Land use and environmental drivers of methane and nitrous oxide emissions in Eswatini peatlands

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SUMMARY

Peatlands play an important role in carbon and nitrogen cycles, functioning as either sinks or sources of greenhouse gases (GHGs) depending on environmental and management conditions. While extensive research has been conducted on peatlands in northern latitudes and the tropics, there is limited knowledge of GHG flux dynamics in southern African peatlands. This study examined methane (CH_4) and nitrous oxide (N_2O) fluxes from two differently managed peatlands in Eswatini over 12 months using the opaque static chamber technique. The Motjane peatland, under community management, functioned as a slight net sink for CH_4-C (-2.92 mg m^{-2} hr^{-1}) but was a slight net source for N_2O-N (0.11 µg m^{-2} hr^{-1}). The Malolotja peatland, located in a nature reserve, was a slight source for N_2O-N (0.26 µg m^{-2} hr^{-1}) and neither a source nor a sink for CH_4-C (0.06 mg m^{-2} hr^{-1}). CH_4-C flux was positively correlated with temperature (below-ground, surface and air), while N_2O-N fluxes showed a negative relationship with rainfall. Seasonal environmental factors and land use management influenced CH_4-C and N_2O-N fluxes. Differences between CH_4-C and N_2O-N fluxes in the two peatlands were linked to variations in the degree of human disturbance, vegetation communities, climatic factors and soil properties. The findings highlight the importance of targeted intervention measures that are informed by continuous ecological monitoring. Sustainable peatland management strategies should focus on restoring indigenous vegetation and stabilising water levels to minimise CH_4 and N_2O emissions and enhance carbon sequestration. Future assessments of the overall GHG balance and carbon sequestration potential should consider the combined effects of all three major greenhouse gases, including CO_2.

KEY WORDS: greenhouse gas fluxes, land use management, Malolotja, Motjane, static chamber method

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INTRODUCTION

Peatlands cover approximately 4 million km², which is about 3 % of the Earth's land surface (UNEP 2024). Despite their limited spatial extent, they store an estimated 455–700 Pg of carbon in organic form (Hugelius *et al*. 2020), making them one of the most carbon-dense ecosystems on Earth. As such, they play a critical role in global climate change mitigation strategies (Were *et al*. 2019). However, their greenhouse gas (GHG) balance can shift depending on both environmental conditions and management practices. Natural peatlands are typically net sinks for carbon dioxide (CO_2), but can emit methane (CH_4) under waterlogged conditions, particularly in nutrient-poor (oligotrophic) systems. Nitrous oxide (N_2O) emissions in these saturated systems are often negligible, except during wetting and rewetting cycles (Li *et al*. 2023, Mander *et al*. 2025).

In contrast, disturbed peatlands often exhibit increased N_2O emissions due to intensified nitrification and denitrification cycles, while CH_4 emissions are typically reduced as oxidation is enhanced under drier soil conditions (Tian *et al*. 2015, Pärn *et al*. 2018, Norberg *et al*. 2021). Under climate change or sustained disturbance (e.g., drainage, grazing, land conversion), peatlands may shift from carbon sinks to net sources of CO_2 and N_2O, and in some cases may even become net CH_4 sinks (Couwenberg *et al*. 2011, Loisel & Gallego-Sala 2022). CH_4 and N_2O are of particular concern due to their global warming potentials, which are 28 and 273 times greater, respectively, than that of CO_2 over a 100-year horizon (IPCC 2023).

CH_4 emissions from peatlands occur through a series of biological processes: (i) production under anaerobic conditions via methanogenesis, carried out by methanogenic archaea; (ii) consumption in aerobic zones by methanotrophic bacteria through oxidation; and (iii) transport to the atmosphere, primarily through plant aerenchyma and to a lesser extent via diffusion and ebullition (Lai 2009, Bridgham *et al*. 2013). N_2O production in peatlands is governed by nitrate and substrate availability combined with alternating anaerobic and aerobic conditions that facilitate nitrification and denitrification. Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), during which N_2O can be produced as a byproduct. Denitrification, by contrast, is an anaerobic process in which nitrate is reduced to nitrogen gas (N_2), with N_2O formed as an intermediate under partial anoxia (Davidson 2009).

Land use intensity is a major factor driving the shift from peatlands as carbon stores to net GHG sources, particularly in tropical and subtropical regions under increasing anthropogenic pressure (Joosten *et al*. 2016). Globally, many peatlands have been degraded during the last century through draining for agriculture, livestock, peat extraction and forestry (Leifeld & Menichetti 2018). In developing countries, unsustainable wetland use is driven by the communities' reliance on resources for improving their livelihoods (von der Heyden 2004, Van Rees & Reed 2014). In Eswatini, wetlands have been degraded by resource exploitation, livestock overstocking, draining for development (roads and settlements), conversion to agricultural land, encroachment by human settlements and alien plant invasion, as well as by groundwater extraction and pollution (Mwendera 2003, Masarirambi *et al*. 2010, Government of Eswatini 2015, Eswatini Environment Authority 2021).

Climatic and anthropogenic drivers of peatland degradation continue to act synergistically, often resulting in abrupt and devastating changes that are difficult, expensive or even impossible to reverse (Finlayson *et al*. 2005). Drained peatlands promote aeration, which enhances microbial activity, leading to carbon loss and increased nitrogen mineralisation (Freeman *et al*. 1993, Frey & Smith 2005, Zhong *et al*. 2020, Mander *et al*. 2025, Yang *et al*. 2025). Restoration efforts often involve rewetting or flooding these ecosystems (Couwenberg *et al*. 2011), which may revert to becoming carbon stores (Günther *et al*. 2020).

Most of the available knowledge of CH_4 and N_2O fluxes from peatland ecosystems comes from the widely studied peatlands in northern latitudes and the tropics, while studies in southern Africa remain scarce. This study focuses specifically on CH_4 and N_2O fluxes, which contribute disproportionately to global warming due to their high warming potentials. A particular gap exists in understanding how degraded peatlands contribute to CH_4 and N_2O emissions relative to near-natural systems in this region, even as peatland loss increases (Grundling *et al*. 2021). Therefore, this study aims to: (1) quantify seasonal CH_4 and N_2O fluxes from two peatlands in northwestern Eswatini with contrasting land use management systems; and (2) identify the environmental drivers (e.g., water table level, vegetation, soil properties) that regulate flux variability. The following questions guided the study:

(i) How do CH_4 and N_2O fluxes differ between protected and community-managed peatlands?

(ii) What site-specific environmental factors explain spatiotemporal flux variation?

METHODS

Study areas

The study was conducted in two distinctly managed peatlands: in Malolotja Nature Reserve and the Motjane community, both of which are in the northwestern Highveld of Eswatini (Figure 1). In comparison to the other physiographic regions in Eswatini, the Highveld receives the most rainfall with annual totals in the range 700 to 1500 mm and the most moderate temperature averages of 11 °C in winter and 18 °C in summer (Government of Eswatini 2016).

Motjane peatland

Motjane peatland (26° 13' 22.08" S, 31° 03' 26.60" E) falls under the Motjane community (Figure 1) and covers about 35 ha. Its elevation ranges from 1381 to 1400 m a.s.l. A tributary of the Lusushwana River, which itself is a tributary of the Usuthu River, flows through the site. Motjane is considered a rural area, on Swazi Nation Land (SNL) where the community still relies heavily on natural resources, such as wetlands, for their livelihoods. SNL is a traditional system of governance where the land and its resources are held in trust by the King for the Swazi people. The peatland is characterised by reeds and a variety of sedges and grasses (Table 1). An area covering approximately 20 ha is characterised by various drainage channels and livestock grazing. The drainage channels were created to facilitate crop farming and the easy movement of both people and livestock across the community's land. An area of about 15 ha, whose vegetation primarily comprises *Phragmites australis*, has been left relatively untouched and is therefore permanently waterlogged.

