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Assessing the Impact of Irrigation and Crop Type on Soil Respiration in Agricultural Soils

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Abstract

Identifying the main drivers of soil CO_2 emissions in tropical agroecosystems is essential for balancing productivity and climate mitigation. This study evaluated the effects of crop type, irrigation, phenological stage, and fertilization on soil respiration in a humid marshland system in Rwanda using a two-season field experiment. Five crops (maize, soybean, common bean, Irish potato, and Brachiaria) were grown under irrigated and rainfed conditions, and soil CO_2 emissions were measured across 19 sampling campaigns in both crop-covered and adjacent bare soil conditions in all plots. Crop type and growth stage were the dominant drivers of soil CO_2 emissions ($p < 0.001$), while irrigation had no significant direct effect despite increasing yields ($p < 0.001$). As a result, irrigation reduced yield-scaled CO_2 emissions for several crops ($p < 0.05$–0.01). Brachiaria showed higher emissions, particularly during the development stage, but its high biomass led to lower emissions per unit yield. Fertilization significantly increased soil respiration ($p < 0.001$), and emissions were higher under crop-covered soils than bare soils ($p < 0.001$). These findings indicate that crop traits and nutrient inputs primarily control soil respiration under moisture-sufficient tropical conditions.

Keywords: soil respiration; tropical agroecosystems; crop type; irrigation; fertilization; carbon emissions

1. Introduction

Soil respiration, defined as the release of carbon dioxide (CO_2) from soil through microbial decomposition of organic matter and plant root respiration, is a major component of the global carbon cycle. Agricultural soils contribute substantially to terrestrial CO_2 emissions, accounting for approximately 10–25% of total terrestrial fluxes depending on land use and management intensity [1,2]. Because soil respiration is highly sensitive to management practices, understanding how agricultural interventions regulate soil CO_2 emissions is essential for improving carbon budget assessments and developing climate-smart agricultural systems.

Among management practices, irrigation plays a key role in regulating soil respiration by altering soil moisture conditions that control microbial activity and root metabolism. In water-limited agroecosystems, irrigation can stimulate soil respiration by alleviating moisture constraints and promoting microbial decomposition and root activity [3]. However, responses are not uniform; while moderate moisture increases may enhance CO_2 emissions, excessive or prolonged wetting can restrict oxygen diffusion and suppress aerobic microbial processes, leading to reduced respiration rates [4]. These contrasting effects highlight the need for field-based assessments under realistic soil moisture conditions.

Crop type also strongly influences soil respiration through differences in root biomass, rooting depth, and rhizosphere interactions. Crops with larger or more active root systems typically exhibit higher soil CO_2 emissions due to increased root respiration and greater carbon inputs to the rhizosphere [5,6]. In addition, crop-specific root exudation patterns regulate microbial activity and organic matter turnover, resulting in substantial variation in soil respiration among crops grown under similar environmental conditions.

Soil respiration is further modulated by crop growth stages and associated changes in root development and microbial activity. Temporal variations in root biomass and physiological activity can lead to seasonal fluctuations in CO_2 emissions, particularly during early growth stages when root expansion and microbial stimulation are pronounced [7,8]. These dynamics indicate that the effects of irrigation and crop type on soil respiration are not static and must be evaluated across growing periods.

Another important aspect is the distinction between crop-covered and bare soil respiration. Vegetated soils generally exhibit higher CO_2 emissions due to combined root respiration and rhizosphere microbial activity, whereas bare soil respiration mainly reflects microbial decomposition of soil organic matter [9,10]. However, direct comparisons within the same experimental framework remain limited, particularly under contrasting irrigation regimes.

Despite substantial advances, important knowledge gaps remain. Few field-based studies have simultaneously assessed the combined effects of irrigation and multiple crop types while directly comparing crop-covered and bare soil respiration under realistic farming conditions. In addition, many studies rely on short-term measurements or controlled experiments that do not adequately capture seasonal variability in agricultural systems.

Therefore, this study aimed to evaluate the combined effects of irrigation and crop type on soil CO_2 emissions under marshland field conditions in Rwanda. Specifically, the objectives were to: (i) assess the effects of crop type and irrigation on soil CO_2 emissions across growth stages; (ii) compare emissions between crop-covered and bare soils; (iii) evaluate seasonal variation; and (iv) examine relationships between soil CO_2 emissions and environmental drivers.

2. Materials and Methods

2.1. Site Description

The field experiment was conducted in Tonga marshland, located in Huye District, Southern Province of Rwanda (2°35′9″ S, 29°43′23″ E). The marshland is owned by the University of Rwanda and has long served as an important agricultural site for local farmers. Historically, it was used for vegetable cultivation until 2014, after which parts of the land were converted to maize farming and clay extraction. Since 2017, a large section has been cultivated for rice production, while the slightly elevated area used in this study has been reserved for experimental research.

The site is characterized by a tropical wet and dry climate (Köppen classification), typical of Rwanda's savanna regions. Mean monthly temperatures are consistently above 18 °C, and annual rainfall ranges between 1200- and 1400-mm. Rainfall follows a bimodal distribution, resulting in two cropping seasons: Season 1 (September–January) and Season 2 (February–May). Irrigation water was supplied from a natural stream traversing the marshland.

2.2. Soil Physical and Chemical Properties

Baseline soil analysis indicated relatively uniform physical properties across the soil profile and generally low soil fertility (Tables 1 and 2). According to the United States Department of Agriculture (USDA) soil texture classification system, soils from 0 to 100 cm depth were classified as sandy loam, with sand contents ranging from 58% to 66%, silt from 26% to 29%, and clay from 8% to 13%. Bulk density increased with depth from 1.32 to 1.78 g cm^{-3}, indicating greater compaction in subsoil layers, while gravimetric moisture content increased from 11.8% in the topsoil to 16.4% at 80–100 cm. Electrical conductivity increased with depth but remained within non-saline ranges.

