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Fluxes of Greehouse Gas (Methane (CH_4), Carbon dioxide (CO_2), and Nitrous oxide (N_2O) Emissions as Influenced by Livestock Production System

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Abstract:
Greenhouse gasses (GHG) from aquatic ecosystems are increasingly appreciated as missed sources of emissions from agricultural, forested and rivers used for livestock watering systems. The rivers and streams receive manure, organic carbon and urea, making them potential hotspots for greenhouse gas (GHG) emissions through biogeochemical processing, but the role of livestock has limited the number of studies. A three-sampling campaign was conducted for GHG fluxes along streams and rivers in the Taita Hills and the semi-arid region low-lands of Taita-Taveta County, Kenya. Sampling was done in December 2021, February 2022, and May 2022 which spanned the transition of the rainy season to the dry season. Water-quality parameters were also measured and related to GHG emissions to assess the relationship between physiochemical parameters and the emissions in different livestock production systems. There were 7 reference sites, 4 low livestock density sites, and 7 high livestock density sites. The results showed higher CH_4 and N_2O fluxes in high livestock density sites compared to low livestock, and reference sites. High livestock density sites recorded higher dissolved organic carbon (DOC) concentrations %FBOM and NO_3-N with lower dissolved oxygen (DO) concentrations. There was a significant positive relationship between CO_2, and CH_4 flux with fine benthic organic matter (FBOM) and DOC, and a negative relationship with NH_4, and NO_3-N suggesting that increased sediment respiration from livestock may be responsible for CO_2 while methanogenesis for CH_4 emissions. The positive relationship of N_2O with NH_4 and NO_3-N, and the negative relationship with DOC, and %FBOM showed that nitrification controlled N_2O production in streams. In addition, negative fluxes of N_2O occurred during the wet season, which suggests complete denitrification of N_2O to N_2. Further research should examine the dry riverbeds as distinct features with the potential to impact greenhouse gas emissions from agropastoral and pastoral streams.

Keywords: Livestock production, methane, nitrous oxide, carbon dioxide.

1. Introduction

Climate change caused by increase in greenhouse gas concentration (Methane, Carbon-dioxide and Nitrous oxide) has raised concerns within the global community (Kang, 2021). The effort to contain greenhouse gas emissions to the atmosphere has gained momentum with the focus to shift economic activities to climate smart and sustainability. Livestock production is one the key economic activities identified by the United Nations as the significant contributor of greenhouse gas (GHG) to the atmosphere (Laborde, Mamun, Martin, Piñeiro, & Vos, 2021). This have led to a number of researches carried out to quantify the emission from livestock production chains (Gachibu, 2019; R. M. Mwanake et al., 2022; Wangari et al., 2022). In sub-Saharan Africa, livestock production systems vary from small scale zero grazing to largely free-range pastoral livestock farming system. Such systems utilize watering points along streams and pasture that tends impact of stream biogeochemistry (Gachibu, 2019). Knowledge about the driver's contribution to GHGs emission from Afromontane streams and assessing the feedback that emerges from biogeochemical cycling of nutrients and carbon in fresh water is important in developing a response to climate change.

The study by Mwanake et al., (2022) on the effects of land cover and land use change on GHGs emission in Mara river basin, Kenya shows that crop farming is associated with the emission on Nitrous oxide, methane and carbon-dioxide emission than headspace forested streams. This is likely due to the increased availability of more labile carbon and nutrients that can undergo respiration, methanogenesis and nitrification. Gachibu, (2019), studying the effects of livestock density on greehouse gas emissions in streams and water pan in Taita taveta found several biogeochemical processes in streams and water pans responsible for emissions. They found that respiration and methanogenisis is responsible for carbon diode while denitrification and nitrificaton are responsible for nitrous oxide emission (Gachibu, 2019). Despite this observed trend, forested streams more so those draining in the swamps and wetlands can significantly significantly contributes to nitrous oxide, carbo-dioxide and methane emission though the observation is not common in the tropical streams (Ricky Mwanake, Gettel, Butterbach-Bahl, & Kiese, 2020). The ratio of the riparian and streams /rivers also play a significant role in retention of labile carbon and nutrients to streams. Additionally, livestock watering points in Afromontane streams leads to alteration of stream morphology increasing the residence time and increases labile nutrients through defection and urination (Herreid, Wymore, Varner, Potter, & McDowell, 2021). The longer residence time and increased organic matter input are likely to alter greenhouse gas in rivers and streams.

