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ORIGINAL ARTICLE

Soil respiration under different N fertilization and irrigation regimes in Bengaluru, S-India

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Abstract Rapid urbanization in many countries of the Global South has led to intensification of urban and peri-urban agriculture (UPA) whose effects on the soils' physical, chemical, and microbial properties have been hardly studied. We therefore investigated the effects of different intensity levels, exemplified by three rates of mineral nitrogen (N) addition and irrigation on CO_2 emissions in typical crops during the wet (*Kharif*) and dry (*Rabi*) season on a Nitisol in Bengaluru, S-India. Respiration data were collected from 2017 to 2021 in two two-factorial split-plot experiments conducted under rainfed and irrigated conditions. Test crops were maize (*Zea mays* L.), finger millet (*Eleusine coracana* Gaertn.), and lablab (*Lablab purpureus* L. Sweet) under rainfed and irrigated conditions, as well as the vegetables cabbage (*Brassica oleracea* var. *capitata*), eggplant (*Solanum melongena* L.), and tomato (*Solanum lycopersicum* L.) or chili (*Capsicum annuum* L.). Carbon dioxide (CO_2) emissions were determined using a Los Gatos Research (LGR) multi-gas analyzer whereby under our study conditions CH_4, NH_3 and N_2O were negligible. Measurements were conducted from 7:00 am to 11:30 am and repeated from 12:30 pm to 6:00 pm. Irrespective of irrigation, season, crops and N fertilizer level, CO_2 emission rates during afternoon hours were significantly higher (2–128%) than during morning hours. In the irrigated field diurnal emission differences between afternoon and morning hours ranged from 0.04 to 1.61 kg CO_2-C ha^{-1} h^{-1} while in the rainfed field they averaged 0.20–1.78 kg CO_2-C ha^{-1} h^{-1}. Irrespective of crops, in the rainfed field CO_2 emissions in high N plots were 56.4% larger than in low N plots whereas in the irrigated field they were only 12.1% larger. The results of a linear mixed model analysis indicated that N fertilization enhanced CO_2 emissions whereby these effects were highest in rainfed crops. Soil moisture enhanced emissions in rainfed crops but decreased them under irrigation where crop-specific CO_2 emissions within a season were independent of N application. Soil temperature at 5 cm depth enhanced CO_2 emissions in both fields. Overall, higher N and soil temperature enhanced CO_2 fluxes whereas effects of soil moisture depended on irrigation.

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Introduction

Worldwide agroecosystems around rapidly growing cities are greatly affected by rural–urban transformation as farmers continuously adapt their crop choices and management intensities in response to the growing competition for land, labour, and water as well as the opportunities of large and close-by urban markets (Swain and Teufel 2017). This leads to intensified crop cultivation which may affect the soils' physical, chemical, and biological properties whose response to the regime-shifts imposed remains poorly studied (Elmqvist et al. 2013; Steinhübel and von Cramon-Taubadel 2020). This is particularly the case for poorly buffered tropical soils of the Global South. Jain et al. (2019) reported that farmers in many peri-urban areas of India have changed their cropping patterns focusing on high-priced horticultural or local specialty crops such as grape (*Vitis vinifera* L.) and finger millet (*Eleusine coracana* Gaertn.). Such crops yield higher revenue per unit of water consumed and are often cultivated year round under drip irrigation. Short duration crops are intensely rotated whereby a major knowledge gap exists on the effects of irrigation and fertilization on CO_2 emissions (Buerkert et al. 2021).

Agriculture is a significant contributor to greenhouse gas (GHG) emissions (Heimsch et al. 2021; Lynch et al. 2021). Thereby the majority of studies agree that CO_2 contributes the largest proportion of GHG emissions from soils and its flux rates are more than hundred times larger than those of N_2O, CH_4, and other gases which is, however, partly compensated for by higher GHG effects of the latter (Ruser et al. 2006; Chen et al. 2010; Abalos et al. 2014; Negassa et al. 2015). CO_2 emissions from soils heavily depend on its water content and N status (Darwish et al. 2006; Abalos et al. 2014) and it is also known that crop rotation in combination with irrigation and fertilizer application lead to changes in soil C and N dynamics by altering plant primary production, nutrient uptake, and recycled plant residues (Snyder et al. 2009; Weiler et al. 2018; Oldfield et al. 2019; Araya et al. 2021).

From a subtropical *Pinus* plantation in southeastern China Iqbal et al. (2008) reported that CO_2 emissions depended on soil temperature and water-filled pore space (WFPS). Tang et al. (2005) and Gaumont-Guay et al. (2006) determined that 70% of the diurnal variation of soil CO_2 fluxes was determined by soil temperature, which was similar to results of Manka'abusi et al. (2020) for CO_2, N_2O, and NH_3 in Quagadougou (Burkina Faso) and Tamale (northern Ghana). In the same study, cropping cycles and seasons also affected CO_2 emissions whereby CO_2 emissions under amaranth (*Amaranthus* L.) were significantly higher (20–83%) than those of other crops in the cycle (lettuce—*Lactuca sativa* L., jute mallow—*Corchorus olitorius* L. and carrot—*Daucus carota subsp. sativus*) across all treatments. It was also observed that mean CO_2 emissions for lettuce and carrot were significantly lower (11–66%) during the cold and dry season compared with the rainy period.