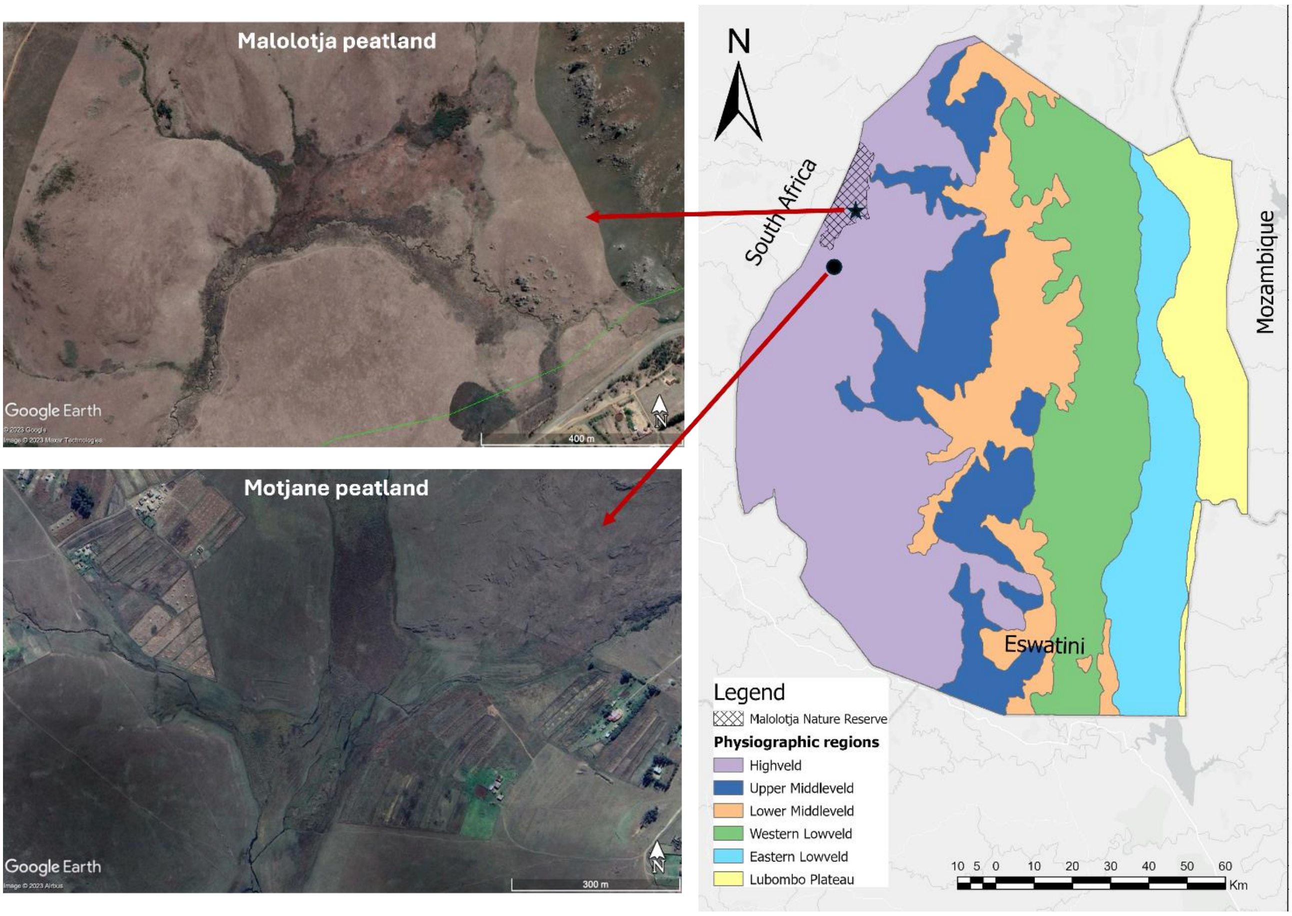

Figure 1. Locations of the two peatlands, Malolotja and Motjane, in the Highveld of Eswatini.

Malolotja peatland

Malolotja peatland (26° 08' 20.65" S, 31° 06' 45.18" E) is located within Malolotja Nature Reserve. The reserve was proclaimed as a protected area in 1977 (Government of Eswatini 2012). The peatland is one of two systems within the reserve that have been documented to contain peat. It lies at an elevation of 1410–1435 m a.s.l. in a grassland valley with fairly steep slopes and covers about 20 ha. The peat depth has been measured to be between 1.5 m and 5 m. A stream containing patches of burnt peat flows through the wetland complex. The peatland contains mixed forbs and a variety of grasses and sedges (Table 1) (Grundling 2018, Ndlela 2021).

Sampling for CH_4 and N_2O

Four flux measurement sites were selected in each peatland (Figure 2), based on preliminary field assessments that considered hydrological conditions, vegetation communities, soil types and the nature of anthropogenic disturbances (e.g., proximity to drainage channels, livestock activity). The opaque closed chamber method, which prevents light transmission, was adopted to measure CH_4 and N_2O fluxes (Parkin & Venterea 2010, Pumpanen *et al.* 2010, Rosenstock *et al.* 2016). While this approach minimises temperature artefacts, it may underestimate CH_4 emissions from vascular plant species with pressurised gas transport systems (e.g., *Phragmites australis*), especially during peak daylight hours (Minke *et al.* 2014). The chamber installations were fabricated from acrylic tubes (internal diameter 39 cm) cut to different lengths for the chamber (height 80 cm) and the collar (height 15 cm), and wrapped with black high-density polyethylene sheeting to achieve the required opacity. The chamber lids were made from 0.5 cm thick polyvinyl chloride (PVC) sheets and lined with aluminium duct tape for thermal insulation (Wagner & Reicosky 1992). Each lid incorporated a vent to minimise pressure differences between the chamber and the atmosphere (Davidson *et al.* 2002), a sampling port, and two fans to promote air mixing and reduce boundary layer effects near the soil and vegetation surface (Denmead & Reicosky 2003, Clough *et al.* 2020) (Figure 3).

Table 1. Summary of monitoring point characteristics at the Motjane and Malolotja peatlands including soil description, dominant vegetation and mean annual water table level.

Site	Point	Soil description (including squeezed water and plant structures)	Primary vegetation	Mean annual water table level (m)
Motjane	MotA	0–10 cm: organic soil 10–30 cm: dense thick clay with 20 % clay content 30–60 cm: highly organic clay	Grasses e.g. *Cymbopogon excavatus*, *Pennisetum clandestinum*	-0.18
	MotB	0–10 cm: fine reed root mat 10–20 cm: brown with clay sediment, H5 20–30 cm: pale brown, H4 30–40 cm: pale brown, H3 40–50 cm: very pale brown with *Typha capensis* remnants, H2	Reed - *Phragmites australis*	-0.06
	MotC	0–30 cm: degraded peat, H9 30–50 cm: clay layer	Sedges e.g. *Cyperus articulatus*, *Cyperus albostriatus*	-0.02
	MotD	0–10 cm: degraded peat, H9, signs of mottling 10–30 cm: organic soil with < 20 % clay content 30–50 cm: organic soil with 40–50 % clay content	Grasses, sedges and reed e.g. *Cymbopogon excavatus*, *Cyperus* spp., *Phragmites australis*	0.00
Malolotja	MalA	0–50 cm: peat, H7	Grasses and shrubs e.g. *Juncus inflexus*, *Thelypteris spp.*	0.03
	MalB	0–50 cm: peat, H4	Ferns and grasses	0.04
	MalC	0–50 cm: peat, H8	Sedges and grasses e.g. *Cyperus* spp., *Cymbopogon excavatus*	-0.09
	MalD	0–30 cm: organic soil 30–50 cm: organic soil with < 20 % clay content	Grasses e.g. *Eucomis autumnalis*	-0.36

