2.2. Experimental Materials

The loquat variety used was "Wuxing Loquat", the peanut variety was Qian Peanut 1 (primarily harvested for its pods), and the sweet potato and corn were both local varieties (corn variety: Guanling White Corn, sweet potato variety: Bangui Red Heart Sweet Potato).

2.3. Experimental Design

The experiment was conducted in a loquat orchard planted in January 2018. Loquat trees with similar growth were selected, with a planting density of 830 trees per hectare, a row spacing of 4 m, and a plant spacing of 3 m. The experiment was conducted from February 2021 to May 2022, with four intercropping modes: intercropping with peanut (IP), intercropping with corn (IC), intercropping with sweet potato (IS), and no intercropping (SC) in the understory. Each plot had an area of 10 m × 10 m and was repeated four times, for a total of 16 plots. Among them, the distance between peanut, corn, and sweet potato and the loquat tree trunk was 0.80 m, and the planting row spacing for peanut, corn, and sweet potato was 0.40 m, with a plant spacing of 0.2 m. The field management was consistent during the experiment in each plot. Local commonly used compound fertilizer ($N:P_2O_5:K_2O = 15:15:15$) was applied with a total amount of 337.5 kg·hm^{-2}, divided into two applications. The first application was carried out on 18 March 2021, with a dosage of 225.0 kg·hm^{-2}. Half of the fertilizer was evenly spread and incorporated into the soil in the interspace of the loquat trees using a hoe. The other half was applied by digging a 20 cm deep circular trench 40 cm away from the loquat tree trunk, and the fertilizer was evenly spread inside the trench, followed by backfilling. On 21 March 2021, intercropping of peanut, corn, and sweet potato was carried out, and after sowing, gas collectors were placed in the experimental field for gas emission collection. The second application was performed on 4 March 2022, using a fertilizer amount of 112.5 kg·hm^{-2}. A 20 cm deep circular trench was dug 50 cm away from the loquat tree trunk, and the fertilizer was evenly applied into the trench. Due to the absence of pest and disease infestation during the experimental period, no pesticides were used. The air temperature and rainfall were monitored by a small weather station during the experiment (Figure 1).

2.4. Soil Sample Collection and Analysis

Soil samples were collected using the "S" type 5-point sampling method at 0–20 cm soil depth in February, May, July, and October 2021 and January and April 2022 (if it rained, samples were collected 2 weeks after the rain). The samples were mixed and placed in aluminum boxes and brought back to the laboratory. After drying in an oven, the soil moisture content was measured. At the same time, a soil thermometer was used to measure the temperature of the 5 cm soil layer at 10 am. The formula for calculating soil moisture content is:

$$\text{Soil moisture content} = (\text{wet soil weight} - \text{dry soil weight})/\text{dry soil weight} \times 100\%. \quad (1)$$

The loquat yield was measured in May 2021 and April 2022 (during the loquat harvesting period). As there was no significant difference in loquat yield under different intercropping modes in 2021, 2022 yield data were used for analysis. Soil samples were collected in October 2021 (after the harvest of peanuts, corn, and sweet potatoes) and May 2022 (after the loquat harvest) using a soil corer (50 mm inner diameter), according to the "S" curve sampling method at five points in the topsoil layer (0–20 cm). The collected soil was sieved to remove stones, debris, and roots; mixed; and then divided into two parts, one for nutrient analysis and the other, which was placed in a foam box at low temperature (4 °C), for soil microbial biomass carbon (MBC) and nitrogen (MBN) analysis in the laboratory.

After natural drying in the laboratory, the soil was ground using a ball mill and sieved using 0.15 mm and 2 mm screens. The soil organic carbon (SOC), total nitrogen (TN), and alkaline nitrogen (AN) content were determined using the "Soil Agricultural Chemistry Analysis" method set out by Bao [21]. The SOC content was determined using the high-temperature external heating potassium dichromate oxidation capacity method. The total nitrogen content of the soil was determined by digesting with H_2SO_4-$HClO_4$ and measuring using an automatic Kjeldahl nitrogen analyzer (Hanon K1160, Shandong, China). The alkaline nitrogen content of the soil was determined using the alkaline diffusion method. The determination of soil MBC and MBN content was performed by the chloroform fumigation–extraction method [22,23].