In Bengaluru rural–urban transition has led to altered cropping patterns (Patil et al. 2019), depletion of ground water sources (Kulkarni et al. 2021), intensification of N fertilizer application (Prasad et al. 2019), and a shift from rainfed agriculture to irrigated systems (Prasad et al. 2016). Under the monsoonal climate conditions of S-India with frequent drought spells irrigation plays an important role in enhancing crop yield, but little is known about changes in soil respiration as a consequence of system intensification exemplified by rising N levels and irrigation on the prevailing heavily leached tropical soils.

To fill this knowledge gap, we therefore have investigated CO_2 emissions from soils (soil respiration) in complex rotation systems to (i) assess diurnal changes in CO_2 emissions across different seasons, (ii) record the effects of N fertilization on CO_2 emissions, and (iii) determine crop specific irrigation effects on CO_2 fluxes. We hypothesized that (1) CO_2 emissions during afternoon hours are significantly higher than during morning hours, (2) N application enhanced CO_2 fluxes, and (3) under irrigated conditions CO_2 emissions were similar for all crops.

Materials and methods

Site overview and experimental design

Two two-factorial cropping experiments were established on the premises of University of Agricultural Sciences, Gandhi Krishi Vignan Kendra (GKVK) Campus, Bengaluru (UASB),, Karnataka State, S-India with cultivated crop in a 3-part rotation and N fertilizer levels as fixed factors. At a distance of 500 m both experiments were established on deeply leached sandy Kandic Paleustalfs (US Soil Taxonomy) or Dystric Nitisols

(World Reference Base) with identical treatments and crop rotations, but a different randomization. One field completely depended on rainwater and thus carried the Rainfed Experiment (RE; 13° 5′19.05"N, 77°34′16.11"E, 927 m asl). The other field had provision of irrigation water and therefore was an Irrigated Experiment (IE; 13° 5′15.32"N, 77°33′59.71"E, 930 m asl; Fig. 1). The RE field had a history of arable cropping of finger millet (*Eleusine coracana* Gaertn.) for more than five years, while the IE was newly established after clear-cutting a > 10-year old *Eucalyptus* plantation. This site was cleaned from all plant debris (tree stumps, roots, and branches) and ploughed followed by disking and several months of fallow prior to cultivation (Buerkert et al. 2023). The local climate in Bengaluru with a mean annual rainfall of 943 mm (Navya 2021) is divided into two distinct periods: the wet season from June to November and the dry season from December to May.

The layout of both experiments comprised 12 main plots (three crops replicated four times) in each field. Each main plot contains three subplots (12 m × 6 m) with randomly allocated a low, medium, and high N fertilizer rate (Fig. 2). High N stands for the officially recommended N application dose for the corresponding crop, whereas medium N was defined as 50% of high N. The low N treatment consisted initially of 1/3rd of the recommended N which was reduced to zero from the 2018 wet season onwards (Table 6, Appendix). During the wet seasons crops rotated in both experiments were maize (*Zea mays* L., cv. Hema), lablab (*Lablab purpureus* L. Sweet, cv. HA3), and finger millet (cv. ML-365). In the dry season only *IE* was planted with cabbage (*Brassica oleracea* var. *capitata*, cv. Unnati), eggplant (*Solanum melongena* L., cv. Ankur), tomato (*Solanum lycopersicum* L., cv. NS-501) from 2017 to 2019, and chili (*Capsicum annum* L., cv. Demon) from 2020 to 2022 (Table 1).

Urea (46% N) was used as a N source and was complemented by a broadcast application of phosphorus (P) as single super phosphate (SSP; 3.1% P) and potassium (K) as muriate of potash (MOP; 41.5% K). Nitrogen was split-applied with 50% during sowing and the remaining amount 30 days after sowing (DAS; Table 6, Appendix).

Rainfall and air temperature data at the experimental locations were recorded from 10th June 2016 until 10th May 2022 at 15 min intervals by an automatic HOBO weather station (Onset Comp. Corp., Bourne, MA, USA). Annual rainfall in the driest year 2018 was only 728 mm, whereas 2021 received 1212 mm. Mean minimum and maximum air temperatures in the wet season were 18 °C and 28 °C, respectively, whereas in the dry season they were 19 °C and 32 °C (Figure 6, Appendix).

Soil sampling and analysis

Soil samples were collected at the beginning, in the middle, and after the experimental period (Table 2). To this end, in each high and low N plot, ten cores of 4.2 cm diameter were randomly collected at 0–15 cm depth, mixed, air-dried, and sieved to 2 mm. Dry-matter and organic matter were determined according to VDLUFA (1997). Soil pH was determined in a 0.01 M

