Environmental Processes (2021) 8:553–571
https://doi.org/10.1007/s40710-021-00497-0

ORIGINAL ARTICLE

Carbon Dioxide and Methane Fluxes from Various Vegetation Communities of a Natural Tropical Freshwater Wetland in Different Seasons

David Were[1,2] · Frank Kansiime[2] · Tadesse Fetahi[1] · Thomas Hein[3,4]

Received: 19 September 2020 / Accepted: 5 January 2021 / Published online: 16 February 2021

Abstract

Emission of carbon dioxide (CO_2) and methane (CH_4) is of interest in tropical wetland studies because the high and relatively stable temperatures year-round enhance both primary productivity and organic matter decomposition. Nonetheless, there is scarcity of data on emission of these carbon-based greenhouse gases from tropical wetlands. We investigated CO_2 and CH_4 fluxes from a natural tropical freshwater wetland in Uganda under different dominant vegetation communities, i.e., *Cyperus papyrus* (Papyrus), *Typha latifolia* (Typha) and *Phragmites mauritianus* (Phragmites), during the dry and wet seasons. Gas samples were collected using static chambers and analyzed by gas chromatography. Fluxes (mg C m^{-2} h^{-1}) of both CO_2 and CH_4 from Papyrus (732.9 ± 48.7 [mean ± standard error] and 14.1 ± 0.8, respectively) and from Typha (759.7 ± 51.4 and 13.5 ± 1.2, respectively) insignificantly varied ($p > 0.05$) during the dry season. However, CO_2 and CH_4 fluxes from both vegetation communities during this season were significantly lower and higher ($p < 0.05$), respectively, than in Phragmites (871.8 ± 56.7 and 8.7 ± 0.5). During the wet season, no significant variation ($p > 0.05$) occurred among the three vegetation communities for both CO_2 and CH_4 fluxes (Phragmites: 691.9 ± 55.8 and 15.6 ± 1.1, Typha: 682.0 ± 53.3 and 16.3 ± 1.2, and Papyrus: 651.2 ± 49.0 and 17.1 ± 1.7, respectively). Water level was the main driver of CO_2 and CH_4 fluxes from the wetland, suggesting its importance in any efforts to regulate fluxes of both gases in tropical wetlands. We estimated total annual CO_2 and CH_4 emissions from Uganda's wetland soils in the ranges of 159.5×10^6–180.2×10^6 t C (tonnes of carbon) and 278.9×10^4–359.7×10^4 t C, respectively.

Highlights

- Vegetation community does not influence CO_2 and CH_4 fluxes from a tropical freshwater wetland soil under continuous flooding
- High water level in a tropical freshwater wetland lowers CO_2 flux but increases CH_4 flux
- A wetland's role in climate change mitigation is a function of carbon sequestration and emission

Keywords Climate change · Greenhouse gases · Papyrus · Phragmites · Typha · Uganda's wetlands

✉ David Were
dwere51@gmail.com; davidwere@caes.mak.ac.ug

Extended author information available on the last page of the article

1 Introduction

Global warming and the subsequent climate change have been attributed to greenhouse gases, whose concentrations in the atmosphere have steadily increased over the past century. The most recent report by the World Meteorological Organization (WMO 2019) recognizes carbon dioxide (CO_2) and methane (CH_4) as the most important greenhouse gases, respectively contributing about 66% and 17% of the radiative forcing by long-lived greenhouse gases. This report further estimated atmospheric concentration of CO_2 in 2018 at 407.8 ppm, a 147% increase from pre-industrial level in 1750. Similarly, within the same period, atmospheric CH_4 concentration increased by 259% to 1869 ppb. While CO_2 accounts for the highest level of radiative forcing, the global warming potential of CH_4 on a 100-year scale is 34 times that of CO_2 (IPCC 2013; Mitsch and Mander 2018). With this in mind, we believe that setting successful climate mitigation strategies requires a clear understanding of sources and controls of both gases.

Natural wetlands provide favourable environments for carbon sequestration, through capture and long-term storage of atmospheric carbon, making them fundamental ecosystems in climate change mitigation efforts. Coupled with hypoxic conditions, the high primary productivity of these ecosystems permit them to accumulate large amounts of carbon in their soils (Lane et al. 2016; Nahlik and Fennessy 2016; Villa and Bernal 2018). With a coverage of only 5–8% of the earth's land surface (Nahlik and Fennessy 2016), wetlands' carbon content is estimated to be as high as one third of the world's carbon stored in organic soils (Were et al. 2019). In contrast, natural wetlands also emit carbon into the atmosphere, in the form of CO_2 and CH_4 (Belger et al. 2011; Butterbach-Bahl et al. 2016; Gutenberg et al. 2019; Ishikura et al. 2019; Mitsch and Mander 2018). For instance, it is estimated that wetlands account for up to 25% of the total natural and anthropogenic sources of CH_4 (Oertel et al. 2016). Thus, understanding the net contribution of wetlands to climate change mitigation entails knowledge of not only their carbon sequestration potential but also their carbon emission rate. Besides, emission of greenhouse gases has been shown to vary across wetland types (Belger et al. 2011; Butterbach-Bahl et al. 2016; Oertel et al. 2016; Sjögersten et al. 2014; Turetsky et al. 2014), suggesting the need for studies across all wetland types for proper accounting of total emission from global wetlands.

Factors controlling CO_2 and CH_4 emissions from wetlands have been relatively well studied and documented (Belger et al. 2011; Duval and Radu 2018; Oertel et al. 2016; Olsson et al. 2015; Veber et al. 2018; Villa and Bernal 2018; Were et al. 2019). One of the important characteristics of wetlands, which has also been reported to affect CO_2 and CH_4 flux from these ecosystems is vegetation. Wetland plants may exert variable effects on CO_2 and CH_4 fluxes from wetlands due to differences in factors such as anatomy, phenology, species composition, density (Maucieri et al. 2017) and age (Oertel et al. 2016). Organic matter originating from different plant species may present varying degrees of recalcitrance, with subsequent variations in the rates of decomposition (Hernandez and Mitsch 2007; Sjögersten et al. 2014). Likewise, the amount of organic matter input into wetland soil varies among plant species (Marín-Muñiz et al. 2015). The implication is that even within the same wetland, CO_2 and CH_4 fluxes from different vegetation communities can vary spatially. For example, in a Swiss wetland, Bhullar et al. (2014) recorded a six-fold difference in CH_4 emission among plant species. Maucieri et al. (2019) reported over 2-times higher emission of CO_2 from wetlands under *A. donax, M. giganteus and P. australis* than under *C. zizanioides* and unvegetated wetlands. In the same study, CH_4 flux from vegetated wetlands significantly exceeded that in the unvegetated wetland. Understanding

CO_2 and CH_4 fluxes from different vegetation communities is, therefore, inevitable in the accurate estimation of whole wetland emissions, for wetlands with different vegetation communities.

Knowledge of current fluxes of CO_2 and CH_4 in wetlands is also necessary since temperature increases associated with climate change could elevate future fluxes of these greenhouse gases (Nahlik and Mitsch 2011; Sjögersten et al. 2014). Despite tropical wetlands covering a large spatial extent (nearly 30% of the world's wetlands area; Marín-Muñiz et al. 2015), most studies have given attention to CO_2 and CH_4 emissions from temperate and boreal wetlands (Marín-Muñiz et al. 2015; Sha et al. 2011; Sjögersten et al. 2014). As a result, CO_2 and CH_4 emissions from tropical wetlands are less understood in comparison to their temperate and boreal counterparts. Moreover, CO_2 and CH_4 emissions are of interest for tropical wetland studies because the high and relatively stable temperatures year-round enhance both primary productivity and organic matter decomposition. Additionally, there is a limited understanding of tropical wetland biogeochemistry compared to boreal peatlands (Mitsch et al. 2010), which could result into disagreements over the controls and magnitude of CO_2 and CH_4 fluxes from tropical wetlands. Indeed, Villa and Bernal (2018) and Were et al. (2019) in their recent review studies on carbon sequestration have recommended more work on tropical wetlands in order to have a candid understanding of how they differ from the well-studied northern wetlands.

