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Original Research

Effects of Different Water Management Practices on Soil Organic Carbon and Carbon Dioxide in Plateau Paddy Fields

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Abstract

To investigate the effects of water management on soil organic carbon (SOC) dynamics and carbon dioxide (CO_2) emissions in highaltitude paddy fields, this study established four water treatments in the Dali Erhai Basin: conventional flooding (W1), controlled irrigation (W2), controlled irrigation combined with 1/3H return flooding (W3), and controlled irrigation combined with 1/4H return flooding (W4), and systematically analyzed the changes in SOC content and CO_2 emission characteristics under different water management regimes. The results showed that different water management practices significantly affected SOC dynamics and CO_2 emission characteristics. The controlled irrigation combined with return flooding treatments maintained relatively high SOC content during the early and midtolate growth stages, especially in the 10-20 cm soil layer; SOC content decreased after drainage at the yellow ripening stage, but the W4 treatment showed the largest increase in deeplayer SOC at harvest (7.44% relative to pretransplant) and also had the highest average SOC content over the entire growth period. Although controlled irrigation (W2) favored shortterm accumulation of SOC in deeper layers, it was detrimental to the longterm stability of the surface carbon pool, and it resulted in the highest soil CO_2 emission flux due to frequent drying–rewetting cycles. The W3 and W4 treatments significantly reduced soil CO_2 emissions, with W4 having the lowest average soil CO_2 flux (80 $mg \cdot m^{-2} \cdot h^{-1}$). Although the W3 treatment had the highest total CO_2 emissions due to vigorous plant growth, W4 achieved higher deeplayer carbon sequestration and lower soil CO_2 emissions while maintaining moderate total emissions (lower than W3). Based on comprehensive evaluation of SOC accumulation, profile distribution, and CO_2 emissions, W4 was identified as the water management regime with the best overall performance. This study provides a theoretical basis for optimizing water management strategies in highaltitude paddy fields and achieving synergistic effects between carbon sequestration and emission reduction.

Keywords: water management, field rice, soil organic carbon, carbon dioxide

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Introduction

Soil organic carbon (SOC) reflects soil health and fertility, and its variations affect productivity, carbon sequestration capability, and greenhouse gas emissions [1]. Global agriculture contributes approximately 10-12% of anthropogenic greenhouse gases, and improper irrigation can accelerate SOC decomposition, releasing CO_2 [2]. Due to the lower temperatures and reduced oxygen partial pressures in plateau regions, the processes of SOC decomposition and greenhouse gas generation differ from those in low-altitude areas, making highland paddy fields an ideal setting to investigate the effects of water management on carbon cycling. Moreover, climate change has heightened agricultural risks, as frequent extreme weather events and water shortages challenge traditional rice cultivation [3]. It is projected that global rice production may decline by 15-20% by 2050 owing to climate change, with inadequate water management being a primary risk factor [4]. To counter this situation, sustainable agricultural practices – such as alternate wetting and drying – are being actively explored worldwide; these measures not only help maintain or boost yields but also reduce greenhouse gas emissions and enhance the soil's carbon sequestration function [5, 6]. However, the effects of various water management regimes on soil organic carbon stability and greenhouse gas emissions still require systematic evaluation [7].

Water management directly affects the carbon cycle and greenhouse gas emissions of paddy field ecosystems by altering the soil's physicochemical environment and microbial metabolic processes, making it a key regulatory factor for achieving sustainable agricultural development [8]. Numerous studies have confirmed that water management is a critical driver of greenhouse gas emissions from paddy fields. Soil moisture regulates the decomposition pathways and rates of organic matter by modulating redox potential, microbial community structure, and activity, thereby determining the balance between the production and consumption of greenhouse gases such as CO_2. Building on this theory, water-saving irrigation practices, exemplified by alternate wetting and drying (AWD), have been extensively studied in major rice-growing regions across Asia. However, most existing research primarily focuses on the mitigation effects of AWD on CH_4 and N_2O emissions, with insufficient attention paid to its impact on the dynamics of the soil organic carbon pool and its complex coupling with CO_2 emissions. On the one hand, while AWD effectively conserves water and reduces CH_4 emissions, its frequent wetting and drying cycles may stimulate soil microbial activity, accelerating the mineralization of existing soil organic carbon (SOC) and posing potential risks of carbon loss. On the other hand, irrigation practices such as continuous flooding may facilitate the migration and stabilization of organic carbon into deeper soil layers, yet their net effect on CO_2 emissions throughout the crop growth period and the underlying regulatory mechanisms remain unclear. Despite significant progress in the study of water management in paddy fields, research on the unique highland paddy ecosystem is still relatively scarce.