Table 1. Soil physical properties of the study site at different depths.

Depth (cm)	Texture class	Sand (%)	Silt (%)	Clay (%)	Bulk density (g cm^{-3})	Gravimetric moisture content (%)	EC (µS cm^{-1})
0–20	Sandy loam	66	26	8	1.32	11.8	27.8
20–40	Sandy loam	64	26	10	1.45	12.4	54.3
40–60	Sandy loam	62	26	12	1.59	13.8	78.4
60–80	Sandy loam	60	28	12	1.68	15.2	98.7
80–100	Sandy loam	58	29	13	1.78	16.4	112

[1] EC = Electrical conductivity.

Table 2. Soil chemical properties of the study site (0–20 cm) before amendment.

Parameter	Unit	Mean value	Range
pH (H_2O)	–	4.6	4.1–5.1
Total nitrogen	%	0.12	0.10–0.14
Organic carbon	%	1.7	1.5–1.8
Available phosphorus	Ppm	20	11–28
Exchangeable Ca	cmol kg^{-1}	2.1	1.6–2.6
Exchangeable Mg	cmol kg^{-1}	0.9	0.7–1.1
Exchangeable K	cmol kg^{-1}	0.25	0.18–0.33

Surface soil chemical properties (0–20 cm) indicated strong acidity and low nutrient status. Soil pH (H_2O) averaged 4.6. Organic carbon (1.7%) and total nitrogen (0.12%) were low, while available phosphorus ranged from low to moderate levels. Exchangeable base cations (Ca, Mg, and K) were generally low, and exchangeable sodium was very low. These conditions necessitated soil amendments, including lime and fertilizers, to support crop growth.

Physical and chemical properties at the study site are consistent with common soil conditions in Rwanda, where about 75% of soils are strongly acidic (pH < 5.5) and generally have low soil organic carbon (<3%), particularly outside valley swamps and natural forests [11]. Such highly weathered tropical soils typically have low base cation contents and limited inherent fertility due to intense weathering and long-term cultivation.

2.3. Fertilizer and Soil Amendment Management

To improve soil fertility and support crop growth, both organic and inorganic fertilizers was applied. Lime and compost were incorporated before planting to correct soil acidity and improve soil organic matter, while mineral fertilizers (DAP, Urea, KCl, and NPK 17:17:17) supplied essential macronutrients (N, P, and K). Fertilizer types, application rates, and nutrient compositions are summarized in Tables 3 and 4.

Table 3. Soil chemical properties of the study site (0–20 cm) before amendment.

Crop	Total N (kg ha^{-1})	Total P_2O_5 (kg ha^{-1})	Total K_2O (kg ha^{-1})	Lime (kg ha^{-1})	Compost (kg ha^{-1})
Irish potato	124	120	126	2000	10000
Maize	72.5	54.5	53.5	2000	10000
Soybeans	72.5	54.5	26.5	2000	10000
Beans	72.5	54.5	26.5	2000	10000
Brachiaria	76.7	58.7	72.7	2000	10000

[2] P_2O_5: Phosphorus pentoxide equivalent; K_2O: potassium oxide.

Table 4. Mean soil CO_2 emissions under different crop types from crop covered conditions.

#	Crop	Mean CO_2 emissions (mg m^{-2} h^{-1})
1	Beans	949.64
2	Brachiaria	1264.26
3	Soybean	917.55
4	Maize	930.17
5	Potato	837.87

Fertilizer application rates followed recommendations from the Rwanda Ministry of Agriculture, which provides region-specific guidelines based on soil classification. However, during the pilot cropping season (February–May 2024), crop performance was constrained partly due to insufficient potassium supply. As a result, we increased potassium application rates in the subsequent season (which was the first season of our study) through additional KCl application, ensuring adequate nutrient availability and more suitable conditions for assessing soil respiration responses under different water management and crop types. Fertilizers were placed around the crop root area at planting (crop initial growing stage) and during the first round of weeding performed in crop development stage. Fertilization effect was evaluated by comparing CO_2 emissions from crop covered conditions measured on the day before fertilizer application with those recorded two weeks later.

DAP: Diammonium phosphate; KCL: Muriate of Potash

The compost used in this study consisted of a mixture of farm-derived organic materials, primarily animal manure and crop residues (e.g., maize stover and bean haulms), following common composting practices in Rwanda. No laboratory analysis of the compost was conducted prior to application. Published agronomic studies from Rwanda and East Africa indicate that compost application rates of 5–15 t ha^{-1} are commonly recommended to improve soil organic matter and nutrient supply in low-fertility tropical soils [12]. In addition, these studies report that similar dry composts typically contain approximately 0.8–1.5% total nitrogen, 0.4–0.8% P_2O_5, and 0.8–1.5% K_2O, with organic matter contents ranging from 30 to 50% [13]. However, only a fraction of these nutrients is immediately plant-available, as nutrient release from compost occurs gradually through mineralization.

2.4. Experimental Design and Crop Management

The experiment followed a Randomized Complete Block Design (RCBD) with four blocks and was replicated in an agricultural season. Treatments consisted of two water management regimes (irrigated and rainfed) and five crop types: maize (*Zea mays*), soybean (*Glycine max*), Irish potato (*Solanum tuberosum*), common bean (*Phaseolus vulgaris*), and *Brachiaria* grass (*Urochloa brizantha*). Crop rotation was performed at the start of the second season for seasonal crops where maize rotated with potato, soya beans rotated with beans, potato rotated with soya beans and beans rotated with maize. Each block therefore included ten treatment combinations, resulting in a total of 40 plots. Each plot measured 48 m^2 (6 m × 8 m).

Water was supplied in the field by drip irrigation where each row has a line with drippers to keep soil moisture above the permitted moisture depletion for the specific crop for the entire growing season. This means that each crop was irrigated according to the specific crop needs. Water was pumped from Tonga natural stream.