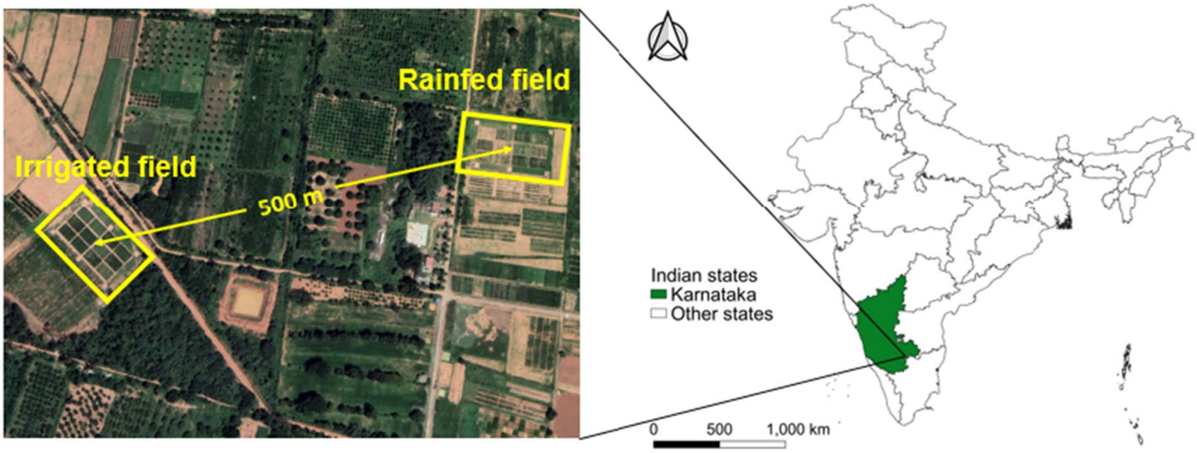

Fig. 1 Location of the two experimental fields at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India. Google Earth, Oct 2017

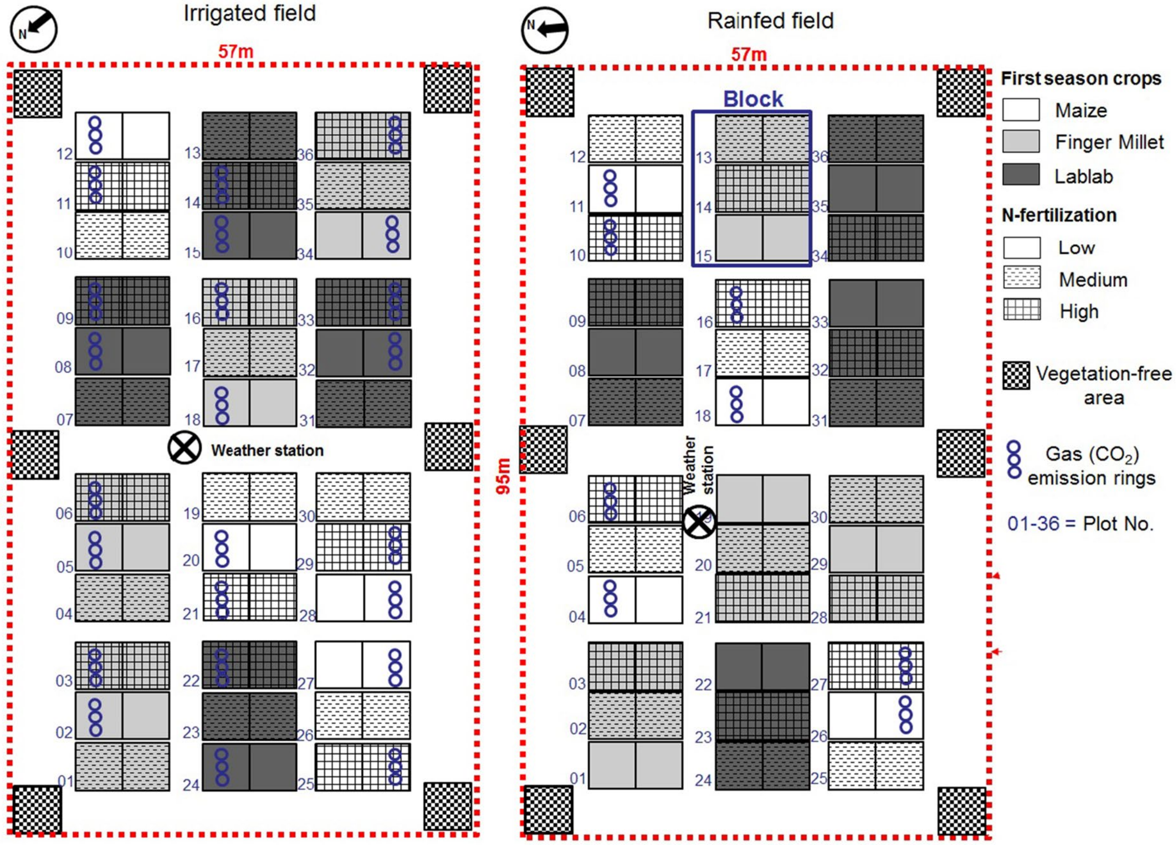

Fig. 2 Layout of the two cropping system experiments at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India (Buerkert et al. 2021)

Table 1 Crop rotation in the two cropping system experiments at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India

Years	Seasons	Rainfed			Irrigated		
2016	Dry	–	–	–	–	–	–
	Wet	Maize	F. millet	Lablab	Maize	F. millet	Lablab
2017	Dry	–	–	–	Cabbage	Eggplant	Tomato
	Wet	F. millet	Lablab	Maize	F. millet	Lablab	Maize
2018	Dry	–	–	–	Eggplant	Tomato	Cabbage
	Wet	Lablab	Maize	F. millet	Lablab	Maize	F. millet
2019	Dry	–	–	–	Tomato	Cabbage	Eggplant
	Wet	Maize	F. millet	Lablab	Maize	F. millet	Lablab
2020	Dry	–	–	–	Cabbage	Eggplant	Chili
	Wet	F. millet	Lablab	Maize	F. millet	Lablab	Maize
2021	Dry	–	–	–	Eggplant	Chili	Cabbage
	Wet	Lablab	Maize	F. millet	Lablab	Maize	F. millet

$CaCl_2$ solution with a freshly calibrated pH electrode (WTW pH3110, Xylem Analytics Germany Sales GmbH & Co. KG, Weilheim, Germany). To measure total soil C and N, a VarioMax CHN-Analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany) was used.