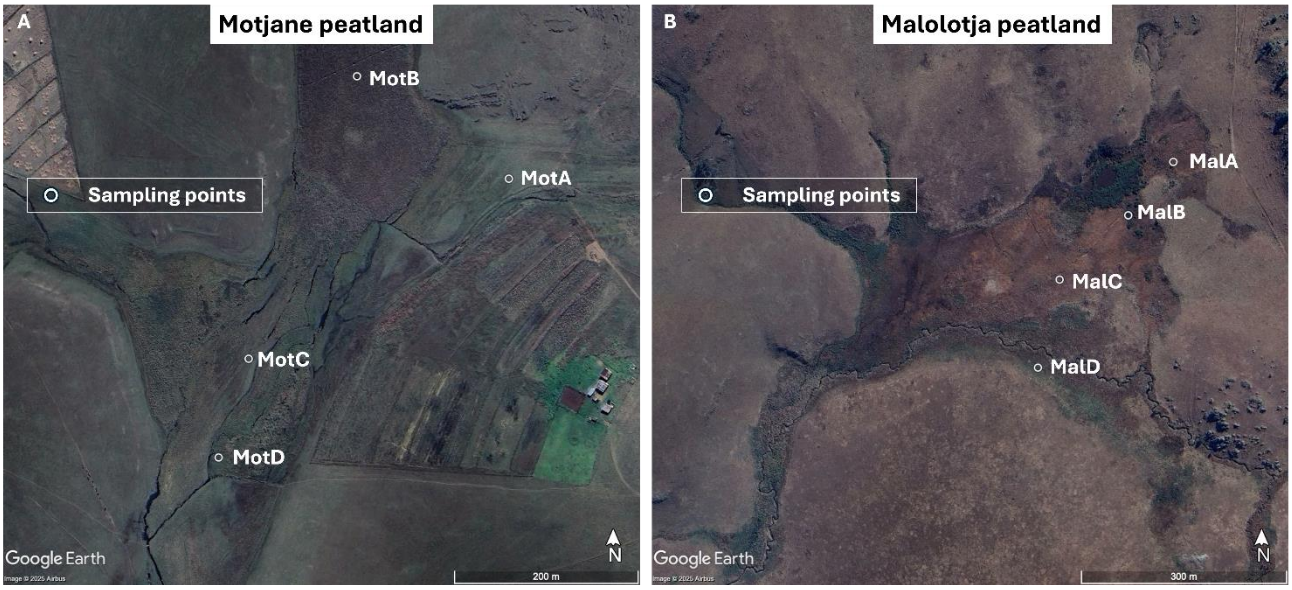

Figure 2. Maps showing the sampling points in (a) Motjane peatland and (b) Malolotja peatland (Google Earth, 2023). The monitoring points are abbreviated "Mal" and "Mot" for the Malolotja and Motjane peatland, respectively. The letters "A, B, C and D" indicate the position of the monitoring points in each peatland.

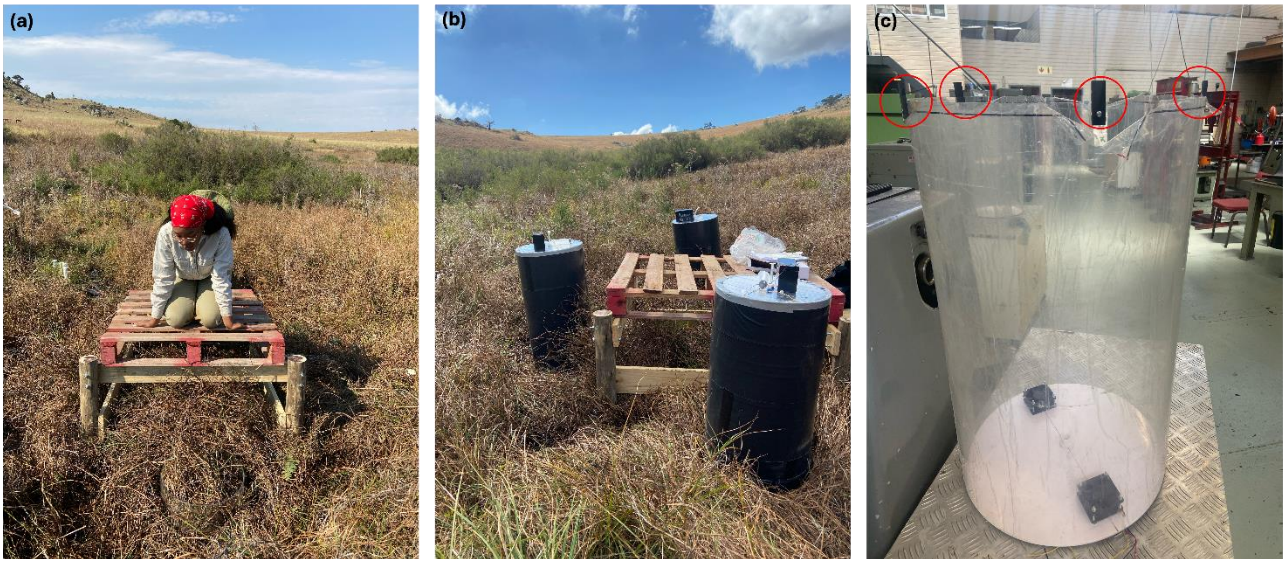

Figure 3. (a) One of the boardwalks installed at a peatland monitoring point; (b) three replicate flux chambers positioned adjacent to a boardwalk platform; and (c) a close-up of a chamber showing internal fans and PVC clamps on the lid (highlighted by red circles).

One week before sampling commenced, three replicate collars were installed 5–7 cm into the ground at each flux measurement site without removing any plants, and they remained there until the last sampling day. Thus, in total, 12 permanent collars were installed in each peatland. Boardwalks were also constructed and installed at the inundated sites to avoid trampling and ebullition (Maier *et al.* 2022) (Figure 3). During measurements, the chamber was sealed to the collar using a rubber gasket and PVC clamps, and air samples were collected through the chamber port via a polysiloxane tube. For each chamber, five air samples were collected at five time intervals (minutes) (i.e., T = 0; T = 5; T = 15; T = 30; and T = 45) using a 60 ml propylene syringe, and immediately transferred into a 20 ml pre-labelled glass vial. The first 20 ml of the sample in the syringe was used to flush the vial, with the remainder over-pressurising and hence minimising leakages and contamination with ambient air. The vials were then packed into a polystyrene coolbox, wrapped and sent to the International Livestock Research Institute Laboratory in Kenya, where gas concentrations were measured using a Gas Chromatograph following standardised calibration protocols. Sampling was conducted monthly, always between 9 am and 2 pm, from June 2023 until May 2024.

Ancillary measurements

TOMST TMS-4 (TOMST s.r.o., Prague, Czech Republic) standard loggers were installed at each sampling point to measure air and soil temperature as well as soil moisture. Temperature and moisture sensors were installed on the same day as the chamber collars to record measurements every five minutes at three positions: 6 cm below ground level (-6 cm), near the surface (+2 cm) and aboveground (+15 cm). Daily rainfall, minimum temperature and maximum temperature data were obtained from a weather station located approximately 2 km from both peatlands, which is operated and maintained by staff at Malolotja Nature Reserve. Peat cores from 0 cm to 50 cm depth were collected using a Russian peat corer, divided into 10 × 5 cm increments, and stored in airtight plastic containers during transportation to the laboratory. The samples were then air-dried and analysed using an elemental analyser for carbon and nitrogen concentration at the Department of Chemistry in the University of Johannesburg (South Africa). For comparative purposes, carbon and nitrogen concentrations were averaged across the profile to represent a site-level mean. Additional peat and soil cores were collected up to a depth of 30 cm, separated into 3 × 10 cm increments, and transported to the Soils Laboratory at Intertek (South Africa), where soil pH was measured in a 1 M potassium chloride (KCl) solution using a 1:2.5 soil-to-solution ratio, following standard procedure. The KCl method reflects the potential acidity of the peat by displacing exchangeable H^+ and Al^{3+} ions and typically yields lower pH values than measurements in distilled water. Before transportation, the soil and peat profiles were described in the field for colour and/or degree of humification using the von Post humification scale, which classifies peat based on plant residues, stage of decomposition, physical properties and genetic processes (von Post 1922). The water table level was measured using dipwells, i.e., perforated PVC pipes (outside diameter 5 cm). A Solinst water level meter (Model 101, Solinst Canada Ltd., Georgetown, Ontario, Canada) was used to measure the depth of the water level during each gas sampling day.