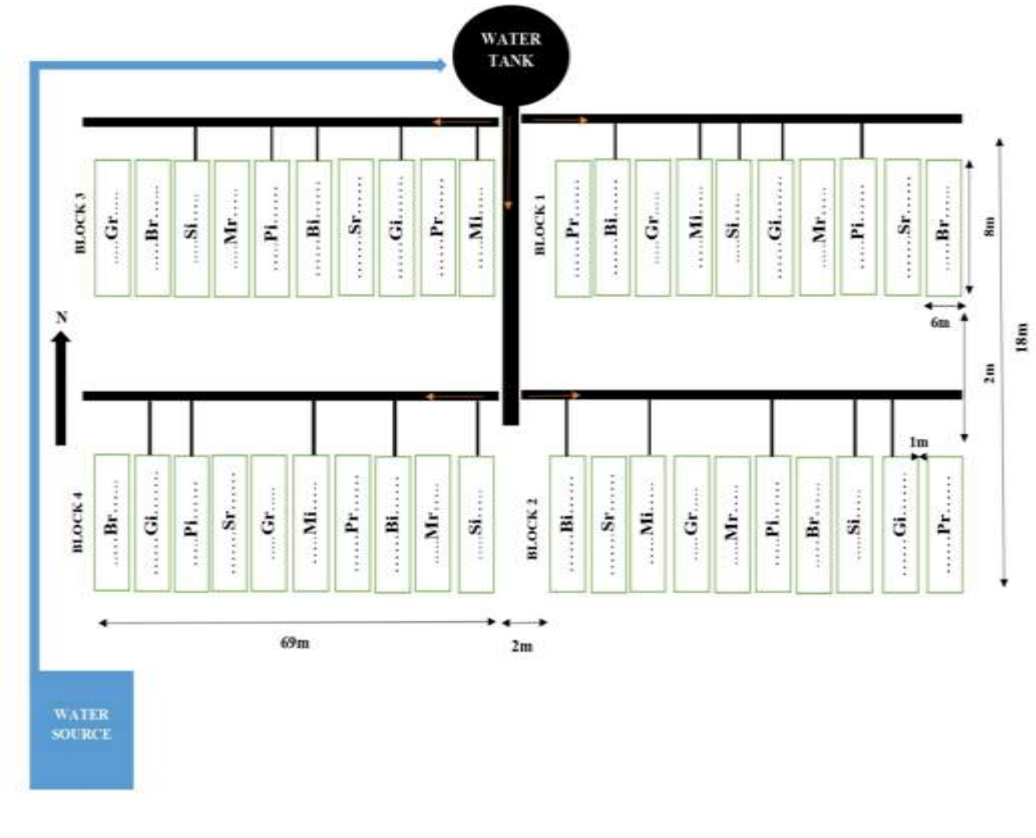

Figure 1. Field experimental set up, where Pr = rainfed potato, Pi = irrigated potato, Sr = irrigated soybean, Si= rainfed soya bean, Gi = irrigated grass (Brachiaria), Gr=rainfed grass (Brachiaria) Mi = irrigated maize, Mr = rainfed maize, Bi = irrigated beans and Br=rainfed beans.

2.5. Data Collection

2.5.1. Soil Respiration Measurement

CO2 samples were collected using closed static chamber method following standard protocols [14,15] directly connected to carbon dioxide probe (GMP343 sensor) and pump to get direct measurements.

Soil CO_2 emissions was measured during 20 sampling campaigns conducted across two consecutive cropping seasons (Season 1: September 2024–January 2025; Season 2: February 2025–June 2025). Measurements were performed at approximately two-week intervals throughout each season. Within each season, sampling was structured to capture crop phenological development, conducting two measurement rounds during the initial growth stage, three during the development stage, three during the mid-growth stage, and two during the late growth stage. On each sampling day, two CO2 measurements were performed per plot: one under crop-covered conditions (from the chamber with standing vegetation inside) and one under adjacent bare soil conditions (from the chamber without vegetation inside placed between two consecutive crops on the same row). This sampling design generated a total of 80 individual flux measurements per campaign. Measurement frames were installed at the sampling locations two weeks before gas sampling day.

For the frame with crop inside, we trimmed the above ground crop biomass five days before measurement to allow plant shock to stabilize, root respiration to decline and microbial activity to reach a new equilibrium. CO_2 concentration was recorded at 15-second intervals for 3 minutes. The chamber height prior to each measurement was measured to calculate chamber volume accurately. CO_2 emissions were calculated from the rate of change in chamber CO_2 concentration over time using the Ideal Gas Law following standard static chamber methods [16].

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$$F = (\Delta C/\Delta t) \times (P / (R \times T)) \times (M \times V / A)$$

where F is CO_2 flux (mg m^{-2} h^{-1}), $\Delta C/\Delta t$ is the rate of change in concentration, P is atmospheric pressure, R is the gas constant, T is temperature, M is molar mass of CO_2, V is chamber volume, and A is surface area.

Figure 2. Field setup for soil respiration measurement using the closed chamber method.

The chamber (1) was placed on a pvc frame (2) inserted 5 cm into the soil and connected via tubing (3) to an external pump (4) which in return connected to GMP343 sensor (5) for CO2 measurement recording. Measurements were recorded every 15 seconds for 3 minutes at both crop-covered and bare soil points.

2.5.2. Weather Data Measurement

Air temperature, soil temperature, soil moisture content (10 cm depth), groundwater level, and photosynthetic active radiation (PAR) were monitored each sampling day. Air temperature data were obtained from the on-site meteorological station (WatchDog 2000 Series, Spectrum Technologies, Inc., Aurora, IL, USA) and recorded prior to CO_2 measurements. Soil temperature and soil moisture were measured using a portable soil moisture meter. Groundwater level to a depth of 1.2 m was measured using an electric water level meter (Model 101, Solinst Canada Ltd., Georgetown, ON, Canada). Photosynthetically active radiation (PAR) was estimated using a smartphone-based method with the photone application [17]. which utilizes the phone’s built-in ambient light sensor, with measurements taken at 60-minutes intervals during sampling days. Every unusual weather condition (e.g., rainfall, strong winds) was recorded to consider them during result interpretation.

