Nitrous Oxide Emission from a Flooded Tropical Wetland across a Vegetation and Land Use Gradient

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Abstract

Whereas wetland ecosystems are among the most vital natural carbon sinks, they are also important sources of nitrous oxide (N₂O), a highly potent greenhouse gas. However, due to differences in wetland characteristics, N₂O emission is likely to vary across wetland types. We investigated the: 1) influence of vegetation community (*Typha latifolia*; Typha, *Phragmites mauritianus*, Phragmites and *Cyperus papyrus*, Papyrus) in a natural tropical freshwater wetland, and 2) impact of converting a natural tropical freshwater wetland into a rice paddy wetland on N₂O emission. Results showed that N₂O emission ($\mu\text{g m}^{-2} \text{ h}^{-1}$) from the natural wetland did not vary significantly ($p > 0.05$) among the vegetation communities during both the dry and wet seasons (Typha = 0.6 ± 1.6 [SE] and 0.5 ± 1.4 , Phragmites = 0.5 ± 1.7 and 0.4 ± 1.5 , Papyrus = 0.5 ± 1.3 and 0.5 ± 1.5 , respectively). These emission rates insignificantly differed ($p > 0.05$) from those recorded in the rice paddy wetland (dry season = 0.7 ± 2.8 and wet season = 0.6 ± 2.7). There was no significant correlation ($p > 0.05$) between soil physico-chemical characteristics and N₂O emission. We concluded that vegetation community does not affect N₂O emission from a natural tropical freshwater wetland under continuous flooding. Similarly, under continuous flooding and no fertilization conditions, converting a natural tropical freshwater wetland into a rice paddy wetland does not influence N₂O emission. We roughly estimated total annual N₂O emissions (T yr^{-1}) and their carbon dioxide equivalents (CO₂e; T yr^{-1}) from all Uganda's natural and rice paddy wetlands as: natural wetlands = 115.1 ± 342.8 (CO₂e = $30,501.5 \pm 90,842$) and rice paddy wetlands = 0.9 ± 2.7 (CO₂e = 242.5 ± 707.6).

1 Introduction

It is inevitable to conclude a conversation on global environmental concerns in the 21st Century without mentioning climate change, which science-based evidence attribute to the increasing emission and concentration of greenhouse gases (GHGs) in atmosphere. Addressing climate change and its impacts is currently no longer an option but a must if survival of humanity and ecosystems is to be sustained. According to the IPCC (2013), the main GHGs implicated in climate change are carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), and account for close to 90% of the radiative forcing by long lived GHGs (WMO 2019). However, even though N₂O has the lowest atmospheric concentration among the three GHGs, its global warming potential (GWP) is 265 times that of CO₂, far higher than that of CH₄, which is only 28 times that of CO₂ on a 100-year timescale (IPCC 2014). This makes N₂O an important greenhouse gas in the global climate change equation, and has since captured the attention of climate change scientists and policy makers worldwide.

Wetlands are recognized by the Millennium Ecosystem Assessment (2005) as vital ecosystems due to their various ecosystem services. Wetlands are among the most important natural ecosystems in climate change mitigation, while their services also help in adaptation to climate change impacts. Natural wetlands, in undisturbed state, are shown to be significant net carbon sinks, where their photosynthetic CO₂ uptake through primary production exceeds CO₂ losses due to ecosystem respiration (Mitsch et al.

2013; Were et al. 2019). However, despite being carbon sinks, a number of studies indicate that wetlands are also important sources of N_2O emitted into the atmosphere (Audet et al. 2014; Liengaard et al. 2013; Wu et al. 2009; Yang et al. 2019).

Unlike CO_2 , N_2O is primarily biogenic (IPCC 2007), with denitrifiers and nitrifiers being key players in the regulation of global sinks and sources of N_2O . Denitrification and nitrification in wetland soils, and the resultant N_2O emission are affected by changes in environmental conditions, which can occur either naturally due to temporal (e.g. diurnal and seasonal) variations, or due to wetland management practices (Ajwang'Ondiek et al. 2021). Intermittent flooding and drying cycles, which are associated with wet and dry seasons respectively in natural wetlands or associated with soil and water management practices in managed wetlands such as rice paddies alter soil parameters which regulate denitrification and nitrification processes (Liengaard et al. 2013). These parameters will likely vary even further under future climate scenarios, which are expected to greatly alter temperature, rainfall and nutrient regimes (Tian et al. 2015). Besides, environmental conditions in wetlands also vary spatially since soil conditions, vegetation/plant cover, and soil and water management practices also change even at small spatial scales (Butterbach-Bahl et al. 2016). Consequently, N_2O emission can also vary across small spatial scales, necessitating measurements in all wetlands situated across different climatic and geographic locations, and under different wetland management practices (especially in agricultural wetlands such as rice paddies).

