



Characterizing the post-monsoon CO₂, CH₄, N₂O, and H₂O vapor fluxes from a tropical wetland in the Himalayan foothill

Asha Raturi · Hukum Singh ·
Parmanand Kumar · Abhra Chanda ·
Navneet Shukla

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Abstract Wetlands are emitters of greenhouse gases. However, many of the wetlands remain understudied (like temperate, boreal, and high-altitude wetlands), which constrains the global budgets. Himalayan foothill is one such data-deficient area. The present study reported (for the first time) the greenhouse gas fluxes (CO₂, CH₄, N₂O, and H₂O vapor) from the soils of the Nakraunda wetland of Uttarakhand in India during the post-monsoon season (October 2020 to January 2021). The sampling points covered six different types of soil within the wetlands. CO₂, CH₄, N₂O, and H₂O vapor emissions ranged from 82.89 to 1052.13 mg m⁻² h⁻¹, 0.56 to 2.25 mg m⁻² h⁻¹, 0.18 to 0.40 mg m⁻² h⁻¹, and 557.96 to 29,397.18 mg m⁻² h⁻¹, respectively, during the study period. Except for CO₂, the other three greenhouse gas effluxes did not show any spatial variability. Soils close to “swamp proper” emitted substantially higher CO₂ than the vegetated soils. Soil temperature exhibited exponential relationships with all the greenhouse gas fluxes, except for H₂O vapor. The Q₁₀ values for CO₂, CH₄, and N₂O varied from 3.42 to 4.90, 1.66 to 2.20, and 1.20 to 1.30,

respectively. Soil moisture showed positive relationships with all the greenhouse gas fluxes, except for N₂O. The fluxes observed from Nakraunda were in parity with global observations. However, this study showed that wetlands experiencing lower temperature regime are also capable of emitting a substantial amount of greenhouse gases and thus, requires more study. Considering the seasonality of greenhouse gas fluxes should improve global wetland emission budgets.

Keywords Soil greenhouse gas fluxes · CO₂ · CH₄ · N₂O · Himalayan wetland · Soil physicochemical parameters

Introduction

Wetlands are one of the most crucial ecosystems of the world that occupy only 6% of the global land surface (Flury et al., 2010). They are known for their rich biodiversity and are defined as the transitional zone between terrestrial and aquatic ecosystems, as they share characteristics of both environments. These are the lands where the water table usually remains at or near the surface or is covered by shallow water (Mitsch & Gosselink, 1986, 2000). The wetlands provide a range of valuable ecosystem services to humankind such as recycling of nutrients, purifying water, attenuating floods, groundwater recharging, and also supplying drinking water, fuels, fish, fodder,

A. Raturi (✉) · H. Singh · P. Kumar · N. Shukla
Forest Ecology and Climate Change Division, Forest
Research Institute, Dehradun, Uttarakhand 248006, India
e-mail: asha.ashafri@gmail.com

A. Chanda
School of Oceanographic Studies, Jadavpur University,
Kolkata, West Bengal 700 0032, India

and habitat for wildlife; in urban areas, they control the rate of runoff, work as buffer shorelines against erosion, and a place for recreation to society (Kundu, 2020). They are described as the “Biological Supermarkets” for the extensive food web and rich biodiversity they hold (Mitsch & Gosselink, 1993). This specialized ecosystem also controls the hydrological and biogeochemical cycles in the biosphere. Due to this unique feature, the scientific community refers to this ecosystem as Nature’s kidneys (Young, 1996; Mitsch et al., 2015). However, at the same time, they have immense potential for greenhouse gas exchange with the atmosphere (He et al., 2014). Though the wetlands act as active net sinks for carbon and nitrogen, these ecosystems emit a substantial quantity of greenhouse gases (GHGs).

Several anthropogenic activities (agricultural practices, housing, and infrastructure development) drain the wetlands. Such disturbances expose soil organic matter to oxygen and consequently release carbon dioxide (CO₂) into the atmosphere. These practices cause impairment of sequestered carbon and ultimately lead to an increase in GHG emissions into the atmosphere, thereby contributing to climate change (Mitchell, 2013; Moomaw et al., 2018). The intrinsic anaerobic character unequivocally makes these wetlands the largest natural source of CH₄ towards the atmosphere. However, the emission budgets continue to remain uncertain (Saunio et al., 2020). Moreover, tropical wetlands rich in nitrogen act as active hotspots for N₂O emissions (Parn et al., 2018). The disturbance in the hydrological cycle, the variability of the wet and dry seasons, and the number and severity of extreme events might have severe impacts on the behavior and magnitude of greenhouse gas (CO₂, CH₄, N₂O, and water vapors) emissions (Meehl et al., 2007; I.P.C.C., 2013; Pascale et al., 2016).

The concentration of greenhouse gases in the atmosphere has grown because of human interventions, which enhanced the natural greenhouse effect. In the last couple of years, different research groups across the globe have observed that greenhouse gas concentrations in the atmosphere have been progressively rising, leading to climate change (Cubaschet et al., 2013; Olivier et al., 2017). The atmospheric GHGs increased from 280 ppm in the 1750s to 418 ppm in 2020 for CO₂, 715 ppb to 1888 ppb for CH₄, and 270 ppb to 334 ppb for N₂O, respectively (current data retrieved on 07/07/2021 from [https://www.esrl](https://www.esrl.noaa.gov)

[noaa.gov](https://www.esrl.noaa.gov)). The greenhouse gases emitted from various sources are responsible for global warming and changing climatic conditions due to their ability to absorb and reflect infrared radiation. Water vapor and carbon dioxide (CO₂) are the predominant greenhouse gases that contribute to > 95% of the greenhouse effect (I.P.C.C., 1990). CO₂, methane (CH₄), and nitrous oxide (N₂O) are the top three GHGs, accounting for 64%, 17%, and 6%, respectively, of the total radiative forcing (Myhre et al., 2013; Tran et al., 2018).

The dynamic of greenhouse gas emission from natural ecosystems, like that of wetlands, is controlled by various macroenvironmental and microenvironmental factors such as soil moisture, temperature, and relative humidity. Soil moisture and soil temperature play a key role in regulating the biochemical processes involving organic matter, which regulate the magnitude of GHG emissions (Dabrowska-Zielinska et al., 2018). Soil temperature governs the pedosphere-related phenomena, like gas diffusion, mineralization, and the kinetics of soil chemical reactions, which eventually govern the emission rates of CO₂, CH₄, and N₂O (Baldock et al., 2012). Similarly, soil moisture, mineralization rate, and subsequent emission of greenhouse gases from wetlands are interlinked. However, the nature of relationships exhibits substantial variability in space and time (Yin et al., 2019). In the recent past, pieces of scientific evidence showed that an increase in soil moisture is associated with an accelerated rate of carbon loss through GHG emissions (Huang & Hall, 2017).

Although studies are available on GHG emissions from wetland ecosystems at a worldwide level, however, as far as India is concerned, the number of studies is scarce (Purvaja & Rmaesh, 2001; Chanda et al., 2019; Shaher et al., 2020), especially in the Himalayan foothills. I.P.C.C. (2007) and Graham et al. (2008) indicated the Himalayas as a “white spot” stressing the lack of data. The changing climatic scenario might alter the structure and function of wetland ecosystems, particularly in the foothill of the Himalayan region (Erwin, 2009; Stewart et al., 2013; Salimi et al., 2021). Therefore, the functioning of Himalayan wetland ecosystems and the potential changes in their GHGs budget is of particular interest because of their large extent and presumed sensitivity to climatic variability and anthropogenic manipulations and disturbances (I.P.C.C., 2003, 2007). Studies related to GHG emissions from these swamps are

urgently required to understand the behavior of GHGs and how much these natural wetlands are contributing to the GHG emission. To incorporate wetlands into international climate policies the countries are being encouraged to include the wetland emission in their national inventory (I.P.C.C. Wetlands Supplement, 2014; Moomaw et al., 2018). As the global climate is changing, there is a slighter shift in the seasonality at the regional level. Such changes can affect greenhouse gas effluxes.