2.5.3. Statistical Analysis

All statistical analyses were conducted using R software version 4.4.3[18]. We analyzed CO_2 emission data using linear mixed-effects models to account for the hierarchical experimental design. Crop type, water management, and crop growing stage were included as fixed effects, and their interactions were tested too. We specified block and plot nested within block as random effects to account for the randomized block design and repeated measurements at the plot level. Model significance was assessed using type III analysis of variance. We computed estimated marginal means for fixed factors and performed pairwise comparisons using Tukey-adjusted contrasts. We determined statistical significance at $p < 0.05$. Data from both cropping seasons were analyzed jointly except when we were comparing emissions from both seasons.

3. Results

This section presents the results of the study evaluating the main and interactive effects of crop type, water management, and crop growing stage on soil CO_2 emissions from both crop-covered and bare soil conditions across two cropping seasons. In addition, we examined seasonal dynamics, fertilization, and relationships between CO_2 emissions and environmental variables to identify key drivers of soil respiration.

3.1. Effects of Crop Type, Irrigation, and Growth Stage on Soil CO_2 Emissions Under Crop-Covered Conditions

Mean soil CO_2 emissions under crop-covered conditions differed among crops, with the highest emissions observed under brachiaria, while soybean and bean showed intermediate values and potato and maize exhibited lower average emissions (Table 4).

Soil CO_2 emissions were significantly affected by crop type ($p < 0.001$) and growing stage ($p < 0.001$), whereas irrigation had no significant effect ($p = 0.159$) (Figure 3).

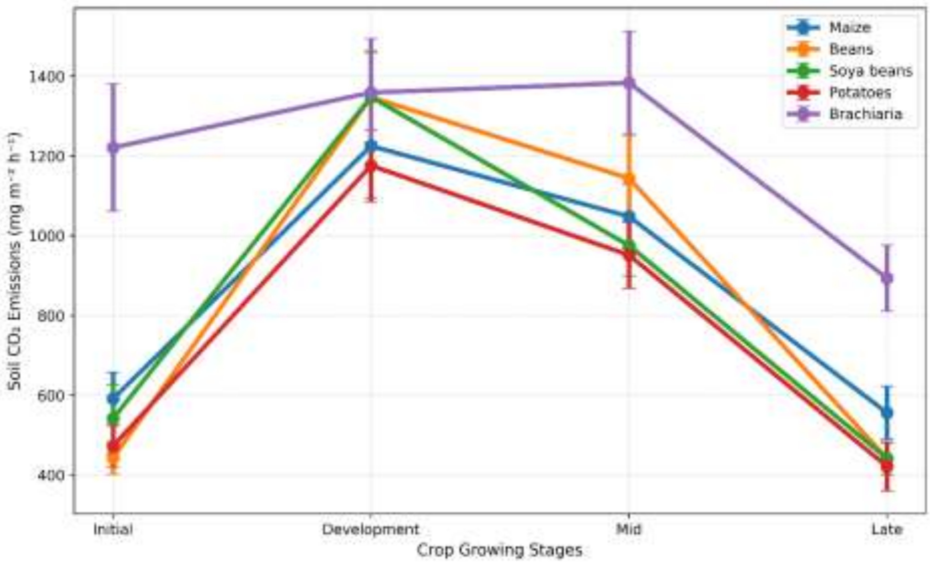


Figure 3. Soil CO_2 emissions across crop growing stages under crop-covered conditions for each crop, averaged across rainfed and irrigated treatments.

Relative to the reference crop (bean), brachiaria showed higher emissions (+231 mg m^{-2} h^{-1}), followed by soybean (+75.5 mg m^{-2} h^{-1}). Potato (−55.1 mg m^{-2} h^{-1}) and maize (+2.8 mg m^{-2} h^{-1}) did not differ significantly from the reference.

Across growing stages, emissions were significantly lower during the initial (−904.2 mg m^{-2} h^{-1}) and late stages (−905.6 mg m^{-2} h^{-1}) compared to the development stage. The mid-stage showed a non-significant reduction (−203.2 mg m^{-2} h^{-1}; $p = 0.12$) (Figure 3).

The Crop × Water interaction was not significant ($p = 0.141$), while the Crop × Growth Stage interaction was marginally significant ($p = 0.0847$). A significant positive interaction effect was observed for brachiaria at the initial stage ($p < 0.001$).

3.2. Effects of Crop Type, Irrigation, and Growth Stage on Soil CO_2 Emissions Under Bare Soil Conditions

Consistent with crop-covered conditions, mean soil CO_2 emissions differed among crop types, with the highest values observed under brachiaria. Beans showed intermediate emissions, while soybean, maize, and potato exhibited lower values (Table 5).

Table 5. Mean soil CO_2 emissions under different crop types from bare soil conditions.

#	**Crop**	**Mean CO_2 emissions (mg m^{-2} h^{-1})**
1	Beans	632.42
2	Brachiaria	755.68
3	Maize	515.8
4	Potatoes	485.48
5	Soya beans	545.04

Soil CO_2 emissions were significantly affected by crop type ($p < 0.001$) and growing stage ($p < 0.001$). Compared to beans, brachiaria showed significantly higher emissions (+370 mg m^{-2} h^{-1}) and differed from all other crops ($p < 0.05$). Maize, soybean, and potato did not differ significantly from beans.

Water management and interaction effects (Crop × Water and Crop × Growth Stage) were not significant ($p > 0.05$) (Figure 4).