Whereas there has been an increase in the knowledge of the sinks and sources of N_2O , the global N_2O budget remains less understood (IPCC 2007; Liengaard et al. 2013). Tropical ecosystems are vital in understanding global N_2O balance because several studies have indicated that the high productivity of these ecosystems is likely to translate into rates of accumulation, recycling, and loss of nitrogen far higher than those of temperate ecosystems (Hedin et al. 2009; Liengaard et al. 2013; Liu et al. 2020; Pärn et al. 2018). Further, with a coverage of about 30% of the global wetland area (Marín-Muñiz et al. 2015), tropical wetlands have present a considerably high influence on global atmospheric N_2O budget. Despite these, studies on N_2O emission from wetlands have mainly focused on temperate wetlands (Ajwang'Ondiek et al. 2021; Liengaard et al. 2013). This has limited a proper understanding of the biochemistry, controls and magnitudes of N_2O emission from tropical wetlands, hence hindering their inclusion in climate models.

Indeed, recent studies by Butterbach-Bahl et al. (2016) and Boateng et al. (2017) have noted with concern, the reliance of field measurements and estimation of GHG fluxes from tropical wetlands using emission factors calibrated from temperate wetlands, despite differences in conditions between the two climate types. Further, with specific reference to Uganda, whereas a few studies have investigated controls and magnitudes of GHG fluxes from the countries wetlands (e.g. Were et al. 2021a, b), they have mainly focused on CO_2 and CH_4 , at the expense of N_2O .

In the aim of this study was to investigate: 1) the influence of different vegetation communities (*Cyperus papyrus*, *Typha latifolia* and *Phragmites mauritianus*) within the same natural tropical freshwater wetland on N₂O emission, 2) the effect of converting a natural tropical freshwater wetland into a rice paddy wetland on N₂O emission, and 3) the environmental parameters regulating N₂O emission from natural freshwater and rice paddy wetlands in the tropics.

2 Materials And Methods

2.1 Study Area

This study was conducted on Naigombwa wetland, which forms part of the complex and interconnected wetland systems of the Lake Kyoga basin in Eastern Uganda (Fig. 1). This extensive wetland has natural and altered sections. Thus, based on land use, the wetland can be subdivided into two different wetland subcategories: natural wetland and rice paddy wetland.

The natural wetland exhibits unaltered hydrology and vegetation characteristics, and can be sub-divided into three different sections in view of the dominant vegetation communities that permanently cover the wetland i.e. *Typha latifolia* (Typha), *Phragmites mauritianus* (Phragmites) and *Cyperus papyrus* (Papyrus) sections. The Papyrus vegetation community occurs downstream of the Typha and Phragmites vegetation communities, and its morphology displays two growth forms; emergent and floating (Were et al. 2020a), unlike the Typha and Phragmites vegetation communities that grow only emergent.

The rice paddy wetland was previously part of the natural wetland, with similar conditions as described above for the natural wetland, before it was altered to enable cultivation of rice. Rice is cultivated on a seasonal basis because it relies on natural flooding, which itself is dependent on seasonal rainfall. The cultivation is done on smallholder scales, where rice is planted through broadcasting of rice seeds by hand into the fields or by transplanting rice seedlings from nursery beds into the main fields. There is no standard planting density, and therefore, plant density varies from field to field.

Surface and ground water level dynamics in these wetlands and their riparian areas have been described by Kayendeke et al. (2018). Seasonal flooding and drying cycles have been reported at wetland edges of the natural wetland in relation to the wet and dry seasons, respectively. However, wetland areas away from the edges are usually flooded throughout the year, but the flooding level varies seasonally. In the rice paddy wetland, intermittent flooding and drying cycles also occur with respect to the wet and dry seasons. However, compared to the natural wetland, both the flooding level and duration in the rice paddy wetland are manually regulated depending on the rice growth/cultivation stage. During the entire sampling course for this study, water was above the soil surface in both the natural and rice paddy wetlands, during both the dry and wet seasons.

The study area temperature can generally be described as warm. Air temperature data for the study area during the sampling period was obtained from the Uganda National Meteorological Authority (UNMA), and it showed a wet season air temperature of $21.3 \pm 0.2^{\circ}\text{C}$ (mean $\pm$ standard error; SE), in comparison to a mean of $23.4 \pm 0.1^{\circ}\text{C}$ during the dry season.