In streams, ecosystem processes are strongly linked to terrestrial input of organic matter and nutrients from the environment. Mwanake et al (2019) found out that input of organic matter in steams fuels microbial processes and nutrients in large quantities that enhances respiration, primary production and nitrification process. Runoffs from the catchment further saturates the stream with terrestrial animal dung, sediments from grazing fields and urine that often loads the streams with labile nutrients and organic carbon (Tagne, Dowling, & assessment, 2020). Sediments in the streams in some places with deep pools arising from livestock stamped during the watering creates anoxic conditions that creates hotspots for anaerobic process which increases metabolic pathways for methane, nitrous oxide and carbon-dioxide. Estimates from livestock watering points in Mara river shows the need to understand the processes involved and pathways that leads to GHGs emission in streams passing through free range livestock production system(RM Mwanake et al., 2019). As methane , carbon dioxide and nitrous oxide emissions from stream remains constrained and poorly documenting, the need to understand biogeochemical processes controlling flux and control the drivers remains in place in science community.

In aquatic ecosystems, different biogeochemical processes are responsible for GHG emissions (Cardoso, Quadra, Resende, & Roland, 2019). Net carbon dioxide and methane fluxes are controlled by heterotrophy, methanogenesis, and methanotrophy. For nitrous oxide, net production is controlled by nitrification and denitrification enhanced by proximate controls such as in-stream oxygen concentration, dissolved inorganic carbon, pH, and organic matter quality and quantity (Borges et al., 2019; Ricky Mwanake et al., 2020; R. M. Mwanake et al., 2022; Wangari et al., 2022). These proximate controls, in turn, can be affected by distal control at the site like nutrients, stream geomorphology, and slope that determines stream water residence times and gas exchange rates, organic matter, or soil GHGs transport to river systems. All these distal factors are controlled by land use activities happening within the rivers and riparian zones.

The overall objective of this study was to estimate greenhouse gas emissions (CO_2, CH_4, and N_2O) from Taita-Taveta agropastoral and pastoral rangelands in Kenya. Specific objectives were to (1) evaluate the effects of seasonality and livestock densities on physiochemical parameters (2) measure fluxes of greenhouse gas emissions in agricultural (reference), low livestock (midland), and high livestock (low lands) impacted sites (; (3) determine the relationship between physiochemical parameters and greenhouse gas emissions in relation to livestock density and seasonality. It was hypothesized that livestock density influence water quality, stream geomorphology and in turn GHGs fluxes. The study also analyzes the association between water chemistry, carbon stock, and their influence on greenhouse gas emissions. The research predicts that streams draining in high livestock-density areas have higher fluxes compared to those draining in agricultural sites.

2.0 Materials and Methods

2.1 Study Area

Taita hills is located in Taita-Taveta county southern part of within coordinates ranging from 3°25′ S and 38°20′ E (Pellikka et al., 2018). The hills receive two annual rainfall characterized by long rains from March to June and short rain from October to December (Abera, Vuorinne, Munyao, Pellikka, & Heiskanen, 2022), however much there are huge changes that has happened recently due to climate change as there was no predictable rainfall pattern within the sampling period. The month of May and June experienced dry and cold weather characteristics throughout the sampling period which forced us to sample gases from dry river beds in the lowland areas. Mean elevation of the sampling area is 1500m above the sea level with the highest point being 2200 m a.s.l while the lowest point is 700 m a.s.l (Munyao et al., 2020). The temperature mean ranges from 18.2°c in the highlands and 23°c in the lowlands with very high amplitude during the dry seasons.