Table 2 Soil carbon (C), nitrogen (N), and pH of the two experimental sites (Irrigated Experiment, IE and Rainfed Experiment, RE) at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India

Mean	2016				2019				2021			
	RE		IE		RE		IE		RE		IE	
	Low N	High N	Low N	High N	Low N	High N	Low N	High N	Low N	High N	Low N	High N
C (%)	0.5	0.5	0.8	0.9	0.4	0.5	0.8	0.8	0.4	0.5	0.8	0.8
N (%)	0.04	0.04	0.07	0.07	0.04	0.05	0.07	0.08	0.04	0.05	0.08	0.08
pH	4.5	4.5	5.0	5.2	4.4	4.2	6.9	6.8	4.2	4.2	6.4	6.4

In situ gas emission measurements

CO_2 emission data were collected from the wet season 2016 to the dry season 2021 for which total aboveground biomass data are available in Buerkert et al. (2023). Measurements were conducted using a closed-chamber system connected to a multi-gas analyzer by a 1.5 m long PVC pipe of diameter 0.005 m. An INNOVA 1312 Photoacoustic Multi-gas Monitor (CO_2, N_2O, CH_4, NH_3 and H_2O; Luma Sense Technologies A/S, Ballerup, Denmark) was used from 2016 until dry season 2019 and thereafter replaced by a Los Gatos Research (LGR) Multi-gas Analyzer (CO_2, CH_4, NH_3 and H_2O; ABB Inc., San Jose, CA, USA) for higher accuracy and data density. To this end, three rings of 0.075 m height and 0.29 m diameter were installed at the beginning of the cropping season in plant rows by pushing the rings 0.05 m deep into the soil, 1 m away from the bunds. The area inside the rings/collars was cleaned from plant debris and weed plants one day before measurement without disturbing the soil. In every season, CO_2 emissions were determined before and after the first and second N application. The one-day measurement before fertilizer application was used as the baseline emission. After N application, emissions were determined for up to three days in the morning (7:00–11:30 am) and afternoon hours (12:30 pm to 6:00 pm) together with air temperature and relative humidity as well as soil temperature (0–0.05 m and 0.10 m depth) and volumetric water content (0.1 m depth) inside the gas emission chambers. In each ring, emissions were recorded for 4 min at a frequency of 1 min with Innova and of 10 s with LGR. One minute of refreshing time was used for flushing out accumulated gas inside Innova/LGR to avoid any carry over effects between measurements.

Under the tropical environmental conditions and management practices on the deeply weathered, well aerated soils of our study, emissions of NH_3 and N_2O were negligible in 65% of all measurements. This created an improper distribution of the gas emission data for both gases among the crops and treatments. CH_4 emissions were always small and negative. Therefore, we excluded these parameters from further analysis and for this study used only CO_2 emission data.

During four years, each crop in the rotation was covered at least once in each plot (2017–2019). In the RE, gas emissions were determined for only one crop per season, starting with millet. CO_2 emission measurements started in the dry season 2017 and ended in 2021. Wet season measurements were taken between 2017 and 2020.

Statistical analysis

All raw data were synchronized with the respective time stamps in STATA 15 software (StataCorp 2017). Subsequently, data were loaded in R 4.2.0 software (R Core Team 2022) to calculate gas fluxes using the linear model of the "gasfluxes" package (Fuss 2020). CO_2 flux rates were calculated by subtracting initial chamber concentrations from final concentrations and dividing the difference by the time period for which gas emission was measured. Data were tested for normality of residuals and non-normal data were discarded for each ring's measurement in a season of a crop at the respective fertilizer application time. The mean difference between two independent groups was analyzed by one-way analysis of variance (ANOVA) adjusted with the Bonferroni procedure in STATA 15. A repeated measures mixed linear (ML) model analysis was used in STATA 15 to investigate the effects of N application, soil temperature, and soil moisture on CO_2 flux rates. Fixed effects were N rate, soil temperature, soil moisture, and their interaction, while crops were considered as random. The equation was determined using backward stepwise regression in

Table 3 Diurnal variation of CO_2 emission within low and high N plots in different crops of a rainfed and irrigated experiment (RE and IE) at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India

Field type	Crop	Difference of CO_2-C emissions (%) (Afternoon–Morning)	
		Low N plots	High N plots
Rainfed	Finger millet	32.4***	11.0
Rainfed	Lablab	15.7	31.3**
Rainfed	Maize	128.4***	101.5***
Irrigated	Cabbage	41.5***	36.8***
Irrigated	Chili	12.2*	9.8
Irrigated	Egg plant	52.7***	36.9***
Irrigated	Tomato	27.5***	21.5***
Irrigated	Finger millet	33.7***	48.1***
Irrigated	Lablab	33.9*	72.0***
Irrigated	Maize	1.8	26.8***

***,**,* Significance at $p < 0.01$, 0.05 and 0.10, respectively

which least significant variables were dropped one after another until no insignificant variables remained.