2.2 Gas Sampling and Analysis

Soil-atmosphere N_2O exchange was measured in each of the wetlands/vegetation communities described in Sect. 2.1. With respect to the Papyrus vegetation community, which has emergent and floating growth forms, the gas sampling design considered both growth forms. Gas samples were collected using steady state flux chambers (Minamikawa et al. 2015). The chamber technique is preferred, and has been widely applied in the measurement of gas fluxes from wetlands because it is less costly and allows for measurements at fine scales (Butterbach-Bahl et al. 2016).

Chamber lids included the following components: a thermometer to monitor internal air temperature, a vent tube to stabilize inside air pressure, and a gas sampling port, which allowed for manual extraction of the gas samples from chambers using a syringe and a needle (Minamikawa et al. 2015). Because of the strong solar radiation in the tropics that increases heating up of the chambers during daytime sampling, white-coloured chambers were used whose external surfaces were further covered with a reflective aluminium tape. Chamber bases were sunk up to 10 cm into the soil (Butterbach-Bahl et al. 2016), onto which chamber lids were firmly fixed to provide a gas tight enclosure. The headspace of the chambers had the following average dimensions: height = 25 cm and basal area = 490.63 cm^2 , amounting to a volume of 10 L.

In each sampling quadrat, three chambers were deployed and sampled consecutively to increase the spatial representativeness (Butterbach-Bahl et al. 2016; Minamikawa et al. 2015). To minimize artificial gas ebullition associated with physical soil disturbance during gas sampling, wooden walking platforms were installed. The wooden walking platforms also eased movement during sampling in these usually waterlogged environments. However, for the floating growth form of the Papyrus vegetation community, it was realized that the walking platforms could not control shaking and artificial gas ebullition during sampling due to the suspended nature of the root mat over the water column. This occurrence was noticed from preliminary measurements that showed abnormally high gas concentrations. Consequently, the final sampling plan excluded the floating growth form of the Papyrus vegetation community.

Sampling was done over a six-month period, equally spread across the dry (February, March and April 2019) and the wet (August, September and October 2019) seasons. During each sampling event, the duration of gas sampling for each chamber was limited to 30 minutes, at intervals of 10 minutes i.e. 0, 10, 20, and 30 minutes (Butterbach-Bahl et al. 2016). Further, prior to the start of each sampling event, ambient air samples outside the chamber were collected for quality control (Butterbach-Bahl et al. 2016). Gas samples in the chambers were collected using 60 ml luer lockable syringes attached to needles. The collected gas samples were stored in 10 ml glass vials under high pressure, after being evacuated using

40 ml of the syringe gas volume. Vial tops were covered with parafilms to prevent contamination of samples prior to analysis. The frequency of sampling in each wetland/vegetation community was twice a month, on a fortnightly basis. As a result, the total number of gas samples collected for each season in each wetland/ vegetation community was 72. Gas samples were analysed by gas chromatography (SRI 8610C gas chromatograph, USA), at the International Livestock Research Institute (ILRI) in Nairobi, Kenya.

Nitrous oxide (N₂O) flux, f ($\mu\text{g m}^{-2} \text{h}^{-1}$) was calculated as in Eq. 1 (Butterbach-Bahl et al. 2011). N₂O flux was computed as linear only if $R^2 \geq 0.70$ (Rochette et al. 2008).

$$f = S \times \frac{V_c}{A_c} \times \frac{M}{V_m} \times \frac{273.15}{273.15 + T} \times P \times 60$$

where: S = slope (ppbv min^{-1}), V_c = volume of the chamber (cm^3), A = basal area of the chamber (cm^2), M = molar weight of N₂O (which is 28 g mol^{-1}), V_m = molecular volume of N₂O ($\text{m}^3 \text{mol}^{-1}$), T is the average chamber temperature during sampling ($^{\circ}\text{C}$), P = Pressure at the time of sampling (atm), and 60 is used to convert minutes to hour.

2.3 Measurement of Environmental Parameters

Environmental (soil and hydrological) parameters were measured during the sampling period. In each wetland/vegetation community, soil samples at top (0–10 cm) soil layer (Inglett et al. 2012) were collected, from which soil physico-chemical characteristics; salinity, pH and total nitrogen (TN) and organic carbon (OC) were determined. Soil temperature was also measured *insitu*, using a digital soil thermometer. Soil moisture content was not investigated since the wetlands were under continuous flooding throughout the course of the sampling period.

Composite soil samples, that were obtained after mixing three samples in each sampling plot were placed in labelled ziploc bags and transported for analysis at the Soil Science Laboratory, Makerere University, Kampala, Uganda. Soil samples were air dried at room temperature in the laboratory for 21 days, ground and sieved through a 2 mm nylon sieve.

Soil OC was obtained from soil organic matter, following loss on ignition procedure and using Van Bemmelen's index of 0.58 as in Were et al. (2020a). Soil TN content was determined following the Kjeldahl digestion procedure. Soil pH and salinity were obtained determined using a portable multi-parameter meter (CyberScan PC 300), after mixing soil and deionized water using a soil : water ratio of 1 : 5 (Were et al. 2021a, b).