Calculations

Linear regression rates, commonly used for static chamber methods, were generated for the five chamber periods (0, 5, 15, 30, 45 mins). A cutoff value of $r^2 \geq 0.7$ was used to ensure data quality and fluxes with lower regression fits were excluded. Based on this criterion, 101 (7 %) of the 1440 chamber measurements were discarded, consistent with thresholds reported in previous static chamber studies (e.g., Lai *et al*. 2012). The concentration of each gas of interest was calculated using the peak areas of the measured calibration gases relative to the peak areas measured from the gas chromatograph. The emission flux rates (mg m^{-2} hr^{-1}) were determined using Equation 1 (Butterbach-Bahl *et al*. 2011), which incorporates the ideal gas law, atmospheric pressure, internal chamber temperature and chamber volume:

$$\text{FluxGHG} = \text{Ct} \times \left(\frac{\text{M}}{\text{Vm}}\right) \times \left(\frac{\text{Vch}}{\text{Ach}}\right) \times \left(\frac{273.15}{273.15+\text{t}}\right) \times \text{P} \times 60 \qquad [1]$$

where:

Ct = slope derived from the linear regression (ppm min^{-1}) for CH_4 and (ppb min^{-1}) for N_2O;
M = molar weight (g mol^{-1}) (C=12 for CH_4 and N=28 for N_2O);
Vm = molar gas volume (m^3 mol^{-1}) (22.41);
Vch = Volume of the gas chamber;
Ach = Area of gas chamber;
t = Chamber temperature (°C);
P = Pressure at time of sampling (atm); and
60 = conversion factor (minutes to hours).

Negative fluxes depict consumption of the gas by the soil and positive fluxes represent emission of the gas from the soil. CH_4-C and N_2O-N flux data were tested for normality using the Shapiro-Wilk test and were found to be non-normally distributed, even after log transformation. Therefore, a non-parametric Kruskal-Wallis H test was used to assess differences in fluxes across monitoring points and between peatlands. The same test was applied to carbon, nitrogen and pH concentrations. Spearman's rank correlation coefficients were calculated to evaluate relationships between gas fluxes and environmental variables. To further explore covariation among variables, principal component analysis (PCA) was conducted using standardised variables including rainfall, air, surface and soil temperature, volumetric moisture and water table level. CH_4-C and N_2O-N fluxes were also included in the analysis. Four components were retained for Motjane and three for Malolotja, based on eigenvalues >1 and visual inspection of PCA scree plots (i.e., plots showing the variance explained by each principal component). While PCA can be sensitive to nonlinearity, its application here provided a useful exploratory tool to identify dominant gradients in environmental variation. Soil chemical variables such as pH, total carbon and nitrogen were excluded from the PCA due to limited spatial replicates, but their summary values were incorporated into the discussion. Statistical analyses were conducted on XLSTAT version 2021.1.

RESULTS

Environmental and site characteristics

Table 1 summarises the key physical and ecological characteristics of each monitoring point across the two peatlands including stratigraphy, dominant vegetation and mean annual water table levels. The Motjane peatland showed greater heterogeneity in peat stratigraphy and land use. MotC and MotD had more degraded peat, with signs of peat oxidation and increased clay content. Vegetation at Motjane ranged from reed-dominated stands (*Phragmites australis*) at MotB to sedges and mixed grasses in the disturbed MotC and MotD monitoring points. Soils at all Malolotja points were dominated by dark, highly organic peat with minimal mineral content. The vegetation was characterised by sedges and grasses, with some shrubs and limited disturbance.

Temperature and rainfall patterns observed during the sampling year were typical of the Highveld region, with the warmest months occurring between October and February and most precipitation falling between October and March (Figure 4). Mean water table levels (WTLs) in both peatlands were within the root zone (< 0.3 m). WTLs varied among the monitoring points, with MotB, MotC and MotD showing minimal fluctuations. Figure 4 shows very stable water table levels (MotB, C and D) with the highest WTL observed at MotD (minimum = -0.01 m and maximum 0.01 m) while the lowest was observed for MotA (minimum = -0.2 m in September, maximum = -0.16 m in July, November and January).

In Malolotja peatland, all monitoring points except for MalD maintained a WTL that was within the root zone (< 0.3 m) throughout the monitoring period. The highest WTL in MalD was observed in

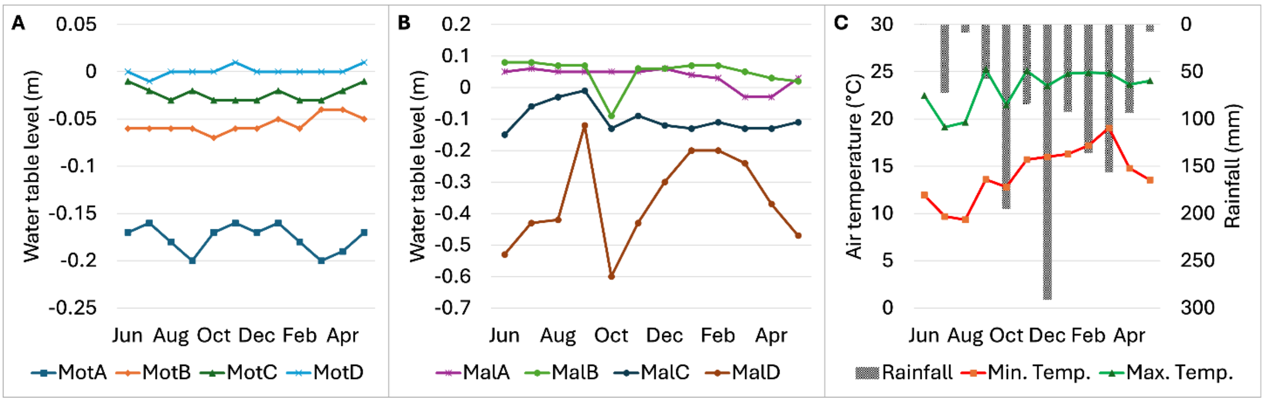

Figure 4. Temporal variation in (a) water table level (m) in Motjane peatland, (b) water table level (m) in Malolotja peatland and (c) rainfall (mm) and temperature (°C).

September (-0.12 m), while the lowest was observed in October (-0.6 m) following the first rainfall. The lowest WTLs in the Malolotja peatland were observed in October, when the second largest rainfall event occurred. Following this initial drop, WTLs gradually increased, peaking in November and stabilising following the December rainfall event.

pH, carbon and nitrogen concentrations of the peat

Although peat samples were collected in increments (5 cm for carbon and nitrogen concentrations, 10 cm for pH), the results varied minimally with depth and were averaged per profile to allow site-level comparison. Figure 5 presents the mean carbon and nitrogen concentration across the 0–50 cm profile and pH across the 0–30 cm profile at each monitoring point. Carbon concentration varied across the Motjane peatland, ranging from 4.45 % to 26.19 %. A Kruskal-Wallis H test indicated that carbon concentrations differed significantly between the monitoring points ($p < 0.05$). The lowest values were recorded at MotA (4.45–12.93 %) and the highest at MotB (5.59–26.19 %). In comparison, the Malolotja peatland showed higher carbon concentrations overall, with values ranging from 4.09 % to 30.02 %. MalC recorded the highest profile concentration (9.70–30.02 %). A Kruskal-Wallis H test comparing the two peatlands confirmed that carbon concentrations were significantly higher in Malolotja than in Motjane ($H = 22.65$, $df = 1$, $p < 0.001$).

The nitrogen concentration in both peatlands was less than 3 %, although the Malolotja peatland had slightly higher levels (Figure 5). Nitrogen concentrations also showed statistically significant differences across monitoring points ($p < 0.05$). At Motjane, nitrogen concentrations ranged from 0.73 % to 1.95 %, with MotC and MotD showing the narrowest range (0.93–1.23 %), reflecting more uniform nitrogen concentration. In the Malolotja peatland, nitrogen concentrations ranged from 0.83 % to 3.00 %. MalA had the broadest pH range (0.89–3.00 %), while the pH in MalB and MalC ranged from 0.83–1.74 % and 1.10–2.51 %, respectively. A separate Kruskal-Wallis H test indicated that nitrogen concentrations were also significantly different between the two peatlands, with higher concentrations in Malolotja than in Motjane ($H = 15.90$, $df = 1$, $p < 0.001$).

pH levels showed significant variability across sites ($p < 0.05$) in Motjane, but not in Malolotja (Figure 5). Motjane exhibited higher and more variable pH values (4.2–5.47), with MotA showing the highest average. In contrast, the Malolotja points remained consistently acidic (4.05–4.54), particularly at MalC, where the lowest mean values were recorded. A Kruskal-Wallis H test comparing the two peatlands showed that the difference between Motjane and Malolotja was not statistically significant ($H = 3.63$, $df = 1$, $p = 0.057$), although a trend toward lower pH in Malolotja was observed.