Results

Mean CO_2-emissions

Soil temperature varied widely from 13.1 °C to 41.2 °C, soil moisture from 0.4% to 96%, internal chamber temperature from 15.8 °C to 48.4 °C, and relative humidity inside the chamber from 1 to 94%. Similarly, CO_2-emissions before and after fertilizer application in the IE (Fig. 3) and RE (Fig. 4) varied widely across time.

Diurnal variation in CO_2 emissions

Across all crops, treatments, and both fields, CO_2 emissions averaged 1.97 ± 1.0 kg C ha^{-1} h^{-1} in the morning

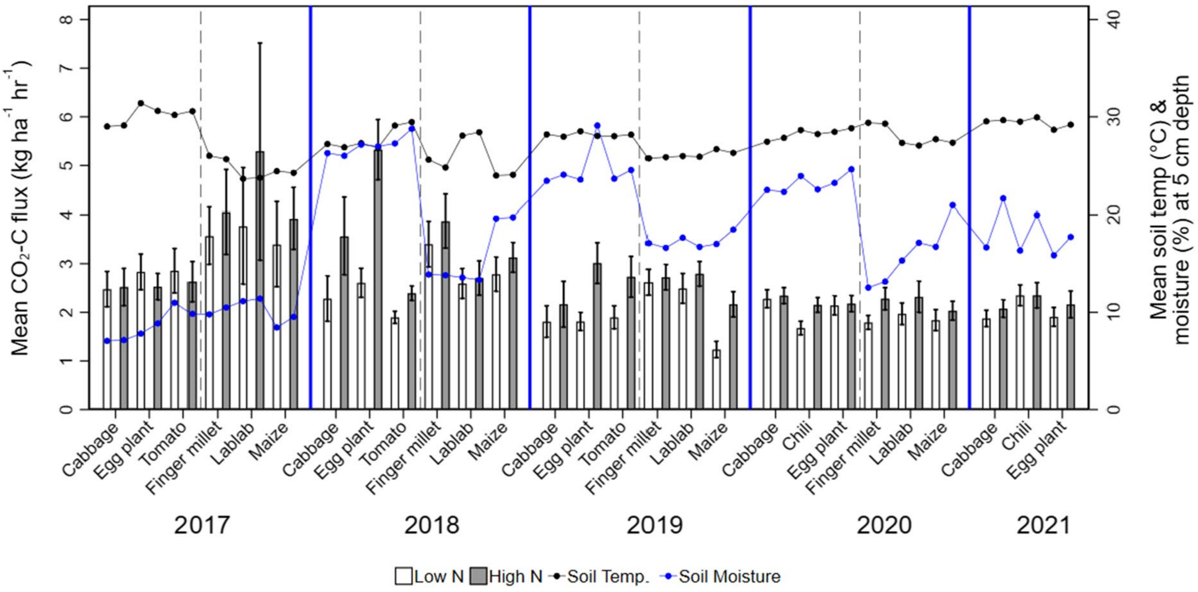

Fig. 3 Mean CO_2-C emissions of irrigated crops before and after different levels of N application under the soil moisture and temperature conditions at GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India

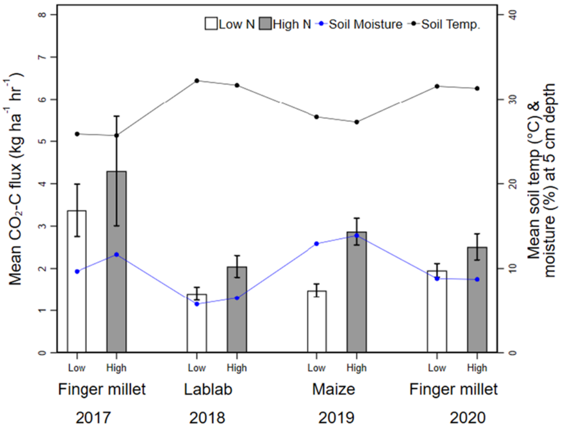

Fig. 4 Mean CO_2-C emissions of rainfed crops under different N application, soil moisture, and temperature conditions at GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India

(7:00 to 11:30 am) and 2.73 ± 1.5 kg C ha^{-1} h^{-1} in the afternoon (12:30 to 06:00 pm). Regardless of crops and treatments, CO_2 emissions during afternoon hours were 46.1% and 8.7% higher than during morning hours in the RE and IE ($p < 0.001$), respectively. Diurnal variations of CO_2 emission in low and high N plots of the RE and IE were high (Table 3) but the differences between afternoon and morning hours were always positive. Differences of diurnal CO_2 emissions across crops were not consistent with N application.