The highland areas are characterized mostly by high human population and small-scale agricultural farming with low livestock density at an average of 4 heads of cattle per homestead mostly remaining under zero grazing (Gachibu, 2019). Mid land is characterized by mixed farming, both crop and livestock with an average of 20 cattle visiting the watering points per day. The source of water for cattle is mostly within the streams and designated watering points are set at each point on the streams while lowland areas are characterized by high livestock density where most people practice free range farming. The ranges occupy around 22% of the county with mostly watering points along the stream (Bisia, 2019). Eighteen sites from two catchments (Bura and Wundany) were selected for the study, of the sites, four are located in Bura. The sites were divided into three livestock production system i.e the reference sites in the high lands characterised by zero-grazing and mixed farming, low livestock density sites characterised by mixed farming and larger number of livestock and High livestock density sites in the low lands with high number of livestock. The density of livestock is estimated at 0-13 heads in the highlands, 14-27 in the low livestock region and 28-41 in the lowlands (Gachibu, 2019). Figure 1 shows sampling points along the stream within Wundanyi and Bura catchment systems.

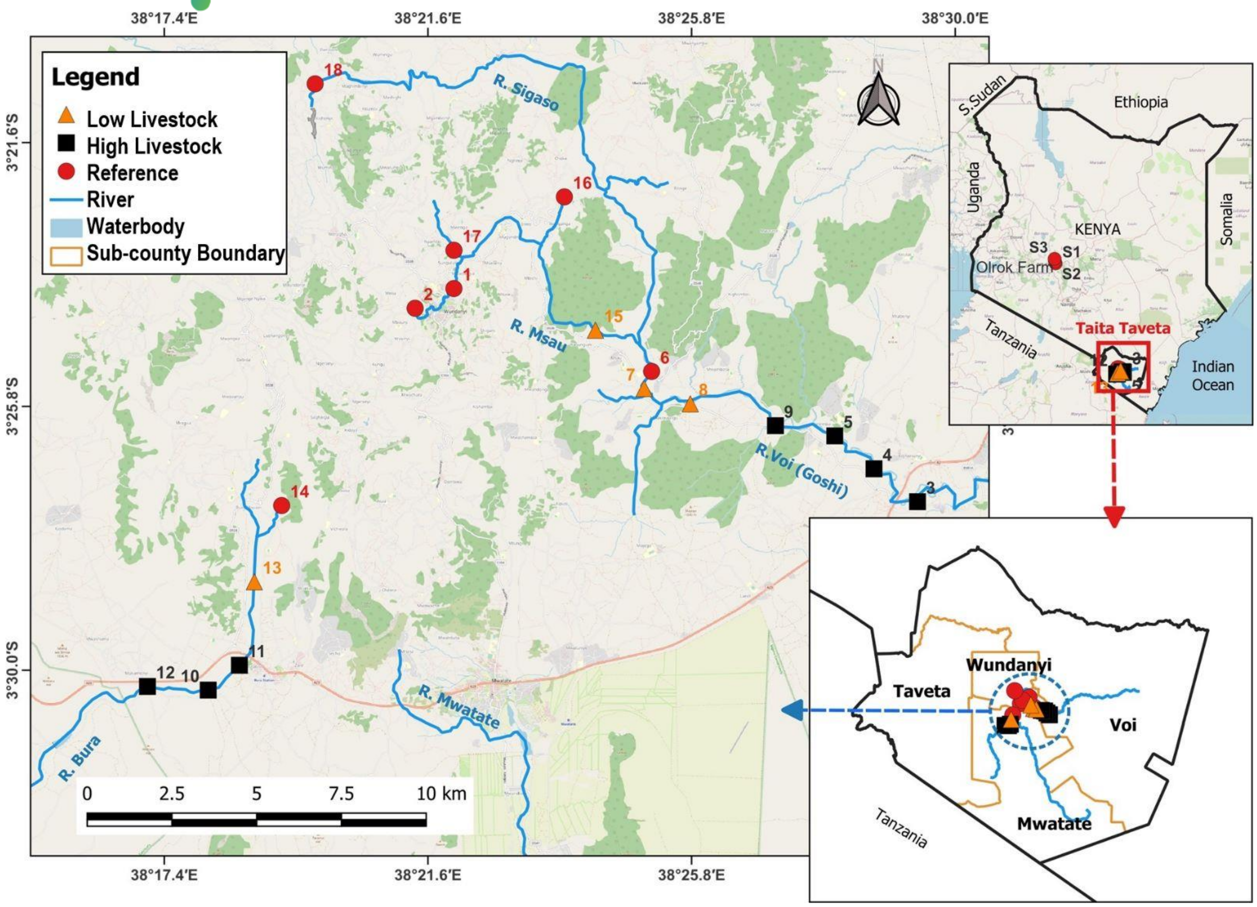

Figure 1: The study area map showing Wundanyi and Bura catchment in Taita-Taveta County, Kenya. Orange triangles represent sampling points in the low livestock density sites, black rectangles represent high livestock density sites, while red circles represent reference sites.

2.2 Sampling strategy

Sampling sites were categorized as reference sites (n=7, low (n=4), and high livestock density (n=7) sites in Bura and Wundanyi. Sampling was done in a synoptic that transitioned from wet season to dry season with a total of three sampling campaigns (December 2021, February 2022, and May 2022). During the dry season, the water dried in four sampling points in the high livestock density sites prompted the use of static chambers to collect gas samples.

2.3 Field Sampling

2.3.1 Stream Characteristics