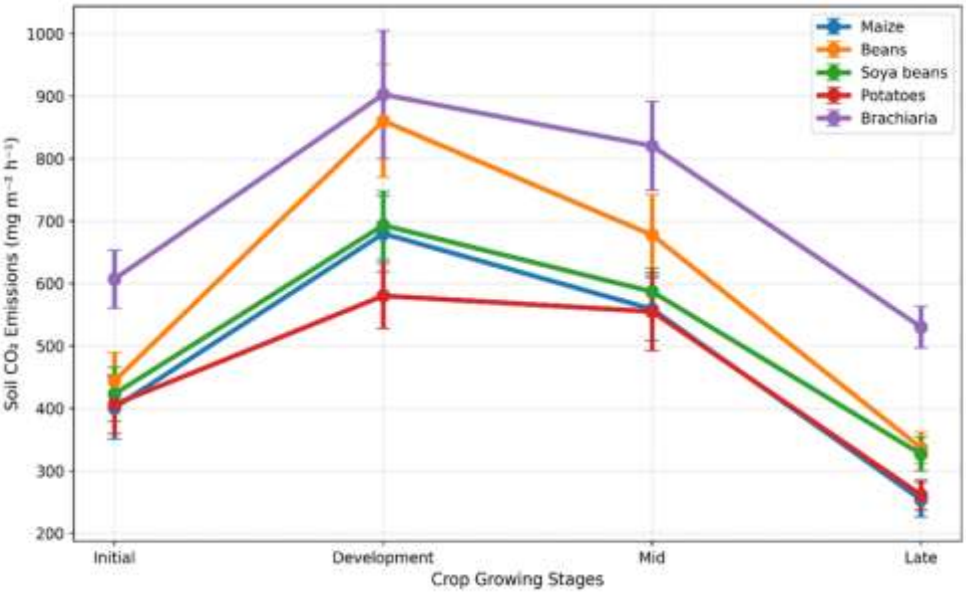


Figure 4. Soil CO_2 emissions across crop growing stages under bare-soil conditions for each crop, averaged across rainfed and irrigated treatments.

3.3. Seasonal Variation in Soil CO_2 Emissions Across Crops and Water Regimes

Cropping season did not significantly affect soil CO_2 emissions ($p = 0.123$). Mean emissions were generally higher in the second season for most crops, including beans (806 vs. 1079 mg m^{-2} h^{-1}), brachiaria (1201 vs. 1321 mg m^{-2} h^{-1}), maize (804 vs. 1043 mg m^{-2} h^{-1}), and soybean (800 vs. 1024 mg m^{-2} h^{-1}), while potato showed lower emissions in the second season (897 vs. 785 mg m^{-2} h^{-1}) (Figure 5).

Crop type had a significant effect on soil CO_2 emissions ($p < 0.001$), whereas water management was not significant ($p = 0.494$).

No significant interaction effects were observed between Season × Crop ($p = 0.183$), Season × Water ($p = 0.533$), or Season × Crop × Water ($p = 0.577$).

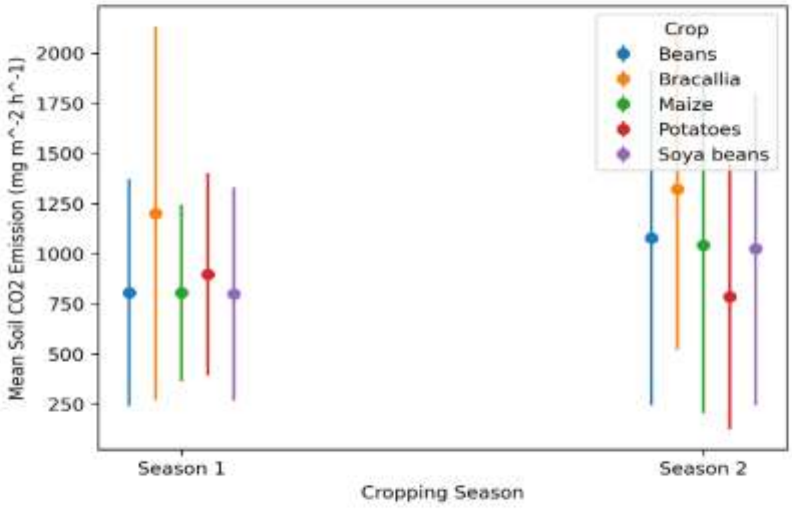
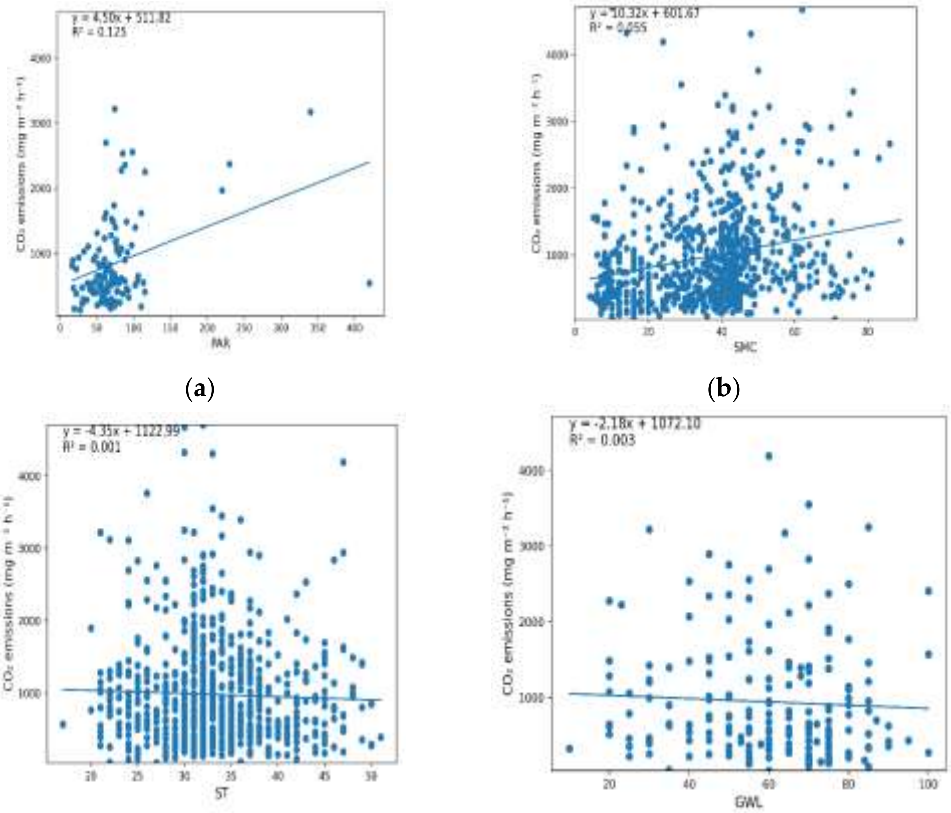


Figure 5. Soil CO_2 emissions across seasons.