The Nakraunda wetland in the Himalayan foothills has been selected in the present study to characterize the GHG emissions during the post-monsoon season, i.e., after the monsoonal spell of rain gets over. This study measured all four greenhouse gases, i.e., CH₄, CO₂, N₂O, and H₂O vapor, along with soil moisture, soil temperature, air temperature, and relative humidity. The present study was conducted in the post-monsoon season when the ambient temperature usually remains low compared to the rest of the year. However, due to climate change, an increase in the annual temperature minima is observed throughout the world, and India is no exception (Kundu et al., 2017). The ambient temperature principally regulates the soil temperature, which in turn the GHG fluxes. Thus the lower range of GHG fluxes is expected to observe in any sediments from India during the post-monsoon season, which coincides with the winter months. Due to this reason, the present study has been undertaken to quantify the CO₂, CH₄, N₂O, and H₂O vapor effluxes from this wetland along with their spatial and intra-seasonal variability during the post-monsoon season. The study also aimed to examine the relationships between the GHG fluxes and the soil physicochemical parameters.

Material and methods

Study site

The Nakraunda wetland of Uttarakhand in India was the area investigated in this study. It is a tropical fresh-water wetland surrounded by the reserve forest, which encompasses 15 ha. This wetland is in Dehradun at an elevation of 512 m above mean sea level. It is situated about 25 km east of Dehradun and lies between latitude 30°14'N and longitude 78°05'E. Swamp forest and swamp proper are the two distinct zones of this wetland (Richards, 1966).

Nakraunda wetland shelters a wide variety of flora and fauna. Besides being a water source for irrigation and domestic purposes, this wetland also facilitates fishing, harvesting shrubs for fodder, outdoor recreation, and tourism.

Sampling strategy

A thorough reconnaissance survey was carried out in the study area before sampling. The main aim of this survey was to identify the different types of subclasses within the wetland habitat based on varying soil types and dominant macrophytes. As per our understanding, the variability in the greenhouse gas fluxes could be due to the changes in soil and vegetation type. These different microhabitats usually experience varying hydrological regimes. Based on this logic, six dominant habitat types were identified by carrying out this pilot survey. The flux measurement focused on six different locations: sloppy soil at the periphery of the swamp (SSA1), soil close to swamp proper (SCSP2), soil with small grassy vegetation (SSGV3), marshy soil with dominant macrophytes, *Calamus* sp. and *Enhydra* sp. (SMM15), and marshy soil with dominant macrophytes, *Acorus* sp., *Ipomea aquatic*, and *Eupatorium* sp. (SMM26) (Fig. 1). Flux measurement was also carried out on a water surface at swamp proper (WS4).

The post-monsoon season in this part of the world spans October, November, December, and January. Sampling was conducted once every month of this season (October, November, December 2020, and January 2021). All six sites were sampled every month. Three replicate samplings were carried out in each of the sites. Thus, a total of 18 flux measurements were conducted every month (for 4 months). The measurement of GHG fluxes and the soil physicochemical parameters were completed between 0900 and 1500 h on every occasion. The flux measurement during the nighttime was deliberately opted out due to safety reasons and risks of wild animals in the forest.

Measurement of micrometeorological parameters and greenhouse gas flux estimation

The closed chamber technique was implemented to measure the GHG fluxes. Gas samples were measured

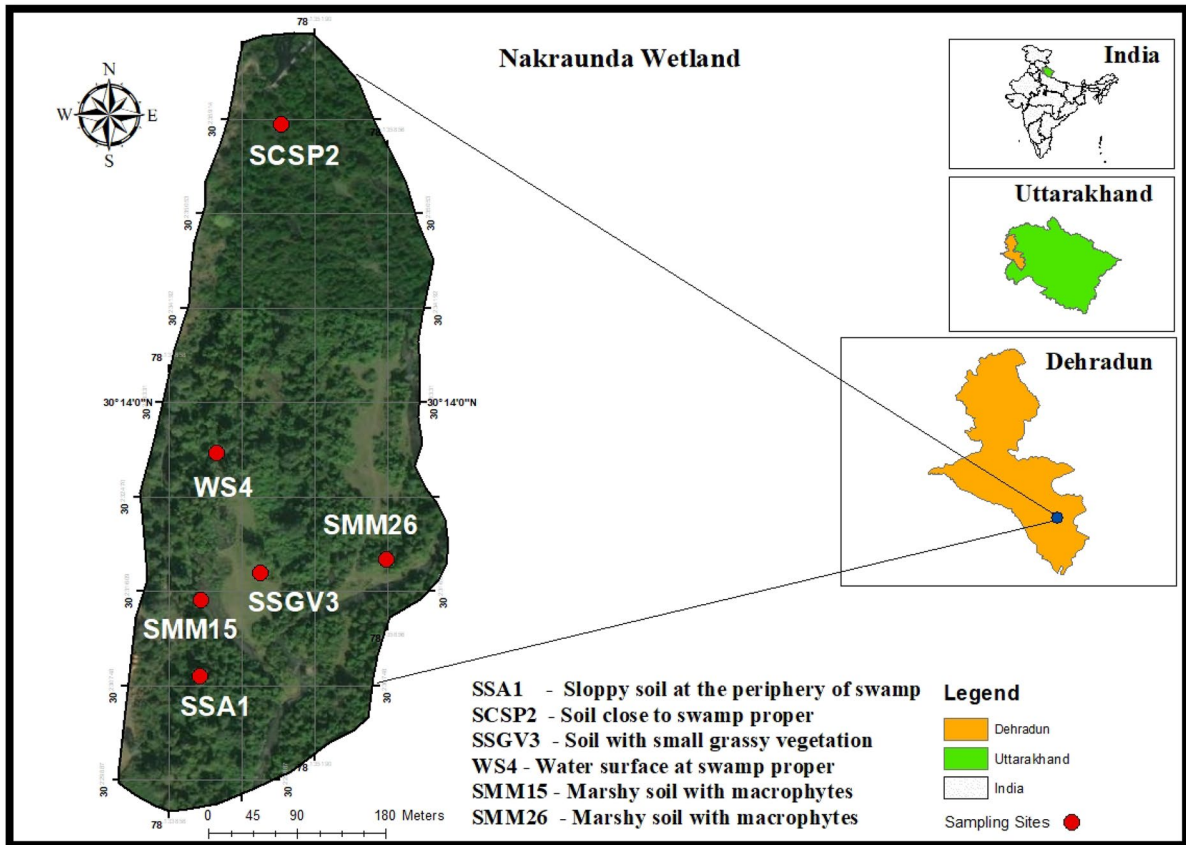


Fig. 1 Study area map with sampling locations

using a closed airtight chamber of opaque acrylic material with dimensions of 20 cm × 20 cm × 20 cm. Three replicates were taken from each site. A quadrat of 10 m × 10 m was established at each site and three replicates were randomly carried out from each of the sites. Chamber was placed on the soil surface after removing litter and fixed properly to avoid leakage. The incubation time for the gases to accumulate within the chamber was fixed for 15 min after trial and error and three replicates were taken from each stratum. The obtained values were put for calculation in the flux equation. The data monitored with the instrument was validated with the help of an infrared gas analyzer (IRGA) (portable photosynthesis system Li-COR 6400 XT, Lincoln NE, USA instrument). The entire experiment, especially the chamber operation, was conducted manually. The portable gas analyzer (Model: IAQ-G-A6, made in India; sensors are imported from Germany: CO₂ range: 0–20%

(vol/vol), resolution: 1 ppm, repeatability: +10 ppm, NDIR principle-based; CH₄ range: 0–2.5%, resolution: 400 ppm, electro-chemical based; N₂O range: 0–2000 ppm, accuracy: +1% fast response (FS) repeatability, resolution: 1 ppm, electro-chemical based, H₂O range: up to 35%, electro-chemical based) is utilized to monitor the emission of greenhouse gases from the wetland ecosystem. To calibrate the instrument, it was placed in fresh ambient air for 15 to 20 min (to auto-calibrate the sensor). The CO₂ sensor is a non-dispersive infra-red (NDIR) type, whereas the other sensors (CH₄, N₂O, and H₂O vapor) are electrochemical, which takes time in heating up; therefore, the instrument has to be turned on 1 h before the operation. The greenhouse gas flux was estimated using formula (Drewitt et al., 2002):

$$F = \left(\frac{PV}{RTA} \right) \Delta C / \Delta T$$

where F is the flux of greenhouse gas, P stands for air pressure, R is the universal gas constant, V represents the volume, A is the surface area of the chamber, T denotes the absolute temperature within the chamber, and dC/dT is the rate of change of each of the greenhouse gas concentrations during the incubation period dT (s).