In this study, we evaluated CO_2 and CH_4 emissions from a natural tropical freshwater wetland under three naturally occurring dominant vegetation communities, on a temporal basis, considering both the dry and wet seasons. We sought to answer the following research questions: (i) do fluxes of CO_2 and CH_4 from a natural tropical freshwater wetland vary among various vegetation communities, and between seasons? and (ii) what are the major environmental factors that influence CO_2 and CH_4 fluxes from a natural tropical freshwater wetland? Understanding of CO_2 and CH_4 emissions and their controlling factors in tropical wetlands is a prerequisite to enable the inclusion of tropical wetlands into global climate change models.

2 Materials and Methods

2.1 Study Area

This study was conducted on Naigombwa wetland ecosystem, located in Iganga District, South-eastern Uganda (Fig. 1). Based on dominant vegetation communities that form a permanent cover throughout the year, this wetland can be sub-divided into three different sections: *Cyperus papyrus* (Papyrus), *Typha latifolia* (Typha) and *Phragmites mauritianus* (Phragmites).

Papyrus vegetation community mainly occur in the downstream areas of the wetland, unlike Phragmites and Typha vegetation communities which are mainly found in the upstream areas. Papyrus plants display two growth forms: emergent (rooted in the sediment, close to the wetland edges) and floating (rooted in the mat above the water column, towards the wetland mid-sections where the water level is high) (Fig. 2). The mat structure is made up of loosely entangled roots and rhizomes, alongside a thin layer of soil formed from dead plant matter (Azza et al. 2000). On the other hand, both Typha and Phragmites plants exhibit only an emergent form, limiting their competition with papyrus plants in

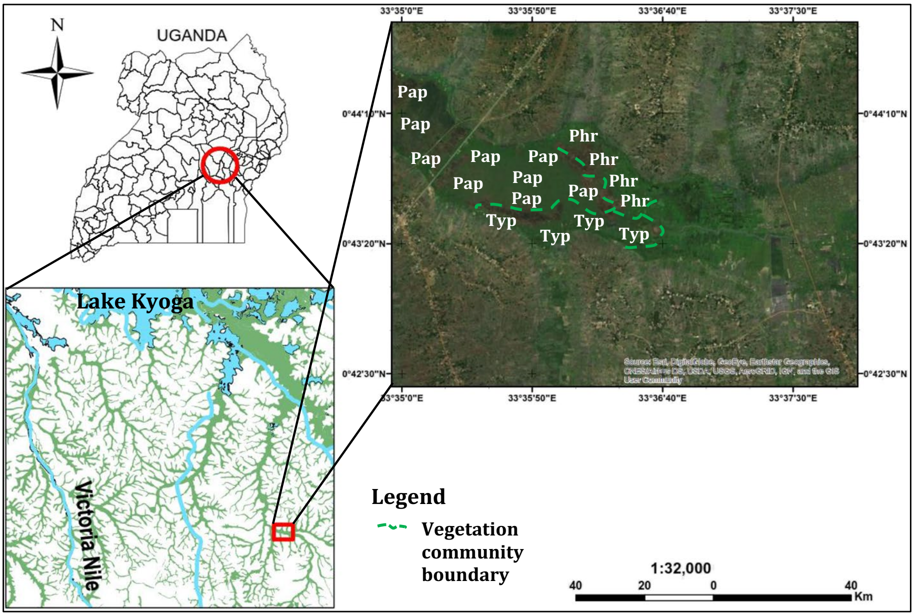


Fig. 1 Location of the study area on the map of Uganda. The specific sampled area was zoomed and geo-referenced from Google Earth. Pap = Papyrus, Typ = Typha, Phr = Phragmites

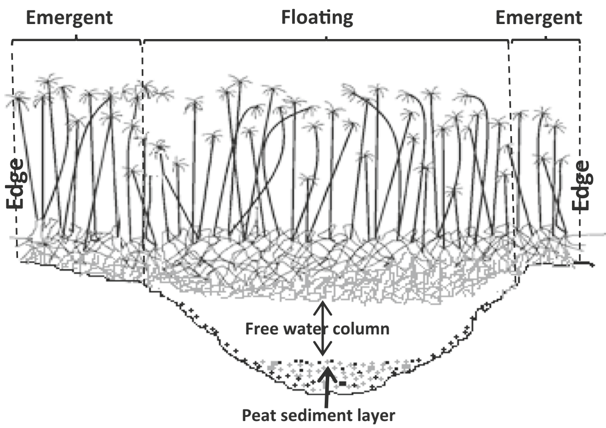


Fig. 2 Schematic overview of a transverse cross-section through a Papyrus wetland section. Generated from this study

high water level areas (Kansiime et al. 2007). All the three vegetation species are native to the wetland, and also dominate many other wetland ecosystems of Uganda.

Variation of water level in Naigombwa wetland is experienced during different seasons of the year (Kayendeke et al. 2018). Intermittent flooding and drying cycles occur at wetland edges during wet and dry seasons, respectively. On the contrary, areas away from the edge are mainly flooded year-round, but experience fluctuations in water level depth between wet and dry seasons. Nevertheless, for the whole sampling period during this study the wetland was continuously flooded. Surface water flow in the wetland is natural, with minimal human alterations. The water flow is sustained by water inflow from the wider catchment, which is dependent on both precipitation, and input from streams.

2.2 Gas Sampling and Analysis

Gas sampling from each of the three vegetation communities described above was done using static gas chambers (Butterbach-Bahl et al. 2016; Nicoloso et al. 2013). For the Papyrus vegetation community which displays two growth forms (Fig. 2), gas sampling targeted both growth forms.

Chambers were fitted with a probe thermometer to monitor inside air temperature, a vent pipe for preventing radical changes of internal air pressure, and a sampling port with a septum, which also provided for manually homogenizing inside air using a syringe and needle (Collier et al. 2014; Minamikawa et al. 2015). White colour chambers, whose outside surfaces were covered using an aluminium reflective tape were selected to minimize heating up of the chambers during sampling due to radiation from the sun. To provide a gas tight enclosure that prevents exchange of inside and outside air, chamber lids were firmly inverted onto the chamber bases that were sunk into the soil to at least 10 cm (Butterbach-Bahl et al. 2016). Installation of chamber bases was done at least 7 days before sampling (Butterbach-Bahl et al. 2016). The chambers used had an average headspace with the following dimensions: height = 25 cm, volume = 10 L and basal area = 490.63 cm^2.

Gas sampling was carried out in quadrats that were randomly selected along transects. Three chambers were deployed and sampled consecutively in each quadrat (Collier et al. 2014). To prevent artificial ebullition of the gases and physical disturbance of soil at sampling points, wooden scaffolds were installed to act as walkways. In the floating growth form of the Papyrus vegetation community, however, due to the suspended nature of the mat over the water column, it was not possible to control artificial ebullition due to the shaking of the mat while moving on it. This was detected from the preliminary gas measurements that showed abnormally high gas concentrations. As a result, the floating growth form of Papyrus was excluded from the final sampling plan.

The gas sampling regime was spread across the months of February, March and April 2019 (dry season) and August, September and October 2019 (wet season). Samples were obtained at time intervals of 0, 10, 20, and 30 min (inside the chamber) (Butterbach-Bahl et al. 2016). Ambient air samples were collected outside the chamber prior to start of each sampling event for quality control. The air accumulated in chambers was obtained using a 60 mL polypropylene syringe, fitted with a luer lock and a needle. Of the 60 mL volume of the gas sample in the syringes, 40 mL was used for evacuation of the 10-mL gas vials and the remaining 20 mL was stored in the gas vials (under high pressure) for analysis. Contamination of samples prior to analysis was prevented by covering gas vial tops with a parafilm. In total, for each season and vegetation community, 72 samples were collected. Gas samples were analysed at the International Livestock Research Institute, Nairobi, Kenya using gas chromatography (SRI 8610C gas chromatograph, USA), and followed the procedure described by Collier et al. (2014) and Minamikawa et al. (2015). Before gas analysis, the gas chromatograph was first calibrated using standards of known concentrations (Minamikawa et al. 2015). Visual inspection of time series concentration plots was undertaken for quality control of gas concentrations (Collier et al. 2014). Gas (CO_2 and CH_4) fluxes were calculated using Eq. (1) (Nicoloso et al. 2013):

$$f = \frac{\Delta Q}{\Delta t} \frac{P}{R} \frac{V}{T} \frac{1}{A} \quad (1)$$

where: f is the CO_2 or CH_4 flux (mg m^{-2} h^{-1}), ΔQ is the change in mass of the gas (mg) inside chamber due to change in sampling time (Δt), P is the atmospheric pressure (atm) inside the chamber, which is assumed as 1 atm, V is the chamber volume (L), R is the constant for ideal gases (0.08205 atm L mol^{-1} K^{-1}), T is the temperature (K) within the chamber at a given sampling time, and A is the basal area of the chamber (m^2).