Fertilization effects on CO_2-C emissions for wet and dry season crops

Nitrogen application significantly ($p < 0.05$) affected CO_2 emissions in all wet season crops of the RE and IE, as well as dry season crops in the IE. Mean CO_2 fluxes ranged from 1.5 to 3.0 kg C ha^{-1} h^{-1} (Table 4). High N plots had significantly higher CO_2 emissions than low N plots across all crops and seasons in both experiments. The difference between high and low N plots' CO_2 emissions (across crops) during the wet season in the IE was 56.4% (0.93 kg C ha^{-1} h^{-1}) whereas it was 12.1% (0.28 kg C ha^{-1} h^{-1}) in the IE. Similarly, during the dry season the difference was 8.0% (0.17 kg CO_2-C ha^{-1} h^{-1}). Analyzed crop-wise, the differences in CO_2 emissions between low and high N plots in the irrigated field were between 0.3 to 0.4 kg C ha^{-1} h^{-1}, except for eggplant which had 1.0 kg C ha^{-1} h^{-1}. On the other hand, rainfed finger millet and lablab had CO_2 flux differences of 0.5 and 0.6 kg C ha^{-1} h^{-1}, respectively, whereas maize had 1.0 kg C ha^{-1} h^{-1}. The amount of urea fertilizer applied in the dry season of 2019–2021 was 15.0% higher than during the wet season. Also, MOP application was 14.8% and SSP 31.8% higher than during the wet season while total dry matter yield in the dry season averaged only 43.0% of the wet season dry matter. Soil moisture content affected CO_2 emissions positively under rainfed condition but negatively under irrigation.

Crop specific CO_2 emissions under irrigation

To analyze the effects of growing crops on CO_2 emissions, we focused on the IE because its plots were intensively cultivated throughout the year. Plots of the dry season crops cabbage, chili, eggplant, and tomato had CO_2 emission rates between 1.8 and 2.5 kg C ha^{-1} h^{-1} (Table 4). On the other hand, plots with the wet season crops finger millet, lablab, and maize had emission rates between 2.3 and 3.0 kg C ha^{-1} h^{-1} with a confidence interval of 0.95. Mean CO_2 emissions within a season did not significantly vary between crops. However, across seasons lablab plots had significantly higher CO_2 emissions than those of cabbage, chili, eggplant, and tomato while emission rates in maize and finger millet plots were significantly higher than those of cabbage, chili, and eggplant (Fig. 5).

Mixed effects of treatment-application, soil temperature, soil moisture, and crops on CO_2 emissions

We also analyzed treatment level, soil moisture, and soil temperature as fixed effect parameters while crops were considered as a random effect parameter (Table 5). Random parameter did not significantly affect the fixed parameters as the variance inflation factor (VIF) for each independent variable in the regression model was close to 1. This indicates that crops had no significant effect on CO_2 emissions. Effects of N application on CO_2 emissions were lowest in dry season crops and highest in rainfed wet season crops. Soil moisture had different effects in irrigated and rainfed plots: in IE it was negatively correlated with CO_2 emissions while in RE it enhanced CO_2 emissions. Effects of soil temperature on CO_2 emissions were highest in rainfed wet season crops and lowest in irrigated dry season crops.

Table 4 Comparison of mean CO_2–C emissions from different crops in the irrigated and rainfed field experiment (RE and IE) at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India

Field type	Crop	Mean CO_2 flux (kg C ha^{-1} h^{-1})		Significance (P)
		Low N plots	High N plots	
Rainfed	Finger millet	2.0 (74)	2.5 (68)	0.003
Rainfed	Lablab	1.4 (34)	2.0 (40)	0.001
Rainfed	Maize	1.5 (83)	2.9 (89)	0.001
Irrigated	Cabbage	2.1 (230)	2.5 (251)	0.003
Irrigated	Chili	2.0 (130)	2.3 (145)	0.008
Irrigated	Egg plant	2.3 (292)	3.3 (314)	0.001
Irrigated	Tomato	2.1 (144)	2.5 (158)	0.001
Irrigated	Finger millet	2.5 (243)	2.8 (243)	0.039
Irrigated	Lablab	2.7 (250)	3.0 (252)	0.045
Irrigated	Maize	2.0 (250)	2.4 (266)	0.002

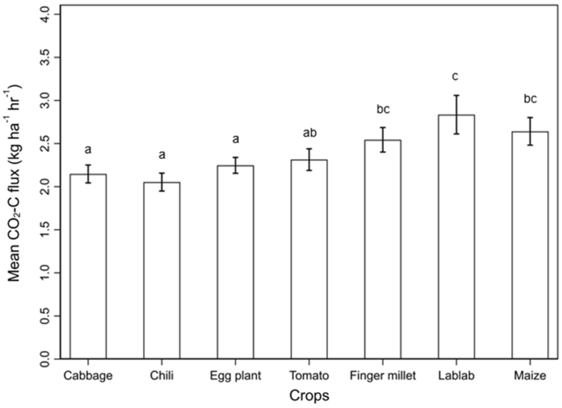

Fig. 5 Crop specific mean CO_2–C emissions in an irrigated crop rotation experiment at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India. Mean CO_2 emissions of both low and high N plots for each crop across years yielded different numbers of replications for each crop: cabbage (5), eggplant (5), tomato (3), chili (2), finger millet (4), lablab (4), and maize (4). Vertical bars indicate ± one standard error of the mean