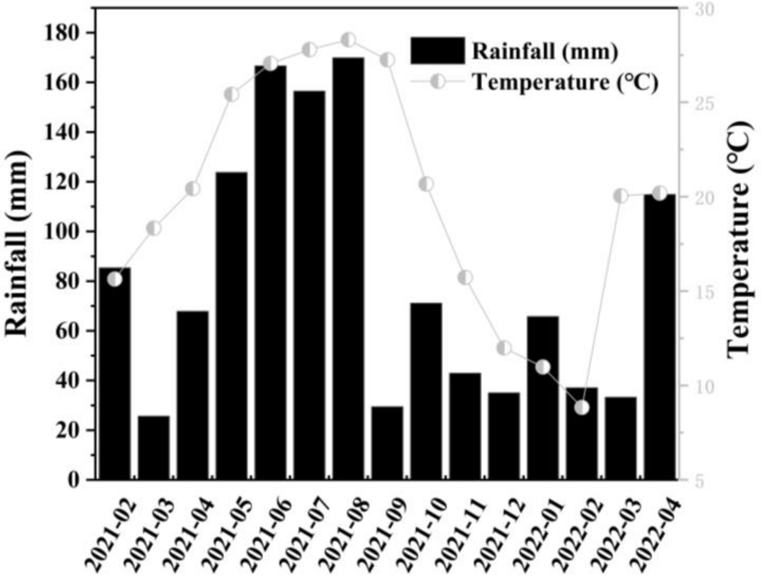

Figure 1. Monthly average rainfall and air temperature during the experiment.

2.5. Gas Collection and Analysis

Gas collection time was consistent with soil moisture collection time. The static box method was used for sampling, and the sampling box was made of acrylic material (20 cm long, 20 cm wide, and 30 cm high), with a three-way valve installed on the top for gas sampling. There was a small fan on the top of the box to mix the gas inside the box. The bottom of the sampling box was inserted into the soil between two loquat trees (10 cm), and the box was fastened to the groove on the base (sealed with water). During the sampling period, there were no crops or weeds in the box, which can represent the soil surface condition of the loquat orchard. Sampling was conducted from 9:00 to 11:00 on each sampling day. After the sampling box was fastened, the switch valve on the top of the sampling box was opened at 0, 15, 30, and 45 min, and 35 mL of gas was extracted with a 50 mL syringe and injected into a 12 mL headspace bottle that had been pre-evacuated. Each sampling was completed within 1 h. Gas concentration analysis was performed using an Agilent Technologies 7890A GC System (Agilent Technologies, Inc., Wilmington, DE, USA), and the CO_2, N_2O, and CH_4 gas emission fluxes were calculated according to the following formula [24]:

$$\mathrm{F} = \frac{\mathrm{M}}{22.4} \times \frac{273}{273 + \mathrm{T}} \times \mathrm{H} \times \frac{\mathrm{dc}}{\mathrm{dt}} \times 60$$

In the formula, F is the emission flux of CO_2, CH_4, and N_2O (the CO_2 unit is $mg \cdot m^{-2} \cdot h^{-1}$; CH_4 and N_2O units are $\mu g \cdot m^{-2} \cdot h^{-1}$); 60 is the conversion factor; H is the effective height of the sampling box (m); M is the molar mass of the gas; T is the temperature inside the sampling box (°C); and dc/dt is the slope of the regression curve of gas concentration and time.

The formula for calculating the cumulative greenhouse gas emissions is

$$G = \sum_{i=1}^{n} \frac{F_i + F_{i+1}}{2} \times (d_{i+1} - d_i) \times 24$$

In the formula, G is the total greenhouse gas emissions (kg/hm^2); F is the gas emission flux at the i-th sampling; d is the number of days between adjacent samplings; and n is the number of determinations.

As the CO_2 gas in the experiment is not a net emission, the global warming potential (GWP) is calculated based on a 100-year time scale. The warming effects per unit mass of CH_4 and N_2O are 25 and 298 times that of CO_2, respectively. The global warming potential values of soil CH_4 and N_2O fluxes are calculated using the following formula [2]:

$$GWP(kg\ CO_2\text{-}eq \cdot hm^{-2}) = 25 \times G(CH_4) + 298 \times G(N_2O)$$

GWP is the global warming potential ($kg \cdot hm^{-2}$); $G(CH_4)$ and $G(N_2O)$ are the cumulative emissions of CH_4 and N_2O, respectively ($kg \cdot hm^{-2}$).

2.6. Data Analysis

The experimental data were analyzed and processed using Excel 2016 and SPSS 13.0 software. Before conducting the statistical analysis, the normality of the dataset was evaluated, and a log10 transformation was performed if necessary to improve normality. One-way ANOVA was used to analyze the significance of soil moisture, soil greenhouse gas emissions, soil nutrient content, loquat yield, and economic benefits under different intercropping patterns at the same sampling time. Multiple comparisons between sampling months/years and intercropping patterns were conducted using the least significant difference (LSD) method. Pearson correlation analysis was used for correlation analysis. OriginPro 2021 (Originlab Lab, Northampton, MA, USA) was used for plotting.