Materials and Methods

Overview of the Experimental Site

The experimental area is located in Gusheng Village, Wanqiao Town, Dali Bai Autonomous Prefecture (100°08'25"E, 25°48'58"N) at an altitude of 1913.6 m, with an onsite atmospheric pressure of 79.92 kPa (Fig. 1). The terrain in this region is predominantly flat, and local agriculture primarily employs a rice-oilseed rotation system, with sandy loam as the dominant soil type. The Erhai Lake Basin, situated in a low-latitude plateau region, exhibits the typical characteristics of a subtropical monsoon climate in low-latitude plateau regions, with mild seasons. The area has an annual mean temperature of 15.7ºC, with maximum temperatures reaching 34ºC and minimum temperatures dropping to –2.3ºC; the annual sunshine duration ranges from 2250 to 2480 hours, and the frost-free period lasts approximately 225 to 345 days. Annual precipitation averages between 1000 and 1200 mm, and although rainfall is abundant, its distribution is notably uneven, with 95% of the total rainfall concentrated from May to October. Over the years, the leaching effects of rainfall through the Cangshan Mountain have resulted in a well-stratified soil structure rich in organic matter. The primary physicochemical properties of the 0-30 cm soil layer are as follows: a bulk density of 1.21 $g \cdot cm^{-3}$, a saturated water content of 50.7%, a pH value of 6.7, and a soil organic carbon content of 37.2 $g \cdot kg^{-1}$.

Experimental Design

The field experiment employed two irrigation methods – conventional flooding irrigation and regulated irrigation – combined with the recharging of upstream dry-land tail water during rainfall periods. In the recharge treatment, the upper limits were set at one-third and one-fourth of the rice plant height (H), thereby establishing four water management regimes: conventional flooding (W1), regulated irrigation (W2), and regulated irrigation combined with recharge (W3 and W4), with the regulated irrigation implemented using a moist irrigation technique. Each treatment was replicated three times (see the water regulation indicators listed in Table 1). The experimental plots were arranged in an alternating pattern of irrigation and drainage channels, and the different treatment groups were isolated using bunds wrapped with plastic film and buried to a depth of 80 cm to prevent water movement between plots.

Before formal planting, sufficient balanced basal fertilizer must be applied, complete tillage performed, and bunds constructed manually along with the application

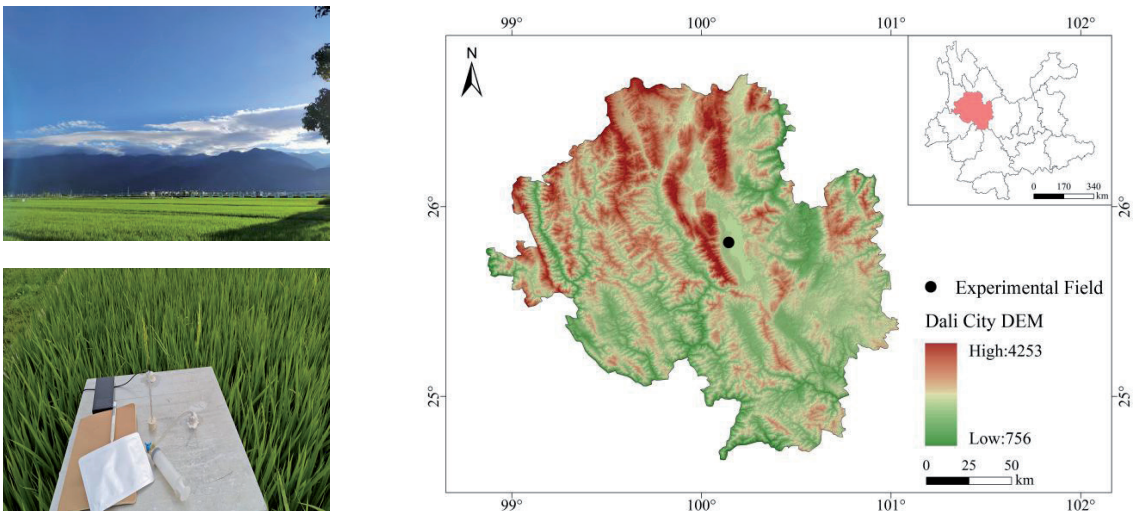


Fig. 1. The location of the experimental site.

of black film to reduce water evaporation and weed growth. Simultaneously, irrigation pipes are arranged in a rational layout to ensure uniform water infiltration. Once all the sub-plots' basic structures and irrigation systems have been tested, the field is soaked for 2 to 3 days according to the predetermined plan to soften the soil, and then mechanically or manually leveled to achieve a level surface. During the cultivation phase, mechanical transplanting is adopted (with a row spacing of 20 cm and a plant spacing of 15 cm), and each sub-plot

Table 1. Water regulation indicators.

Treatment	Water layer control (mm)	Regreening stage	Tillering stage			Jointing-booting stage	Heading and flowering period	Milk stage	Ripening stage
			Initial	Middle	Late				
W1	Upper limit of flooding	25	50	50	50	50	50	50	Natural drying
	Lower limit of flooding	5	100%θs	100%θs	100%θs	100%θs	100%θs	100%θs	
	Drainage upper limit	25	1/4H	1/4H	50	1/4H	1/4H	1/4H	
W2	Upper limit of flooding	25	100%θs	100%θs	100%θs	100%θs	100%θs	100%θs	
	Lower limit of flooding	5	80%θs	70%θs	65%θs	80%θs	85%θs	75%θs	
	Drainage upper limit	25	1/3H	1/3H	50	1/3H	1/3H	1/3H	
W3	Upper limit of flooding	25	100%θs	100%θs	100%θs	100%θs	100%θs	100%θs	
	Lower limit of flooding	5	80%θs	70%θs	65%θs	80%θs	85%θs	75%θs	
	Maximum reinjection limit	25	1/3H	1/3H	50	1/3H	1/3H	1/3H	
	Drainage upper limit	-	1/3H	1/3H	50	1/3H	1/3H	1/3H	
W4	Upper limit of flooding	25	100%θs	100%θs	100%θs	100%θs	100%θs	100%θs	
	Lower limit of flooding	5	80%θs	70%θs	65%θs	80%θs	85%θs	75%θs	
	Maximum reinjection limit	25	1/4H	1/4H	50	1/4H	1/4H	1/4H	
	Drainage upper limit	-	1/3H	1/3H	50	1/3H	1/3H	1/3H	