CH_4-C and N_2O-N fluxes from Motjane peatland

The fluxes of CH_4-C showed spatial and temporal variation across the four monitoring points (MotA, MotB, MotC and MotD) as shown in Figures 6 and 7. Negative values represent net uptake from the atmosphere, while positive values indicate net emissions. A Kruskal-Wallis H test showed that CH_4-C fluxes differed significantly between the monitoring points ($p < 0.05$), while N_2O-N fluxes did not ($p > 0.05$). In the Motjane peatland, mean CH_4-C fluxes ranged between -45.77 and 24.64 mg m^{-2} hr^{-1}, with a net site-wide flux of -2.92 mg m^{-2} hr^{-1}. N_2O-N fluxes were in the range of -2.77 to 1.99 µg m^{-2} hr^{-1}, with a net site-wide flux of 0.11 µg m^{-2} hr^{-1}. Figure 7 shows that the CH_4-C fluxes fluctuated markedly from June 2023 to May 2024, with noticeable peaks and declines. The highest CH_4-C peaks were

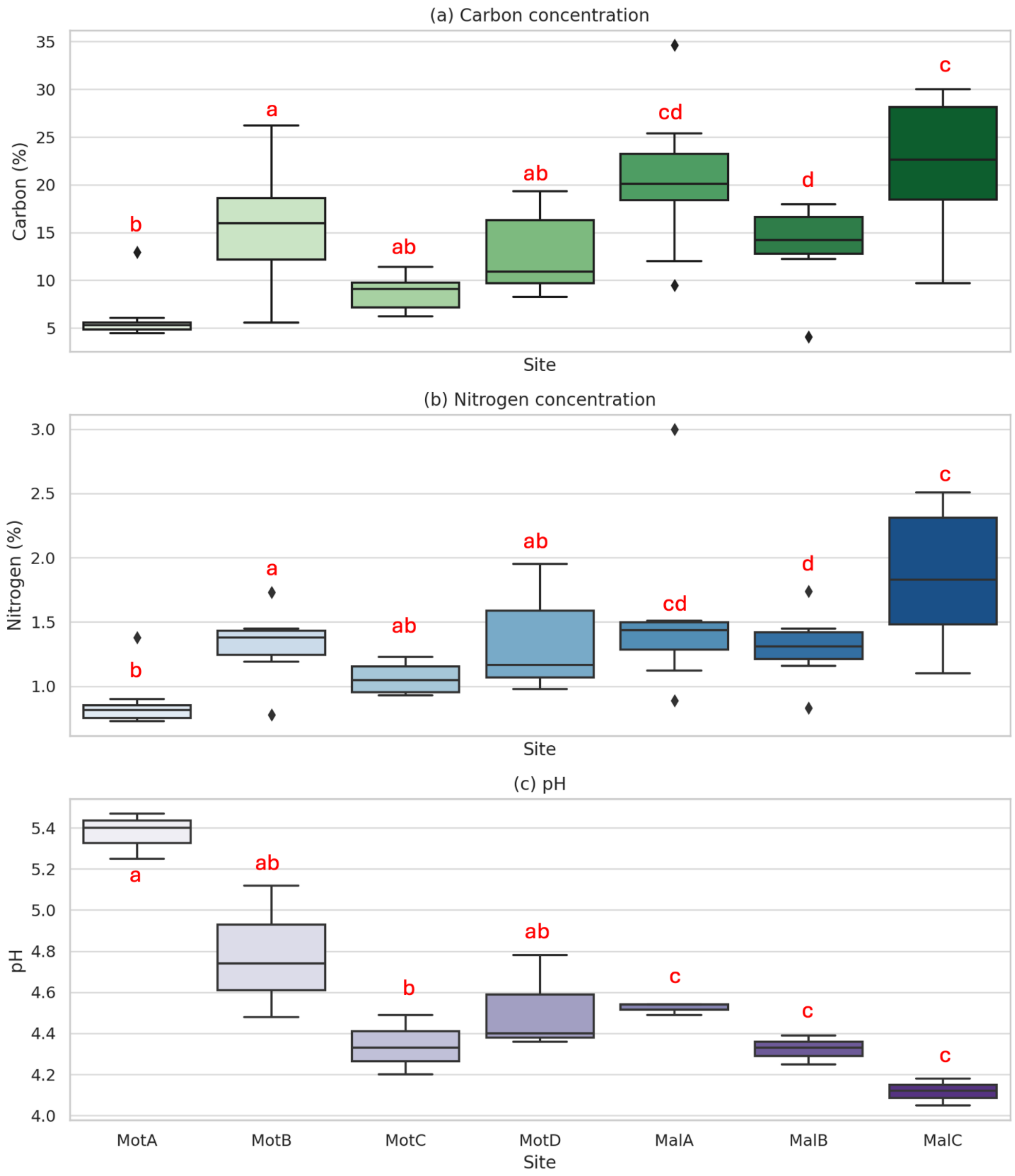

Figure 5. Boxplots showing (a) carbon concentrations (%), (b) nitrogen concentrations (%) and (c) pH across monitoring points in the Motjane (“Mot”) and Malolotja (“Mal”) peatlands. Monitoring points (A, B, C, etc.) represent spatial replicates within each site. Statistical differences across sites were assessed using Kruskal-Wallis tests followed by pairwise comparisons. Red letters indicate statistically distinct groups at α = 0.05; sites not sharing a letter differ significantly.

observed from monitoring points MotC in October 2023 (24.64 mg m^{-2} hr^{-1}) and MotB in April 2024 (18.19 mg m^{-2} hr^{-1}). The lowest flux of -45.77 mg m^{-2} hr^{-1} was recorded from MotC in April 2024. N_2O-N fluxes remained low throughout the monitoring period. There were occasional peaks and declines of N_2O-N fluxes, but they were less pronounced than those of CH_4-C. The largest uptake of N_2O-N was recorded from MotB in October 2023 (-2.77 µg m^{-2} hr^{-1}).

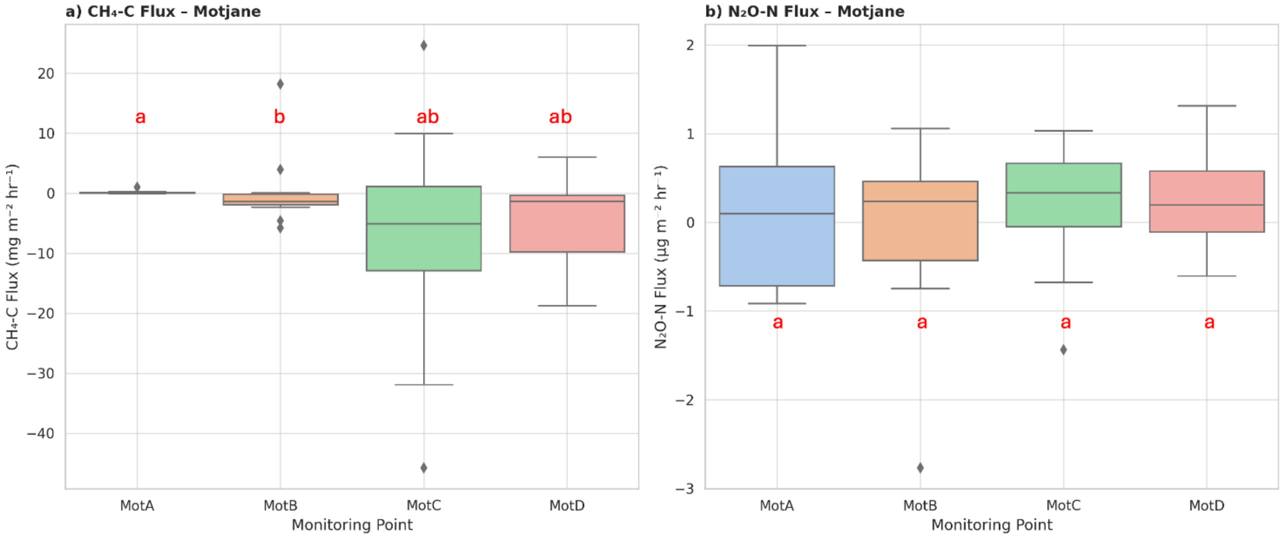

Figure 6. Boxplots comparing the fluxes of (a) CH_4-C (mg m^{-2} hr^{-1}) and (b) N_2O-N (μg m^{-2} hr^{-1}) across monitoring points in the Motjane peatland. Each box represents monthly flux values (n = 12) from June 2023 to May 2024. Statistical differences across sites were assessed using Kruskal-Wallis tests followed by pairwise comparisons. Red letters indicate statistically distinct groups at α = 0.05; sites not sharing a letter differ significantly. N_2O-N fluxes did not differ significantly across monitoring points.