3. Results

3.1. Seasonal Variation of Soil Moisture and Temperature under Different Intercropping Patterns

Soil moisture and soil water storage showed similar trends (Figure 2a,c). Intercropping patterns and sampling time significantly influenced soil moisture and water storage ($p < 0.001$) (Figure 2a). Throughout the experimental period, the average soil moisture content was highest in the IP treatment, followed by IC, IS, and SC, and IP was significantly higher than IS and SC ($p < 0.05$). The average water storage followed the order IP > IS > IC > SC (Figure 2d), with IP significantly higher than SC ($p < 0.05$). In October 2021, the soil moisture content and water storage were the lowest for all treatments, but IP significantly surpassed the other intercropping patterns. Compared to IC, IS, and SC, IP had 37.45%, 22.97%, and 42.40% higher soil moisture content, and 41.89%, 23.16%, and 47.95% higher water storage, respectively. This indicates that intercropping with peanut in the understory has a certain water conservation effect.

Soil temperature was significantly influenced by different sampling times ($p < 0.001$) (Figure 2b). The lowest soil temperature was recorded in January 2022, consistent with the trend of air temperature (Figure 2b), but there were no significant differences among the intercropping patterns.

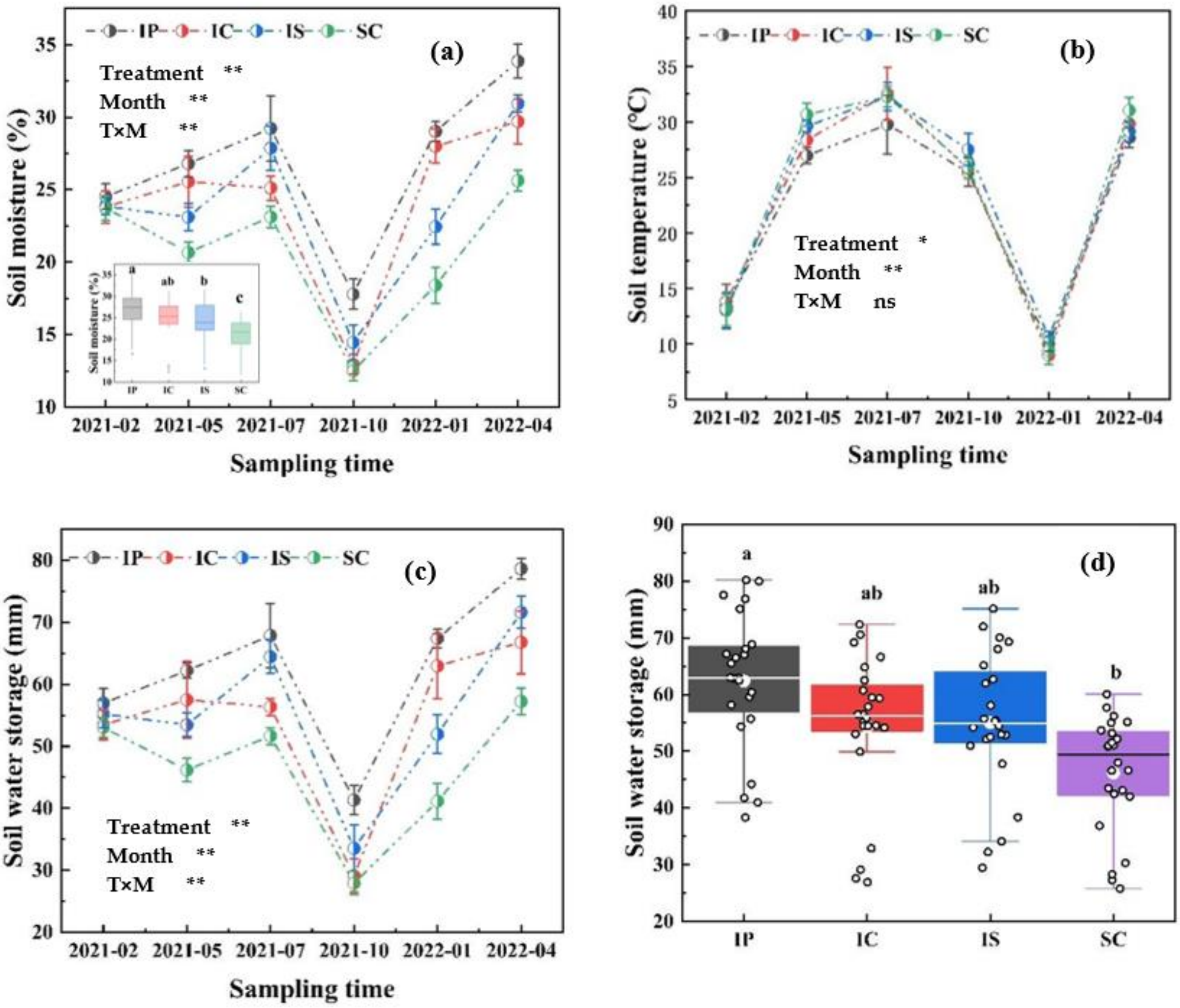

Figure 2. The seasonal variation of soil moisture (**a**), temperature (**b**), water storage (**c**), and average water storage (**d**) under different intercropping patterns of loquat with peanut (IP), corn (IC), sweet potato (IS), and no intercropping (SC). Error bars represent standard deviation ($n = 4$). * $p < 0.05$; ** $p < 0.01$; ns, not significant. Different lowercase letters indicate significant differences among different intercropping modes ($p < 0.05$). The same applies to the following.