Note: "θs" represents the soil's saturated water content; H represents the average plant height of the corresponding treatment on the irrigation day; W1 corresponds to conventional flooding irrigation; W2 indicates controlled irrigation using a moist irrigation method; W3 and W4 represent combined modes of moist irrigation and re-irrigation, with re-irrigation upper limits of 1/3H and 1/4H, respectively; the water used for re-irrigation is sourced from the drainage water discharged into canals from upstream dry-land runoff after rainfall.

is equipped with a pipeline system and water meter to monitor irrigation and drainage in real time. To ensure the accuracy of the water table data, ten vertical rulers are fixed at different positions in each sub-plot. If a water table is present, an average value is taken; otherwise, the average value from a nearby area obtained using a TDR soil moisture meter or soil sampling drill is used as a reference. After the installation of the irrigation facilities and completion of all preparations, water management is initiated in accordance with a scientific irrigation scheme. During the rice growth period, prevention and control measures are implemented based on local standards: approximately one week after mechanical transplanting, a closed-type herbicide is sprayed, followed by a combined application of insecticides and herbicides, supplemented with several rounds of manual weeding to ensure clean fields and healthy crops. Fertilizer management is also strictly carried out in compliance with local agricultural standards and technical specifications.

This study implemented fertilization management using green smart fertilizer promoted by the Science and Technology Academy. During the entire growth period, the total amounts of fertilizer applied were 213.5 kg $N \cdot hm^{-2}$, 88.02 kg $P_2O_5 \cdot hm^{-2}$, and 147.3 kg $K_2O \cdot hm^{-2}$. Specifically, nitrogen fertilizer was applied in two installments, with a 1:1 ratio between the basal and tiller applications; phosphorus fertilizer was applied entirely as basal fertilizer; and potassium fertilizer was applied in two stages, with the basal and jointing applications in a 7:3 ratio. The fertilizers used included green smart fertilizer (with nitrogen, phosphorus, and potassium contents of 15%, 11%, and 14%, respectively), biological microbial fertilizer (with nitrogen, phosphorus, and potassium contents of 3.22%, 3.67%, and 3.05%, respectively), urea (containing 46.3% nitrogen), and potassium oxide (containing 60% K_2O). The sowing date was May 26, 2024, and the harvest date was October 20, 2024, corresponding to a growth period of 148 days. Furthermore, three fertilization operations were scheduled on May 19, 2024, June 9, 2024, and July 25, 2024, respectively.

Sampling Methods and Measurement Indicators

Collection and Measurement of Soil Samples

This study employed a five-point sampling method for site layout and used a soil auger with an inner diameter of 5 cm to sequentially collect soil samples from the 0-10 cm and 10-20 cm layers. Within each experimental plot, soil samples collected from corresponding layers were thoroughly mixed to form representative composite samples, with 3 replicates set up in each plot. Sampling was conducted at two critical stages: before rice planting and after harvest. Additionally, during the rice growth period, the interval for soil parameter measurements was set at 12-16 days, with specific measurement dates and frequencies appropriately adjusted based on actual field fertilizer application and precipitation events, thereby more accurately reflecting the impact of external management practices and environmental factors on soil properties.

Immediately after the intact soil samples were brought back from the field, subsampling was carried out. One portion of the sample, after the removal of fine roots, was stored at 4ºC under low-temperature conditions. Prior to low-temperature storage of the fresh soil samples, fine roots and visible plant residues were carefully removed, as these biological residues could affect the accuracy of subsequent measurements of microbial and enzyme activities. The remaining portion of the samples was air-dried in a cool and well-ventilated place, ground, and passed through a 100-mesh sieve for uniform processing, and then sent to the laboratory for the determination of various soil physicochemical parameters.

Soil organic carbon is determined using the potassium dichromate wet oxidation method with heating [9]. The specific procedure is as follows: accurately weigh 0.5 g of air-dried soil sample, and under heated conditions, add an excess of potassium dichromate-sulfuric acid ($K_2Cr_2O_7$-H_2SO_4) solution to digest the sample, thus ensuring complete oxidation of the organic carbon in the soil. After the reaction is complete, the remaining unreacted potassium dichromate is back-titrated using a standard ferrous sulfate ($FeSO_4$) solution. Finally, by comparing the amount of potassium dichromate consumed in the soil sample with that in the blank control, the actual content of soil organic carbon is calculated.