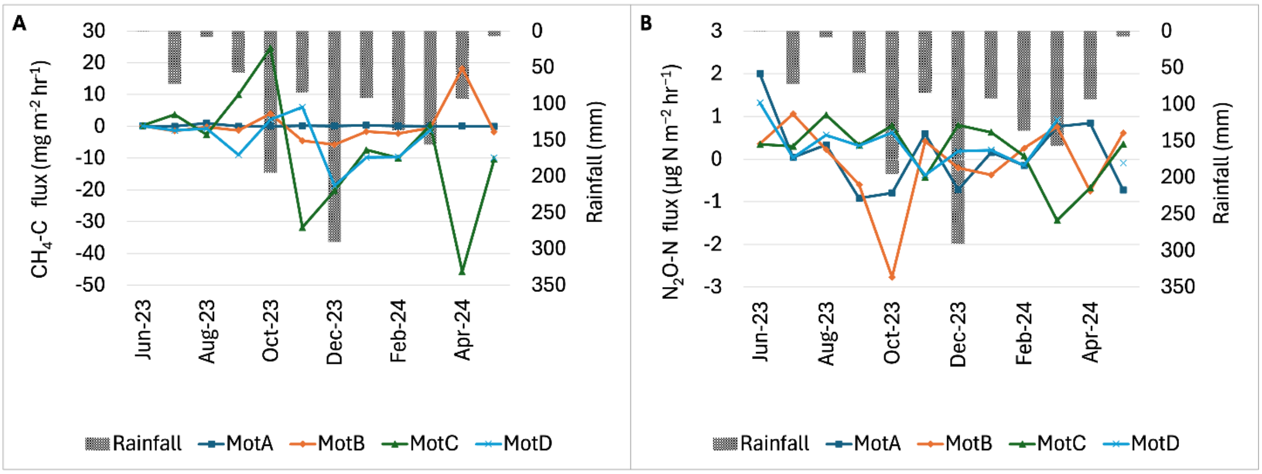

Figure 7. Temporal variation of (a) CH_4-C (mg m^{-2} hr^{-1}) and (b) N_2O-N (μg m^{-2} hr^{-1}) in the Motjane peatland from June 2023 to May 2024. Monthly values represent the mean flux for each monitoring point on each sampling day.

CH_4-C and N_2O-N fluxes from Malolotja peatland

A Kruskal-Wallis H test comparing CH_4-C fluxes between Motjane and Malolotja indicated a statistically significant difference (H = 4.05, df = 1, p = 0.044), with CH_4-C values at Motjane exhibiting greater variability. In contrast, N_2O-N fluxes did not differ significantly between the two peatlands (H = 0.10, df = 1, p = 0.753).

The Kruskal-Wallis H test for Malolotja showed that N_2O-N fluxes did not differ significantly between monitoring points ($p > 0.05$), while CH_4-C did ($p < 0.05$). Figures 8 and 9 show that CH_4-C fluxes ranged between -0.004 and 0.31 mg m^{-2} hr^{-1}, with a net site-wide flux of 0.06 mg m^{-2} hr^{-1}. N_2O-N fluxes ranged between -2.04 and 3.34 μg m^{-2} hr^{-1}, with a net site-wide flux of 0.26 μg m^{-2} hr^{-1}. Figure 9 illustrates the temporal variation in CH_4-C and N_2O-N fluxes from June 2023 to May 2024, showing several sharp peaks. The highest CH_4-C flux was recorded at MalC in November 2023 (0.31 mg m^{-2} hr^{-1}), during a period of elevated rainfall (Figure 4). N_2O-N fluxes remained low throughout the

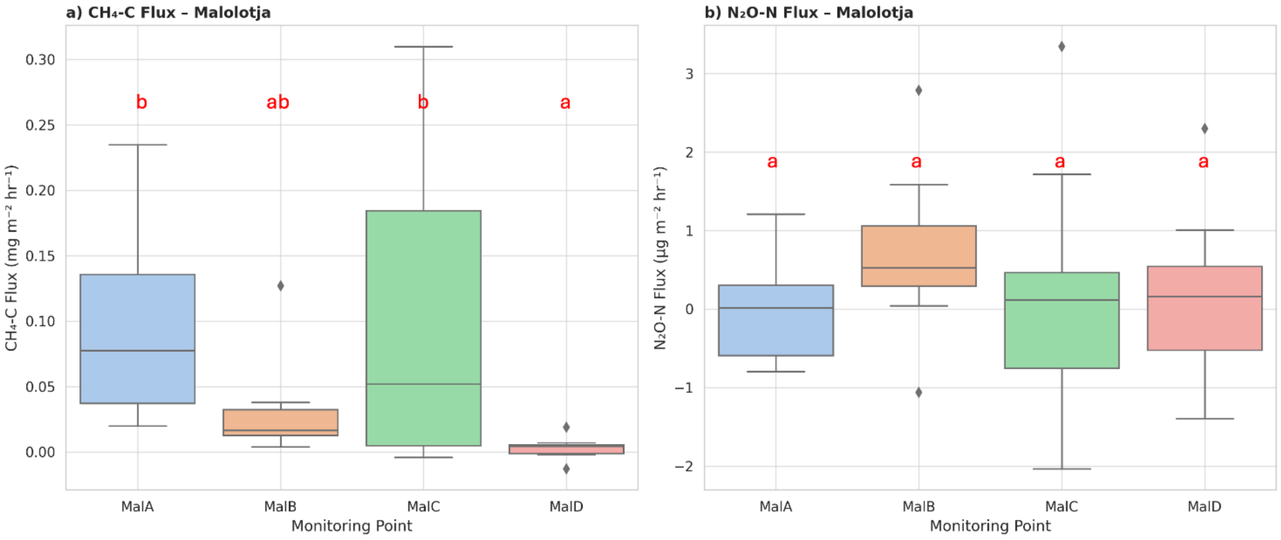

Figure 8. Boxplots comparing the fluxes of (a) CH_4-C (mg m^{-2} hr^{-1}) and (b) N_2O-N (μg m^{-2} hr^{-1}) across monitoring points in the Malolotja peatland. Each box represents monthly flux values (n = 12) from June 2023 to May 2024. Statistical differences across sites were assessed using Kruskal-Wallis tests followed by pairwise comparisons. Red letters indicate statistically distinct groups at α = 0.05; sites not sharing a letter differ significantly. N_2O-N fluxes did not differ significantly across the monitoring points.

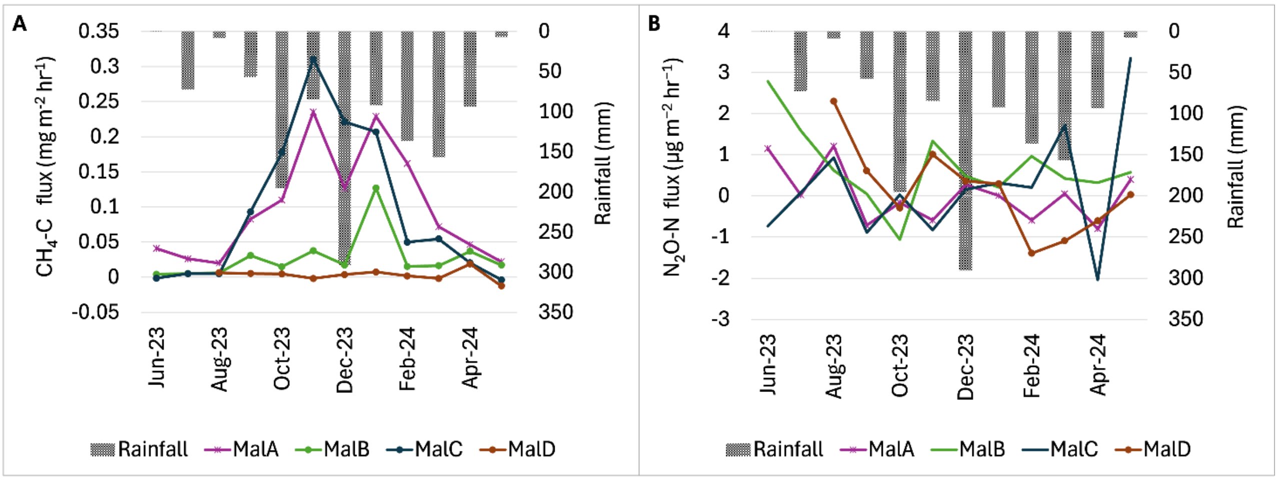

Figure 9. Temporal variation of (a) CH_4-C (mg m^{-2} hr^{-1}) and (b) N_2O-N (μg m^{-2} hr^{-1}) in the Malolotja peatland from June 2023 to May 2024. Monthly values represent the mean flux for each monitoring point on each sampling day.

monitoring period, with modest peaks observed at MalB in June 2023 (2.79 μg m^{-2} hr^{-1}) and MalC in May 2024 (3.35 μg m^{-2} hr^{-1}).