The wetland hydrological parameter considered in this study was water level, and specifically surface water level since water was above the soil surface for the entire sampling period. Surface water levels in the wetlands/vegetation communities were measured at the gas sampling location during each sampling event, using a cm-marked wooden stick.

2.4 Data Analysis

Data was sorted, and statistically analysed using the Microsoft Excel (2016) and R programming software (version 4.0.5). The data was first tested for normal distribution and homogeneity of variance. Whereas soil and surface water level data showed normal distribution, N₂O flux data did not satisfy conditions for normal distribution. Consequently, parametric one-way ANOVA, alongside the Tukey HSD post-hoc tests were used to examine the significance of mean values of soil and water level characteristics between the wetlands/vegetation communities and seasons, at $p < 0.05$ significance. On the hand, Kruskal-Wallis H test was used to test the significance of mean N₂O fluxes between the wetlands/vegetation communities and seasons, at $p < 0.05$ significance. The effect of environmental conditions on N₂O fluxes was investigated by determining the Spearman's rank-order correlations between soil and surface water level characteristics and N₂O flux, at $p < 0.05$ significance. Unless stated otherwise, all values are presented as mean $\pm$ standard error (SE).

3 Results

3.1 Soil Physico-chemical and Water Level Characteristics

Soil physico-chemical characteristics did not vary significantly either between the wetlands/among vegetation communities or between seasons, except OC and C: N ratio (Table 1). Whereas mean OC contents of the three vegetation communities did not differ significantly ($p > 0.05$) during both the dry and wet seasons, they were over 2-fold higher compared to the rice paddy wetland. Mean C:N ratios of the Typha vegetation community (dry season = 33.2:1 and wet season = 33.3:1) were significantly higher ($p < 0.05$) than those measured in the other two vegetation communities of the natural wetland and rice paddy wetland. Mean pH values during the wet and dry seasons in both wetlands were slightly acidic, ranging from 5.98–6.54 and 6.00–6.87 during the wet and dry seasons, respectively. Temperature had mean values in both wetlands ranging from 26.3–26.9 and 26.6–27.0, with respect to the wet and dry seasons.

Water was above the soil surface even during the dry season, and rapidly increased significantly during the wet season (Fig. 2). Comparing the two wetlands, surface water levels in the three vegetation communities of the natural wetland during the dry season (Typha = 7.1 ± 5.0 cm Phragmites 1.9 ± 1.3 = cm and Papyrus = 7.5 ± 5.5 cm) and wet season (Typha = 29.1 ± 6.0 cm, Phragmites = 21.0 ± 5.2 cm and Papyrus = 31.5 ± 6.1 cm) were significantly higher ($p < 0.05$) than those recorded in the rice paddy wetland (dry season = 0.4 ± 0.1 cm and wet season = 10.9 ± 1.7 cm).

Table 1
Soil physico-chemical characteristics in the natural and rice paddy wetlands
(n = 36)

Soil/ hydrological Parameter	Wetland	Season	
pH	Natural	Dry	Wet
	Typha	6.23 ± 0.01	6.24 ± 0.02
	Phragmites	6.06 ± 0.01	6.20 ± 0.01
	Papyrus	6.00 ± 0.01	5.98 ± 0.01
	Rice paddy	6.87 ± 0.03	6.54 ± 0.02
Temperature (°C)	Natural		
	Typha	26.9 ± 0.1	26.8 ± 0.1
	Phragmites	26.6 ± 0.1	26.5 ± 0.1
	Papyrus	26.6 ± 0.0	26.3 ± 0.0
	Rice paddy	27.0 ± 0.1	26.9 ± 0.1
TN (%)	Natural		
	Typha	0.4 ± 0.0	0.4 ± 0.0
	Phragmites	0.5 ± 0.0	0.5 ± 0.0
	Papyrus	0.7 ± 0.0	0.8 ± 0.0
	Rice paddy	0.4 ± 0.0	0.4 ± 0.0
OC (%)	Natural		
	Typha	12.9 ± 0.1	13.3 ± 0.2
	Phragmites	12.1.0 ± 0.1	12.7 ± 0.1
	Papyrus	15.0 ± 0.1	16.3 ± 0.0
	Rice paddy	6.00 ± 0.1*	6.2 ± 0.0*
C:N	Natural		
	Typha	32.3 ± 0.0*	33.3:1 ± 0.0*
	Phragmites	20.0 ± 0.0	23.4 ± 0.0
	Papyrus	21.4 ± 0.0	20.4 ± 0.0
	Rice paddy	20.0 ± 0.0	21.7 ± 0.0
Salinity (mS m ⁻¹)	Natural		