Discussion

Soil temperature and moisture increases CO_2 emissions

Agriculture along the rural–urban gradients in the S-Indian megacity of Bengaluru with its 12 Mio inhabitants is characterized by the intensive use of agricultural inputs, continuous cropping, and increasingly year-round irrigation despite notorious water scarcity. Our experiments aimed at mimicking cultivation patterns in this transformative environment. It is well known that soil temperature and moisture greatly influence a soil's C and N mineralization rates (Sierra 1997; Rey et al. 2005). Under non-limiting moisture conditions higher temperature enhances microbial metabolism which leads to higher C and N decomposition by increasing microbial respiration (Lloyd and Taylor 1994; Rey et al. 2005; Allison et al. 2010). Davidson and Janssens (2006) stated that a significant proportion of labile soil organic carbon is subject to temperature sensitive decomposition, while other fractions remain stable under environmental constraints. This often masks temperature effects on soil organic matter (SOM) decomposition. In our study differences in mean soil temperature to 5 cm depth between afternoon and morning hours in rainfed and irrigated fields were 4.1 °C and 5.9 °C, respectively. The temperature difference was higher in the IE than the RE, most likely due to the cooling effect of irrigation water applied during morning hours. In the RE, overall CO_2 emission rates during afternoon hours were 46% higher than during morning hours while in the IE CO_2 emissions during afternoon hours were 40% higher than during morning hours in the wet season. The lower diurnal variation of emissions in the irrigated field may be due to the limiting effects of higher soil moisture on CO_2 emission and to reduced respiration during the wet season. Peng et al. (2011) reported in their study that soil moisture became a limiting factor for CO_2 emission during the growing season (July–September) within a similar moisture content (2–22%) and temperature (20–40 °C) range.

N fertilization increases CO_2 emissions

At low soil C such as in our study higher N is known to stimulate soil microbial activity which in turn

Table 5 Mixed model coefficients of fixed effect parameters and estimates of random parameters on CO_2 emissions (kg C ha^{-1} h^{-1}) in a rainfed and irrigated crop rotation experiment at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India

	Dry season	Wet season	
	Irrigated	Rainfed	Irrigated
Fixed effect	Coefficients	Coefficients	Coefficients
Treatment level (0- low, 1- high)	0.280***	0.974***	0.419***
Soil moisture (%)	– 0.012***	0.062***	– 0.023***
Soil temperature at 5 cm (°C)	0.044***	0.069***	0.068***
Random effect	Estimate	Estimate	Estimate
Crops (crop Id)	0.002	2.81e−18	2.61e−14

*** Significance at $p<0.01$

increases SOC mineralization thereby emitting more CO_2 (Häring et al. 2017). Another mechanism by which higher N fertilization increases CO_2 emissions is the sequestration of higher carbon (C) inputs from increased crop growth (Adviento-Borbe et al. 2007). In our study irrespective of irrigation, CO_2 emissions in all crops significantly increased with N application. However, the relative increase in CO_2 emissions of wet season crops from low N plots was greater in rainfed plots than in irrigated plots. The mean CO_2 emission in rainfed high N plots was 56.4% higher than in low N plots. In the IE the same set of wet season crops grown on high N plots had only 12.1% higher CO_2 emissions than those in low N controls.

Development of root and shoot growth in plants also induces increased CO_2 emissions (Magill et al. 1997). On our experimental plots, high N plots had significantly higher aboveground plant biomass than low N plots (Moran-Rodas et al. 2022; Buerkert et al. 2023). Higher CO_2 emissions from the high N plots align with the results of previous studies. Correlations between dry matter yield and CO_2 emissions were r = 0.37 (P = 0.018). Under irrigation crop specific CO_2 emissions are unrelated to N fertilization.

Over the entire experimental period, crop types within a season didn't affect CO_2 emissions under different soil C, N, temperature, and moisture conditions. Differences in CO_2 emissions among different crop species may also be due to differences in root respiration of these crops. In this context, it has been shown that plant root respiration may contribute 10–90% of the total soil CO_2 emissions (Rochette et al. 1999; Hanson et al. 2000). In our study the wet season crop lablab had higher mean CO_2 emissions than maize and finger millet. Being a legume, lablab has comparatively higher energy demands than cereals and vegetable crops which is positively correlated with root respiration (Rao and Ito 1998).

CO_2 emissions of all crops in wet season averaged 2.6 kg C ha^{-1} h^{-1}, whereas in dry season it was 2.2 kg C ha^{-1} h^{-1} (Fig. 3). This difference in seasonal CO_2 emissions may be attributed to a lower soil moisture content (17%) and higher biomass production during the wet season and residual effects of higher N rates applied in the dry season (22%). Among all grown crops in our experiment, maize was the most sensitive in terms of biomass production to limited N and produced higher biomass than other crops. The combined effect of lower biomass production and higher soil moisture content in dry season may have led to residual N at the onset of the following wet season.

Combined effects of N fertilization, soil moisture, and soil temperature on CO_2 emissions

The magnitude of N fertilization effect was highest in rainfed crops whereby high N plots had 2–5 times higher biomass production than plots without N (Buerkert et al. 2023). In the IE the high N treatment led to an only 20–30% higher biomass compared with zero N plots. N fertilization induces microbial activity and root respiration in the plants and the findings of this study agree with the results of previous studies (Sainju et al. 2008; Peng et al. 2011). Soil moisture affected CO_2 emission differently depending on irrigation. In the RE field, soil moisture positively correlated with CO_2 emissions but negatively in the IE field. Usually, irrigation or rain in dry soil increases

C mineralization and root respiration, resulting in higher CO_2 flux rates (Curtin et al. 2000; Abalos et al. 2014). Soil moisture has been reported to have a parabolic relationship with soil surface CO_2 emissions thereby controlling the diffusivity of the CO_2 along air filled pores (Hashimoto and Komatsu 2006). Also it is well known that water-filled pores restrict soil aeration thereby hampering microbial activity which determines soil respiration (Linn and Doran 1984). However, in our experiment these processes were not measured. Temperature plays an important role in decomposing soil organic matter (SOM). In our study, soil temperature (up to 5 cm depth) affected the CO_2 emission equally in IE and RE fields during the wet season but had slightly lower effect during the dry season (Table 5). In the latter season diurnal soil temperature differences were greater than in the wet season but on the other hand soil moisture content was comparatively higher due to continuous irrigation. Thus, the higher soil moisture content may have masked the temperature effects during the dry season.