3.2. Analysis of Soil Greenhouse Gas Emission Flux, Cumulative Emissions, and Their Global Warming Potential

The soil CO_2 emission flux exhibited significant seasonal dynamics ($p < 0.001$) (Figure 3a), and the intercropping pattern had a significant effect on it. Except for IC, the CO_2 emission flux gradually increased from February to July 2021 (Figure 3a) and then decreased, with the lowest emission in January 2022. The cumulative emissions were highest in SC, significantly higher than IP, IC, and IS ($p < 0.05$).

The intercropping pattern had a significant effect on the soil CH_4 emission flux ($p < 0.001$) (Figure 3b) and exhibited significant seasonal dynamics. The soil CH_4 emission flux showed a fluctuating trend during the experiment. The cumulative emissions of CH_4 were highest in SC (Figure 3d), followed by IS, significantly higher than IP and IC ($p < 0.05$). Overall, the cumulative CH_4 emission exhibited negative values, indicating that the soil had a certain absorption capacity for CH_4 during plant growth, and IP and IC had relatively high absorption rates, at 11.02 kg·hm^{-2} and 11.40 kg·hm^{-2}, respectively.

The soil N_2O emission flux exhibited significant seasonal dynamics ($p < 0.001$) (Figure 3c), and different intercropping patterns had a significant effect on it ($p < 0.001$). Except for IS in July 2021, which was significantly lower than other treatments, IP had the lowest emission flux in other seasons. The highest N_2O emission flux among the same intercropping systems occurred in April 2022. IP had the lowest cumulative emissions (Figure 3d), with a value of 5.28 $kg{\cdot}hm^{-2}$, followed by IS with a value of 6.02 $kg{\cdot}hm^{-2}$, significantly lower than SC ($p < 0.05$).

The global warming potential of different intercropping systems was ranked as SC > IC > IS > IP, with IP, IC, and IS being 44.76%, 30.29%, and 34.25% lower than SC, respectively, and the differences were significant ($p < 0.05$) (Figure 3d).