2.3 Soil Physico-chemical Characteristics, Water Level and Air Temperature

Soil samples of the top (0–10 cm) soil layer (Järveoja et al. 2016; Nahlik and Mitsch 2011) were collected in triplicate in each quadrat using a Russian peat borer for determination of selected physico-chemical characteristics (pH, salinity and organic carbon). Soil temperature measurement was done *in-situ* using a digital soil thermometer. Because the study was carried out under flooding conditions, there was no need to measure soil moisture content.

Samples were composited by mixing three samples in each sampling plot within a quadrat. Samples were sorted using polyethylene bags, placed in a cool box and transported to the Soil Science Laboratory, College of Agricultural and Environmental Sciences, Makerere University, Kampala, Uganda for analysis. Before the analysis, samples were re-mixed to homogenise them. Samples were ground and sieved through a 2 mm nylon sieve, after being air-dried at room temperature for 21 days. To obtain soil organic matter (SOM) content, 2 g of dry soil samples were placed in pre-weighed crucibles and then dried in an oven (CARBOLITE CWF 13/5) at 105 °C to constant weight. The samples were then ignited at 450 °C for 4 h (Bernal and Mitsch 2008). Soil organic matter percentage (SOM%) of each sample was calculated following weight loss on ignition (LOI), from where soil organic carbon percentage (SOC%) was obtained as a portion of SOM%, using Van Bemmelen's index of 0.58 (Marín-Muñiz et al. 2014).

Soil pH and salinity (obtained after conversion from electrical conductivity) were determined using a CyberScan PC 300 multi-parameter meter, after equilibration of soil with deionized water (ratio of soil: water = 1:5) (Wang et al. 2018). Water level was determined using a cm-marked wooden stick by measuring the distance from the soil surface to the surface of the overlying water layer. Data of ambient air temperature characteristics during the sampling period were obtained from the Uganda National Meteorological Authority (UNMA).

2.4 Data Analysis

Data analysis was carried out using Microsoft Excel (2016) and R programming software (version 3.2.2). Prior to analysis, data were first subjected to a normal distribution test using Shapiro–Wilk test. Although soil physico-chemical characteristics and water level data were normally distributed, gas flux data did not meet the criteria for normal distribution. Consequently, ANOVA alongside Tukey HSD post-hoc test were used to test the statistical significance of soil physico-chemical characteristics and water level among wetland vegetation communities and between seasons. In contrast, ANOVA together with Kruskal–Wallis H post-hoc test were used to test the significance of CO_2 and CH_4 fluxes among the wetland vegetation communities and between seasons ($p < 0.05$). Given the significance of median values in the description of non-normally distributed gas flux data (Nahlik and Mitsch 2011; Sha et al. 2011), box plots were used. Spearman rank correlation, at $p < 0.05$ significance was used to determine the relationship between soil physico-chemical characteristics, water level and ambient air temperature, and CO_2 and CH_4 fluxes.

3 Results

3.1 Soil Physico-chemical Characteristics, Water Level and Air Temperature

Soil temperature, salinity and SOC did not vary significantly ($p > 0.05$) among the three vegetation communities across the two sampling seasons (Table 1). Although the wetland was continuously flooded throughout the sampling period, water levels were significantly higher ($p < 0.05$) during the wet season for all the three vegetation communities. Regarding the vegetation communities, water levels during the dry season in the Papyrus and Typha vegetation communities were not significantly different ($p > 0.05$), but they were both significantly higher ($p < 0.05$) than those recorded in the Phragmites vegetation community. However, in the wet season, water levels in the three vegetation communities did not differ significantly ($p > 0.05$).

Because all the three vegetation communities occur in the same wetland and in the same climatic zone, variation of climatic conditions among the vegetation communities were assumed negligible. Therefore, ambient air temperature data, which was collected at the whole wetland scale from UNMA were applied uniformly to all the three vegetation communities in the wetland. Mean air temperature during the dry season was 23.4 ± 0.1 (mean ± standard error [SE]) °C, and insignificantly varied ($p > 0.05$) from that (21.3 ± 0.2 °C) recorded in the wet season.

Table 1 Soil physico-chemical characteristics and water levels in the different vegetation communities of the wetland

Parameter	Vegetation community					
	Papyrus		Typha		Phragmites	
	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season
Temperature (°C)	26.6 ± 0.0	26.3 ± 0.0	26.9 ± 0.1	26.8 ± 0.1	26.6 ± 0.1	26.5 ± 0.1
pH	6.00 ± 0.01	5.98 ± 0.01	6.23 ± 0.01	6.24 ± 0.02	6.06 ± 0.01	6.20 ± 0.01
Salinity (mS m^{-1})	132.8 ± 4.9	128.7 ± 3.8	129.2 ± 2.4	125.9 ± 1.7	118.6 ± 2.5	91.3 ± 1.4
SOC (%)	16.3 ± 0.0	15.0 ± 0.1	13.3 ± 0.2	12.9 ± 0.1	11.7 ± 0.1	10.0 ± 0.1
Water level (cm)	7.5 ± 3.2	31.5 ± 4.4**	7.1 ± 3.2	29.1 ± 4.2**	1.9 ± 0.8[a]	21.0 ± 4.1**

Values are mean ± SE ($n = 36$)

[a] Significant seasonal variation among vegetation communities

** Significant seasonal variation ($p < 0.05$) within the same vegetation community

3.2 Carbon Dioxide and Methane Fluxes

Carbon dioxide (CO_2) fluxes from the wetland did not show variations among the vegetation communities, except in Phragmites. However, in all the three vegetation communities, it accounted for over 97% of the total carbon flux (Table 2). Mean CO_2 flux from Phragmites during the dry season was 871.8 ± 56.7 mg C m^{-2} h^{-1}, significantly higher ($p < 0.05$) than those in Typha (759.7 ± 51.4 mg C m^{-2} h^{-1}) and Papyrus (732.9 ± 48.7 mg C m^{-2} h^{-1}) (Fig. 3a). During the wet season, mean CO_2 fluxes (mg C m^{-2} h^{-1}) from the vegetation communities were 691.9 ± 55.8, 682.0 ± 53.3, and 651.2 ± 49.0 from Phragmites, Typha and Papyrus, respectively (Fig. 3b). Nonetheless, the magnitudes of variation among the vegetation communities during this season were insignificant ($p > 0.05$).

As for CO_2, also CH_4 fluxes did not show variabilities among vegetation communities, except only in Phragmites. During the dry season, mean CH_4 fluxes (mg C m^{-2} h^{-1}) of 14.1 ± 0.8 and 13.5 ± 1.2 were measured in Papyrus and Typha, respectively, which did not vary significantly ($p > 0.05$), but both were significantly higher ($p < 0.05$) than in Phragmites (8.7 ± 0.5) (Fig. 3c). During the wet season, mean CH_4 fluxes were 17.1 ± 1.7, 16.3 ± 1.2, and 15.6 ± 1.1 mg C m^{-2} h^{-1} in Papyrus, Typha and Phragmites, respectively (Fig. 3d). Again, just as it was the case with CO_2, variations in mean CH_4 fluxes among the three vegetation communities during the wet season were of negligible significance ($p > 0.05$).

Regarding season effect, whereas CO_2 fluxes during the dry season in all the three vegetation communities were generally higher than during the wet season, the variations were insignificant ($p > 0.05$), except only for Phragmites ($p < 0.05$). Similarly, whereas seasonal CH_4 flux values observed during the wet season in the three vegetation communities were generally higher than those in the dry season, the variations were not statistically significant ($p > 0.05$), except for Phragmites ($p < 0.05$).