Measurements of the slope, velocity and depth were taken during the sampling campaigns where the slope measurements were taken from the clinometer that was used to calculate the flux (Hall Jr & Ulseth, 2020). The stream width, velocity and depth were taken using the velocity plunk while discharge was computed from the velocity and discharge of the ridge as described . Velocity was computed from the upper value and lower value difference from the horizontally placed velocity plunk and table values obtained as described by (Hall Jr & Ulseth, 2020). Other observations made during the sampling period was recorded in the book such as site activities and riparian modifications.

2.2.2 Water Sampling

Acid washed HDPE plastic bottles was used to collect water sample for Ammonium (NH_4), Dissolved Organic Carbon (DOC), Total Phosphate (TP), Nitrates (NO_3^-), Nitrites (NO_2^-) and Soluble Reactive Phosphorus (SRP). 60ml syrench was used to collect water, then fitted with pre-combusted (450^{o}c for 3hours) GF/F glass fibre filter in a filter cartridge to allow filtered water into the sampling bottles until the filter clog. Unfiltered water sample was collected in 500ml HDPE bottles for TP, NO_3 and NO_2 analysis. The bottles were rinsed three times before sample collection and collected in triplicate. One drop of Concentrated sulphuric acid was added in every sampling bottle for fixation and stored in a cooler box with frozen ice brick to reduce the temperature to 4^{o}c until analysis (Leonard, 2021).

2.2.3 Sampling of Fine Benthic Organic Matter

60ml syrench was improvised to make one end open was used to collect sediments from the stream bed up to 10ml mark emptied into aluminium envelop and store at 4^{o}c to prevent microbial degradation (Schumacher, 2002). The samples were collected in triplicated and transported to the laboratory for analysis.

2.2.4 Gas Sampling from The Stream Sites

Gas samples were collected in triplicate using headspace equilibrium technique by Rymond et al., (2012). A 140ml syrench was filled with water and a 30ml ambient air was introduced. Equilibration was done by shaking the syrench continuously for 2 minutes and allow to displace air in the headspace (Raymond et al., 2012). 20ml sample of the gas was transferred to 10ml gas vial using a three-way cork fitted with a need. 20ml atmospheric gas was taken at each sampling site, air pressure measured using barometer and the slope of the stream measured using the clinometer.