Soil/ hydrological Parameter	Wetland	Season	
	Typha	129.2 ± 2.4	125.9 ± 1.7
	Phragmites	118.6 ± 2.5	91.3 ± 1.4
	Papyrus	132.8 ± 4.9	128.7 ± 3.8
	Rice paddy	102.9 ± 5.8	91.1 ± 2.2

*Significant ($p < 0.05$) within the same season, OC = Organic carbon, TN = Total nitrogen

3.2 Nitrous Oxide Emission

Generally, fluxes of N_2O from both the natural and rice paddy wetlands were very low (close to zero) during the two sampling seasons. Considering the impact of vegetation community (in the natural wetland) on N_2O fluxes, no significant variation ($p > 0.05$) in N_2O flux was noted among the three vegetation communities during both seasons (Table 2). Mean N_2O fluxes from the three vegetation communities of the natural wetland ranged from $0.5\text{--}0.6 \mu\text{g m}^{-2} \text{h}^{-1}$ during the dry season, and from $0.4\text{--}0.5 \mu\text{g m}^{-2} \text{h}^{-1}$ during the wet season.

In view of the impact of land use change (from natural to rice paddy wetland) on N_2O fluxes, the difference between N_2O fluxes from the natural and rice paddy wetlands was insignificant ($p > 0.05$), with the latter recording mean flux values of 0.7 and $0.6 \mu\text{g m}^{-2} \text{h}^{-1}$ during the dry and wet seasons, respectively. Further, in both wetlands, seasonal changes (dry vs wet) did not affect N_2O fluxes significantly ($p > 0.05$). Cumulatively, mean annual N_2O fluxes from the natural and rice paddy wetlands ranged from $4.4\text{--}6.1 \text{mg m}^{-2} \text{yr}^{-1}$, with annual carbon dioxide equivalents (CO_2e) ranging from $1.2\text{--}1.6 \text{g m}^{-2} \text{yr}^{-1}$ (Table 2).

Whereas mean N_2O fluxes did not vary significantly between both wetlands and seasons, individual fluxes showed great variations even within the same wetland/vegetation community and season. However, the variations were much more pronounced in the rice paddy wetland, as can be shown by the extent of whiskers in Figs. 3 and 4. For instances, during the dry season, individual N_2O fluxes varied from $-5.2\text{--}5.5$, $-4.9\text{--}6.3$ and $-4.4\text{--}5.8 \mu\text{g m}^{-2} \text{h}^{-1}$ with respect to the Typha, Phragmites and Papyrus vegetation communities of the natural wetland, compared to $-10.1\text{--}14 \mu\text{g m}^{-2} \text{h}^{-1}$ from the rice paddy wetland. During the wet season, individual N_2O fluxes ranged from $-4.4\text{--}5.2$, $-4.5\text{--}4.7$, $-4.7\text{--}4.9 \mu\text{g m}^{-2} \text{h}^{-1}$ from Typha, Phragmites and Papyrus respectively, compared to $-7.5\text{--}11.8 \mu\text{g m}^{-2} \text{h}^{-1}$ from the rice paddy wetland. This can explain the big divergence of the mean and median N_2O flux values in both wetlands during the two sampling seasons (Figs. 3 and 4).

Table 2
Nitrous oxide (N₂O) fluxes from the natural and rice paddy wetlands and their carbon dioxide equivalents (CO₂e; n = 72)

Wetland	N ₂ O (μg m ⁻² h ⁻¹)			N ₂ O (μg m ⁻² d ⁻¹)	N ₂ O (mg m ⁻² yr ⁻¹)	CO ₂ e* (g m ⁻² yr ⁻¹)
Natural	Wet season	Dry season	Average			
<i>Typha</i>	0.5 ± 1.4	0.6 ± 1.6	0.6 ± 1.5	14.4 ± 36.0	5.3 ± 13.1	1.4 ± 3.5
<i>Phragmites</i>	0.4 ± 1.5	0.5 ± 1.7	0.5 ± 1.6	12.0 ± 38.4	4.4 ± 14.0	1.2 ± 3.7
<i>Papyrus</i>	0.5 ± 1.5	0.5 ± 1.3	0.5 ± 1.4	12.0 ± 33.6	4.4 ± 12.3	1.2 ± 3.2
Average	0.5 ± 1.5	0.5 ± 1.5	0.5 ± 1.5	12.0 ± 36.0	4.4 ± 13.1	1.2 ± 3.5
Rice paddy	0.6 ± 2.7	0.7 ± 2.8	0.7 ± 2.8	16.8 ± 48.8	6.1 ± 17.8	1.6 ± 4.7
*CO ₂ e calculated considering a N ₂ O global warming potential of 265 times that of CO ₂ (IPPC 2014), and considering 365 days in a year						