3.4. Relationships Between CO_2 Emissions and Environmental Parameters

Photosynthetic active radiation (PAR) was the only environmental variable significantly associated with CO_2 emissions ($\beta = 4.29 \pm 1.30$ SE, $z = 3.29$, $p = 0.001$). CO_2 emissions increased by approximately 4.3 mg m^{-2} h^{-1} per 1 μmol m^{-2} s^{-1} increase in PAR (Figure 6a).

Soil moisture content (SMC) showed a positive but non-significant association with CO_2 emissions ($\beta = 12.34 \pm 7.84$ SE, $p = 0.115$). Soil temperature (ST) exhibited a negative, non-significant relationship ($\beta = -16.74 \pm 14.15$ SE, $p = 0.237$). Groundwater level (GWL) did not significantly affect CO_2 emissions ($\beta = -3.99 \pm 4.60$ SE, $p > 0.05$). Scatterplots indicated a wide dispersion of observations for SMC, ST, and GWL (Figure 6b–d).



(**a**) (**b**)

(**c**) (**d**)

Figure 6. Soil CO_2 emissions versus environmental parameters.

3.5. Effects of Fertilization on Soil CO_2 Emissions

Soil CO_2 emissions differed significantly between the period before fertilization and period after fertilization where emissions measured before fertilization were on average 648.95 mg m^{-2} h^{-1} lower than those recorded two weeks after fertilizer application (, $p < 0.001$) (Figure 7).

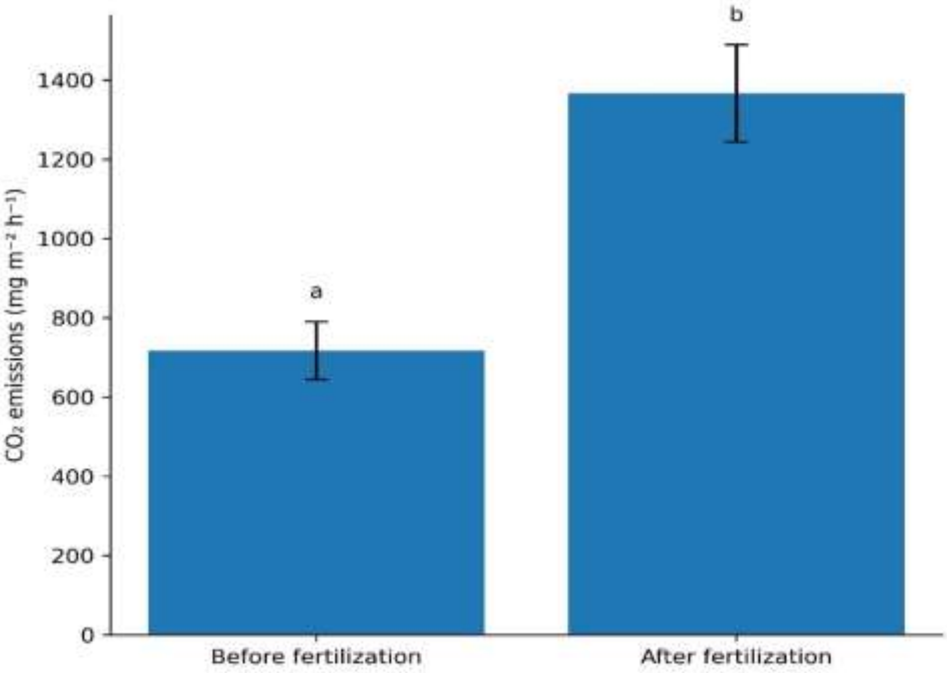


Figure 7. Soil CO_2 emissions versus fertilization.

3.6. Productivity–Soil Respiration Dynamics Under Irrigated and Rainfed Systems

Irrigation significantly increased crop productivity across all crops ($p < 0.001$) (Table 6). In contrast, mean soil CO_2 emissions from crop-covered soils did not differ significantly between irrigated and rainfed treatments, although slightly higher values were observed under irrigation.

Table 6. Mean soil CO_2 emissions, crop yield, and yield-scaled CO_2 emissions under irrigated and rainfed conditions.

Crop	Water management	Mean CO_2 (mg m^{-2} h^{-1})	Dry yield (kg ha^{-1})	kg CO_2 kg^{-1} dry yield	p value (total dry yield: irrigated and rainfed conditions)	p-value (CO_2 Kg per kg of dry yield: irrigated and rainfed conditions)
Beans	Irrigated	880.25	5350	0.164	<0.001	0.018
Beans	Rainfed	1 019.02	4630	0.219	-	-
Brachiaria	Irrigated	1 414.2	32150	0.044	<0.001	0.28
Brachiaria	Rainfed	1 114.33	22300	0.05	-	-
Maize	Irrigated	985.71	9400	0.105	<0.001	0.406
Maize	Rainfed	874.63	7570	0.116	-	-
Irish potatoes	Irrigated	884.67	14150	0.062	<0.001	<0.001

Irish potatoes	Rainfed	791.08	7570	0.11	-	-
Soybeans	Irrigated	922.66	4810	0.193	<0.001	0.197
Soybeans	Rainfed	912.43	4020	0.225		

At the crop level, yields were consistently higher under irrigated conditions for all crops ($p < 0.001$), while differences in soil CO_2 emissions remained small and not statistically significant (Table 6). Brachiaria exhibited relatively high CO_2 emissions under both water regimes, whereas maize, beans, soybean, and Irish potato showed only minor variation between treatments.