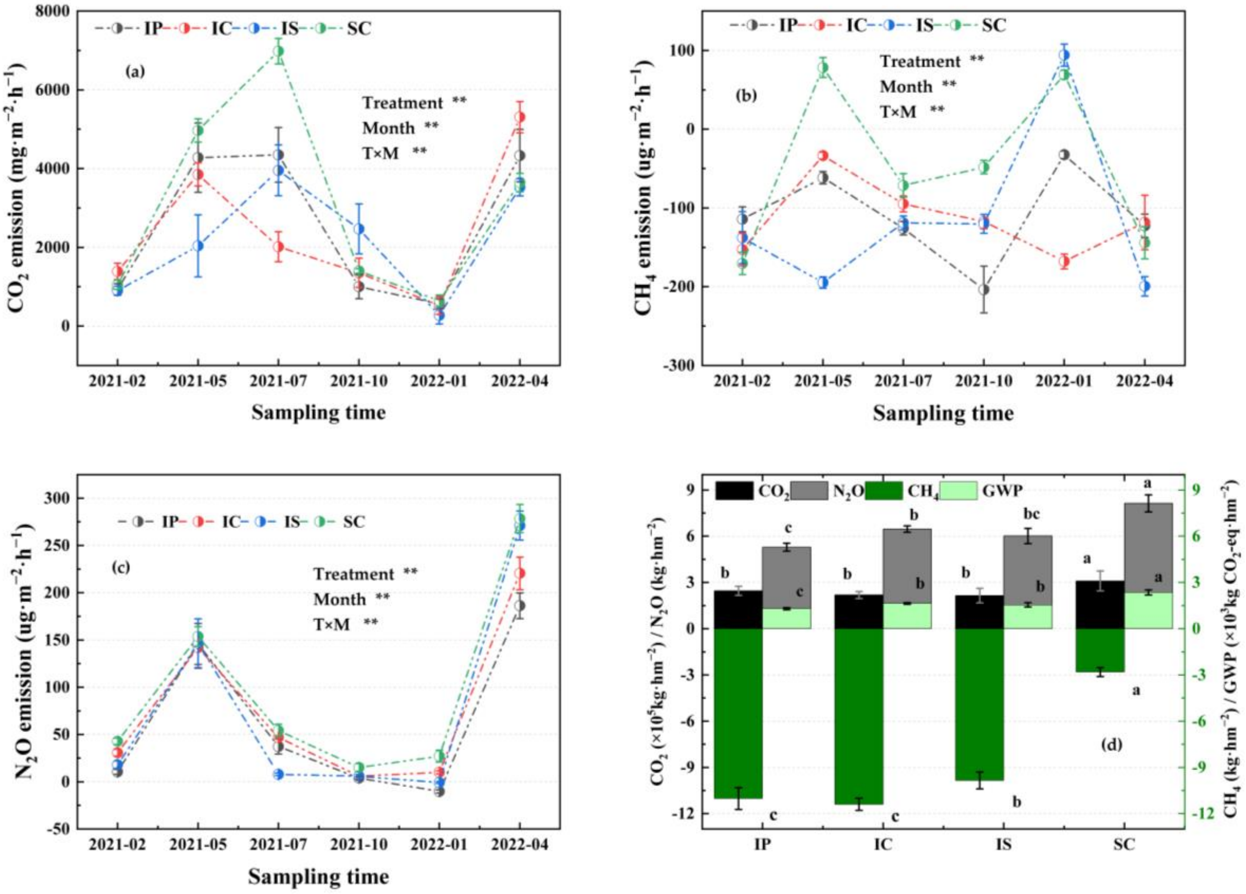

Figure 3. The soil CO_2 emission flux (**a**), soil CH_4 emission flux (**b**), soil N_2O emission flux (**c**), and cumulative emissions and global warming potential (**d**) under different intercropping patterns of loquat with peanut (IP), corn (IC), sweet potato (IS), and no intercropping (SC) ($n = 4$). ** $p < 0.01$; Different lowercase letters indicate significant differences among different intercropping modes ($p < 0.05$).

3.3. Analysis of Soil C and N Content

Soil SOC, TN, AN, MBC, and MBN content showed significant differences among different years and intercropping patterns ($p < 0.001$) (Figure 4). The trends of SOC under different intercropping treatments were basically consistent in 2021 and 2022 (Figure 4a). It showed that IP > IC > IS > SC, and IP was significantly higher than IS and SC ($p < 0.05$). Soil TN content in 2021 showed that IP > IS > IC > SC (Figure 4b), and IP was significantly higher than IC and SC ($p < 0.05$); in 2022, it showed that IS > IP > IC > SC, and IS, IP, and IC were all significantly higher than SC ($p < 0.05$). Soil AN content in 2021 showed that IP > IC > IS > SC (Figure 4c), and IP and IC were significantly higher than IS and SC ($p < 0.05$); in 2022, it showed that IP > IS > SC > IC, but the difference was not significant ($p > 0.05$).