3.3 Effect of Soil Physico-chemical and Water Level Characteristics on Nitrous Oxide Emission

The relationship between soil physico-chemical and surface water level characteristics and N₂O fluxes from the wetlands is depicted in Table 3. As shown by the Spearman's rank order correlation coefficients, soil physical chemical parameters temperature, pH and TN positively correlated with N₂O flux, unlike OC, salinity and C: N that showed negative correlations. Similarly, the correlation between surface water level and N₂O flux was negative. In terms of the magnitude of the correlations, neither soil physico-chemical characteristics nor surface water level significantly correlated ($p > 0.05$) with N₂O.

Table 3
Correlation between N₂O flux and soil temperature, pH, nitrogen, organic carbon, salinity, carbon to nitrogen ration, and surface water level (n = 36)

	N2O	Temp	pH	N	OC	Salinity	C:N	S. water level
N2O	1.00							
Temp	0.26	1.00						
pH	0.03	0.19	1.00					
TN	0.28	-0.21	-0.29	1.00				
OC	-0.05	-0.34*	-0.10	-0.46*	1.00			
Sal	-0.06	0.07	-0.03	0.24	-0.16	1.00		
C:N	-0.21	0.17	-0.23	-0.21	0.25	0.09	1.00	
S. water level	-0.26	-0.55	-0.40	0.42	0.37	0.35	0.32	1.00
*Significant at p < 0.05, Temp = Temperature, N = Nitrogen, OC = Organic carbon, S. Water level = Surface water level								

4 Discussion

4.1 Nitrous Oxide Emission from the Natural and Rice Paddy Wetlands

Within the natural wetland, N₂O fluxes did vary significantly across vegetation communities. Similar results have been reported from other studies elsewhere, such as North Dakota, USA (Phillips and Beerli, 2008), Denmark (Audet et al. 2014) and Mexico (Hernández and Junca-Gómez 2020). Some studies have shown that vegetation community affects N₂O fluxes from wetlands. Liu et al. (2014) showed that emissions of N₂O from two vegetated coastal wetland zones, one dominated by *Spartina* spp. and the other dominated by *Phragmites* spp. differed significantly, with the *Phragmites* spp. zone showing higher N₂O flux, even though both zones were at the same altitude. This observation was explained by differences in biomass productivity, which affects the resultant organic matter and nitrogen input into soil. This is further supported by Piñeiro-Guerra et al. (2019), whose study across several sites in Argentina showed that N₂O emission increased with primary productivity. Wang et al. (2008) investigated the impact of plant species on N₂O emission, using constructed wetlands. Results indicated that the wetland planted with *Zizania latifolia* had a higher emission of N₂O compared to those planted with *Phragmites australis* and *Typha latifolia*. They attributed the results to differences in root structure of the plant species, where the root structure of *Zizania latifolia* was favored by ammonia oxidizing bacteria for N₂O formation. Abalos et al. (2018) investigated plant functional traits that may affect N₂O emission and

noted that specific leaf area and root length density were key traits that did not only regulate N₂O emission but also biomass productivity.

Wetland conversion/land use change, from natural to rice paddy wetland has been shown to enhance N₂O emissions from wetlands (Liengaard et al. 2013; Owino et al. 2020). This is attached two reasons: i) water table drawdown through drainage favors oxygen availability, thus increasing the mineralization of soil organic nitrogen and nitrification processes (Ajwang'Ondiek et al. 2021; Liengaard et al. 2013), and ii) nitrogen fertilization of rice paddy fields to enhance rice yields increases nitrogen availability in soil, a substrate for nitrification/denitrification processes (Owino et al. 2020). Liengaard et al. (2013) reported that partial soil wetting by light rain in a tropical South American freshwater wetland resulted into high N₂O emission compared to long-term soil waterlogging following heavy rain. In China, Yang et al. (2013) observed that N₂O emission from a natural marsh wetland increased by 120% as the water level reduced from +14 cm to -11 cm. Liu et al. (2020) have estimated that agricultural drainage of European (EU-28) peatlands has caused annual N₂O emissions from these managed peatlands of 145 Gg N yr⁻¹. They further indicated that rewetting of all drained European peatlands could cut the cumulative N₂O emissions by 70%. Similarly, a recent synthesis of several studies on the effect of wetting and drying cycles on N₂O emission from freshwater sediments has reported N₂O pulses following sediment drying and rewetting events, with exposed sediments being active spots for N₂O emissions during dry phases (Pinto et al. 2021).