Great variations in fluxes occurred for both CO_2 and CH_4 even within the same sampling season. For instance, point CO_2 emissions (mg C m^{-2} h^{-1}) ranged from 422.1–1044.5 from Papyrus, 411.5–1073.8 from Typha and 583.8–1196.2 from Phragmites during the dry season, compared to 333.5–958.3, 337.9–1015.9 and 395.5–1092.5, respectively, during the wet season. Similarly, point CH_4 emissions (mg C m^{-2} h^{-1}) ranged from 7.3–21.0, 7.2–19.6 and 6.4–10.8 from Papyrus, Typha and Phragmites vegetation communities, respectively, during the dry season in comparison with 9.2–30.0, 9.1–21.4 and 8.3–20.9, respectively, during the wet season.

3.3 Influence of Soil Physico-chemical Characteristics, Water Level and Air Temperature on Carbon Dioxide and Methane Fluxes

The Spearman rank correlations (Table 3) indicated that none of the soil physico-chemical parameters had a significant correlation ($p > 0.05$) with gas fluxes. The same observation was true for air temperature ($p > 0.05$). These observations are not surprising since throughout the sampling period both soil physico-chemical characteristics (Table 1) and air temperature did not present significant variations ($p > 0.05$) either among vegetation communities or between seasons. On the other hand, water level was found to have significant correlations ($p < 0.05$) with both CO_2 and CH_4 fluxes. A significant negative correlation ($p < 0.05$) was obtained between water level and CO_2 flux, while CH_4 flux showed a significant positive correlation ($p < 0.05$) with water level.

Table 2 Carbon dioxide (CO_2) and CH_4 fluxes from different vegetation communities of the wetland as a percentage of the total carbon flux

Vegetation community	CO_2 (mg C m^{-2} h^{-1})			CH_4 (mg C m^{-2} h^{-1})			Total C flux (mg C m^{-2} h^{-1})	CO_2 (% of Total C flux)	CH_4 (% of Total C flux)
	Dry season	Wet season	Average	Dry season	Wet season	Average			
Papyrus	732.9 ± 48.7	651.2 ± 49.0	692.1 ± 48.8	14.1 ± 0.8	17.1 ± 1.7	15.6 ± 1.3	707.7 ± 50.1	97.8	2.2
Typha	759.7 ± 51.4	681.9 ± 53.3	720.8 ± 52.3	13.5 ± 1.2	16.3 ± 1.2	14.9 ± 1.2	735.7 ± 53.6	98.0	2.0
Phragmites	871.8 ± 56.7	691.9 ± 55.7	781.8 ± 56.2	8.7 ± 0.5	15.6 ± 1.1	12.1 ± 0.8	794.0 ± 57.0	98.5	1.5

Values are mean ± SE (n = 36). Total C flux is the sum of average CO_2 and CH_4 fluxes

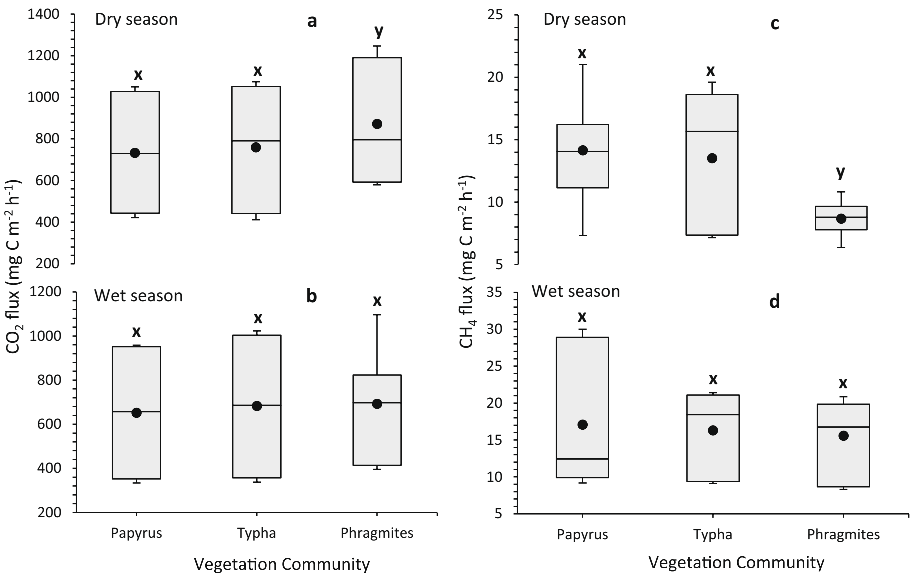


Fig. 3 Comparison of CO_2 and CH_4 fluxes from the Papyrus, Typha and Phragmites vegetation communities during the dry (**a** and **c**, respectively) and wet (**b** and **d**, respectively) seasons. Box lines indicate upper and lower quartiles. Horizontal lines within boxes show medians, while black dots show means. Whiskers extend up to the minimum and maximum values. Letters on box plots indicate significance, based on the mean and SE ($n = 72$). Similar letters show no significant difference ($p > 0.05$)

Table 3 Spearman rank correlations between soil physico-chemical characteristics, water level, air temperature and CO_2 and CH_4 fluxes ($n = 36$)

	CO_2	CH_4	Soil temp	SOC	Soil pH	Soil salinity	Water level	Air temp
CO_2	1.00							
CH_4	−0.99*	1.00						
Soil temp	0.30	0.23	1.00					
SOC	0.24	0.25	−0.05	1.00				
Soil pH	−0.07	0.12	−0.39	−0.06	1.00			
Soil salinity	0.04	−0.01	0.28	0.26	−0.36	1.00		
Water level	−0.87*	0.86*	−0.39	0.04	0.08	−0.08	1.00	
Air temp	0.29	0.26	0.45*	0.27	−0.20	0.31	−0.34	1.00

Soil temp Soil temperature, *Air temp* Air temperature

* Significant correlation ($p < 0.05$)

These relationships between water level and CO_2 and CH_4 fluxes are further clearly depicted in Fig. 4. Also, the correlation between CO_2 and CH_4 fluxes was significantly negative ($p < 0.05$), implying that at any given time organic matter degradation and carbon emission processes favoured one gas over the other, as reflected in Fig. 5.

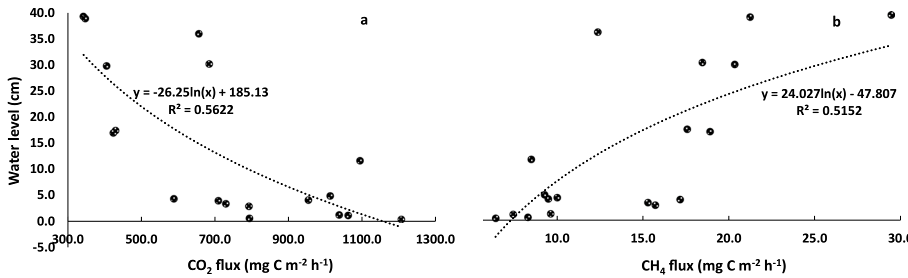
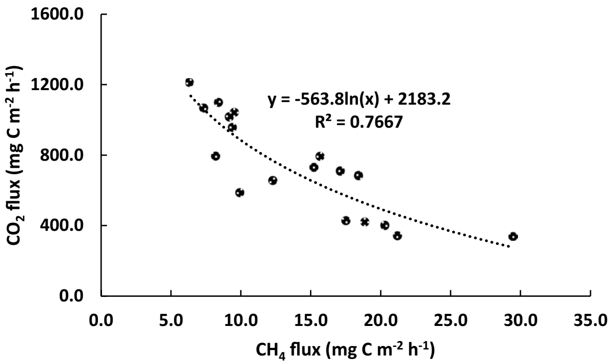


Fig. 4 Relationship between water level and CO_2 (**a**) and CH_4 (**b**) fluxes from the wetland