Collection and Determination of Gas Samples

Gas sample collection utilizes a static chamber–gas chromatography observation system [10]. The static chamber is custom-made from 2 mm thick stainless steel, initially sized at 50 cm × 50 cm × 50 cm, and elevated to 100 cm during the later growth stage of rice. To mitigate temperature fluctuations within the chamber caused by solar radiation, the exterior is wrapped with a 2 cm thick layer of thermal insulation sponge. During sampling, the stainless steel base is permanently inserted approximately 5 cm into the field soil. To separately quantify the contributions of soil and plants to CO_2 emissions, two independent measurement schemes were designed in this study: (1) 6 to 7 healthy rice plants were retained within the base, and a static chamber was sealed over them for sampling; the resulting flux was recorded as the total CO_2 emission flux (i.e., the sum of soil CO_2 emission flux and plant CO_2 emission flux). (2) In an adjacent location within the same plot, another base was installed with the same number of plants, but the aboveground parts of the plants were completely isolated from the soil surface using polyethylene film to block CO_2 emitted from root and soil respiration from entering the chamber, allowing only CO_2 from plant respiration to be measured, which was recorded as the plant CO_2

emission flux. The actual soil CO_2 emission flux was then indirectly calculated by subtracting the plant CO_2 emission flux from the total CO_2 emission flux. Once the static chamber and the base reservoir are tightly sealed, sampling can commence. The top of the chamber is designed with three interfaces: one for connecting a temperature probe to monitor the internal temperature in real time; a second that links to a sampling gas pipeline comprising a 20 cm section within the chamber and a 30 cm section outside, with the external end of the line connected to a 50 mL plastic syringe equipped with a three-way valve; and a third for connecting an external power supply to an internal electric fan.

Before formal sampling, the fan is turned on to facilitate mixing of the gases within the chamber, and the syringe is flushed 2 to 3 times. Finally, the gas sample is transferred into a gas bag using the syringe and a three-way valve. Gas samples of 50 mL are collected at four time points (0, 10, 20, and 30 minutes) after sealing the chamber, with the chamber temperature and field water layer thickness recorded concurrently. After the green-up stage, sampling is conducted every 7 days; following fertilizer application, sampling is performed twice every 7 days, reverting to a 7-day interval after four rounds of sampling. All gas sample collections are scheduled between 9:00 and 11:00 a.m.

Gas detection was performed using the GS-8900A gas analyzer, which operates based on gas chromatography principles. To reduce measurement errors and enhance data stability, the instrument must be fully preheated before measurements are taken. After preheating, the gas sample is introduced into the analyzer from the gas bag using a syringe; the gas is then separated within the chromatographic column and subsequently detected by a thermal conductivity detector (TCD). Finally, the workstation performs qualitative analysis based on the retention times obtained from a standard curve, and quantitative analysis is achieved by calculating the peak area or peak height to determine the CO_2 concentration. By combining the concentration data with auxiliary parameters, the CO_2 emission flux is further computed.

The CO_2 emission flux is calculated according to Equation (1), as follows:

$$F = \rho \times h \times \frac{\Delta c}{\Delta t} \times \frac{273}{273 + T} \quad (1)$$

In the formula, F represents the flux of CO_2 emissions ($mg \cdot m^{-2} \cdot h^{-1}$); ρ denotes the density of CO_2 at standard atmospheric pressure, which is taken as 1.997 $kg \cdot m^{-3}$ in this study; h represents the effective height within the static chamber (m); $\Delta c/\Delta t$ indicates the rate of change of CO_2 concentration within the static chamber ($mL \cdot m^{-3} \cdot h^{-1}$); and T represents the average temperature (ºC) inside the static chamber during the sampling process.

Data Analysis

All measurement data are presented as mean values derived from uniformly processed data. The experimental data were subjected to significance testing using SPSS 24.0 statistical software, with the least significant difference (LSD) method employed for each indicator.

Results

Dynamic Changes in Soil Organic Carbon under Different Water Management Regimes

As shown in Fig. 2 (variation of soil organic carbon during different growth stages), the SOC content in the 0-10 cm soil layer throughout the entire rice growth period exhibited obvious fluctuations, forming a typical "peak curve" after the application of tillering and panicle fertilizers. In terms of the average SOC content over the whole growth period, treatments W1 and W2 recorded the lowest values, at 39.75 and 39.74 $g \cdot kg^{-1}$, respectively, while treatments W3 and W4 maintained relatively high levels during the early and mid-growth stages; this may be associated with the increased depth of submergence that suppressed the mineralization activity of soil microorganisms. After drainage in the yellow ripening stage, SOC changes varied significantly among the treatments: SOC in treatments W3 and W4 decreased by 4.66% and 4.42%, respectively, whereas treatments W1 and W2 experienced slight increases. In the 10-20 cm soil layer, SOC content under treatment W2 was significantly higher than that under W1 during the tillering to jointing stages. However, after the onset of the flowering stage, SOC content in treatments W1, W3, and W4 quickly surpassed that of W2. After the yellow ripening stage, all treatments exhibited clear spatiotemporal coupling in SOC: rapid decreases in the upper layer (0-10 cm) were accompanied by swift increases in the deeper layer, confirming the vertical redistribution of soil organic carbon. At harvest, the SOC in the deep layer was higher in all treatments than in the pre-transplanting period, with treatments W4 and W3 showing increases of 7.44% and 3.37%, respectively. Overall, the average SOC over the entire growth period followed the order: W4>W3>W2>W1.