Owino et al. (2020) reported that conversion of Papyrus wetlands into nitrogen fertilized rice paddies in Kenya significantly increased N₂O emission ($4.37 \pm 3.18 \mu\text{g m}^{-2} \text{h}^{-1}$ from the fertilized fields against $-3.59 \pm 2.56 \mu\text{g m}^{-2} \text{h}^{-1}$ from the unfertilized fields). Zhang et al. (2014) also reported a positive correlation between the amount of nitrogen fertilizer application and N₂O emissions from rice paddies, irrespective of the rice growth stage. Therefore, the lack of significant difference in N₂O fluxes from the natural and rice paddy wetlands in this study could be explained as follows: i) both the natural and rice paddy wetlands were continuously flooded throughout the sampling period, so water table could not significantly affect N₂O fluxes from both wetlands, as was indeed shown by lack of a significant correlation between water level and N₂O flux (Table 3), and ii) fertilization of the rice paddy fields studied is not done, as rice cultivation is only reliant on the natural fertility of the soil. Undoubtedly, soil nitrogen contents of natural and rice paddy wetlands were not different, as was seen in Table 1.

Seasonal variations did not affect N₂O fluxes from both wetlands. Seasonal variation in N₂O emissions, especially associated with temperature differences (summer vs winter seasons) have been reported in temperate wetlands (Czóbel et al. 2020; Jørgensen and Elberling 2012). Warmer soil temperatures during summer seasons have been shown to enhance microbial activities, resulting into increased mineralization of organic nitrogen in soils. However, in tropical regions, it is shown that temperature is unlikely to exert a minimal control on GHGs fluxes from wetlands because temperatures are relatively stable, irrespective of season (Sjögersten et al. 2014). However, in many tropical wetlands, seasonal

changes are usually associated with changes in water table e.g. drying and flooding cycles during the dry and wet seasons, respectively (Bernal and Mitsch 2013). Therefore, in such cases (drying and wetting cycles), seasonal N_2O flux from those wetlands is likely to be driven more by changes in the water table depth rather than soil temperature. However, it has also been indicated that seasonal N_2O fluxes based on wetting and drying cycles are more pronounced in wetland systems influenced by anthropogenic input on nitrogen (Hernandez and Mitsch et al. 2006). In the present study, seasonal changes (dry vs wet) were not associated with drying and wetting cycles as water level was above the soil surface in both seasons, and neither were the wetlands affected by anthropogenic nitrogen input. Thus, this could explain why N_2O emission did not vary between the dry and wet seasons.

This study showed great variations in individual N_2O fluxes even within the same wetland/vegetation community/season, with values ranging from negative (indicating N_2O consumption) to positive (indicating N_2O emission) (Figs. 3 and 4). This has also been reported by other studies (Ajwang'Ondiek et al. 2021; Audet et al. 2014; Owino et al. 2020), where it is attributed to wetland soils acting as both N_2O sinks and sources. Schlesinger (2013) and Wu et al (2013) have explained that soils act as sinks of N_2O when N_2O is consumed during either nitrification or denitrification, largely under conditions of limited nitrate (NO_3^-).

In this study, we observed no significant correlation between soil physico-chemical characteristic and N_2O from the wetlands. Audet et al. (2014) explored the factors controlling N_2O uptake and emission from several natural wetlands. They also established that no significant correlation between N_2O emission and soil physico-chemical characteristics. Instead, they observed that ammonium concentration in the groundwater was the only parameter that exerted a significant control on N_2O fluxes from the wetlands. Richards and Craft (2015) have explained that emission of GHGs, including N_2O from wetlands is an interplay between several factors, with the key controlling factor(s) varying depending on the existing conditions.

In Uganda, no study has evaluated the totality of N_2O emissions from the country's natural and rice paddy wetlands. Therefore, to provide a basis for future studies, we used our study findings to roughly estimate total annual N_2O emissions from Uganda's natural and rice paddy wetlands. To achieve this, we made a simple assumption that other natural and rice paddy wetlands in the country present more or less similar conditions to our study wetlands. Natural wetlands in the Uganda cover about 26,165 km^2 compared to 150 km^2 occupied by rice paddy wetlands (Were et al. 2021b). We obtained mean annual N_2O emission from the natural and rice paddy as $4.4 \pm 13.1 \text{ mg m}^{-2} \text{ yr}^{-1}$ and $6.1 \pm 17.8 \text{ mg m}^{-2} \text{ yr}^{-1}$ (Table 2). Therefore, total N_2O emissions from Uganda's natural and rice paddy wetlands are estimated at $115.1 \pm 342.8 \text{ T yr}^{-1}$ ($\text{CO}_2\text{e} = 30,501.5 \pm 90,842 \text{ T yr}^{-1}$) and $0.9 \pm 2.7 \text{ T yr}^{-1}$ ($\text{CO}_2\text{e} = 242.5 \pm 707.6 \text{ T yr}^{-1}$), respectively.