The relationship between the soil GHG fluxes and soil temperature was estimated based on the exponential model of Lloyd and Taylor (1994) as per the relation

$$SCE = ae^{bT}$$

where a and b are the constants and T is the soil temperature at a particular depth. Consequently, the Q_{10} values, which denote the factor to be multiplied to the efflux rate for a 10 °C rise in temperature, are evaluated as per the formula (Xu & Qi, 2001).

$$Q_{10} = e^{(b \times 10)}$$

Soil moisture and soil temperature were measured by the Pro Check meter (Decagon Devices, Inc., 2365 NE Hopkins Ct. Pullman, WA, 99,163, USA, PC-1, sensor: GS3) at different depths, viz., 0–15 cm, 15–30 cm, and 30–45 cm. The soil was dug out at each site at the aforementioned depths using a spade. A digital thermometer was used for measuring the air temperature. Relative humidity was calculated using the traditional “dry and wet bulb” method.

Measurement of soil physicochemical parameters

Soil samples were collected from five locations once in the post-monsoon season. A quadrat of 10 m × 10 m was established at each site, and then three replicates of soil samples were collected near the GHG flux measured site. The litter and humus were removed from the top soil before the sample collection. The samples were divided into depth ranges of 0–15, 15–30, and 30–45. At SSA1, SCSP2, and SSGV3, the sample was collected from 0–15-, 15–30-, and 30–45-cm depths; however, at SMM15 and SMM26, only 0–15-cm depth was considered as beyond this depth soil was not stable due to interference of water. At every site, the replicates for each layer were then mixed to prepare a composite sample. Thereafter, soil samples were packed in a polythene bag and brought to the laboratory where they were

air-dried, sieved (2 mm), and gently broken down hard clumps using pestle and mortar.

The soil samples were analyzed in the laboratory of Forest Ecology & Climate Change Division of Forest Research Institute of Dehradun. Soil pH was determined in a 1:2.5 (soil:water suspension) ratio after half an hour of equilibrium using a glass electrode on a digital pH meter (Jackson, 1967). The electrical conductivity of the soil sample was measured in 1:2 (soil:water suspension) at 25 °C using a conductivity meter (Bower & Wilcox, 1965). Available nitrogen in the soil was extracted through the alkaline potassium permanganate method (Subbiah & Asija, 1956). Available phosphorus was determined by sodium bicarbonate extractant (0.5 M NaHCO₃) adjusted to pH 8.5 by the method of Olsen et al. (1954). Available potassium in soil was analyzed by extraction with 1 N ammonium acetate (pH 7) and K concentration was determined by a flame photometer (Perur et al., 1973). The soil organic carbon content was measured by the modified (Walkley & Black, 1934) method as described by Jackson (1967).

During the estimation of soil physicochemical parameters, the standardized quality assurance procedure and precaution were followed for ensuring the reliability of results. Analytical quality was assured by repeated measurement of the blank procedure, reagent blank, and duplicate samples. All the reagents of analytical grade were used throughout the analysis. To prevent contamination, all the glassware was washed thoroughly with dilute HNO₃ acid and deionized water before the analysis.

Statistical analyses

The normality of all the data of the respective parameters was checked by performing the Shapiro–Wilk W test. The statistical significance of the differences in the parameters observed between the six sites was tested by conducting a one-way analysis of variance (ANOVA). The site-specific differences were analyzed by performing a posthoc test (Tukey’s honest significant difference test). Pearson correlation coefficient was calculated to examine the relationships between soil physicochemical parameters and GHG efflux. All statistical analyses were carried out with the help of SPSS software (SPSS Inc., USA, version 16.0). The results were considered significant at $p < 0.05$.

Results

Variability of microclimatic and soil physicochemical parameters

Table 1 shows the descriptive statistics of the air temperature (°C) and relative humidity (%) measured in all the sites. The maximum and minimum average air temperature was 25.97 ± 0.30 °C in SSGV3 and 21.90 ± 0.27 °C in SSA1, respectively. The maximum and minimum relative humidity were $75.85 \pm 0.12\%$ in SMM15 and 61.35 ± 0.16 in SMM26, respectively. However, neither air temperature nor relative humidity showed any significant difference among the sites ($F=0.38$, $p>0.05$; $F=1.11$, $p>0.05$, respectively). Soil temperature at 0–15-cm depth varied between 17.46 °C and 22.61°C, and exhibited significant spatial variability ($F=7.12$, $p<0.05$). The posthoc analysis showed that the site SMM26 showed the most significant difference with all the other sites. The soil temperature at the other depths did not show any significant variation among the sites SSA1, SCSP2, and SSGV3. Soil moisture showed significant spatial variability (varying between 6.81% and 47.19%) at all three depths ($F=4.3$, $p<0.05$); however, posthoc analysis revealed that the site SSA1 showed the most significant difference with all the other sites.

Further, the one-way ANOVA test was conducted for all soil physicochemical parameters (Table 2). The maximum and minimum average pH was 7.7 ± 0.05 in SCSP2 (15–30 cm) and 6.3 ± 0.20 in SSA1 (30–45 cm), respectively. The maximum and minimum electrical conductivity (EC) was 1.94 ± 0.05 mS/cm in SMM26 (0–15 cm) and 0.08 ± 0.05 in SSA1 (30–45 cm) and SSGV3 (15–30 cm), respectively. The statistical results indicated that soil pH were significantly different in the sites at different depths (0–15 cm, 15–30 cm, and 30–45 cm) ($F=14.68$, $p<0.05$; $F=27.6$, $p<0.05$; $F=32.53$, $p<0.05$, respectively). However, soil electrical conductivity at depths 0–15 cm and 15–30 cm did not show any significant difference among the sites ($F=2110.23$, $p>0.05$; $F=7.11$, $p>0.05$; $F=1.23$, $p>0.05$, respectively). The maximum and minimum average NPK values were 598.45 ± 34.17 in SMM26 (0–15 cm) and 155.17 ± 4.6 in SSGV3 (30–45 cm) for nitrogen 95.77 ± 0.9 in SMM15 (0–15 cm) and 72.76 ± 1.2 in SSGV3 (15–30 cm) for phosphorous and 560 ± 13.4 in SSA1 (0–15 cm) and 196.06 ± 25.5 in SCSP2 (30–45 cm) for potassium. The results for NPK indicated that nitrogen was significantly different in the sites at depths 15–30 cm and 30–45 cm ($F=7.97$, $p<0.05$; $F=7.59$, $p<0.05$, respectively). However, phosphorous was significantly different in the sites at all the depths, i.e., 0–15 cm, 15–30 cm,

Table 1 Mean \pm standard deviation (SD) along with the range of microclimatic parameters observed in the different soil types

Microclimatic parameters	SSA1	SCSP2	SSGV3	WS4	SMM15	SMM26
Air temperature (°C)	21.90 ± 0.27 15.33–27.71	22.08 ± 0.28 18.68–25.37	25.97 ± 0.30 22.33–35.53	24.27 ± 0.45 20.43–30.46	23.62 ± 0.25 20.60–30.47	23.09 ± 0.25 19.43–30.54
Relative humidity (%)	63.48 ± 0.22 58.55–69.11	74.45 ± 0.20 55.40–83.11	69.48 ± 0.12 53.46–91.10	75.69 ± 0.19 61.44–82.14	75.85 ± 0.12 71.12–80.73	61.35 ± 0.16 38.13–76.55
Soil temperature (°C) (0–15 cm)	24.22 ± 0.07 21.63–29.78	25.13 ± 0.13 22.61–30.30	23.07 ± 0.05 17.63–29.85	-	20.77 ± 0.09 17.46–27.57	24.50 ± 0.26 19.76–34.70
Soil temperature (°C) (15–30 cm)	23.65 ± 0.07 21.43–28.74	25.16 ± 0.10 22.67–30.14	22.07 ± 0.10 17.64–26.18	-	-	-
Soil temperature (°C) (30–45 cm)	22.50 ± 0.10 19.85–26.21	25.47 ± 0.08 22.63–30.42	21.89 ± 0.10 18.42–25.62	-	-	-
Soil moisture (%) (0–15 cm)	12.09 ± 0.06 6.81–15.44	37.65 ± 0.13 20.87–48.17	42.91 ± 1.48 36.83–47.66	-	58.12 ± 0.10 47.19–78.34	55.54 ± 0.14 45.29–63.64
Soil moisture (%) (15–30 cm)	11.26 ± 0.05 7.23–15.94	39.43 ± 0.30 26.07–48.26	41.12 ± 0.05 31.34–52.10	-	-	-
Soil moisture (%) (30–45 cm)	11.82 ± 0.08 9.12–14.16	42.76 ± 0.18 37.97–49.17	42.74 ± 0.10 32.65–56.19	-	-	-