2.2.5 Gas Sampling in Pools and Dry Stream Bed

During the dry season, gas sampling from the dry streambed was done using modified chambers fitted with rubber corks (Parkin, Venterea, & Hargreaves, 2012). The chambers measured 30cm by 60cm by 12cm bound together with by a Styrofoam. A 60ml syrench was first flushed through the chamber three times before sampling. 20ml gas was taken from each of the three replicate chambers, mixed thoroughly before releasing the gas to 20ml mark. The gas was then transferred to 10ml pre-evacuated until it is over pressurized. Time series samples were taken at an interval of 15minutes for 45 minutes at each sampling point (Parkin et al., 2012). The chambers were fitted with the thermometer to record the chamber temperature, while ambient pressure and temperature was as well taken for flux calculation.

2.3.0 Laboratory Analysis

2.3.1 Water Quality

Water samples were taken to University of Eldoret for analysis of TP, NH_4, NO_3, NO_2 and SRP while DOC was analyzed at ILRI laboratories. (Beutler et al., 2014) procedures were used to analyze nutrients, soluble nutrients (NH_4, NO_3, NO_2, DOC and SRP), were analyzed from filtered water samples while particulate inorganic nutrients, TP, was analyzed from unfiltered samples. Ascorbic acid was used to analyze SRP and TP and Absorbance values red at a wavelength of 885nm in the spectrophotometer. For TP, the samples were first digested using potassium persulphate and head for one hour before analysis (Beutler et al., 2014). The reaction of hypochlorite and salicylate solutions was used to analyze NH_4 and the spectrophotometer absorbance values obtained at 543nm (Beutler et al., 2014). Total Suspended Solids (TSS) and Particulate Organic Matter (POM) was determined using loss on combustion method (Schumacher, 2002). GF/F filters embedded with sediments were first oven dried at 60^{o}c for 72hours until constant weight achieved. To determine TSS, the filters were re-weighed an analytical balance then determined by TSS (mg/l) = ((X-Y)/V) *10^6 where X is the mass of filter + dried residue (g), Y is the dry mass of filter (g), and V = volume of sample filtered (L) (Schumacher, 2002). Filters were then ashed at

450°c for 4hrs in the furnace then re-weighed to determine POM using the equation POM (mg/l) = ((Z-Y)/V) * 10^6 where Z is the weight of the ashed filters.

2.3.2 Fine Benthic Organic Matter

FBOM was determined using Loss-on-Ignition method by Schumacher (2002) where the samples were first oven dried at 60°c for 72hours then weighed. The samples were then combusted at 450°c for 4 hours, cooled and %FBOM determined using the equation %FBOM = ((Initial weight (g) – Final weight (g))/Initial weight (g)) * 100.

2.3.3 Gas Sample Analysis

Gas samples were analyzed at ILRI Mazingira using gas chromatograph sri 8610C where the concentration of (CO_2, CH_4 and N_2O) was determined from the peak areas from the known standard concentration (Raymond et al., 2012).

2.3.4 Flux Calculation from Headspace Equilibrium Technique

GHGs fluxes from the headspace equilibrium in (mmolm-2d-1) were estimated using the gas transfer velocity based on Maclntre et al., (1995) equation. Flux = K (Dissolved gas concentration – atm equilibrium gas concentration) where k is the estimated gas transfer velocity. K was calculated from the second and third equation in Raymond et al., (2012) as K= K_{600}* (600/Schmidt numbers) ^1/2 and K_{600} = VS0.72 * 951.5 where V and S is velocity and slope. The atmospheric equilibrium concentration was obtained from the forth equation of henrys law with solubility constant (KH) as ATM equilibrium gas concentration = KH* ATM concentration (Raymond et al., 2012).