Based on the analysis of the data in Table 2, different water management practices have a significant impact ($p<0.05$) on the soil organic carbon (SOC) content in the 0-20 cm soil layer of paddy fields. The water depth regulates SOC dynamics by altering soil oxygen conditions: in the 0-10 cm soil layer, deep flooding decreases oxygen availability, which suppresses microbial activity and thereby slows the mineralization of organic carbon; however, after drainage, enhanced microbial activity leads to a reduction in the SOC content in this layer. In the 10-20 cm soil layer, water infiltration carries organic carbon from the surface

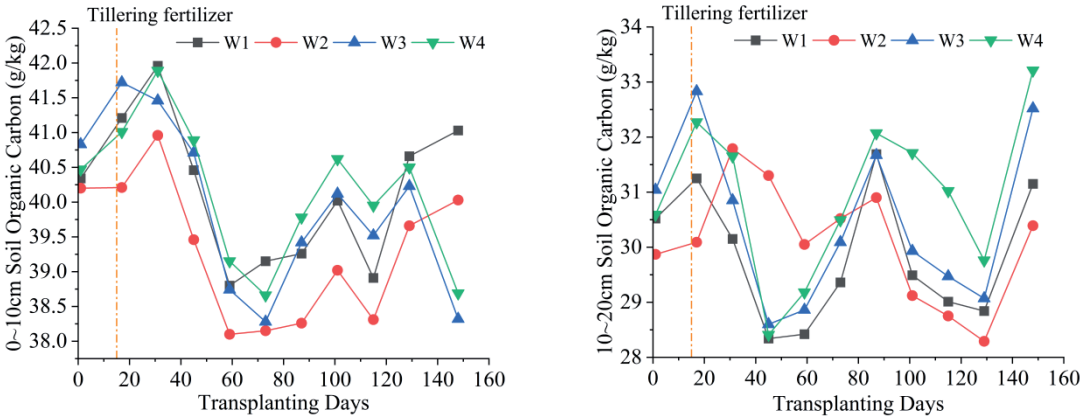


Fig. 2. Changes in soil organic carbon during the growth period under different treatments.

Table 2. Soil organic carbon content in different soil layers under various treatments.

Water management	Soil organic carbon content ($g \cdot kg^{-1}$)	
	0~10 cm Soil layer	10~20 cm Soil layer
W1	39.75±0.06b	29.81±0.42c
W2	39.18±0.03a	30.06±0.30bc
W3	39.74±0.48a	30.48±0.04ab
W4	40.17±0.07a	31.02±0.33a

Note: The values in the table are expressed as mean±standard deviation; different lowercase letters within the same column indicate significant differences among treatments ($p<0.05$).

downward, and combined with the anoxic conditions during flooding, this process promotes the accumulation of SOC in the deeper soil layers. Although controlled irrigation may facilitate the accumulation of deep SOC in the short term, long-term implementation could potentially compromise the stability of the surface carbon pool.

The Impact of Different Water Management Practices on CO_2 Emissions

Soil Carbon Dioxide Emission Flux

The observational results of soil CO_2 emission flux are shown in Fig. 3. Throughout the entire rice growth period, the emission flux under different water management modes exhibited an overall trend of first increasing and then decreasing. In each treatment, a distinct peak in soil CO_2 emission flux was observed during the late tillering stage. Notably, the W2 treatment consistently displayed significantly higher emission levels than the other treatments throughout the observation period, with a maximum value of 526 $mg \cdot m^{-2} \cdot h^{-1}$ recorded on day 60 – a particularly pronounced peak. In contrast, the soil CO_2 emission fluxes in the W1, W3, and W4 treatments remained generally lower, which may be attributed to the continuous flooding or high moisture conditions creating anaerobic environments in the soil, thereby suppressing the respiratory activity of aerobic microorganisms and significantly limiting CO_2 production. After the paddy fields were drained and dried, the CO_2 emission fluxes in the W1, W3, and W4 treatments gradually rebounded. Overall, the average soil CO_2 emission flux throughout the growth period followed a clear decreasing order: W2>W1>W3>W4.

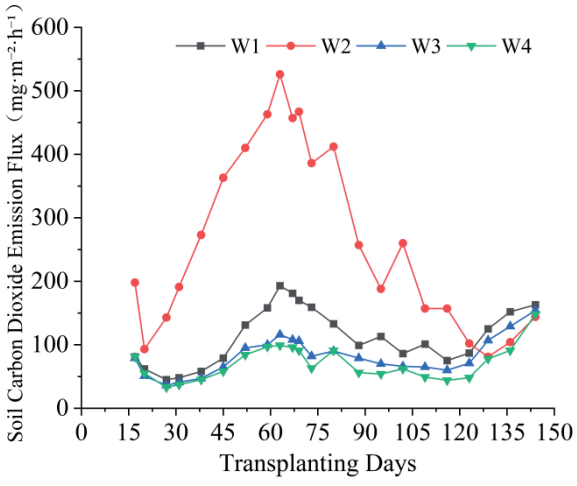


Fig. 3. Soil CO_2 emission fluxes during the growth period under different treatments.