SSA1 soil sloppy area; SCSP2 soil close to swamp proper; SSGV3 soil small grassy vegetation; WS4 water surface at swamp proper; SMM15 marshy soil with macrophytes; SMM26 marshy soil with macrophytes

Table 2 Mean ± standard deviation of physicochemical parameters (pH, EC, NPK, and SOC) observed in the different soil types under different depths in the post-monsoon season

Site soil depth (cm)	Physicochemical parameters					
	pH	EC (mS/cm)	N (kg/ha)	P (kg/ha)	K (kg/ha)	SOC (%)
SSA1						
0–15	6.7 ± 0.17	0.13 ± 0.005	284.36 ± 3.25	82.41 ± 6.09	560.59 ± 13.4	2.8 ± 0.3
15–30	6.6 ± 0.34	0.09 ± 0	272.88 ± 2.4	81.07 ± 5.6	409.31 ± 40.89	1.4 ± 0.12
30–45	6.3 ± 0.20	0.08 ± 0.005	248.18 ± 6.41	87.15 ± 2.2	314.59 ± 2.6	1.9 ± 0.5
Avg	6.64 ± 0.24	0.10 ± 0.00	268.47 ± 4.05	83.55 ± 4.66	428.17 ± 18.97	2.07 ± 0.34
SCSP2						
0–15	7.3 ± 0.1	0.48 ± 0.01	212.58 ± 2.07	87.79 ± 0.5	454.21 ± 3.4	1.8 ± 0.21
15–30	7.7 ± 0.05	0.21 ± 0.01	199.89 ± 49.7	95.43 ± 0.8	385.81 ± 2.11	1.24 ± 0.01
30–45	7.4 ± 0.07	0.10 ± 0.06	314.33 ± 86.69	91.74 ± 0.85	196.06 ± 25.5	0.65 ± 0.02
Avg	7.49 ± 0.08	0.27 ± 0.03	230.26 ± 46.19	91.65 ± 0.77	345.37 ± 10.38	1.33 ± 0.08
SSGV3						
0–15	7.5 ± 0.11	0.15 ± 0.01	265 ± 17.4	76.82 ± 0.9	352.41 ± 6.4	1.18 ± 0.22
15–30	7.5 ± 0.05	0.08 ± 0.005	184.88 ± 4.12	72.76 ± 1.2	372.89 ± 2.0	0.65 ± 0.18
30–45	7.4 ± 0.05	0.13 ± 0.005	155.17 ± 4.6	78.54 ± 0.98	441.69 ± 29.5	0.32 ± 0.02
Avg	7.51 ± 0.08	0.12 ± 0.01	201.80 ± 8.73	76.05 ± 1.40	389.00 ± 12.67	0.72 ± 0.15
SMM15						
0–15	7.4 ± 0.28	0.53 ± 0.05	178.27 ± 16.6	95.77 ± 0.9	304.06 ± 7.1	0.51 ± 0.05
SMM26						
0–15	6.6 ± 0.28	1.94 ± 0.05	598.45 ± 34.17	84.77 ± 0.3	313.22 ± 1.19	0.51 ± 0.51

pH potential of hydrogen; EC electrical conductivity; N nitrogen; P phosphorous, K potassium; SOC soil organic carbon

and 30–45 cm, respectively ($F=17.33$, $p<0.05$; $F=34.68$, $p<0.05$; $F=59.95$, $p<0.05$, respectively). Potassium did not show any significant difference among the sites at various depths (0–15 cm, 15–30 cm, and 30–45 cm) ($F=627.35$, $p>0.05$; $F=1.83$, $p>0.05$; $F=88.60$, $p>3.51$, respectively). The maximum and minimum average soil organic carbon (SOC) was 2.8 ± 0.3 in SSA1 (0–15 cm) and 0.32 ± 0.02 in SSGV3 (30–45 cm), respectively. The statistical results for SOC represented the significant difference in the sites at depths 15–30 cm and 30–45 cm ($F=28.87$, $p<0.05$; $F=22.93$, $p<0.05$, respectively).

Variability of GHG fluxes

The in-situ CO₂, CH₄, N₂O, and H₂O vapor emissions ranged from 82.89 (SMM26) to 1052.13 mg m⁻² h⁻¹ (SSGV3), 0.56 (SSA1, SMM15) to 2.25 mg m⁻² h⁻¹ (WS4), 0.18 (WS4) to 0.40 mg m⁻² h⁻¹ (WS4), and 557.96 (SSA1) to 29,397.18 mg m⁻² h⁻¹ (WS4) during the study period, with means of 397.27 mg m⁻² h⁻¹,

1.16 mg m⁻² h⁻¹, 0.28 mg m⁻² h⁻¹, and 4404.73 mg m⁻² h⁻¹, respectively (Table 3). One-way ANOVA results indicated that CO₂ fluxes were significantly different in the sites ($F=5.1$, $p<0.05$). The posthoc analysis showed that the site SCSP2 exhibited significantly different CO₂ fluxes from the other sites. However, CH₄, N₂O, and H₂O fluxes did not show any significant spatial variability among the sites ($F=0.4$, $p>0.05$; $F=1.1$, $p>0.05$; $F=1.1$, $p>0.05$, respectively).

Relationship between GHG fluxes, microclimatic and soil physicochemical parameters

CO₂ effluxes exhibited significant exponential relationships with soil temperature at varying depths (R^2 ranging between 0.34 and 0.51; $p<0.05$). The Q_{10} values for CO₂ varied between 3.42 and 4.9. The soil moisture levels at the surface did not show any significant relationship with the soil CO₂ fluxes; however, the soil moisture at depths 15–30 cm and 30–45 cm showed a significant positive relationship

Table 3 Mean \pm standard deviation (SD) along with the range of CO₂, CH₄, N₂O, and H₂O fluxes observed in the different soil types

GHGs flux (mg m ⁻² h ⁻¹)	SSA1	SCSP2	SSGV3	WS4	SMM15	SMM26
CO ₂ efflux	257.13 \pm 37.29 139.76–402.34	827.82 \pm 30.10 786.52–924.47	445.60 \pm 30.12 205.71–1052.13	452.71 \pm 29.57 156.09–600.18	222.34 \pm 24.89 113.74–362.41	178.03 \pm 40.81 82.89–257.13
CH ₄ efflux	0.99 \pm 0.17 0.56–1.81	1.29 \pm 0.20 1.21–1.47	1.18 \pm 0.11 0.77–1.78	1.39 \pm 0.20 0.60–2.25	1.01 \pm 0.20 0.56–1.51	1.09 \pm 0.11 0.60–1.71
N ₂ O efflux	0.32 \pm 0.10 0.25–0.38	0.30 \pm 0.12 0.34–0.28	0.25 \pm 0.09 0.21–0.28	0.26 \pm 0.08 0.18–0.40	0.25 \pm 0.09 0.20–0.30	0.31 \pm 0.10 0.21–0.39
H ₂ O efflux	2624.27 \pm 54.82 557.96–557.96	1502.46 \pm 36.15 1247.01–2245.29	2538.56 \pm 52.36 1482.30–3525.91	9930.71 \pm 57.44 2994.84–29,397.18	5553.57 \pm 56.93 1260.46–13,038.15	4278.83 \pm 51.85 2739.39–6829.99

SSA1 soil sloppy area; SCSP2 soil close to swamp proper; SSGV3 soil small grassy vegetation; WS4 water surface at swamp proper; SMM15 marshy soil with macrophytes; SMM26 marshy soil with macrophytes

with the CO₂ fluxes (R^2 ranged between 0.38 and 0.48; $p < 0.05$) (Fig. 2). CH₄ and N₂O fluxes also followed the same pattern as CO₂ fluxes, showing significant exponential relationships with soil temperature at all depths (R^2 ranging between 0.33 and 0.45; $p < 0.05$ for CH₄, and R^2 ranging between 0.37 and 0.51; $p < 0.05$). The Q_{10} values for CH₄ and N₂O ranged from 1.66 to 2.2 and 1.2 to 1.3, respectively. CH₄ fluxes showed significant positive relationships with soil moisture at all depths (R^2 ranging from 0.36 to 0.43; $p < 0.05$) (Fig. 3). However, N₂O fluxes exhibited a moderate but significant negative relationship with soil moisture at all depths (R^2 ranging from 0.22 to 0.29; $p < 0.05$) (Fig. 4). H₂O vapor fluxes did not show any significant relationship with soil temperature at any of the depths; however, it showed positive significant relationships with soil moisture at all depths (R^2 ranging from 0.35 to 0.55; $p < 0.05$). The R^2 values decreased with depth (Fig. 5).