When expressed per unit of dry yield, soil CO_2 emission intensity was significantly lower under irrigation for beans ($p < 0.05$), brachiaria ($p < 0.01$), maize ($p < 0.05$), and Irish potato ($p < 0.01$), while no significant difference was observed for soybean ($p > 0.05$). Across crops, emission intensity varied markedly, with lower values for brachiaria and higher values for grain legumes (Table 6).

4. Discussion

4.1. Effects of Crop Type, Irrigation, and Growth Stage on Soil CO_2 Emissions Under Crop-Covered Conditions

The strong effect of crop growth stage on soil CO_2 emissions indicates a close coupling between plant development and rhizosphere carbon dynamics. Lower emissions observed during the initial stage likely reflect limited root biomass and reduced carbon inputs to the soil. In contrast, higher emissions during the development and mid stages can be attributed to increased belowground carbon allocation and enhanced microbial activity. The subsequent decline at the late stage is consistent with reduced photosynthetic activity and progressive root senescence.

Differences among crop types further suggest that species-specific traits regulate soil CO_2 emissions, likely through variations in root biomass, architecture, and exudate composition. The higher emissions observed under brachiaria compared to other crops may be associated with its dense root system and greater carbon input to the soil.

The absence of a significant irrigation effect suggests that soil moisture conditions were not limiting for soil respiration during the study period. This may be explained by the prevailing environmental conditions, as data collection occurred during the rainy seasons, with rainfall preceding most sampling events. Under such conditions, both root and microbial respiration are likely maintained within an optimal moisture range, reducing the influence of additional water inputs.

These findings are consistent with previous studies highlighting plant phenology and rhizosphere carbon inputs as key regulators of soil respiration in agricultural systems [19,20]. Overall, the results support the hypothesis that biological factors, particularly crop type and growth stage, play a dominant role in controlling soil CO_2 emissions under crop-covered conditions.

4.2. Effects of Crop Type, Irrigation, and Growth Stage on Soil CO_2 Emissions Under Crop-Covered Conditions

Soil CO_2 emissions were significantly higher under crop-covered than bare soil conditions, indicating a strong contribution of plant-associated respiration to total soil carbon fluxes. The magnitude of this difference varied among crops, with a significant soil condition × crop interaction observed for brachiaria, while other crops showed no differential response. The covered–bare contrast was also stage-dependent and most pronounced during the initial and late growth stages, highlighting temporal variation in plant-driven carbon inputs.

The persistence of crop effects under bare soil conditions suggests that plant identity influenced soil respiration beyond the immediate rhizosphere. This pattern indicates that crop-specific differences in belowground carbon allocation and root development may stimulate microbial activity and enhance carbon turnover in surrounding bulk soil. The relatively higher emissions associated with brachiaria under both soil conditions may reflect its extensive root system and greater belowground carbon inputs, which can sustain microbial processes over time.

The significant effect of growth stage further supports the role of plant developmental dynamics in regulating soil respiration at the system scale, even in areas without direct root presence at the measurement point.

The absence of irrigation effects under both soil conditions suggests that moisture was not a limiting factor for soil respiration during the study period. This is likely related to the prevailing environmental conditions, as no pronounced dry periods occurred. Under drier conditions, irrigation may exert a stronger influence on soil CO_2 emissions.

These findings are consistent with previous studies showing that root-derived carbon inputs and rhizosphere priming effects can extend beyond the immediate root zone into adjacent bulk soil [21–23]. Similarly, it was reported higher soil respiration rates in vegetated soils compared to bare soils due to the direct and indirect effects of living roots on soil carbon dynamics [24,25].

4.3. Seasonal Variation in Soil CO_2 Emissions Across Crops and Water Regimes

Seasonal variation had a limited effect on soil CO_2 emissions, indicating that short-term differences between cropping seasons were insufficient to significantly alter soil biological activity. Although emissions were generally higher in the second season for most crops, this trend was not statistically significant, suggesting a relatively stable system response across seasons.

The slightly higher emissions observed in the second season may be associated with cumulative biological effects, including residual organic inputs from the preceding crop. Root residues and remaining plant-derived carbon could increase the availability of decomposable substrates, thereby sustaining microbial activity and CO_2 production.

The lower emissions observed under potato in the second season may reflect crop rotation effects, as potato replaced maize during this period. Differences in residue quality and carbon inputs between crops, as well as variation in root architecture and carbon allocation patterns, may contribute to reduced microbial activity and lower CO_2 emissions under potato compared with other crops.

In contrast to seasonal effects, crop type remained a significant driver of soil CO_2 emissions, highlighting the importance of plant functional traits in regulating belowground carbon dynamics. Variations in root biomass, carbon allocation, and rhizosphere activity among crops likely influenced microbial processes and soil respiration rates.

The absence of significant water and interaction effects suggests that soil moisture conditions were not limiting during the study period. Under such conditions, biologically driven processes appear to dominate the regulation of soil CO_2 emissions across seasons.

These findings are consistent with previous studies showing that plant functional traits and root-derived carbon inputs exert stronger control over soil respiration than short-term climatic variability [9,26]. Generally, the results indicate that crop identity plays a more prominent role than seasonal variation in shaping soil CO_2 emissions in this system.

4.4. Relationships Between CO_2 Emissions and Environmental Parameters

Photosynthetically active radiation (PAR) was the only environmental variable significantly associated with soil CO_2 emissions, indicating a close link between carbon fluxes and plant physiological activity. Higher radiation levels are associated with increased photosynthesis and greater belowground carbon allocation, which can enhance root and rhizosphere respiration.