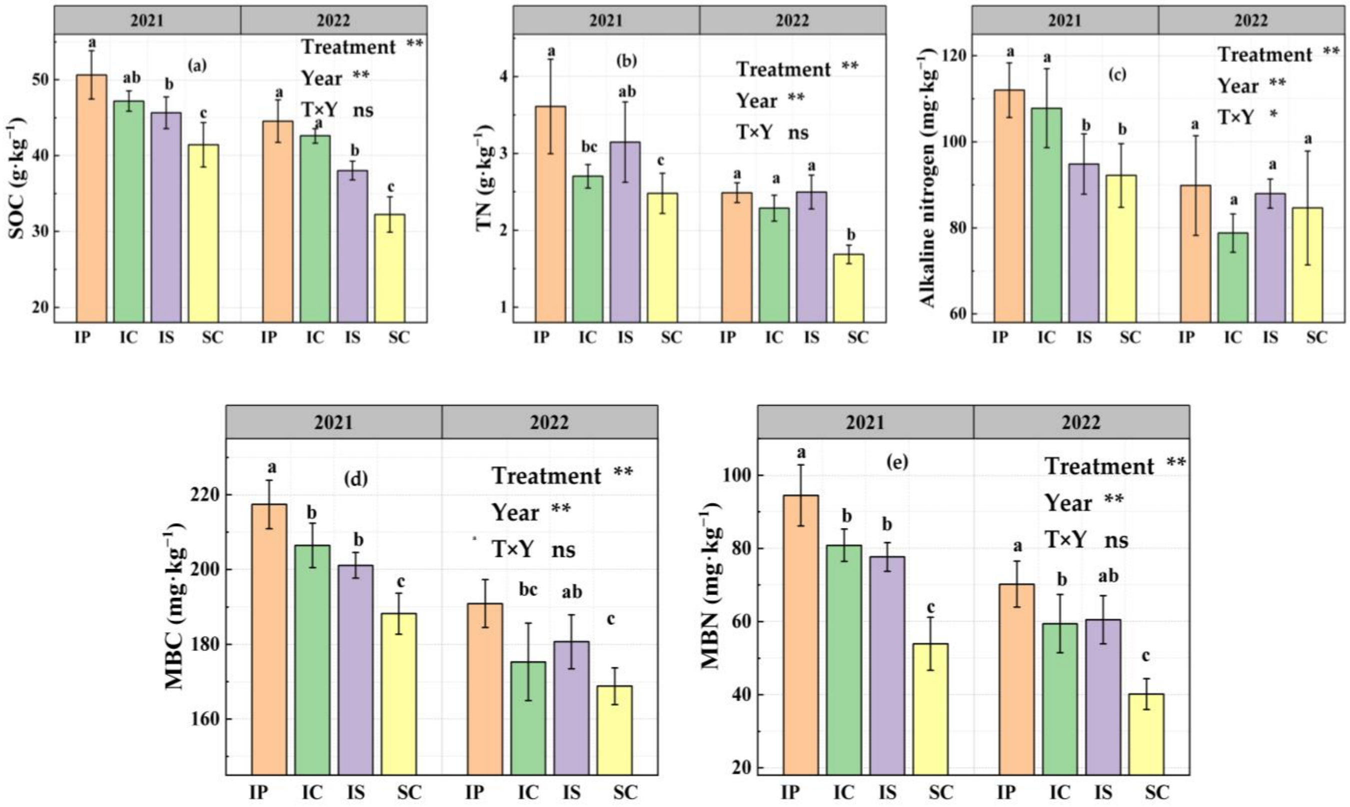

Figure 4. The soil organic carbon (SOC) (**a**), total nitrogen (TN) (**b**), alkaline nitrogen (AN) (**c**), soil microbial biomass carbon (MBC) (**d**), and soil microbial biomass nitrogen (MBN) (**e**) content of intercropped peanut (IP), intercropped corn (IC), intercropped sweet potato (IS), and non-intercropped (SC) in four replicates ($n = 4$). * $p < 0.05$; ** $p < 0.01$; ns, not significant. Different lowercase letters indicate significant differences among different intercropping modes ($p < 0.05$).

The trends in soil MBC and MBN contents were similar among different intercropping modes (Figure 4d,e). In 2021, both MBC and MBN showed the order of IP > IC > IS > SC, and in 2022 the order was IP > IS > IC > SC, with IP significantly higher than IC and SC ($p < 0.05$).

3.4. Yield and Economic Benefit Analysis

The yield and economic benefit analysis results for different intercropping modes are shown in Table 1. Loquat yield showed that IP > IS > IC > SC, and IP and IS were significantly higher than IC and SC ($p < 0.05$). IP had the highest total input cost, valued at 13,485 CNY·hm^{-2}, followed by IS at 13,275 CNY·hm^{-2}. The total output value and net profit of different intercropping modes exhibited consistent trends. The highest net profit was observed in the IP treatment, valued at 40,419.8 CNY·hm^{-2}, followed by IS at 35,473.4 CNY·hm^{-2}. In comparison to the non-intercropping mode (SC: 20,917.5 CNY·hm^{-2}), IP and IS demonstrated net profit increases of 93.2% and 69.6%, respectively, with significant differences ($p < 0.05$). The intercropping mode with the highest output–input ratio was IP (4.00), significantly higher than SC ($p < 0.05$).

3.5. Correlation Analysis

The soil temperature and soil moisture had a significantly positive correlation with CO_2 emissions and N_2O emissions ($p < 0.01$) (Figure 5a), while the CH_4 emissions showed a significant negative correlation with soil moisture ($p < 0.05$). There was a positive correlation between loquat yield and soil C and N content (Figure 5b) and a negative correlation with cumulative emissions of soil CO_2, CH_4, N_2O, and GWP. SOC, TN, MBC, and MBN content showed a highly significant negative correlation with cumulative emissions of soil CH_4, N_2O, and GWP ($p < 0.01$).

Table 1. Yield and economic benefit analysis under different intercropping modes (mean ± SD).