Table 4 shows the Pearson correlation coefficients computed between the greenhouse gas fluxes and the soil physicochemical parameters. CO₂ efflux moderately correlated with pH (0.58) and EC (−0.46), weakly with nitrogen (−0.38), and showed an extremely weak correlation among phosphorus,

potassium, and soil organic carbon. CH₄ efflux is moderately correlated with pH (0.53) and showed a weak relationship with other soil parameters. However, N₂O efflux was strongly correlated with soil pH (−0.76), moderately with nitrogen (0.57) and SOC (0.62), weakly with EC (0.28) and K (0.28), and extremely weak with phosphorus (−0.04). In addition to this, H₂O vapor efflux was strongly correlated with potassium (−0.64); moderately with soil EC (0.50), phosphorus (0.41), and SOC (−0.60); and weakly correlated with pH (−0.10) and nitrogen (0.20).

Discussion

Soil CO₂ efflux dynamics

The lower and the higher CO₂ fluxes observed in this study were an order of magnitude different from one another, which shows that this study area exhibited substantial spatial variability. The SCSP2, SSGV3, and WS4 sites recorded very high CO₂ fluxes, which imply that sites close to the swamp proper, soil with small grassy vegetation, and water surface at swamp proper can emit more CO₂ than other sites (i.e.,

Table 4 Pearson coefficient correlation between the GHG flux and soil physicochemical parameters

Parameters	pH	EC	N	P	K	SOC
CO ₂ efflux	0.64*	−0.31	−0.31	0.32	−0.13	−0.06
CH ₄ efflux	0.72*	−0.07	−0.15	0.14	−0.20	−0.32
N ₂ O efflux	−0.70*	0.16	0.47	0.31	0.12	0.62*
H ₂ O efflux	−0.22	0.53	0.25	0.13	−0.19	−0.33

*Statistically significant

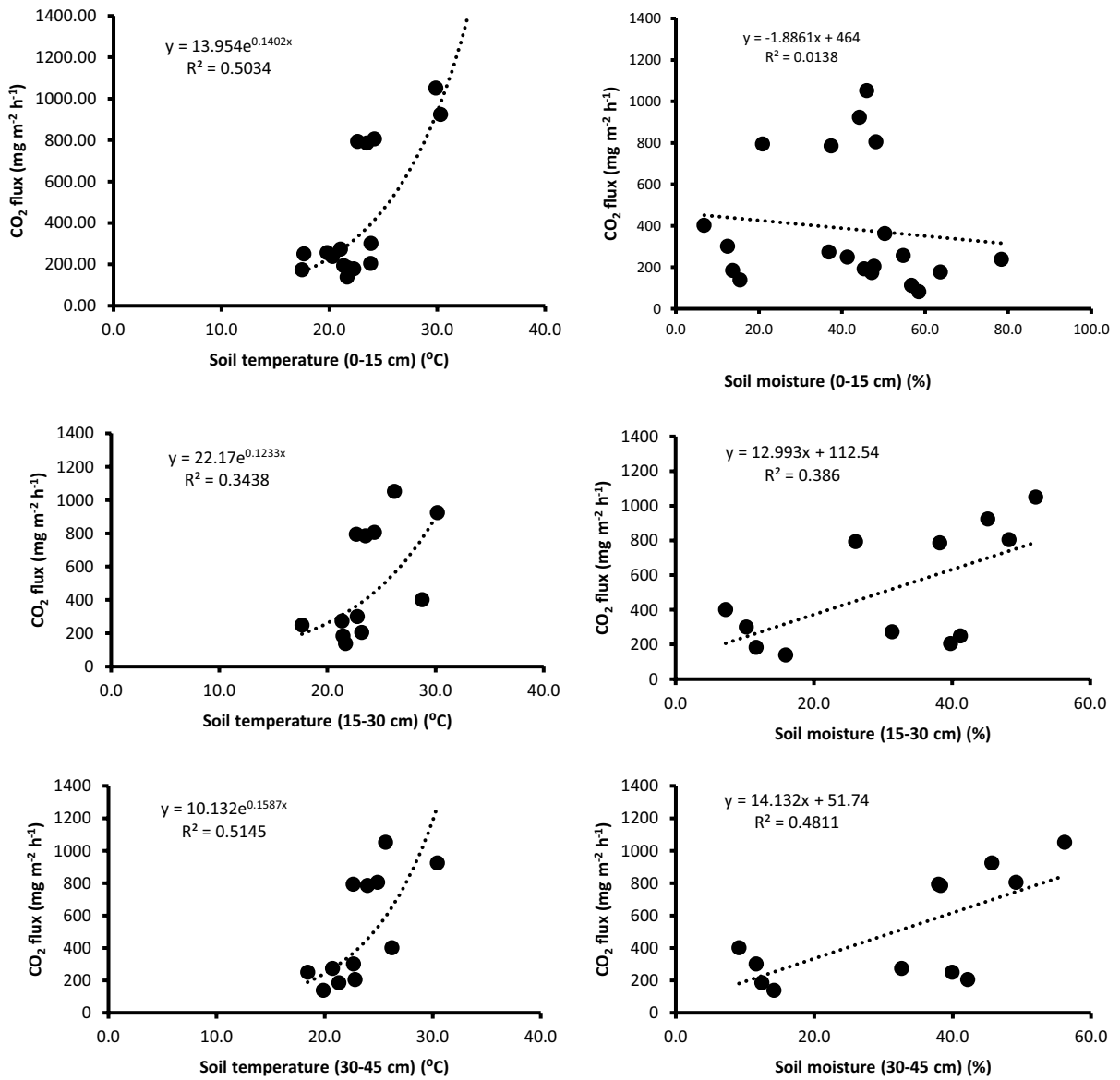


Fig. 2 The relationship between soil temperature and soil moisture at varying depths with CO₂ flux

marshy soils and sloppy areas). This observation indicates that the swampy regions are rich in organic substrates, and the microbial community finds these sites suitable for producing CO₂ (as observed by Jauhiainen et al., 2005) compared to the marshy soils within this wetland. SSA1 site had the highest mean organic carbon content. However, this site had the lowest soil moisture content, which led to unfavorable conditions for microbial community respiration. Sánchez-García et al. (2020) reported such reduced

CO₂ emission from soils under moisture-scarce conditions. However, the CO₂ fluxes from this wetland, on the whole, exhibited a strong dependence on soil temperature, as observed in many other studies (Van den Bos, 2003; Gao et al., 2011; Mikha et al., 2005; Xu et al., 2003).