Fig. 5 Relationship between CO_2 and CH_4 fluxes from the wetland



4 Discussion

4.1 Effect of Vegetation Community on Carbon Dioxide and Methane Fluxes

Organic matter availability is recognized as one of the most important factors influencing fluxes of carbon-based greenhouse gases in wetland soils. Both the amount and quality of organic matter deposited onto wetland soils are dependent on the type of plants (Hernandez and Mitsch 2007; Maucieri et al. 2017; Sjögersten et al. 2014). Ding et al. (2005) noted that CH_4 emissions resulting from decomposition of plant organic matter are as high as 90%. Inglett et al. (2012) further linked variations in methanogenic activity in wetlands under differing vegetation types to differences in carbon availability and input rate into soil. Duval and Radu (2018) made an observation of dissimilar flux rates of both CO_2 and CH_4 in peat samples collected from three fen areas with each representing distinct vegetation communities: sedges, shrubs, and non-vascular communities (*Carex oligosperma, Chamaedaphne calyculata, Sphagnum capillifolium, Carex livida*, *Cornus stolonifera*, and *Chara* spp.). The authors observed a negative correlation between gas flux rates and the content of lignin and cellulose. Following a microcosm experiment, Sun et al. (2019) have recently reported that presence of *Pontederia cordata* and *Phragmites australis* in a wetland enhanced CO_2 emission, while the influences of both *Typha orientalis* and *Lythrum salicaria* on CO_2 emissions were negligible. Maucieri et al. (2019) have also found variable rates of CO_2 fluxes from Mediterranean wetlands with different vegetation communities, which they attached to differences in organic matter input into soils. With this knowledge, our expectation was to observe significant differences of both CO_2 and CH_4 fluxes among the three vegetation communities we studied. However, during the dry season, no significant variations of both CO_2 and CH_4 fluxes among the three vegetation communities were noticed, except for Phragmites (Fig. 3a, c). Similarly, during the wet season, variations of both CO_2 and CH_4 flux rates among all the three vegetation communities were insignificant (Fig. 3b, d). The lack of a significant difference in organic carbon content among the vegetation communities (Table 1) could be used to explain our findings. While studying on Mexican wetlands, Marín-Muñiz et al. (2015) did not find significant variation of both CO_2 and CH_4 fluxes among vegetation communities with similar organic carbon contents. Gagnon et al. (2007) understood that fluxes of carbon-based greenhouse gases in wetland soils are impacted by organic matter input because it influences bacterial activity, with high organic matter content being associated with intensive bacterial activity. Further, Were et al. (2020) have reported comparable lignin contents of Papyrus, Typha and Phragmites, and suggested that they could not account for differences in SOC contents among the three plant species. Therefore, our observation of a significant difference in CO_2 and CH_4 fluxes only in Phragmites during the dry season could be attributed to other factors such as water level (Marín-Muñiz et al. 2015). During the dry season, water level in the Phragmites vegetation community was significantly lower than in both Papyrus and Typha vegetation communities (Table 1).

4.1.1 Effect of Water Level on Carbon Dioxide and Methane Fluxes

For the entire sampling period, the wetland was continuously flooded, though variations in water level occurred between the dry and wet seasons (Table 1). Soil anaerobicity was enhanced under conditions of continuous flooding because soil pore spaces were filled (Marín-Muñiz et al. 2015). CO_2 emission from wetland soil is minimized under anaerobic conditions that impede aerobic organic matter decomposition, while methanogenesis and the ensuing CH_4 emissions are promoted at the same time (Brooker et al. 2014). Irrespective of vegetation community, Marín-Muñiz et al. (2015) noted that high water levels during the wet (rain) season significantly enhanced CH_4 emissions but lowered CO_2 emissions from several freshwater wetlands, including that dominated by Typha plants. Lawrence et al. (2017) observed variations in CH_4 emissions under high (+ 10 cm) and low (−10 cm) water tables in wetland mesocosms with Typha plants. Reducing water level from high water table positions (2 to 14 cm) to lower water table positions (0 to -11 cm) increased CO_2 emissions by 120% and reduced CH_4 emissions by 75% (Yang et al. 2013). Olsson et al. (2015) found significant variations in CH_4 emission rates in two Phragmites wetlands, as water level moved from the soil surface to below the surface. Liu et al. (2015) reported that varying water levels significantly influenced flux rates of both CO_2 and CH_4 in a Chinese wetland. Ishikura et al. (2019) recently noticed that lowering groundwater level in a Malaysian wetland increased daily mean flux of CO_2. Bernal and Mitsch (2013) and Batson et al. (2015) also noted variations in gas fluxes from wetlands that experienced marked drying and wetting cycles. Similarly, in the USA, a study by Gutenberg et al. (2019) on the influence of water level on CH_4 fluxes from a wetland has reported that increasing soil moisture content by 1 unit increased CH_4 flux by 457 μg m^{-2} h^{-1}. These observations are further supported by Maucieri et al. (2017), who in a literature review found significantly higher emission rates of CO_2 under low water table, and significantly higher emission rates of CH_4 under high water table. In the present study, nevertheless, flux rates of both CO_2 and CH_4 in Papyrus and Typha differed insignificantly between the dry and wet seasons, despite water levels differing significantly between the two seasons. Our view is that the soils might have already reached maximum saturation during the dry season such that any further increase in water level during the wet season could not affect gas fluxes (Mander et al. 2011; Moore and Knowles 1989; Nahlik and Mitsch 2011; Yang et al. 2013).

Apart from water level, gas fluxes have been shown to be affected by soil physico-chemical characteristics such as soil temperature (Duval and Radu 2018; Nahlik and Mitsch 2011; Oertel et al. 2016; Olsson et al. 2015; Veber et al. 2018), pH (Oertel et al. 2016; Wanyama et al. 2019; Veber et al. 2018), C:N ratio (Batson et al. 2015; Wanyama et al. 2019), and bulk density (Wanyama et al. 2019). However, in line with our findings, a number of other studies also have not found significant correlation between soil physico-chemical characteristics and gas fluxes. Wanyama et al. (2019) observed weak correlations between soil temperature and CO_2 and CH_4 fluxes. Sjögersten et al. (2014) showed that soil temperature was unlikely to be a major factor influencing decomposition and gas flux from tropical wetlands. Villa and Bernal (2018) also supported this, understanding that low O_2 availability under anaerobic conditions, due to water saturation in wetland soils, is more important in driving decomposition (and the resultant gas fluxes) than soil temperature. Wang et al. (2018) noted no significant correlation between C:N ratio and SOC, suggesting its insignificant influence on CO_2 and CH_4 fluxes. Batson et al. (2015) reported insignificant correlations between soil bulk density and fluxes of both CO_2 and CH_4. Bhullar et al. (2014) found no correlation between soil pH and CH_4 emission. Richards and Craft (2015) observed no correlations between greenhouse gas fluxes and all measured soil properties in both natural and restored wetlands. Richards and Craft (2015) explained that disagreements over correlations between soil parameters and gas fluxes, as reported by different studies, could arise because CH_4 and CO_2 emission is an interplay between several factors and processes, and the dominant one may vary according to existing conditions. Therefore, possibly the lack of correlations between soil properties and CO_2 and CH_4 fluxes in this study could be because they were not the major limiting factors.

4.2 Comparison of Carbon Dioxide and Methane Fluxes with Literature Data

By combining dry season and wet season fluxes, we obtained average CO_2 fluxes among the three vegetation communities in the range of 692.1–781.8 mg C m^{-2} h^{-1}, while CH_4 emissions ranged from 12.1–15.6 mg C m^{-2} h^{-1} (Table 2). In comparison with other studies, we noticed that CO_2 flux rates recorded in our study were lower than those obtained in other tropical wetlands, though higher than those reported in boreal and temperate wetlands (Table 4). Conversely, our CH_4 flux rates were both higher and lower than some reported values for other tropical wetlands, but higher than reported rates for boreal and temperate wetlands. The low CO_2 flux rates compared to those from other tropical wetlands could be attributed to the fact that our study wetland was under continuous flooding, which suppressed aerobic organic matter decomposition (Liu et al. 2015). Differences in flux rates of CO_2 and CH_4 between our tropical wetland and those of temperate and boreal wetlands could be explained by temperature differences (Gomez et al. 2017; Oertel et al. 2016; Sha et al. 2011). High temperatures in tropical regions are associated with high organic matter decomposition rates in wetland soils, which enhance gas emissions (Villa and Bernal 2018; Were et al. 2019).