Conclusions

This study confirmed that on the deeply weathered Nitisols of S-India N application leads to higher CO_2 emissions whereby the magnitude of C losses depends on soil moisture. The effects of N application on C losses were considerably higher under rainfed than under irrigated conditions. Soil moisture content affected CO_2 emissions positively under rainfed but negatively under irrigated conditions. There was no indication of crop effects on CO_2 emissions but wet season crops had significantly higher CO_2 emission under irrigation. This calls for further research on the interactions between soil moisture and CO_2 emissions under more controlled conditions.

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Declarations

Competing interests The authors declare no competing interests.

Appendix

See Fig. 6 and Table 6.

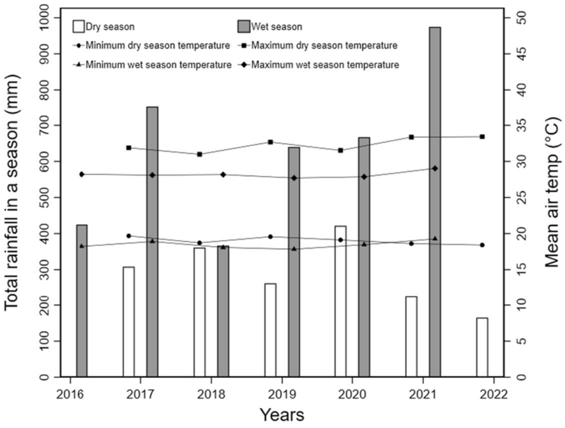

Fig. 6 Maximum and minimum mean air temperature and total rainfall distribution at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India from June 2016 until June 2022

Table 6 Fertilizer dosages (in kg ha^{-1}) in the two cropping system experiments at the GKVK Campus of the University of Agricultural Sciences Bangalore (UASB), S-India. Adapted from Buerkert et al. (2021)

Years	Fertilizer	Rainfed			Irrigated						
		Dry season			Dry season				Wet season		
		Maize	F.Millet	Lablab	Cabbage	Tomato	Chili	Eggplant	Maize	F.Millet	Lablab
2016	N_{low}	50	25	10	–	–	–	–	50	50	10
	N_{medium}	75	37.5	15	–	–	–	–	100	75	15
	N_{high}	100	50	25	–	–	–	–	150	100	25
	P	21.8	17.5	4.4	–	–	–	–	32.7	21.8	4.4
	K	31.1	31.1	8.3	–	–	–	–	41.5	41.5	8.3
2017	N_{low}	50	25	10	30	23	–	25	50	50	10
	N_{medium}	75	37.5	15	60	46	–	50	100	75	15
	N_{high}	100	50	25	90	69	–	75	150	100	25
	P	21.8	17.5	4.4	17.5	17.5	–	17.5	32.7	21.8	4.4
	K	31.1	31.1	8.3	41.5	19.9	–	16.6	41.5	41.5	8.3
2018	N_{low}	0	0	0	0	0	–	0	0	0	0
	N_{medium}	50	25	12.5	30	23	–	25	50	25	12.5
	N_{high}	150	50	25	60	46	–	50	150	50	25
	P	21.8	17.5	4.4	17.5	17.5	–	17.5	32.7	21.8	4.4
	K	31.1	31.1	8.3	41.5	19.9	–	16.6	41.5	41.5	8.3
2019	N_{low}	0	0	0	0	–	0	0	0	0	0
	N_{medium}	50	25	12.5	30	–	75	25	50	25	12.5
	N_{high}	150	50	25	60	–	150	50	150	50	25
	P	21.8	17.5	4.4	17.5	–	32.7	17.5	32.7	21.8	4.4
	K	31.1	31.1	8.3	41.5	–	62.3	16.6	41.5	41.5	8.3
2020	N_{low}	0	0	0	0	–	0	0	0	0	0
	N_{medium}	50	25	12.5	30	–	75	25	50	25	12.5
	N_{high}	150	50	25	60	–	150	50	150	50	25
	P	21.8	17.5	4.4	17.5	–	32.7	17.5	32.7	21.8	4.4
	K	31.1	31.1	8.3	41.5	–	62.3	16.6	41.5	41.5	8.3
2021	N_{low}	0	0	0	0	–	0	0	0	0	0
	N_{medium}	50	25	12.5	30	–	75	25	50	25	12.5
	N_{high}	150	50	25	60	–	150	50	150	50	25
	P	21.8	17.5	4.4	17.5	–	32.7	17.5	32.7	21.8	4.4
	K	31.1	31.1	8.3	41.5	–	62.3	16.6	41.5	41.5	8.3

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