2.3.5 Dry Flux from Static Chamber Technique

Concentration from the GC were converted to volumetric mass density (mgm^{-3}) using ideal gas law (equation 6) PV = nRT where P is the atmospheric pressure, T is the chamber temperature and n is the molar gas and V = molar volume (Healy, Striegl, Russell, Hutchinson, & Livingston, 1996). Estimates of flux calculation based on linear changes of the gas concentration over time, Flux = dc(t)/dt = (A/V) fo where c(t) is gas concentration per unit, A= inner area chamber and V= inner volume chamber while fo is gas flux at time T0. Initial pre-deployed gas flux fo was calculated from the slope of the resulting linear regression model as C (t) = (A/V) f0(t) + C_0 and Slope = (A/V) fo. Hourly rate flux was obtained from the sampling intervals converted to hours as fo = Slope * (V/A) * (60 minutes/Sampling interval in minutes).

2.4.0 Data Analysis

Data from the field and laboratory was entered in the excel 2016 version for storage and descriptive analysis performed to determine the mean physiochemical parameters that is, POM, OM, TN, SRP, TSS, NO^{-}_{3}, NO^{-}_{2}, NH_4^{-}, DO, suspended solids, DOC, Temperature, pH, ATM pressure, Depth, Wind speed. Descriptive statistics for degassing of GHGs emission in mmol per area, per time and per litre for $CH_{4(g)}$, $N_2O_{(g)}$, and $CO_{2(g)}$, per site per season and Bar plots done to show the significance difference. Principal Component Analysis (PCA) analysis was carried out to determine the physiochemical parameters that are linked each livestock production system. Correlations was done to determine the relationship between physiochemical parameter and greenhouse gas fluxes. All the data analysis was performed in r-Software.

3.0 Results

3.1 Livestock production system and seasonal variability in carbon stock, and water quality variables

The temperature, electric conductivity, dissolved oxygen, total phosphorus, dissolved organic carbon, nitrates, nitrites, ammonium, and fine benthic organic matter differed significantly with the livestock densities. There was the high temperature (27.3±4.1oC), electric conductivity (713.1±98.0 mg/l), total phosphorus (0.6±1.2 mg/l), dissolved organic matter (26.9±43.2 mg/l), nitrates (0.5±0.5 mg/l), nitrites (0.3±0.3 mg/l) and ammonium (4.0±3.9 mg/l) in high livestock density sites compared to the reference and low livestock density sites. However, fine benthic organic matter was high in reference (Agricultural sites) (5.5±0.9%) compared to low and high livestock density sites.

Based on seasonality, temperature, conductivity, total dissolved solids, salinity, dissolved oxygen, total suspended solids, particulate organic matter, total phosphorus, dissolved organic carbon, nitrates, nitrites, ammonium, and fine benthic organic matter varied significantly. During the pick dry in May, temperature (25.4±4.5oC), total dissolved solids (113.4±142.0 mg/l), salinity (1.6±0.9 mg/l), and fine benthic organic matter (1.8±2.4%) were significantly high. During the early period of the dry season in February, total suspended solids (128.1±24.6 mg/l), and ammonium (5.0±3.7 mg/l) were high while conductivity (687.9±19.1 mg/l), dissolved oxygen (7.2±1.4 mg/l), particulate organic matter (14.9±7.1 mg/l), total phosphate (1.0±1.1 mg/l), dissolved organic matter (36.7±37.5 mg/l), nitrates (0.3±0.1 mg/l), and nitrates (0.6±0.5 mg/l), was high during the pick of the wet season in December.

Table 1: Means (± SE) variation of physio-chemical variables, nutrient concentrations, in the different land-use sites. EC = electrical conductivity, SRP = soluble reactive phosphorus, TSS = total suspended solids, POM = particulate organic matter TDS = total dissolved solids, DOC = dissolved organic carbon, SRP = soluble reactive phosphorus, D.O = dissolved oxygen, TP = total phosphorus and FBOM = fine benthic organic matter.