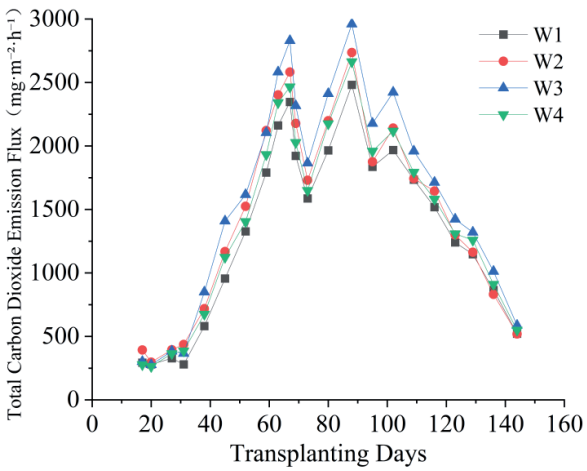


Fig. 4. Total CO_2 emission fluxes during the growth period under different treatments.

Total Carbon Dioxide Emission Flux

As shown in Fig. 4, the total CO_2 emission flux (from both plants and soil) in all treatments exhibited a typical peak-shaped curve. During the late tillering stage, each treatment displayed its first emission peak, although the intensity of the peak varied significantly among treatments. Notably, the W3 treatment had the highest emission flux, reaching 2721 $mg \cdot m^{-2} \cdot h^{-1}$, while the peaks for treatments W1 and W2 were lower, at 2164 $mg \cdot m^{-2} \cdot h^{-1}$ and 2125 $mg \cdot m^{-2} \cdot h^{-1}$, respectively. After the tillering stage, the emission flux in each treatment briefly declined, a change that may be closely related to the drop in temperature and the occurrence of rainfall during that period. At the end of the booting and panicle-primordium stages, a second CO_2 emission peak was observed, coinciding with the critical transition of rice from vegetative growth to reproductive growth. However, as the rice entered the flowering stage and gradually progressed to maturity and senescence, the reduction in root vitality led to diminished autotrophic respiration, while the activity of soil microorganisms may have also decreased, resulting in a gradual decline in CO_2 emissions [11]. Ultimately, during the ripening stage, as the plant neared the end of its life cycle, further reductions in root activity and overall metabolic rate caused the CO_2 emission levels to return to the baseline observed before transplanting.

According to the analysis of the data in Table 3, different water management regimes have a significant effect on both the average soil CO_2 emission flux during the rice growing season and cumulative soil CO_2 emissions ($p<0.05$). Based on the comparison of average soil CO_2 emission fluxes across treatments (W2>W1>W3>W4), increasing the amount of irrigation water exerted a marked suppressive effect on soil CO_2 emissions. Specifically, relative to the W4 treatment, the average soil CO_2 emission fluxes in the W3, W1, and W2 treatments were higher by 16%, 58%, and 255%, respectively.

Based on the total CO_2 emissions (including both plant and soil emissions) throughout the entire growth period of rice, significant differences were observed among the treatment groups. Specifically, the CO_2 emission fluxes differed significantly between the W1 and W3, W1 and W4, and W3 and W4 treatment groups ($p<0.05$), while the difference between the W1 and W2 treatments was not significant ($p>0.05$). Furthermore, in terms of cumulative emissions, the W3 and W4 treatments reached 60,460 $kg \cdot ha^{-1}$ and 54,410 $kg \cdot ha^{-1}$, respectively, which were the highest among all treatments, whereas the cumulative emissions of the W1 treatment were slightly higher than those of the W2 treatment.

Discussion

Effects of Different Water Management Practices on Soil Organic Carbon Dynamics

This study indicates that water management in high-altitude paddy fields exhibits clear layer-differentiated characteristics in the dynamic regulation of soil organic carbon (SOC) pools. In the 0-10 cm soil layer, SOC content shows a peak pattern primarily driven by an activation effect induced by exogenous inputs [12]. Fertilizer application provides abundant and easily

Table 3. Average soil CO_2 and total CO_2 emission fluxes during the growth period under different treatments.

Water management	Average soil CO_2 emission flux ($mg \cdot m^{-2} \cdot h^{-1}$)	Cumulative soil CO_2 emission flux ($kg \cdot ha^{-1}$)	Average CO_2 emission flux from plants and soil ($mg \cdot m^{-2} \cdot h^{-1}$)	Cumulative CO_2 emission flux from plants and soil ($kg \cdot ha^{-1}$)
W1	126±4b	4464±135b	1387±15c	48916±520c
W2	284±7a	10032±243a	1373±19c	48467±652c
W3	93±5c	3310±162c	1714±29a	60460±1020a
W4	80±4d	2821±119d	1542±25b	54410±872b

Note: The table data are expressed as mean±standard deviation; different lowercase letters in the same column indicate significant differences among treatments ($p<0.05$).