The significant relationship between the soil temperature and soil CO₂ effluxes at all depths indicates that the increase in soil temperature enhanced the microbial community respiration even in the deeper

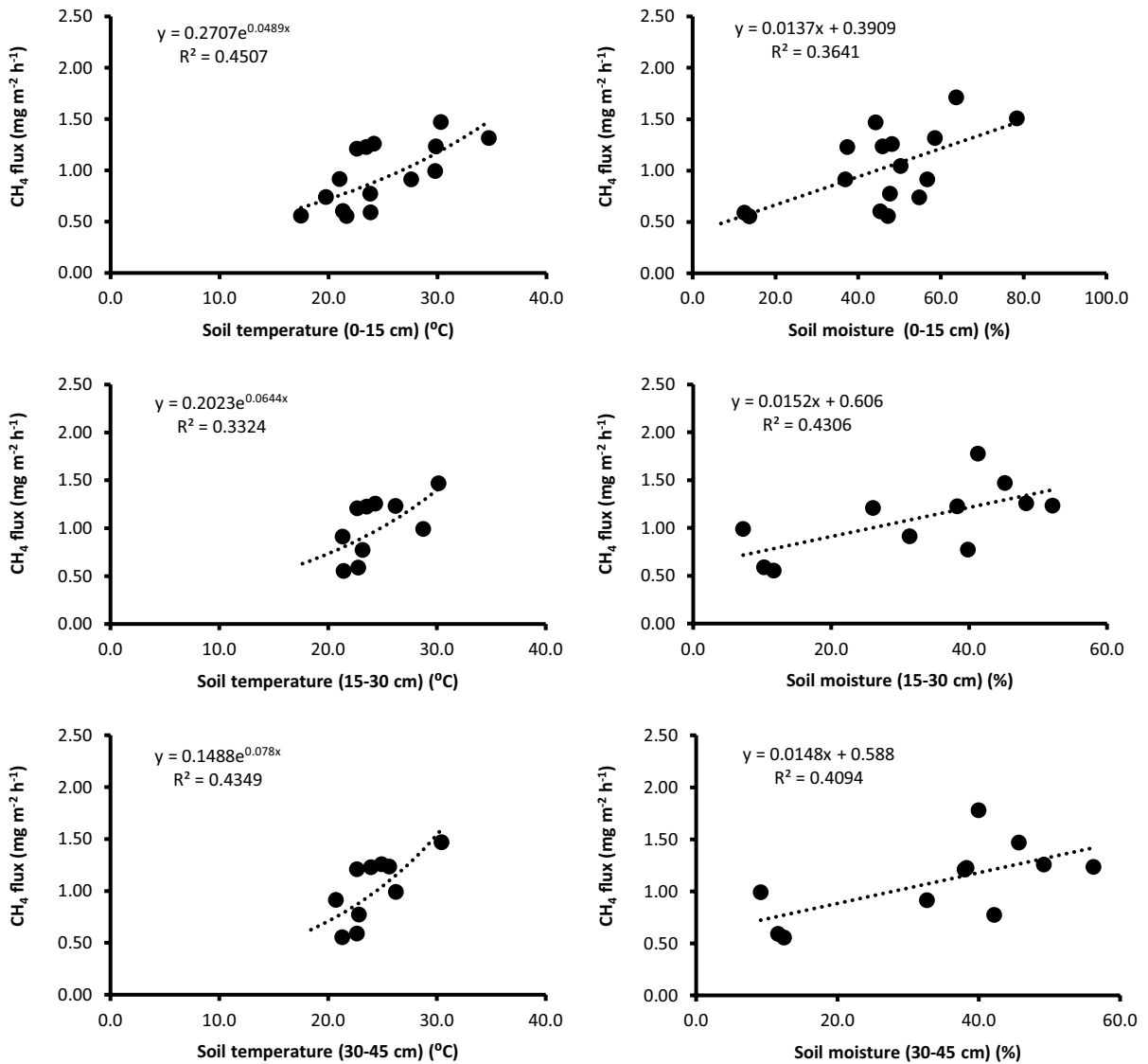


Fig. 3 The relationship between soil temperature and soil moisture at varying depths with CH₄ flux

subsurface layers (Bouma et al., 1997; Chanda et al., 2011; Epron et al., 1999). The present result is in parity with other studies where the CO₂ production increased with temperature (Chanda et al., 2013; Schauffer et al., 2010). Several researchers observed a non-linear increase in CO₂ emission rate with rising temperature (Chanda et al., 2013; Hao et al., 2011; He et al., 2014; Hirota et al., 2010; Wang et al., 2010).

The Q_{10} coefficient estimates the relative increase in the efflux rate for an elevation in temperature by 10 °C (Pang et al., 2019). In the present study, the Q_{10} values

were higher than the global median Q_{10} value of 2.40 estimated by Raich and Schlesinger (1992). The Q_{10} values increased with depth in almost all other wetlands of the world. Apart from the soil surface layer, the subsurface layers portrayed significant positive relationships with soil moisture. The microbial community in the subsurface layers of this wetland relies substantially on soil moisture to respire. Earlier studies reported similar observations (Schauffer et al., 2010). Soil moisture boosts the growth of fungal biomass, and soil temperature enhances the biochemical kinetics of

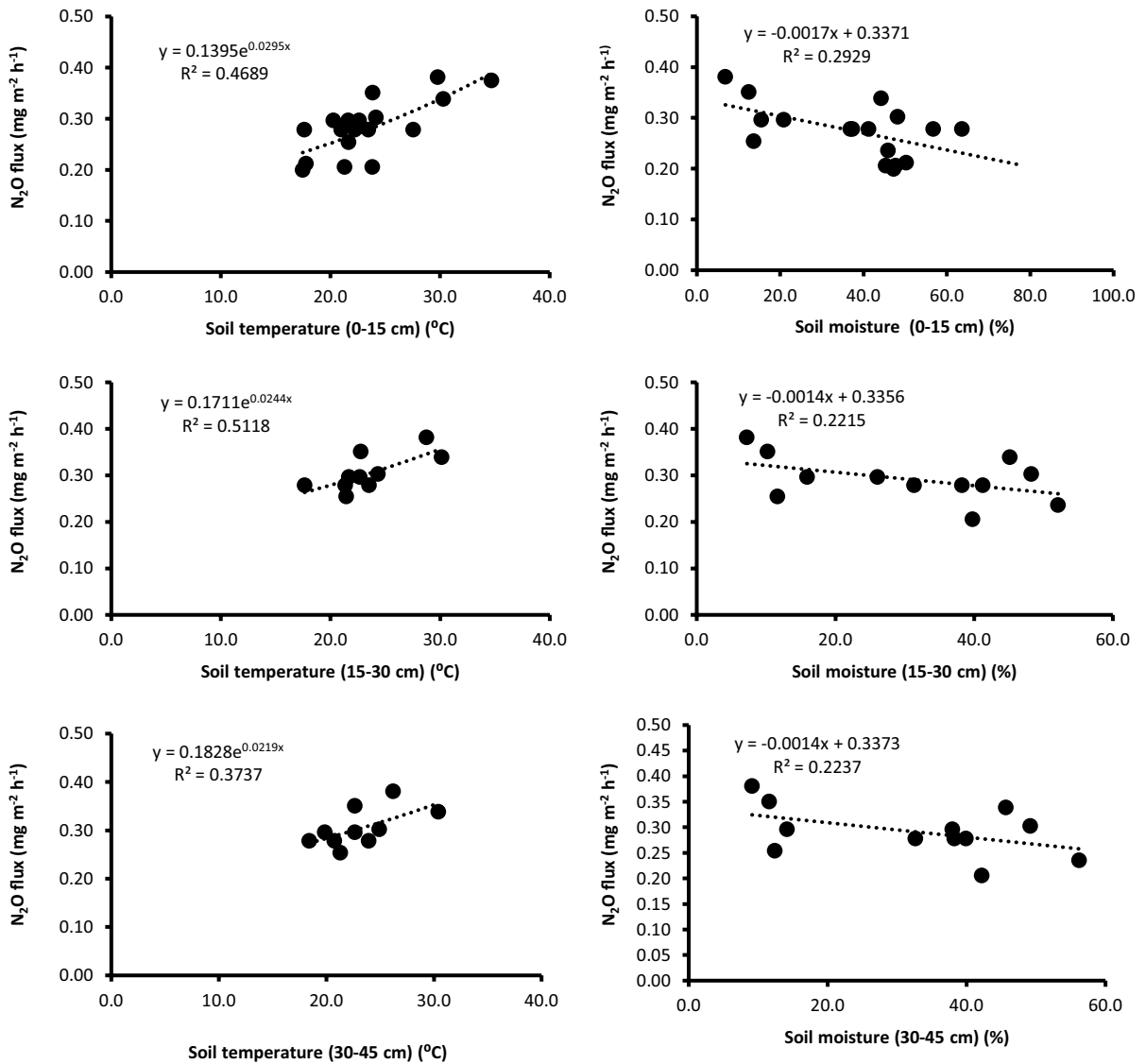


Fig. 4 The relationship between soil temperature and soil moisture at varying depths with N₂O flux

the microbial respiration process. The increase in the microbial biomass and activities increases soil aeration and respiration rate, which amplifies the production of CO₂ (Liu et al., 2019; Unger et al., 2010). However, the R² values of the relationship indicate that soil temperature plays a more crucial role in governing the soil CO₂ effluxes than soil moisture in different soil depths, and similar observations are prevalent in other wetland and forest ecosystems (Frank, 2002; Rey et al., 2005). Besides, other interrelated factors like soil type and vegetation cover can lead to varying CO₂ effluxes (Boone et al., 1998).