Treatment	Loquat Yield ($kg \cdot hm^{-2}$)	Yield of Intercropped Crops ($kg \cdot hm^{-2}$)	Total Investment ($CNY \cdot hm^{-2}$)	Total Output Value ($CNY \cdot hm^{-2}$)	Net Profit ($CNY \cdot hm^{-2}$)	Output–Input Ratio
IP	9124.5 ± 845.6 a	920.3 ± 101.7	13,485	53,904.8 ± 4345.6 a	40,419.8 a	4.00 ± 0.32 a
IC	6833.1 ± 798.6 b	3511.6 ± 230.1	13,125	42,944.3 ± 3758.1 b	29,819.3 b	3.27 ± 0.29 ab
IS	8056.1 ± 752.1 a	5292.3 ± 401.7	13,275	48,748.4 ± 4375.6 ab	35,473.4 ab	3.67 ± 0.33 ab
SC	5758.5 ± 638.2 b		7875	28,792.5 ± 3190.8 c	20,917.5 c	3.66 ± 0.41 b

Note: IP, IC, IS, and SC, respectively, represent intercropping of peanut with loquat, intercropping of corn, intercropping of sweet potato, and no intercropping. Peanut yield was calculated based on dry weight of pods, corn yield was calculated based on dry weight of grains, and sweet potato and loquat yield were calculated based on fresh weight; total output value was calculated based on the local minimum prices, where the price of peanuts was 9.0 $CNY \cdot kg^{-1}$, loquat was 5.0 $CNY \cdot kg^{-1}$, corn was 2.5 $CNY \cdot kg^{-1}$,and sweet potato was 1.6 $CNY \cdot kg^{-1}$. Different lowercase letters within the same column indicate significant differences between different intercropping modes ($p < 0.05$).

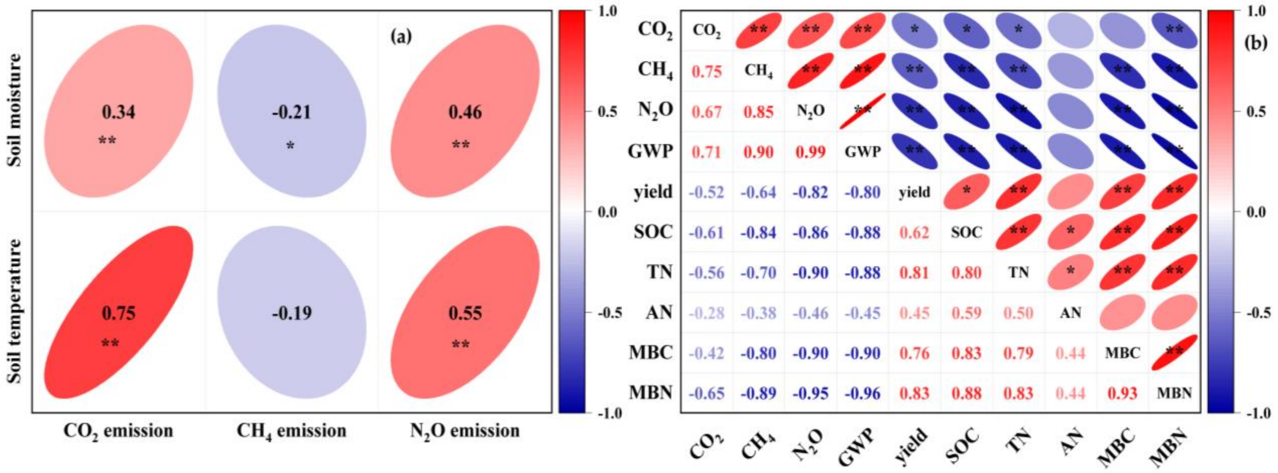

Figure 5. Correlation analysis of soil temperature, soil moisture content, and greenhouse gas emission flux (**a**), and the correlation analysis between loquat yield and soil C and N content, greenhouse gas cumulative emission, and warming potential (**b**). * The correlation is significant at the 0.05 level; ** significant at the 0.01 level.

4. Discussion

4.1. Intercropping Peanut Improved Loquat Yield and Soil Water and Fertilizer Environment in the Karst Plateau Canyon Desertification Control

Due to the high land and thermal resource utilization efficiency of intercropping systems [25], the area of intercropping peanuts with other crops has been increasing [26]. There are many factors that affect crop yield, and different intercropping treatments showed that IP and IS were significantly higher than IC and SC in loquat yield ($p < 0.05$) (Table 1). The IP treatment had the highest total output value, net profit, and output–input ratio, followed by the IS treatment, and these were both significantly higher than the IC and SC treatments ($p < 0.05$). This indicates that intercropping with dwarf nitrogen-fixing crops can promote loquat growth and yield formation, improve economic benefits, and achieve the purpose of promoting management through planting. Although intercropping with sweet potato can also achieve higher economic benefits, the nutrient requirements are high, making it unsuitable for intercropping in the poor and barren soil of karst desertification. There was a positive correlation between loquat yield and soil C and N content (Figure 5b). This indicates that soil C and N play an important role in crop growth, which is consistent with previous research results [27].