Correlations between CH_4-C, N_2O-N and environmental variables

Although carbon, nitrogen and pH data were collected across the monitoring points, these variables were not included in the Spearman's correlation due to limited temporal replication. Each was measured once per point and thus lacked the monthly resolution required for the multivariate correlation. In the Malolotja peatland, CH_4-C fluxes showed significant positive correlations with below-ground soil temperature (ρ = 0.323, α = 0.05) and surface temperature (ρ = 0.319, α = 0.05) and a significant negative correlation with volumetric moisture (ρ = -0.606, α = 0.01). N_2O-N fluxes in Malolotja peatland also showed significant negative correlations with rainfall (ρ = -0.316, α = 0.05) (Table 2).

Table 2. Spearman’s rho correlations (ρ) between the variables in Motjane peatland (where n = 47) and at Malolotja peatland (where n = 46). Asterisks indicate significance levels (*p < 0.05, **p < 0.01).

Site		Water table level	Soil temperature (-6 cm)	Surface temperature (+2 cm)	Air temperature (+15 cm)	Volumetric moisture	Rainfall
Motjane	CH_4-C	-0.284	-0.221	-0.224	-0.183	-0.102	-0.010
	N_2O-N	0.113	-0.186	-0.168	-0.180	-0.100	-0.287
Malolotja	CH_4-C	0.325	**0.323***	**0.319***	0.276	**-0.606****	0.282
	N_2O-N	0.279	-0.195	-0.189	-0.181	0.169	**-0.316***

Principal Component Analysis of CH_4-C, N_2O-N and environmental variables

Tables 3 and 4 present the results of the principal component analysis (PCA) for the two peatlands examining relationships between CH_4-C and N_2O-N fluxes and six environmental variables: air temperature (+15 cm), surface temperature (+2 cm), soil temperature (-6 cm), rainfall, volumetric moisture and water table level. Soil chemical properties such as carbon, nitrogen and pH were excluded due to lower temporal resolution. Loadings represent the correlation between the original variables and the principal components (PCs). A high positive or negative loading indicates that the variable strongly influences that component. In this study, a loading of ± 0.6 was interpreted as a strong contribution to each component. At Motjane, four principal components (PCs) with eigenvalues >1 were retained, whereas at Malolotja, only three PCs met this threshold. At Motjane peatland, the PCA revealed four components, with PC1 capturing most of the variation (Table 3). PC1 showed strong positive loadings from surface temperature (0.961), soil temperature (0.934), air temperature (0.892) and rainfall (0.755), possibly reflecting a composite climate factor. PC2 was primarily defined by a strong negative loading of water table depth (-0.771), likely representing a hydrological gradient. PC3 showed a positive loading for CH_4-C (0.646) but also a negative loading for volumetric moisture (-0.646), possibly showing site-level variability. PC4 was strongly defined by N_2O-N (0.874) and a moderate negative loading for water table level (-0.355), representing a different set of environmental variables.

At Malolotja peatland, the PCA identified three key components (Table 4). PC1 accounted for most of the variation and showed strong positive loadings from surface temperature at (0.966), soil temperature (0.949), air temperature (0.910) and rainfall (0.731), along with a moderate positive loading from CH_4-C (0.492), probably reflecting a climatic gradient. PC2 was primarily characterised by a strong negative loading for volumetric moisture (-0.823) and a strong positive loading for water table depth (0.775); with CH_4-C also loading positively (0.608), indicating a possible response of methane emissions to hydrological variation. PC3 showed a strong positive loading from N_2O-N (0.749) and a secondary loading from water table depth (0.383), indicating that N_2O-N fluxes were influenced by different environmental variables from CH_4-C.

DISCUSSION

This study examined CH_4 and N_2O fluxes from two distinctly managed peatlands, namely Motjane peatland, situated on community land, and Malolotja peatland, located within a nature reserve. Between June 2023 and May 2024, the Motjane peatland acted as a slight net sink for CH_4-C (-2.92 mg m^{-2} hr^{-1}) while the Malolotja peatland was neither a source nor a sink for CH_4-C (0.06 mg m^{-2} hr^{-1}). For both peatlands, CH_4-C fluxes varied significantly between the four individual monitoring points. Motjane exhibited greater flux variability with isolated CH_4-C peaks at MotB and MotC, although fluxes remained low for most of the year. At MotB, which is characterised by a high water table and *Phragmites australis*, CH_4-C fluxes remained low for much of the year despite isolated peaks. This may reflect suppression of light-mediated fluxes due to the use of opaque chambers (Minke *et al.* 2014, van den Berg *et al.* 2020), limited methanogenic substrate input, or plant-mediated oxygen transport which enhances CH_4 oxidation. At MotC, a disturbed point located adjacent to a drainage channel, the recorded high water table likely reflects surface pooling rather than stable subsurface saturation. The localised drainage may have increased the aerobic layer within the peat, enhancing oxygen diffusion and favouring methanotrophic activity (Schrier-Uijl *et al.* 2010).

Table 3. Principal Component Analysis loading matrix for Motjane peatland showing variable loadings on four retained components. Loadings > |0.6| are interpreted as strong contributions.

Variable	Component			
	PC1	PC2	PC3	PC4
Soil temperature (-6 cm)	**0.934**			
Surface temperature (+2 cm)	**0.961**			
Air temperature (+15 cm)	**0.892**			
Rainfall	**0.755**			
Water table level		**-0.771**	0.331	-0.355
CH_4-C		**0.640**	**0.646**	
Volumetric moisture		**0.644**	**-0.646**	
N_2O-N		-0.320		**0.874**

Table 4. Principal Component Analysis loading matrix for Malolotja peatland showing variable loadings on three retained components. Loadings > |0.6| are interpreted as strong contributions.

Variable	Component		
	PC1	PC2	PC3
Soil temperature (-6 cm)	**0.949**		
Surface temperature (+2 cm)	**0.966**		
Air temperature (+15 cm)	**0.910**		
Rainfall	**0.731**		
Volumetric moisture		**-0.823**	
Water table level		**0.775**	0.383
CH_4-C	0.492	**0.608**	
N_2O-N	-0.416		**0.749**

Reduced surface vegetation in the disturbed areas of Motjane may further influence soil temperature dynamics and microbial processes. In contrast, the Malolotja peatland showed less CH_4-C flux variability, although MalA and MalB recorded higher temporal flux fluctuations compared to MalC and MalD. At MalA and MalB, where vascular plants such as sedges and shrubs were abundant, CH_4 release was likely supported by root exudates that fuel microbial activity (Liu & Greaver 2009). Studies by Greenup *et al*. (2000) in the United Kingdom and Couwenberg *et al*. (2011) in Germany identified a positive relationship between vascular plants and CH_4 emissions. The spatial contrast between Motjane and Malolotja may also reflect underlying differences in soil carbon concentration, as generally high carbon concentrations were recorded at Malolotja. Organic carbon provides the substrate for methanogenic activity (Doroski *et al*. 2019, ITPS 2021, Luo *et al*. 2022), which may partly explain the relatively higher CH_4-C emissions at MalB despite limited anthropogenic disturbance.

Peat characteristics also appeared to influence CH_4 dynamics. At Motjane, MotC and MotD had highly humified (H9) peat and clay sublayers, potentially limiting microbial activity and gas transport. Conversely, MotB had weakly decomposed (H2–H5) peat, typically associated with greater CH_4 production. Nonetheless, emissions from MotB remained low, likely due to the combined effects of opaque chambers, low substrate input and plant-mediated oxidation. At Malolotja, moderately decomposed peat may have supported more stable anaerobic microsites and sustained CH_4 production.