The soil pH influences many biogeochemical processes (Neina, 2019). The present study recorded a near-neutral pH, as observed by other researchers in other wetland sites (Singh et al., 2000) due to the high groundwater table and precipitation. CO₂ efflux and soil pH showed a significant strong positive correlation. Cuhel et al. (2010) reported identical observations. Electrical conductivity is the measurement of the dissolved material in an aqueous solution. Soil CO₂ emission showed a weak correlation with soil electrical conductivity. Adviento-Borbe et al. (2006) recorded similar findings. They observed that the

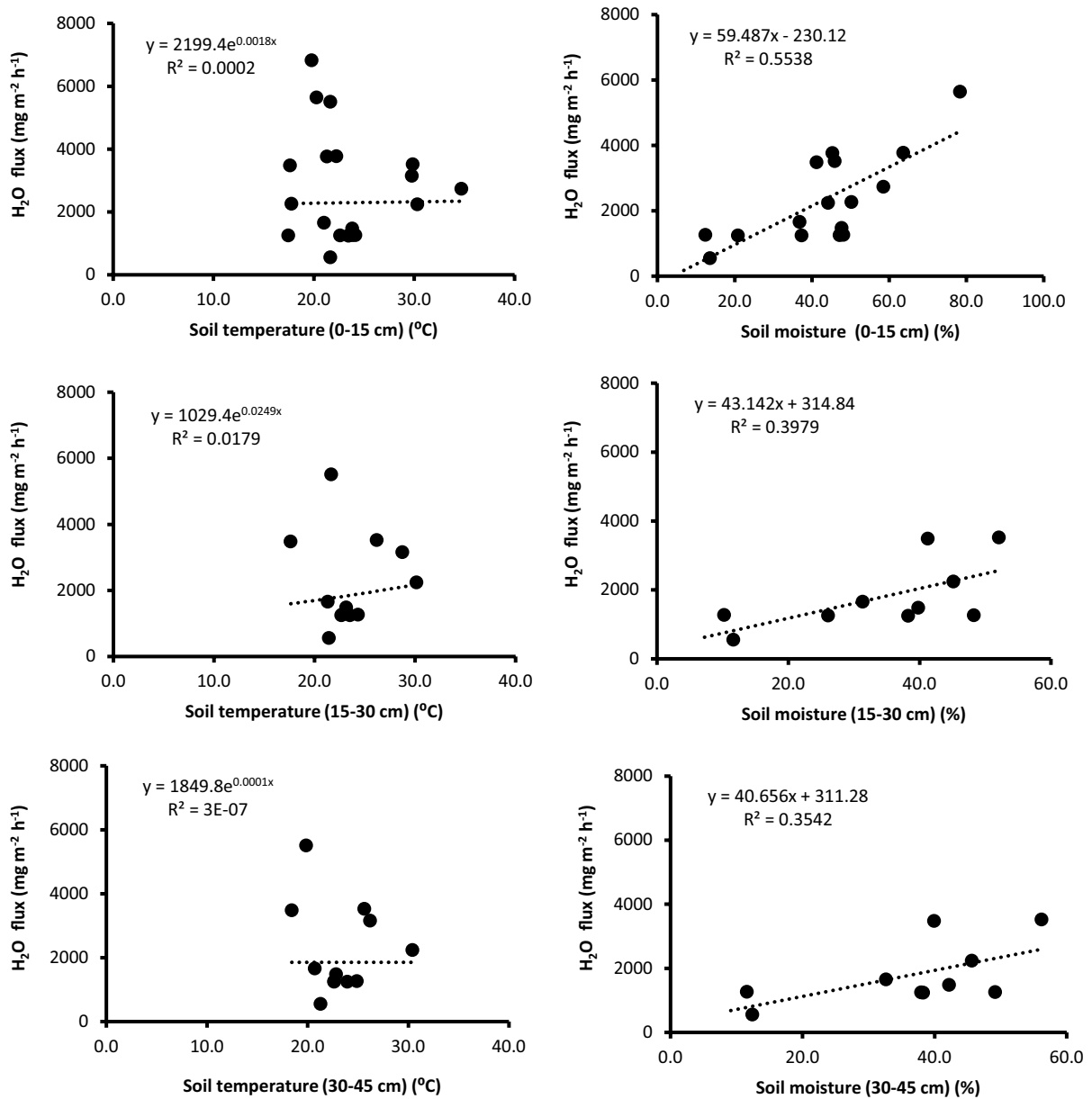


Fig. 5 The relationship between soil temperature and soil moisture at varying depths with H₂O flux

increased soil EC reduces the heterotrophic soil respiration, i.e., soil CO₂ emission, which further reduces microbial activity due to increased osmotic stress on the microbial communities. Soil nitrogen and soil CO₂ efflux also exhibited a weak correlation. However, phosphorus, potassium, and soil organic carbon showed an extremely weak correlation with soil CO₂ efflux during the study period.

Soil CH₄ efflux dynamics

No significant spatial differences in the soil CH₄ effluxes indicate that all the sites had more or less similar strength of methanogenic bacterial community (Nazaries et al., 2011). Though the mean magnitudes were not significantly different, the maximum fluxes occurred in the same sites with very high CO₂ effluxes.

This observation indicated that the optimum availability of organic matter as substrate and soil moisture conditions that led to higher effluxes of CO_2 also facilitated higher CH_4 emissions. Similar records are prevalent worldwide (Cameron et al., 2021; Lazcano et al., 2018). Like CO_2 , CH_4 effluxes also exhibited significant relationships with soil temperature (Bridgham & Richardson, 1992; Krauss & Whitbeck, 2012). However, the power raised to exponential function was significantly less than that observed for CO_2 , which led to lower Q_{10} values. Though the Q_{10} values observed in this study were in parity with other observations in the subtropical latitudes (Liu et al., 2017), the Q_{10} magnitudes of the same region in the summer months would be much higher than that observed during the post-monsoon season. It could be a point of concern. Q_{10} , as high as 6–7, is available from the alpine wetlands of China (Gao et al., 2011). Thus, the present observations lied intermediate to the Q_{10} ranges observed in the wetlands throughout the globe. Previous studies like that of Werner et al. (2003) observed that level of water table imposes the most significant influence on CH_4 emission rate. For the wetland soil, soil temperature and soil moisture play an equally crucial role in controlling methane dynamics as CH_4 production occurs under anaerobic conditions and therefore requires saturated soils (Jones et al., 2005). However, CH_4 consumption is obligatory aerobic and requires unsaturated soils (Gulledge & Schimel, 1998). Mazzetto et al. (2014) have also observed high CH_4 emissions with high soil moisture and high temperature, as observed in this study. Soil properties affect soil's potential to take up atmospheric CH_4 (Oertel et al., 2016). In this study, there were no signatures of CH_4 influx towards the pedosphere, which indicates the lesser abundance of methanotrophs compared to the methanogens. The soil organic carbon content was in the range of 0.51 to 2.8%, which is substantially higher than the global observations. The main factor for emitting the CH_4 from the wetland was the anaerobic decomposition of organic matter through methane fermentation (Tsai et al., 2020).

As far as the CH_4 efflux is concerned, the methanotrophic activity occurs under a range of conditions with pH ranging from 4.0 to 7.5 (Saari et al., 2004). Like CO_2 , CH_4 effluxes also exhibited a significant strong positive correlation with pH (Dalal & Allen, 2008). However, some researchers suggested that soil pH did not influence the production of CH_4 gas;

therefore, it might not be responsible for low or high CH_4 efflux (Singh et al., 2000). However, soil electrical conductivity, nitrogen, phosphorus, potassium, and soil organic carbon showed a weak correlation with soil CH_4 efflux during the study period.