Some studies have shown that reasonable intercropping of leguminous crops can reduce soil erosion, reduce nitrogen loss, and increase soil organic matter and nitrogen content [28,29]. In this study, the average soil moisture content, soil water storage, SOC, TN, MBC, and MBN content of loquat intercropped with peanut were significantly higher than those of the non-intercropped plots ($p < 0.05$). Especially in October 2021, which experienced a long period of drought, the soil moisture content and water storage of loquat intercropped with peanut were significantly higher than the non-intercropping treatment (Figure 2a,c) ($p < 0.05$). This is consistent with previous studies on intercropping peanut in walnut forests [30]. This indicates that intercropping dwarf and nitrogen-fixing crops (peanut) can effectively improve soil water and fertilizer conditions in vegetation restoration of karst desertification control.

4.2. Intercropping Peanut with Young Loquat Forests Reduces N_2O Emissions

In agricultural production, there have been many reports on reducing soil N_2O emissions. Agronomic measures such as applying biochar [4,31,32], nitrification inhibitors [33], and slow-release fertilizers [34,35] and using optimized tillage methods [36] can reduce N_2O emissions. Previous studies have shown that reasonable intercropping and crop rotation with peanut can offset some of the external nitrogen input, increase crop nitrogen uptake, and reduce soil N_2O emissions [37–40], thereby ensuring the sustainability of the agricultural environment [41,42]. In this study, intercropping peanut with loquat significantly reduced the cumulative emissions of soil N_2O, CO_2, and CH_4 ($p < 0.05$) (Figure 3d). Among them, soil N_2O had the lowest cumulative emissions (Figure 3d), possibly because rhizobium is a diverse group of soil bacteria that can form symbiotic nitrogen-fixing associations with leguminous plants such as peanut, and many of these rhizobia can also perform denitrification [43]. Under anaerobic conditions, denitrifying microorganisms in the surrounding soil, including rhizobia cells released from decomposing nodules, can convert NO_3^- or NO_2^- to nitrogen gas [44,45], effectively reducing N_2O emissions [45–48]. The highest N_2O emissions under the same intercropping pattern were in April 2022 (Figure 3c). This may be related to the significantly positive correlation between soil N_2O emissions and soil temperature and moisture content (Figure 5a), and previous studies have shown that water management significantly affects soil N_2O emissions [49]. Therefore, this may be related to the higher rainfall (Figure 1), soil moisture content (Figure 2a), and soil temperature (Figure 2b) in April 2022.Furthermore, this study indicated that in July 2021, the N_2O emissions from the IS treatment were significantly lower than the other treatments, which may be due to the higher nitrogen consumption during the starch bulking period of sweet potatoes, resulting in lower N_2O emissions.

In addition, soil C and N content have a certain impact on soil greenhouse gas emissions. Previous studies [50–52] have shown that adding N reduces forest soil CO_2 and CH_4 emissions while increasing N_2O emissions; furthermore, increasing C reduces N_2O emissions. The cumulative CH_4 emissions in this study were negative, indicating that the soil has a certain absorption capacity for CH_4 during plant growth, especially in the IP and IC treatments, where the absorption was higher, which may be related to the higher availability of nitrogen in the soil under this intercropping pattern. In this study, it was found that SOC, TN, MBC, and MBN content showed a highly significant negative correlation with the cumulative emissions of soil CH_4, N_2O, and GWP ($p < 0.01$) (Figure 5b). This is different from the results of previous studies [51,52]. This may be related to the fact that the study area belongs to a severe karst desertification environment, with thin soil layers, high soil erosion, and long-term soil moisture deficiency (Figure 2a).

5. Conclusions

From the perspective of loquat yield and comprehensive economic benefits in the vegetation restoration of karst desertification, intercropping with peanut was a more suitable intercropping pattern, followed by intercropping with sweet potato. Understory intercropping of peanut improved soil moisture, water storage, soil carbon, and nitrogen content. Karst area soils exhibited higher N_2O emissions, but intercropping with peanut effectively reduced soil N_2O emissions. The lowest cumulative N_2O-N emissions and global warming potential were observed when peanuts were intercropped under the forest. N_2O emissions primarily occurred in April and May, and the emission levels were strongly positively correlated with soil moisture and temperature. Additionally, the soils in karst desertification control demonstrated a certain capacity for CH_4 absorption.

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Data Availability Statement: All data supporting the results of this study are included in the manuscript, and data sets are available upon request.

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