Compared to global wetland studies, the CH_4-C values observed in this study are notably low. For context, Turetsky *et al*. (2014) reported mean CH_4 emissions (not corrected for carbon content) of ~48 mg m^{-2} day^{-1} (~2.0 mg m^{-2} hr^{-1}) for undisturbed subtropical wetlands and ~4.5 mg m^{-2} hr^{-1} for temperate peatlands, while disturbed drying sites averaged at ~0.18 mg m^{-2} hr^{-1}. In contrast, Kinyua (2018) reported CH_4-C fluxes ranging from -0.07 to 0.09 mg m^{-2} hr^{-1} in converted wetlands and up to 40.6 mg m^{-2} hr^{-1} in unconverted sites. The CH_4-C sink observed at Motjane falls well below these averages, aligning more closely with disturbed systems and reflecting limited methanogenic activity under human-impacted conditions.

A positive relationship between CH_4-C below-ground temperature and surface temperature was observed in the Malolotja peatland. This aligns with findings from other researchers that CH_4 production tends to increase with rising soil temperatures due to its positive effect on methanogenic bacteria (Mohanty *et al*. 2007). Several studies have documented a positive (sometimes exponential) correlation between CH_4 emission and soil temperature (Westermann *et al*. 1989, Zinder 1993, Dobbie & Smith 2001, Gondwe & Masamba 2014). However, this relationship was not observed in the Motjane peatland, likely because soil temperature alone is not sufficient to drive CH_4-C production, as other environmental factors such as oxygen availability play a crucial role (Mustamo 2017). Another possible explanation is that the subtropical climate of the Highveld region maintains relatively warm soil temperatures year-round, reducing seasonal variability in microbial activity. This is in contrast to temperate and boreal peatlands, where CH_4 production often follows strong seasonal cycles tied to thaw periods. Additionally, CH_4 oxidation is influenced by methanotrophic organisms, which are less sensitive to less-than-optimal temperatures (Le Mer & Roger 2001). This might explain why the Motjane peatland functioned as a slight sink for CH_4-C, as methanogens are more sensitive to redox changes driven by soil aeration fluctuations than methanotrophs (Altor & Mitsch 2006, Butterbach-Bahl & Dannenmann 2011). Additionally, in Malolotja, a negative relationship was documented between CH_4-C fluxes and volumetric soil moisture. This interpretation aligns with findings by Krüger *et al*. (2012) who found that groundwater level was the dominant driver of CH_4 emissions in two South African wetlands in the Drakensberg.

N_2O-N fluxes at both sites remained low throughout the monitoring period, with minor peaks recorded in July 2023 and January 2024. Slightly higher N_2O-N fluxes were recorded from the Malolotja peatland (net site-wide flux: 0.26 µg m^{-2} hr^{-1}) compared to the Motjane peatland (net site-wide flux: 0.11 µg m^{-2} hr^{-1}). Both sites functioned as minor sources of N_2O-N, though these values were relatively low compared to synthesis estimates from European peatlands. Lin *et al*. (2022) reported mean N_2O emissions of 4.0 µg m^{-2} hr^{-1} for natural peatlands, over 52 µg m^{-2} hr^{-1} for drained sites and around 6.4 µg m^{-2} hr^{-1} for nutrient-poor, acidic ombrotrophic sites. Krüger *et al*. (2012) observed peak N_2O fluxes reaching up to 5.8 mg m^{-2} hr^{-1}, driven by sharp fluctuations in water table and fire disturbance. Kinyua (2018) similarly reported high N_2O-N fluxes in disturbed areas (187.06 ± 25.41 µg m^{-2} hr^{-1}) in Kenya.

Site-level nitrogen concentrations were below 3 % at both locations, consistent with ombrotrophic or nutrient-poor systems (Rydin & Jeglum 2013), which may have limited microbial N_2O production overall. Soil pH showed acidic conditions (pH 4.1–5.4), with slightly higher pH values at Motjane. Low pH can inhibit nitrification and limit N_2O production (Mäkelä *et al*. 2022, Rubaiyat *et al*. 2023, Zheng *et al*. 2023, Midot *et al*. 2025). It is also possible that the monthly sampling frequency may have missed short-lived N_2O peaks, which are often triggered by rainfall or redox fluctuations (Barton *et al*. 2015). Physical characteristics such as peat humification and clay-rich horizons at MotC and MotD may have also influenced redox dynamics conducive to denitrification. At Malolotja, although peat profiles were more uniformly organic, the acidic conditions and low nitrogen availability may have constrained microbial nitrogen cycling.

Unlike CH_4-C fluxes, N_2O-N fluxes did not differ significantly across monitoring points or between the two peatlands. Similar findings were reported by Yamulki *et al*. (2013), who observed no significant differences in N_2O emissions between a near-pristine peatland and a disturbed site. The hydrological stability observed in the peatlands may also have limited the occurrence of favourable conditions for N_2O production. The relationship between N_2O fluxes, water table level and soil moisture is often complex, as N_2O can be produced during both nitrification under aerobic conditions and denitrification under anaerobic conditions (Chapuis-Lardy *et al*. 2007, Maljanen *et al*. 2013). Regina *et al*. (1996) found that lower groundwater levels were associated with higher N_2O emissions, while Flessa *et al*. (1998) observed peak emissions when the water level was between -15 and -50 cm, with lower fluxes when the water level dropped below 50 cm.

The PCA findings further support that CH_4-C and N_2O-N fluxes were driven by different environmental variables across the two peatlands. CH_4-C fluxes were associated with temperature and water table depth, confirming the role of warm, saturated conditions in methanogenesis. This was consistent with higher emissions observed at sites like MalC and

MotB. In contrast, N_2O-N fluxes appeared largely independent of temperature and appeared to be more influenced by substrate availability and redox variability. This pattern is also suggested by the site-level nitrogen data and stable water tables. These findings have implications for peatland management in southern Africa. The CH_4 sink potential observed in disturbed but hydrologically stable sites like Motjane suggests that maintaining water tables above critical thresholds may suppress emissions. Meanwhile, the minimal N_2O fluxes under steady hydrological regimes reinforce the importance of hydrological regulation. Restoration strategies should, therefore, prioritise water level stabilisation and vegetation management, particularly in community peatland systems.

The Highveld region of Eswatini experiences a mild, humid and warm temperate climate. The findings demonstrate that the fluxes of these gases are not only dependent on land use and management practices, but also on site-level environmental conditions. Despite their geographical proximity, the Motjane and Malolotja peatlands exhibit distinct CH_4 and N_2O dynamics. The Motjane peatland acted as a slight net sink for CH_4 and a minor net source of N_2O, while the protected Malolotja peatland was neither a source nor a sink for CH_4, and a slight net source of N_2O. These differences were linked to local hydrology, vegetation communities, substrate availability, soil characteristics and land use disturbances. While the study contributes important baseline data from a region with limited flux monitoring, it is constrained by the exclusion of CO_2 measurements and low temporal resolution. In addition, variables such as water chemistry and dissolved oxygen, which are known to influence GHG production and oxidation processes, were not monitored and should be included in future studies. Future research should also adopt high-frequency monitoring to capture short-term variability and incorporate CO_2 flux measurements to enable full carbon budget assessments. From a policy perspective, peatland management strategies should prioritise community-led conservation and controlled grazing in communal areas like Motjane. In protected sites such as Malolotja, continued hydrological monitoring is essential to safeguard the carbon function. Given the multiple and interacting pathways that regulate CH_4 and N_2O emissions, targeted intervention measures are necessary. These should be site-specific and informed by continuous ecological monitoring to ensure effective mitigation of emissions. These findings reinforce the need for integrated approaches to peatland management that combine scientific assessment with local engagement.

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AUTHOR CONTRIBUTIONS

TN developed the research concept, conducted the fieldwork, performed the statistical analyses and calculations, wrote the first draft of the manuscript and is the lead author. HB supervised the research and provided feedback throughout. SG contributed to interpreting the results and contributed towards the editing of the manuscript. PLG also contributed to the writing and editing of the manuscript. All authors discussed and approved the final version.

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