Soil N_2O and H_2O efflux dynamics

Like CH_4 , the N_2O fluxes did not exhibit significant spatial variability. It indicated that the factors regulating these fluxes did not vary across the sites. The rates of microbial nitrification and denitrification primarily regulate N_2O production. N_2O production correlates with nitrogen availability in soil (Barnard et al., 2005; Bouwman, 1990; Bremner, 1997; Kremen et al., 2005; Liu et al., 2007). All the sites sampled in this study had a significant quantity of nitrogen. Like the other two greenhouse gases, N_2O also showed an exponential relationship with soil temperature. Previous studies observed that aerobic and anaerobic microbes exist within soil aggregates (Renault & Stengel, 1994), and nitrification and denitrification take place simultaneously, carried out by different microbial communities in the same soil. Both these biochemical processes are temperature-dependent as well as depend on the oxidation–reduction potential of the soils. Unlike soil temperature, soil moisture at all depth ranges showed a significantly negative relationship with the soil N_2O fluxes. Usually, N_2O emissions peak with increasing soil moisture content (Davidson et al., 2000; Ruser et al., 2006), and nitric oxide (NO) emissions decreased under higher soil moisture (Schindlbacher et al., 2004). However, the observations in this study were opposite to such generalized understanding. Therefore, the magnitude of soil N_2O fluxes in this study area depends on soil temperature, soil water content, O_2 availability, and associated biochemical processes in the substrate (Farquharson & Baldock, 2008).

Water vapor flux is an important parameter that regulates the water cycle in the ecosphere and the energy balance of the Earth (Li et al., 2006; Irmak et al., 2011; Shu et al., 2016). In our study, we have found no significant relationship between soil and temperature and H_2O vapor flux. Usually, a higher temperature in the soil surface facilitates higher water vapor fluxes; however, in this study, the comparatively low relative humidity in the ambient atmosphere (which is a characteristic of the post-monsoon season in this part of

Table 5 Comparative analysis of GHG fluxes (CO₂ and CH₄) between the present observations and the emissions observed in other wetlands during winter season

Location	CO ₂ efflux (mg m ⁻² h ⁻¹)	CH ₄ efflux (mg m ⁻² h ⁻¹)	References
Nakraunda Wetland, Dehradun	82.89–1052.13 397.27 ± 32.13 (<i>n</i> = 18)	0.56–2.25 1.16 ± 0.17 (<i>n</i> = 18)	Present study
Wetlands, Lucknow, India (October–January)	–	0.09–14.92	Singh et al. (2000)
North Indian subtropical wetland, floodplain of river Yamuna, India (September–January)	–	–0.36 ± 0.27– 0.664 ± 0.27 (vegetated) 0.56 ± 0.29–0.0014 (unvegetated)	Mallick and Dutta (2009)
The different ecosystem of North-East India (November–February)	153.22 ± 11.57 (grassland) 222.30 ± 0.84 (bamboo) 318.57 ± 3.82 (Dipterocarpus forest site)	–	Thokchom and Yadava (2014)
Subtropical reservoir near flood plains of river Yamuna, India	–	0.45 (exposed soil zone) 3.86 (shallow water zone) 0.71 (deepwater zone)	Bansal et al. (2015)
Coniferous forest types of Kasmir Himalaya	39.06–49.63 (2012) 30.92–44.75 (2013)	–	Dar et al. (2015)
Tropical Montane Rainforest on Hainan Island, China (November–April)	155.71–206.56	–	Jiang et al. (2016)
Moist Tropical Forest Soils of Himalayan Foothills, India, Dehradun	1602 ± 64 (termite mound) 788 ± 17 (surrounding forest soil)	0.30 ± 0.013 –0.04 ± 0.0013	Chakraborty et al. (2021)

the world) might have been the main controlling factor in regulating the water vapor fluxes. More observations are necessary (preferably throughout the year) to properly understand the role of soil temperature and water vapor fluxes from this region. Currently, pieces of research carried out on water vapor flux from wetland ecosystems are scarce. A positive relationship between soil moisture and water vapor fluxes was inevitable. The WS4 site, which had a water layer, showed the highest rate of evaporation (water vapor fluxes). The marshy soils had the highest soil moisture levels, which led to considerably high water vapor fluxes. Thus, this study inferred with certainty that the water vapor fluxes were governed exclusively by physical processes and not biologically governed, unlike the other three greenhouse gases.

Like CO₂ and CH₄, N₂O emission also showed a significantly strong correlation with pH. Other studies strongly supported our findings suggesting that ammonia-oxidizing and nitrifier communities might remain active at low soil pH contributing to soil N₂O emission (Ariani et al., 2020; Zebarth et al., 2015).

Soil organic carbon also showed a significant positive correlation with the soil N₂O emission. Whereas, soil nitrogen showed a moderate positive but statistically insignificant correlation with N₂O emission. Our findings are in parity with global observations (Abdalla et al., 2011; Butterbach et al., 2011; Smith, 2017). However, the relation of soil N₂O emission among soil electrical conductivity, potassium, and phosphorus was found extremely weak.

In addition to this, H₂O vapor flux correlated with all the above physicochemical parameters of soil. H₂O vapor efflux showed a moderate correlation with EC. However, a weak correlation was obtained with pH, nitrogen, phosphorous, potassium, and SOC. Studies on the relationship of soil physicochemical parameters with H₂O vapor efflux from wetland systems are scarce. In the present study, we attempted to find some relation between these parameters; however, the data revealed no meaningful correlation (Table 4). Additionally, there were some weak relations between the soil physicochemical parameters and GHG fluxes (Table 4), which require further studies.

Comparison with observations from other wetlands in the winter season

The comparative data for GHG emissions (CO_2 and CH_4) in the winter season across the globe in different wetland sites have been presented in Table 5. The present study is perhaps the first one of its kind to study the GHG efflux of a wetland situated in the Himalayan foothills with a wider range of fluxes with a comparison of other wetlands of India and the world. Singh et al. (2000) reported winter season (October–January) CH_4 efflux within the range of 0.09 to $14.92 \text{ mg m}^{-2} \text{ h}^{-1}$, which is higher than the observations made in the present study. North Indian subtropical wetland showed a winter (September–January) CH_4 efflux range of -0.36 ± 0.27 to $0.66 \pm 0.27 \text{ mg m}^{-2} \text{ h}^{-1}$ (Mallick & Dutta, 2009). Bansal (2015) reported winter CH_4 efflux ranging from 0.45 to $3.86 \text{ mg m}^{-2} \text{ h}^{-1}$ in the floodplains of river Yamuna.

The CO_2 efflux during the winter season (November–February) was ranged from $153.22 \pm 11.57 \text{ mg m}^{-2} \text{ h}^{-1}$ (grassland) to $318.57 \pm 3.82 \text{ mg m}^{-2} \text{ h}^{-1}$ (*Dipterocarpus* forest site) in a different ecosystem of North-East India (Thokchom & Yadava, 2014).

Dar et al. (2015) observed 39.06 – $49.63 \text{ mg m}^{-2} \text{ h}^{-1}$ in the year 2012 and 30.92 – $44.75 \text{ mg m}^{-2} \text{ h}^{-1}$ in the year 2013 for the winter season CO_2 efflux. In the Moist Tropical Forest Soils of Himalayan Foothills, India, Dehradun Chakraborty et al. (2021) reported $1602 \pm 64 \text{ CO}_2 \text{ mg m}^{-2} \text{ h}^{-1}$ (termite mound) and $788 \pm 17 \text{ CO}_2 \text{ mg m}^{-2} \text{ h}^{-1}$ (surrounding forest soil) winter efflux.

Conclusion

The present study enabled us to infer that the wetlands in the foothills of the Himalayas emit substantial quantities of CO_2 , CH_4 , N_2O , and H_2O vapor. The study period included only the winter months (post-monsoon season). Given the exponential relationship observed between soil temperature and greenhouse gas fluxes, these wetland soils should emit much higher quantities in the pre-monsoon and monsoon seasons when the temperature remains higher. The present study indicated that CH_4 and N_2O fluxes did not vary spatially; however, the CO_2 emission

depended on the soil type. Among the soil physico-chemical parameters, pH had a strong influence on the greenhouse gas fluxes. The Q_{10} ranges indicate that these wetlands would emit more CO_2 compared to CH_4 and N_2O in the future. The emission rates observed in this study were in parity with the observations from many freshwater and brackish water wetlands. Thus, there is no reason to neglect this type of wetlands while strengthening the global budgets of greenhouse gases. Overall, the data acquired from this study would fill in a critical gap in the data-deficient Himalayan wetlands.

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Data availability The dataset generated and analyzed during the current study is available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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