Despite this relationship, the wide dispersion of observations suggests that PAR alone does not fully explain the variability in soil CO_2 emissions, and that additional biotic or environmental factors may contribute to the observed patterns.

In contrast, soil moisture content and soil temperature did not show significant independent effects on CO_2 emissions. The lack of clear relationships, together with the high variability in the data, indicates that these factors were not primary controls of soil respiration under the conditions of this study. Similarly, groundwater level showed no consistent influence on CO_2 emissions, suggesting a limited short-term role of hydrological fluctuations in regulating soil aeration and microbial activity.

These findings are consistent with previous studies demonstrating strong coupling between radiation-driven photosynthesis and ecosystem respiration [27], as well as the dominant role of plant-mediated processes in controlling short-term soil respiration dynamics during active growth periods [28].

4.5. *Effects of Fertilization on Soil CO_2 Emissions*

The significant increase in soil CO_2 emissions following fertilization indicates a stimulation of soil biological activity during the crop growth period. The higher emissions observed two weeks after fertilizer application suggest enhanced soil respiration under increased nutrient availability.

This response may be associated with increased microbial decomposition of organic matter, as well as enhanced root growth and respiration following nutrient addition. The combined contribution of microbial and root respiration likely contributed to the observed increase in CO_2 emissions, reflecting accelerated carbon turnover in the soil.

These findings are consistent with previous studies showing that nitrogen fertilization can increase soil CO_2 emissions by stimulating microbial activity and soil carbon decomposition [29], supporting the role of nutrient inputs in regulating soil respiration dynamics.

4.6. *Productivity–Soil Respiration Dynamics Under Irrigated and Rainfed Systems*

Irrigation significantly increased crop productivity without a corresponding increase in soil CO_2 emissions. This indicates that yield gains were achieved without proportional increases in soil carbon efflux, suggesting a decoupling between productivity and soil respiration under the conditions of this study. The similar CO_2 emissions observed under irrigated and rainfed treatments further suggest that soil moisture remained within a range that supported both microbial and root activity, limiting additional stimulation of respiration by irrigation.

When emissions were expressed per unit of dry yield, irrigation reduced CO_2 emission intensity for several crops, with significant reductions observed for beans and Irish potato. This demonstrates that increased productivity can lower emission intensity even when absolute CO_2 fluxes remain unchanged. For maize and brachiaria, similar trends were observed but were not statistically significant.

These results highlight the importance of yield-scaled metrics in evaluating the environmental performance of agricultural systems, as they provide a more integrated assessment of productivity and associated emissions. Under such an approach, irrigation can improve the efficiency of production by increasing yields without increasing soil CO_2 emissions.

4.7. *Limitations of the Study, Implications and Future Research Directions*

4.7.1. Limitations

Several limitations should be considered. The moderate sample size may have reduced the ability to detect subtle treatment effects, particularly short-term responses to irrigation and fertilization. Rainfall events occurring before sampling likely reduced differences in soil moisture between irrigated and rainfed plots, potentially masking irrigation effects. In addition, the study was conducted at a single marshland site, which limits the generalization of the findings to other systems. Finally, the study covered only two cropping seasons, whereas longer-term observations are needed to capture interannual variability in soil respiration.

4.7.2. Implications and Future Research Directions

The results indicate that crop type is a stronger driver of soil CO_2 emissions than irrigation, while irrigation mainly enhances productivity without increasing emissions. This suggests that irrigation can improve yields without substantially intensifying soil carbon losses under humid marshland conditions.

Future research should focus on partitioning soil respiration into autotrophic and heterotrophic components, conducting long-term studies across varying climatic conditions, and evaluating irrigation strategies under drier environments. Such work would support the development of climate-smart management practices for marshland agroecosystems.

5. Conclusions

Soil CO_2 emissions in the Tonga marshland agroecosystem were primarily driven by crop type, phenological stage, and fertilization, while irrigation had no significant effect on total soil respiration. Emissions differed significantly among crops, with Brachiaria showing the highest fluxes, and peaked during the crop development stage, highlighting the strong influence of plant physiological activity on belowground carbon dynamics. Fertilization significantly increased soil CO_2 emissions, likely due to stimulation of microbial decomposition and root respiration following nutrient inputs.

Despite its limited influence on absolute soil respiration, irrigation substantially increased crop yields. Consequently, CO_2 emissions per unit of production were significantly lower for beans and Irish potato under irrigated conditions, reflecting improved production efficiency.

Despite its limited influence on absolute soil respiration, irrigation substantially increased crop yields. Consequently, CO_2 emissions per unit of production were significantly lower for beans and irish potato irrigated conditions, reflecting improved production efficiency. This suggests that irrigation can reduce the carbon intensity of crop production even when total soil CO_2 fluxes remain unchanged. Higher emissions observed in cropped soils compared with bare soil further confirm the dominant role of root and rhizosphere processes in regulating soil respiration. Overall, these findings emphasize the importance of evaluating greenhouse gas emissions on a yield-scaled basis to better assess trade-offs between agricultural productivity and climate mitigation in tropical agroecosystems.

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Abbreviations

The following abbreviations are used in this manuscript:

CO_2	Carbon dioxide
CAFF	College of Agriculture, Forestry and Food Sciences
CVAS	College of Veterinary Medicine and Animal Sciences
SLU	Swedish University of Agricultural Sciences
EC	Electrical conductivity
DAP	Diammonium phosphate
KCl	Potassium chloride (Muriate of Potash)
NPK	Nitrogen, phosphorus, and potassium fertilizer
P_2O_5	Phosphorus pentoxide equivalent
K_2O	Potassium oxide
RCBD	Randomized Complete Block Design
PAR	Photosynthetically Active Radiation
SMC	Soil moisture content
ST	Soil temperature
GWL	Groundwater level
SE	Standard error
R	R statistical software

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