decomposable energy and substrates, which significantly activates microbial activity in the short term [13]. This activation not only accelerates the decomposition of recalcitrant organic carbon but also contributes microbial biomass and metabolic products that form a vital part of the soil organic carbon pool [14], leading to a temporary SOC peak. Compared with those in lowland paddy fields, the temperatures and oxygen partial pressures in high-altitude areas are lower and may reduce the microbial response rate to substrates, resulting in a more gradual and delayed fluctuation of SOC peak values. During the mid-to-late tillering stage, the growth center of rice shifts upward, reducing carbon inputs to the roots. Meanwhile, the easily decomposable organic carbon from earlier stages activates microorganisms, accelerating the decomposition of pre-existing organic carbon and leading to a temporary trough in SOC. In W1, prolonged flooding creates an anaerobic environment that diminishes microbial activity and slows the rate of organic matter transformation, resulting in relatively low SOC. In contrast, W2 experiences alternating wetting and drying, which introduces oxygen, activates aerobic microorganisms, and accelerates carbon mineralization [15], similarly reducing SOC. Meanwhile, W3 and W4 maintain a stable and moderate soil moisture level, thereby avoiding the strong reductive effects of prolonged flooding that inhibit aerobic mineralization as well as the negative impacts of extreme drought on microorganisms [16] and resulting in higher SOC content. These findings indicate that extreme or frequently fluctuating moisture conditions weaken the long-term stability of surface organic carbon [17, 18], while a stable, moist environment favors the retention of organic carbon [19]. However, following drainage during the yellow maturity stage, the environment rapidly transitions from anaerobic to aerobic, which activates aerobic microorganisms and triggers a "pulsed"mineralization process that causes a significant decline in SOC in W3 and W4 [20, 21]. This indicates that the organic carbon pool under stable moist conditions contains unstable components that rapidly mineralize when the environment turns aerobic, thereby increasing the risk of carbon loss [15]. Furthermore, the carbon mineralization rate induced by alternating dry and wet conditions in highland rice paddies is lower than that in lowland rice paddies, likely because lower temperatures in highland areas constrain the peak of microbial metabolism, suggesting a lower risk of carbon loss under water-saving irrigation in these regions.

For soil layers between 10 and 20 cm, the initial average SOC under treatment W2 was higher than that under W1. This is because, under treatment W2, frequent alternations between wetting and drying in the upper soil lead to the breakdown of soil aggregates and the release of organic matter, while also promoting a massive short-term proliferation of aerobic microorganisms that accelerate the decomposition of fresh organic matter. The resulting soluble organic carbon (DOC) is leached to deeper layers during irrigation or rainfall, thereby increasing the SOC content at depth [22-24]. After the rice entered the flowering stage, the SOC under treatments W1, W3, and W4 quickly surpassed that of W2, which can be attributed to the synergistic effects of the anaerobic conditions and root growth. Rice roots extend into deeper layers and secrete large amounts of exudates and sloughed-off materials, serving as a major carbon source for SOC. Research indicates that root systems and their exudates may have a greater impact on SOC accumulation than the aboveground parts. Under continuous flooding, the strongly reducing conditions in deep soil layers inhibit carbon mineralization by aerobic microorganisms, thereby more effectively preserving root-derived carbon and DOC; in contrast, the frequent alternation of wet and dry conditions in the W2 treatment leads to intermittent aerobic mineralization, resulting in net carbon loss rather than accumulation [14, 25]. Following drainage during the maturity stage, the restored connectivity of the surface soil allows portions of DOC and colloidal organic carbon to percolate downward and become sequestered in the deeper layers [26]. Treatments W3 and W4 maintain favorable soil structure and water connectivity throughout the entire growth period, exhibiting a significant "carbon downward migration" effect.

The above results indicate that water management not only regulates the surface carbon cycle but also facilitates the transport of photosynthetic carbon to deeper soil layers. Due to the stable conditions, minimal physical disturbance, and low carbon turnover rate in deep soils, the carbon sequestration effects under the W3 and W4 modes are more enduring and stable [27]. This study reveals the response mechanisms of deep soils: the moist irrigation and tailwater reuse modes maintain the highest SOC content throughout the growing period, with a significant increase observed at harvest compared to pre-transplanting. These practices effectively promote the migration and sequestration of organic carbon to deeper layers. Given that low-oxygen and minimally disturbed deep soils provide an ideal environment for long-term organic carbon storage, sequestering carbon in deep soils represents a promising carbon sequestration strategy.

Regulation of CO_2 Emission Fluxes by Different Water Management Strategies

At the end of the tillering stage, all treatment groups exhibited an initial peak in soil CO_2 flux, primarily attributable to vigorous rice root respiration, enhanced soil microbial activity, and an increased organic matter decomposition rate under high-temperature conditions [28]. Following the drainage of the paddy fields, the disappearance of the water layer enabled oxygen to infiltrate the soil, thereby activating aerobic microorganisms and resulting in a short-term rebound in CO_2 emissions observed in the W1, W3, and W4 groups. Studies have demonstrated that soil CO_2 flux is significantly negatively correlated with irrigation water volume; however, the W2 treatment, due to frequent

wet–dry alternation, allowed the soil to be fully exposed to oxygen during dry periods, continually activating aerobic microorganisms and accelerating organic matter mineralization, which led to significantly higher CO_2 emissions compared to the other treatments [29]. Across the entire growth period, the average soil CO_2 flux trend was W2>W1>W3>W4, not only underscoring the critical role of water management in controlling paddy field CO_2 emissions but also indicating that reducing irrigation water, while ensuring proper rice growth, is an effective strategy.