4.2 Implication of Permanently Flooded Rice Cultivation under no Fertilization on Climate Change Mitigation

To mitigate climate change and its impacts, the IPCC (2014) has emphasized increasing carbon sequestration while at the same time minimizing emission of GHGs into the atmosphere. Some of the suggested measures to increase carbon sequestration include protection and conservation of natural ecosystems such as forests, grasslands, and wetlands. Wetlands are unique ecosystems, where water is the terminal parameter that influence the development of soil and plant characteristics different from other ecosystems. These unique characteristics have a great influence on carbon and nitrogen cycling in these ecosystems (Mitsch et al. 2013). Several studies have acknowledged that conversion of natural wetlands in farmed wetlands compromises climate change mitigation by enhancing carbon and nitrogen emission (Ajwang'Ondiek et al. 2021; Owino et al. 2020; Were et al. 2020b). As earlier explained, water drawdown in rice paddy has been attributed to enhanced carbon emissions from these ecosystems (Were et al. 2019; Were et al. 2021b), while water table drawdown alongside nitrogen fertilizer application are responsible for high nitrogen fluxes from these ecosystems (Owino et al. 2020). With the increasing human population globally, increased food demand implies natural tropical freshwater wetlands will remain under high pressure of conversion into rice paddies. Indeed, Davidson and Finlayson (2018) have reported an average increase in rice paddy acreage of 0.62% per year. As result, climate change mitigation efforts need to explore ways of optimizing carbon sequestration while minimizing emission of GHGs such as N_2O from rice paddy wetlands. Basing on the results of this study, therefore, rice cultivation under continuous flooding and no nitrogen fertilizer application enhances climate change mitigation as it minimizes N_2O fluxes into the atmosphere. However, continuously flooded conditions in wetlands are also known to enhance CH_4 emission to the atmosphere (Were et al. 2019). Nevertheless, it has already been shown that undrained wetlands represent net carbon sinks of about 830 T C yr^{-1} (Mitsch et al. 2013), indicating that the emitted CH_4 is compensated by the CO_2 sequestered.

5 Conclusions

Emission of N_2O from the natural tropical freshwater wetland was not affected by vegetation community, as emission rates from the Typha, Phragmites and Papyrus vegetation communities did not differ significantly. Further, N_2O emission did not vary between the natural and rice paddy wetlands. Therefore, under conditions of continuous flooding, vegetation community has no effect on N_2O emission from a natural tropical freshwater wetland. Likewise, under continuous flooding and no fertilizer (nitrogen) application, conversion of a natural tropical wetland into a rice paddy wetland does not affect N_2O emission. Additionally, seasonal variations (dry vs wet) has no effect on N_2O emission from a natural tropical freshwater wetland and rice paddy under conditions of continuous flooding and no nitrogen fertilizer application. Soil physico-chemical characteristics showed no significant correlation with N_2O flux from the wetlands, implying that N_2O emission was an interplay between several factors, with no single dominant factor.

Declarations

Authors' Contributions

The study was conceptualized and designed by DW. DW carried out data collection and analysis, and wrote, edited and reviewed the first draft manuscript. TH edited, reviewed and contributed to the discussion of the manuscript. Funding acquisition was by TH. The study was supervised by TH. All authors read and approved the final manuscript.

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Conflict of interest

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

Ethics approval

Ethics approval was not required for this study

Consent to participate

Not Applicable

Consent for publication

Not Applicable

Availability of data and material

Not Applicable

Code availability

Not Applicable

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Figures

Figure 1

Location of study wetland. The study area was zoomed and geo-referenced from Google Earth

Figure 2

Variation of surface water level the natural (Typha, Phragmites and Papyrus) and rice paddy (Rice) wetlands during the dry (February, March and April) and wet (August, September and October) seasons

Figure 3

Comparison of N₂O fluxes from the natural (Papyrus, Typha and Phragmites) and rice paddy (Rice) wetlands during the dry season. Box lines show upper and lower quartiles, while horizontal lines within boxes show median values (n = 72). Whiskers extend to the minimum and maximum values. Mean values are not significant across wetlands/vegetation communities (p > 0.05)

Figure 4

Comparison of N₂O fluxes from the natural (Papyrus, Typha and Phragmites) and rice paddy (Rice) wetlands during the wet season. Box lines show upper and lower quartiles, while horizontal lines within boxes show median values (n = 72). Whiskers extend to the minimum and maximum values. Mean values are not significant across wetlands/vegetation communities (p > 0.05)