Nonetheless, both CO_2 and CH_4 flux rates recorded in our study are within ranges reported for wetland types with more or less similar conditions to our study wetland. Sjögersten et al. (2014) have reported CO_2 emission from related tropical wetlands ranging

Table 4 Carbon dioxide (CO_2) and methane (CH_4) emissions from wetland soil from different studies

Study location/Climate	CO_2 (g C m^{-2} yr^{-1})	CH_4 (g C m^{-2} yr^{-1})	Reference
Uganda/tropical	6062.8–6848.6	106.0–136.7	Current study
Malaysia/tropical	926.0	3.9	Ishikura et al. (2019)
Brazil/tropical	1022.4	27.5	Belger et al. (2011)
Zimbabwe/tropical	7850.7	258.4	Nyamadzawo et al. (2015)
Indonesia/tropical	7743.8	10.6	Sjögersten et al. (2014)
Malaysia/tropical	7928.8	na	Sjögersten et al. (2014)
Virginia, USA/temperate	543.12	20.2	Gutenberg et al. (2019)
New York, USA/temperate	222.7	na	Gomez et al. (2017)
Northeast China/temperate	3534.4	1.2	Liu et al. (2015)
Poland/temperate	na	20.0–29.0	Fortuniak et al. (2017)
Ohio, USA/ temperate	57.8	44.7	Brooker et al. (2014)
Switzerland/temperate	na	0.002–0.01	Bhullar et al. (2014)
Virginia, USA/temperate	4301.5	−0.02	Batson et al. (2015)
Several/temperate	na	39.8	Turetsky et al. (2014)
Russia/boreal	na	21.9	Schneider et al. (2018)
Several/boreal	na	26.5	Turetsky et al. (2014)

For the ease of comparison, emission values have been computed to similar units. Values are given as single means or ranges of means (where means of several sampling sites are provided in the source document)

na: not available

from 317.0–905.0 g C m^{-2} yr^{-1}, while Nahlik and Mitsch (2011) have reported CH_4 emission ranging from 6.0 g C m^{-2} yr^{-1} to 788.0 g C m^{-2} yr^{-1}.

4.3 Carbon Dioxide and Methane Emission from Uganda's Wetlands

Wetlands cover a considerably big portion of Uganda's land surface. According to the most recent Uganda Wetland Atlas (https://www.mwe.go.ug/library/uganda-wetlands-atlas) published by the Ministry of Water and Environment in 2016, wetlands cover about 11% (representing 26,315 km^2) of the country's land area. Whereas there exists a wide body of literature on Uganda's wetlands, carbon flux from wetlands is a relatively newer concept with a limited number of studies. Currently, no single study has estimated the totality of carbon-based greenhouse gases emitted from Uganda's wetlands. We, therefore, used our study findings to give an estimate of CO_2 and CH_4 emissions from Uganda's wetlands so as to provide a rough estimate for future studies on gas emissions from the country's wetlands. To make this possible, we made assumptions that all the country's wetlands present more or less similar conditions to our study wetland or if variations exist, they are minimal to exert significant variations on gas fluxes. Our study obtained CO_2 and CH_4 emissions ranging from 6062.8–6848.6 g C m^{-2} yr^{-1} and 106.0–136.7 g C m^{-2} yr^{-1}, respectively. With 26,315 km^2 of the country's land area under wetlands, we estimated total CO_2 and CH_4 emissions from Uganda's wetlands to be in the range of 159.5×10^6–180.2×10^6 t C (tonnes of carbon) yr^{-1} and 278.9×10^4–359.7×10^4 t C yr^{-1}, respectively. However, we also acknowledge that whereas Uganda's wetlands (and indeed other wetlands in general) are defined by common characteristics (water, hydric soils and hydrophytic plants), particular wetland conditions can differ even at local scales (Belger et al. 2011), which may affect the accuracy of our rough estimates. Additionally, the lack of other studies to compare our gas flux estimates from Uganda's wetlands limits an understanding of the robustness of our estimates.

Further, it is important to note that our study only considered CO_2 and CH_4 from wetland soil. Nevertheless, CO_2 emission involving plants (plant respiration) (Maucieri et al. 2019; Mitsch and Mander 2018; Sjögersten et al. 2014; Sun et al. 2019; Xi et al. 2019) and plant-mediated CH_4 emission (Bhattacharyya et al. 2019; Bhullar et al. 2014; Jeffrey et al. 2019; Turetsky et al. 2014) have also been shown to be important processes of CO_2 and CH_4 emissions from wetlands. However, carbon emitted can be offset by carbon fixed through photosynthesis (Maucieri et al. 2019; Mitsch and Mander 2018). A clearer understanding of carbon balance of Uganda's wetlands, therefore, requires full knowledge of total carbon emission and assimilation. Globally, Mitsch et al. (2013) demonstrated that wetlands may be net C sinks of about 0.83 Pg C yr^{-1}, with an average net C retention of 118 g C m^{-2} yr^{-1}.

5 Conclusions

Carbon dioxide (CO_2) and CH_4 fluxes did not vary significantly among vegetation communities during the wet and dry seasons, except only for Phragmites. During the dry season, Phragmites had the highest impact on climate as it emitted more CO_2 per unit area than both Papyrus and Typha vegetation communities. However, in terms of CH_4, Phragmites had the lowest impact on climate during this season as it emitted less CH_4 per unit area than Papyrus and Typha. During the wet season, nonetheless, no variation in flux (for both CO_2 and CH_4) was noticed among the three vegetation communities. In view of seasonal variabilities among wetland vegetation communities, significant differences in CO_2 and CH_4 fluxes between the dry and wet seasons were observed only in the Phragmites vegetation community as well. Dry season CO_2 flux from Phragmites exceeded its wet season counterpart, while dry season CH_4 flux from this vegetation community was less than that observed during the wet season. Water level was the main driver of CO_2 and CH_4 fluxes from the wetland. High water levels were associated with lower CO_2 fluxes but higher CH_4 fluxes. The reverse was true for lower water levels. This suggests the importance of understanding water level dynamics for regulation of CO_2 and CH_4 fluxes from tropical freshwater wetlands.

Acknowledgement Financial support for this study was provided by the African Centre of Excellence for Water Management (ACEWM), under the World Bank's African Centres of Excellence (ACE II) Project. Additional funding was provided by University of Natural Resources and Life Sciences (BOKU), Vienna, Austria, with the support of Mag. Gerold Winkler and Prof. Thomas Hein. Mr. Enock Kajubi is very much appreciated for mapping the study area. We extend thanks to the local community members neighbouring Naigombwa wetland for the good hospitality during field sampling. More thanks go to the Department of Environmental Management, Makerere University for offering laboratory and working space. Lastly, we thank Mr. Peter Mutua at the International Livestock Research Institute, Nairobi, Kenya for the technical assistance with analysis of gas samples.

Author Contributions Conceptualization: David Were, Frank Kansiime, Tadesse Fetahi; Methodology: David Were; Formal analysis and investigation: David Were, Writing—original draft preparation: David Were; Writing—review and editing: Frank Kansiime, Tadesse Fetahi, Thomas Hein; Funding acquisition: Tadesse Fetahi, Thomas Hein; Resources: Frank Kansiime, Tadesse Fetahi, Thomas Hein; Supervision: Frank Kansiime, Tadesse Fetahi, Thomas Hein.

Funding This work was supported by the African Center of Excellence for Water Management (ACEWM) (Grant No. ACEWM/GSR/9813/10), under the World Bank's African Centers of Excellence (ACE II) Project.

Data Availability The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Code Availability Not applicable.

Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Azza NG, Kansiime F, Nalubega M, Denny P (2000) Differential permeability of Papyrus and Miscanthidium root mats in Nakivubo swamp, Uganda. Aquat Bot 67:169–178. https://doi.org/10.1016/S0304-3770(00)00093-0

Batson J, Noe GB, Hupp CR, Krauss KW, Rybicki NB, Schenk ER (2015) Soil greenhouse gas emissions and carbon budgeting in a short-hydroperiod floodplain wetland. J Geophys Res Biogeosci 120:77–95. https://doi.org/10.1002/2014JG002817

Belger L, Forsberg BR, Melack JM (2011) Carbon dioxide and methane emissions from interfluvial wetlands in the upper Negro River basin, Brazil. Biogeochemistry 105:171–183. https://doi.org/10.1007/s10533-010-9536-0

Bernal B, Mitsch WJ (2008) A comparison of soil carbon pools and profiles in wetlands in Costa Rica and Ohio. Ecol Eng 34:311–323. https://doi.org/10.1016/j.ecoleng.2008.09.005

Bernal B, Mitsch WJ (2013) Carbon sequestration in two created riverine wetlands in the Midwestern United States. J Environ Qual 42:1236–1244. https://doi.org/10.2134/jeq2012.0229

Bhattacharyya P, Dash PK, Swain CK, Padhy SR, Roy KS, Neogi S, Berliner J, Adak T, Pokhare SS, Baig MJ, Mohapatra T (2019) Mechanism of plant mediated methane emission in tropical lowland rice. Sci Total Environ 651:84–92. https://doi.org/10.1016/j.scitotenv.2018.09.141

Bhullar GS, Edwards PJ, Venterink HO (2014) Influence of different plant species on methane emissions from soil in a restored Swiss wetland. PLoS ONE 9:e89588. https://doi.org/10.1371/journal.pone.0089588

Brooker MR, Bohrer G, Mouser PJ (2014) Variations in potential CH_4 flux and CO_2 respiration from freshwater wetland sediments that differ by microsite location, depth and temperature. Ecol Eng 72:84–94. https://doi.org/10.1016/j.ecoleng.2014.05.028

Butterbach-Bahl K, Sander BO, Pelster D, Díaz-Pinés E (2016) Quantifying greenhouse gas emissions from managed and natural soils. In: Methods for measuring greenhouse gas balances and evaluating mitigation options in smallholder agriculture. Springer, Cham, pp 71–96

Collier SM, Ruark MD, Oates LG, Jokela WE, Dell CJ (2014) Measurement of greenhouse gas flux from agricultural soils using static chambers. J Vis Exp 3:e52110. https://doi.org/10.3791/52110

Ding W, Cai Z, Tsuruta H (2005) Plant species effects on methane emissions from freshwater marshes. Atmos Environ 39:3199–3207. https://doi.org/10.1016/j.atmosenv.2005.02.022

Duval TP, Radu DD (2018) Effect of temperature and soil organic matter quality on greenhouse-gas production from temperate poor and rich fen soils. Ecol Eng 114:66–75. https://doi.org/10.1016/j.ecoleng.2017.05.011

Fortuniak K, Pawlak W, Bednorz L, Grygoruk M, Siedlecki M, Zieliński M (2017) Methane and carbon dioxide fluxes of a temperate mire in Central Europe. Agric For Meteorol 232:306–318. https://doi.org/10.1016/j.agrformet.2016.08.023

Gagnon V, Chazarenc F, Comeau Y, Brisson J (2007) Influence of macrophyte species on microbial density and activity in constructed wetlands. Water Sci Technol 56:249–254. https://doi.org/10.2166/wst.2007.510

Gomez J, Vidon P, Gross J, Beier C, Mitchell M (2017) Spatial and temporal patterns of CO_2, CH_4, and N_2O Fluxes at the soil-atmosphere interface in a northern temperate forested watershed. Insights For Res 1:1–12. https://doi.org/10.36959/948/457

Gutenberg L, Krauss KW, Qu JJ, Ahn C, Hogan D, Zhu Z, Xu C (2019) Carbon dioxide emissions and methane flux from forested wetland soils of the Great Dismal Swamp, USA. Environ Manag 64:190–200. https://doi.org/10.1007/s00267-019-01177-4

Hernandez ME, Mitsch WJ (2007) Denitrification potential and organic matter as affected by vegetation community, wetland age, and plant introduction in created wetlands. J Environ Qual 36:333–342. https://doi.org/10.2134/jeq2006.0139

IPCC (2013) Climate change 2013: the physical science basis. In: Stocker TF, Qin, D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 1535. https://www.ipcc.ch/site/assets/uploads/2017/09/WG1AR5_Frontmatter_FINAL.pdf. Accessed 14 Nov 2020

Inglett KS, Inglett PW, Reddy KR, Osborne TZ (2012) Temperature sensitivity of greenhouse gas production in wetland soils of different vegetation. Biogeochemistry 108:77–90. https://doi.org/10.1007/s10533-011-9573-3

Ishikura K, Hirata R, Hirano T, Okimoto Y, Wong GX, Melling L, Aeries EB, Kiew F, San Lo K, Musin KK, Waili JW (2019) Carbon dioxide and methane emissions from peat soil in an undrained tropical peat swamp forest. Ecosystems 2:1852–1868. https://doi.org/10.1007/s10021-019-00376-8

Järveoja J, Peichl M, Maddison M, Soosaar K, Vellak K, Karofeld E, Teemusk A, Mander Ü (2016) Impact of water table level on annual carbon and greenhouse gas balances of a restored peat extraction area. Biogeosciences 13(2637):2651. https://doi.org/10.5194/bg-13-2637-2016

Jeffrey LC, Maher DT, Johnston SG, Kelaher BP, Steven A, Tait DR (2019) Wetland methane emissions dominated by plant-mediated fluxes: contrasting emissions pathways and seasons within a shallow freshwater subtropical wetland. Limnol Oceanogr 64:1895–1912. https://doi.org/10.1002/lno.11158

Kansiime F, Saunders MJ, Loiselle SA (2007) Functioning and dynamics of wetland vegetation of Lake Victoria: an overview. Wetl Ecol Manag 15:443–451. https://doi.org/10.1007/s11273-007-9043-9

Kayendeke EJ, Kansiime F, French HK, Bamutaze Y (2018) Spatial and temporal variation of papyrus root mat thickness and water storage in a tropical wetland system. Sci Total Environ 642:925–936. https://doi.org/10.1016/j.scitotenv.2018.06.087

Lane RR, Mack SK, Day JW, DeLaune RD, Madison MJ, Precht PR (2016) Fate of soil organic carbon during wetland loss. Wetlands 36:1167–1181. https://doi.org/10.1007/s13157-016-0834-8

Lawrence BA, Lishawa SC, Hurst N, Castillo BT, Tuchman NC (2017) Wetland invasion by Typha × glauca increases soil methane emissions. Aquat Bot 137:80–87. https://doi.org/10.1016/j.aquabot.2016.11.012

Liu X, Guo Y, Hu H, Sun C, Zhao X, Wei C (2015) Dynamics and controls of CO_2 and CH_4 emissions in the wetland of a montane permafrost region, northeast China. Atmos Environ 122:454–462. https://doi.org/10.1016/j.atmosenv.2015.10.007

Mander Ü, Maddison M, Soosaar K, Karabelnik K (2011) The impact of pulsing hydrology and fluctuating water table on greenhouse gas emissions from constructed wetlands. Wetlands 31:1023–1032. https://doi.org/10.1007/s13157-011-0218-z

Marín-Muñiz JL, Hernández ME, Moreno-Casasola P (2014) Comparing soil carbon sequestration in coastal freshwater wetlands with various geomorphic features and plant communities in Veracruz, Mexico. Plant Soil 378:189–203. https://doi.org/10.1007/s11104-013-2011-7

Marín-Muñiz JL, Hernández ME, Moreno-Casasola P (2015) Greenhouse gas emissions from coastal freshwater wetlands in Veracruz Mexico: effect of plant community and seasonal dynamics. Atmos Environ 107:107–117. https://doi.org/10.1016/j.atmosenv.2015.02.036

Maucieri C, Barbera AC, Vymazal J, Borin M (2017) A review on the main affecting factors of greenhouse gases emission in constructed wetlands. Agric For Meteorol 236:175–193. https://doi.org/10.1016/j.agrformet.2017.01.006