Studies have shown that water management can regulate the overall CO_2 emissions of the system by modulating soil microbial processes and altering plant growth, which respectively affect heterotrophic and autotrophic respiration [11]. After the tillering stage, the total CO_2 flux in all treatment groups temporarily decreases, possibly due to low temperatures that inhibit root respiration and microbial metabolism, thereby slowing down soil organic matter decomposition [30, 31]. A CO_2 emission peak observed during the jointing to booting stages marks the transition of rice from vegetative to reproductive growth; at this time, the peak in plant metabolism, enhanced root respiration, and secretion-induced activation of microbial activity jointly elevate CO_2 emissions. Although the W3 treatment reduces soil CO_2 emissions to some extent, its water management significantly promotes plant growth, leading to the highest overall system emissions. The optimized moisture conditions provided by wet irrigation and backfilling patterns facilitate tillering and plant development, resulting in a more developed canopy and root system, which enhance autotrophic respiration and increase ecosystem CO_2 emissions [32, 33]. Under the W3 condition, the contribution of plant autotrophic respiration to the overall carbon emissions is particularly significant, and such a relationship between growth processes and emissions has rarely been reported in lowland rice fields. This suggests that, when water management is optimized to promote crop growth, this process may play a key role in regulating the carbon balance in highland agriculture by enhancing carbon emissions dominated by autotrophic respiration.

Limitations and Prospects

(1) This study primarily focuses on the dynamic evolution of total soil organic carbon but does not provide an in-depth analysis of the responses of particulate organic carbon, mineral-associated organic carbon, and other physicochemical forms. (2) There is a lack of direct quantitative evidence for the key processes driving the downward migration of carbon, leading to an insufficient explanation of the mechanisms determining carbon fate. (3) Current technical approaches have certain limitations, as they are unable to differentiate the specific contributions of autotrophic and heterotrophic respiration to total CO_2 fluxes, thereby hindering precise quantification of regulatory intensities under different emission pathways. (4) This study concentrated solely on CO_2 monitoring without concurrently monitoring other critical greenhouse gases such as CH_4 and N_2O, which makes it difficult to comprehensively assess the net impact of management measures on the overall greenhouse effect.

To address the aforementioned shortcomings, future research can be expanded from several perspectives. (1) To elucidate the mechanisms of carbon sequestration, it is recommended to combine in situ micro-root tube techniques with stable isotope labeling methods to directly track the transport and stabilization of photosynthetic carbon across the soil profile, while also conducting long-term monitoring of soil carbon pool dynamics and stability under varying water management practices. (2) In terms of greenhouse gas monitoring, ^{13}C isotopic tracing or root-isolated soil chambers could be employed to differentiate and quantify autotrophic and heterotrophic respiration. (3) The establishment of a synchronized continuous monitoring system for CO_2, CH_4, and N_2O, coupled with a full life-cycle carbon footprint assessment, will provide a robust scientific basis for highland rice paddy water management strategies, aiding in climate change mitigation and the advancement of low-carbon agricultural development.

Conclusions

This study conducted field experiments in the Erhai Basin of Dali to investigate the effects of four water management regimes – conventional flooding (W1), controlled irrigation (W2), controlled irrigation combined with 1/3H return water (W3), and controlled irrigation combined with 1/4H return water (W4) – on soil organic carbon (SOC) dynamics and CO_2 emissions. Based on the analysis of the vertical distribution of SOC and the variation in CO_2 emission flux under different water management practices, the following conclusions were drawn: (1) Different water management regimes had significant impacts on SOC accumulation and its vertical distribution. In the 0-10 cm topsoil, although SOC in the W3 and W4 treatments decreased by 4.66% and 4.42%, respectively, after drainage during the maturity stage, the deeper 10-20 cm soil layer exhibited a strong carbon sequestration capacity – with SOC increases of 3.37% and 7.44% at harvest compared to the pre-transplantation stage. (2) Soil CO_2 emissions were significantly negatively correlated with the amount of irrigation water applied. Specifically, the frequent alternation between wetting and drying in the W2 treatment notably stimulated the activity of aerobic microorganisms, resulting in the highest average soil CO_2 emission flux. Under continuously moist conditions, however, the W3 and W4 treatments effectively suppressed soil-derived CO_2 emissions. Nonetheless, owing to the more vigorous plant growth observed in the W3 treatment, the total system CO_2 emission flux reached the highest value, further highlighting the

dominant role of autotrophic respiration in the overall system carbon emissions.

The integrated approach of controlled irrigation combined with return irrigation has shown significant potential in regulating crop growth and managing soil carbon: it not only suppresses soil CO_2 emissions but also facilitates the migration and sequestration of organic carbon into deeper layers, while concurrently enabling the circular utilization of upland runoff. This method balances resource conservation with environmental protection, thereby providing a pathway for the green, low-carbon development of plateau rice paddies. However, this study focused solely on total soil organic carbon and CO_2 emissions without elucidating the response mechanisms of individual carbon components or quantifying the contributions of autotrophic and heterotrophic respiration. Future research could incorporate ^{13}C isotope tracing alongside rhizosphere isolation techniques to accurately distinguish between carbon source-sink pathways and develop a concurrent monitoring system for CO_2, CH_4, and N_2O, thereby facilitating a full life-cycle carbon footprint assessment to further optimize water management practices in highland rice paddies.

Data Availability

Data will be made available on request.

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AI Usage Disclosure Statement

This manuscript used DeepSeek V4 solely for text polishing and language organization during the initial writing stage; it was not involved in research design, data acquisition, analysis, or conclusion derivation. All data originate from actual experiments and are independently verifiable, not AIgenerated. All AImodified content has been manually reviewed and revised sentence by sentence by the authors to ensure accuracy. All AIassisted content has been carefully reviewed, revised, and validated by the authors, who take full responsibility for the content of the published article.

Conflict of Interest

The authors declare no conflict of interest.

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