Maucieri C, Borin M, Milani M, Cirelli GL, Barbera AC (2019) Plant species effect on CO_2 and CH_4 emissions from pilot constructed wetlands in Mediterranean area. Ecol Eng 134:112–117. https://doi.org/10.1016/j.ecoleng.2019.04.019

Minamikawa K, Tokida T, Sudo S, Padre A, Yagi K (2015) Guidelines for measuring CH_4 and N_2O emissions from rice paddies by a manually operated closed chamber method. National Institute for Agro-Environmental Sciences, Tsukuba. http://www.naro.affrc.go.jp/archive/niaes/techdoc/mirsa_guidelines.pdf. Accessed 12 May 2020

Mitsch WJ, Mander Ü (2018) Wetlands and carbon revisited. Ecol Eng 114:1–6. https://doi.org/10.1016/j.ecoleng.2017.12.027

Mitsch WJ, Nahlik A, Wolski P, Bernal B, Zhang L, Ramberg L (2010) Tropical wetlands: seasonal hydrologic pulsing, carbon sequestration, and methane emissions. Wetl Ecol Manag 18:573–586. https://doi.org/10.1007/s11273-009-9164-4

Mitsch WJ, Bernal B, Nahlik AM, Mander Ü, Zhang L, Anderson CJ, Jørgensen SE, Brix H (2013) Wetlands, carbon, and climate change. Landsc Ecol 28:583–597. https://doi.org/10.1007/s10980-012-9758-8

Moore TR, Knowles R (1989) The influence of water table levels on methane and carbon dioxide emissions from peatland soils. Can J Soil Sci 69:33–38. https://doi.org/10.4141/cjss89-004

Nahlik AM, Mitsch WJ (2011) Methane emissions from tropical freshwater wetlands located in different climatic zones of Costa Rica. Glob Chang Biol 17:1321–1334. https://doi.org/10.1111/j.1365-2486.2010.02190.x

Nahlik AM, Fennessy MS (2016) Carbon storage in US wetlands. Nat Commun 7:13835. https://doi.org/10.1038/ncomms13835

Nicoloso RD, Bayer C, Denega GL, Oliveira PA, Higarashi MM, Corrêa JC, Lopes LD (2013) Gas chromatography and photoacoustic spectroscopy for the assessment of soil greenhouse gases emissions. Cienc Rural 43:262–269. https://doi.org/10.1590/S0103-84782013000200012

Nyamadzawo G, Wuta M, Nyamangara J, Rees RM, Smith JL (2015) The effects of catena positions on greenhouse gas emissions along a seasonal wetland (dambo) transect in tropical Zimbabwe. Arch Agron Soil Sci 61(2):203–221. https://doi.org/10.1080/03650340.2014.926332

Oertel C, Matschullat J, Zurba K, Zimmermann F, Erasmi S (2016) Greenhouse gas emissions from soils—a review. Geochemistry 76:327–352. https://doi.org/10.1016/j.chemer.2016.04.002

Olsson L, Ye S, Yu X, Wei M, Krauss KW, Brix H (2015) Factors influencing CO_2 and CH_4 emissions from coastal wetlands in the Liaohe Delta, Northeast China. Biogeosciences 12:4965–4977. https://doi.org/10.5194/bg-12-4965-2015

Richards B, Craft CB (2015) Greenhouse gas fluxes from restored agricultural wetlands and natural wetlands, Northwestern Indiana. In: Vymazal J (ed) The role of natural and constructed wetlands in nutrient cycling and retention on the landscape. Springer, Cham, pp 17–32. https://doi.org/10.1007/978-3-319-08177-9_2

Schneider J, Ťupek B, Lukasheva M, Gudyrev V, Miglovets M, Jungkunst HF (2018) Methane emissions from paludified boreal soils in European Russia as measured and modelled. Ecosyst 21(5):827–838. https://doi.org/10.1007/s10021-017-0188-y

Sha C, Mitsch WJ, Mander Ü, Lu J, Batson J, Zhang L, He W (2011) Methane emissions from freshwater riverine wetlands. Ecol Eng 37:16–24. https://doi.org/10.1016/j.ecoleng.2010.07.022

Sjögersten S, Black CR, Evers S, Hoyos-Santillan J, Wright EL, Turner BL (2014) Tropical wetlands: a missing link in the global carbon cycle? Glob Biogeochem Cycles 28:1371–1386. https://doi.org/10.1002/2014GB004844

Sun H, Xin Q, Ma Z, Lan S (2019) Effects of plant diversity on carbon dioxide emissions and carbon removal in laboratory-scale constructed wetland. Environ Sci Pollut Res 26:5076–5082. https://doi.org/10.1007/s11356-018-3988-5

Turetsky MR, Kotowska A, Bubier J, Dise NB, Crill P, Hornibrook ER, Minkkinen K, Moore TR, Myers-Smith IH, Nykänen H, Olefeldt D (2014) A synthesis of methane emissions from 71 northern, temperate, and subtropical wetlands. Glob Change Biol 20:2183–2197. https://doi.org/10.1111/gcb.12580

Veber G, Kull A, Villa JA, Maddison M, Paal J, Oja T, Iturraspe R, Pärn J, Teemusk A, Mander Ü (2018) Greenhouse gas emissions in natural and managed peatlands of America: case studies along a latitudinal gradient. Ecol Eng 114:34–45. https://doi.org/10.1016/j.ecoleng.2017.06.068

Villa JA, Bernal B (2018) Carbon sequestration in wetlands, from science to practice: an overview of the biogeochemical process, measurement methods, and policy framework. Ecol Eng 114:115–128. https://doi.org/10.1016/j.ecoleng.2017.06.037

Wang W, Sardans J, Wang C, Asensio D, Bartrons M, Peñuelas J (2018) Species-specific impacts of invasive plant success on vertical profiles of soil carbon accumulation and nutrient retention in the Minjiang River tidal estuarine wetlands of China. Soil Syst 2:5. https://doi.org/10.3390/soils2010005

Wanyama I, Pelster DE, Butterbach-Bahl K, Verchot LV, Martius C, Rufino MC (2019) Soil carbon dioxide and methane fluxes from forests and other land use types in an African tropical montane region. Biogeochemistry 143:171–190. https://doi.org/10.1007/s10533-019-00555-8

Were D, Kansiime F, Fetahi T, Cooper A, Jjuuko C (2019) Carbon sequestration by wetlands: a critical review of enhancement measures for climate change mitigation. Earth Syst Environ 3:327–340. https://doi.org/10.1007/s41748-019-00094-0

Were D, Kansiime F, Fetahi T, Hein T (2020) Soil organic carbon storage in a tropical freshwater wetland: the influence of vegetation type. Afr J Aquat Sci. https://doi.org/10.2989/16085914.2020.1804821

WMO (2019) WMO greenhouse gas bulletin: the state of greenhouse gases in the atmosphere based on global observations through 2018. https://library.wmo.int/index.php?lvl=notice_display&id=21620#.Xwh21igzbIV. Accessed 08 July 2020

Xi M, Zhang X, Kong F, Li Y, Sui X, Wang X (2019) CO_2 exchange under different vegetation covers in a coastal wetland of Jiaozhou Bay, China. Ecol Eng 137:26–33. https://doi.org/10.1016/j.ecoleng.2018.12.025

Yang J, Liu J, Hu X, Li X, Wang Y, Li H (2013) Effect of water table level on CO_2, CH_4 and N_2O emissions in a freshwater marsh of Northeast China. Soil Biol Biochem 61:52–60. https://doi.org/10.1016/j.soilbio.2013.02.009

Authors and Affiliations

David Were[1,2] · Frank Kansiime[2] · Tadesse Fetahi[1] · Thomas Hein[3,4]

[1] African Centre of Excellence for Water Management, Addis Ababa University, Addis Ababa, Ethiopia

[2] Department of Environmental Management, Makerere University, Kampala, Uganda

[3] Institute of Hydrobiology and Aquatic Ecosystem Management, University of Natural Resources and Life Sciences (BOKU), Max Emanuel Str. 17, 1180 Vienna, Austria

[4] Wasser Cluster Lunz-Inter University Center for Aquatic Ecosystem Research, Dr Carl Kupelwieser Promenade 5, 3293 Lunz am See, Austria