LPS	Reference	Low livestock	High livestock	F-Value	P-Value
Temp (°C)	22.5±3.1^{c}	25.2±4.1^{b}	27.3±4.1^{a}	29.99	>0.001*
EC (µS/cm)	644.1±72.3^{b}	695.5±15.2^{a}	713.1±98.0^{a}	16.84	>0.001*
TDS (mg/L)	106.0±77.1^{ab}	129.3±145.3^{a}	84.6±41.1^{b}	4.86	0.009*
Salinity (mg/L)	0.3±0.2^{ab}	1.8±7.5^{a}	0.2±0.2^{b}	3.40	0.035*
D.O(mg/l)	6.2±1.3^{ab}	6.7±1.4^{a}	5.9±1.4^{b}	7.91	>0.001*
pH	8.2±0.5^{a}	8.1±0.7^{a}	7.9±0.5^{a}	2.83	0.061
TSS (mg/l)	88.6±68.5^{ab}	47.8±45.0^{b}	124.8±224.1^{a}	5.36	0.005*
POM (mg/l)	28.1±33.1^{a}	29.3±44.8^{a}	64.5±190.3^{a}	2.24	0.109
TP (mg/L)	0.2±0.5^{b}	0.1±0.1^{b}	0.9±1.3^{a}	16.64	>0.001*
DOC (mg/L)	13.7±15.7^{b}	17.5±19.1^{b}	27.4±34.8^{a}	6.00	0.003*
Nitrites (mg/l)	0.2±0.1^{b}	0.3±0.1^{ab}	0.3±0.3^{a}	5.39	0.005*
Nitrates (mg/l)	0.7±0.5^{a}	0.3±0.3^{b}	0.4±0.3^{b}	16.22	>0.001*
SRP (mg/L)	0.1±0.1^{b}	0.2±0.5^{a}	0.2±0.3^{a}	5.67	0.004*
Ammonium (mg/l)	3.0±2.2^{a}	2.9±2.3^{a}	4.0±3.9^{a}	3.23	0.041
% FBOM	5.5±0.9^{b}	1.1±0.5^{b}	1.8±2.4^{a}	13.21	>0.001*
Seasonality	**December**	**February**	**May**	**F-Value**	**P-Value**
Temp (°C)	20.8±9.0^{b}	24.7±8.2^{a}	25.4±4.5^{a}	9.62	>0.001*
Cond' (µS/cm)	687.9±19.1^{a}	643.1±225.4^{ab}	590.5±239.5^{b}	5.77	0.004*
TDS (mg/L)	71.5±16.2^{b}	105.4±76.0^{a}	113.4±142.0^{a}	4.87	0.008*
Salinity (mg/L)	0.3±0.2^{ab}	0.1±0.1^{b}	1.6±0.9^{a}	3.47	0.033*
D.O	7.2±1.4^{a}	5.3±2.0^{b}	4.9±2.1^{b}	41.01	>0.001*
pH	7.9±0.7^{a}	7.4±2.1^{a}	7.2±2.9^{a}	2.62	0.075
TSS (mg/l)	83.6±78.9^{ab}	128.1±24.6^{a}	38.6±37.8^{b}	8.00	>0.001*
POM (mg/l)	14.9±7.1^{b}	10.3±3.5^{a}	7.4±8.2^{b}	16.74	>0.001*
TP (mg/L)	1.0±1.1^{a}	0.5±1.1^{b}	0.05±0.06^{c}	15.8	>0.001*
DOC (mg/L)	36.7±37.5^{a}	18.9±14.7^{b}	4.4±3.4^{c}	36.03	>0.001*
Nitrites (mg/l)	0.3±0.1^{a}	0.3±0.3^{a}	0.1±0.1^{b}	34.32	>0.001*
Nitrates (mg/l)	0.6±0.5^{a}	0.5±0.4^{a}	0.2±0.2^{b}	18.34	>0.001*
SRP (mg/L)	0.2±0.4^{a}	0.2±0.3^{a}	0.1±0.2^{a}	0.12	0.889

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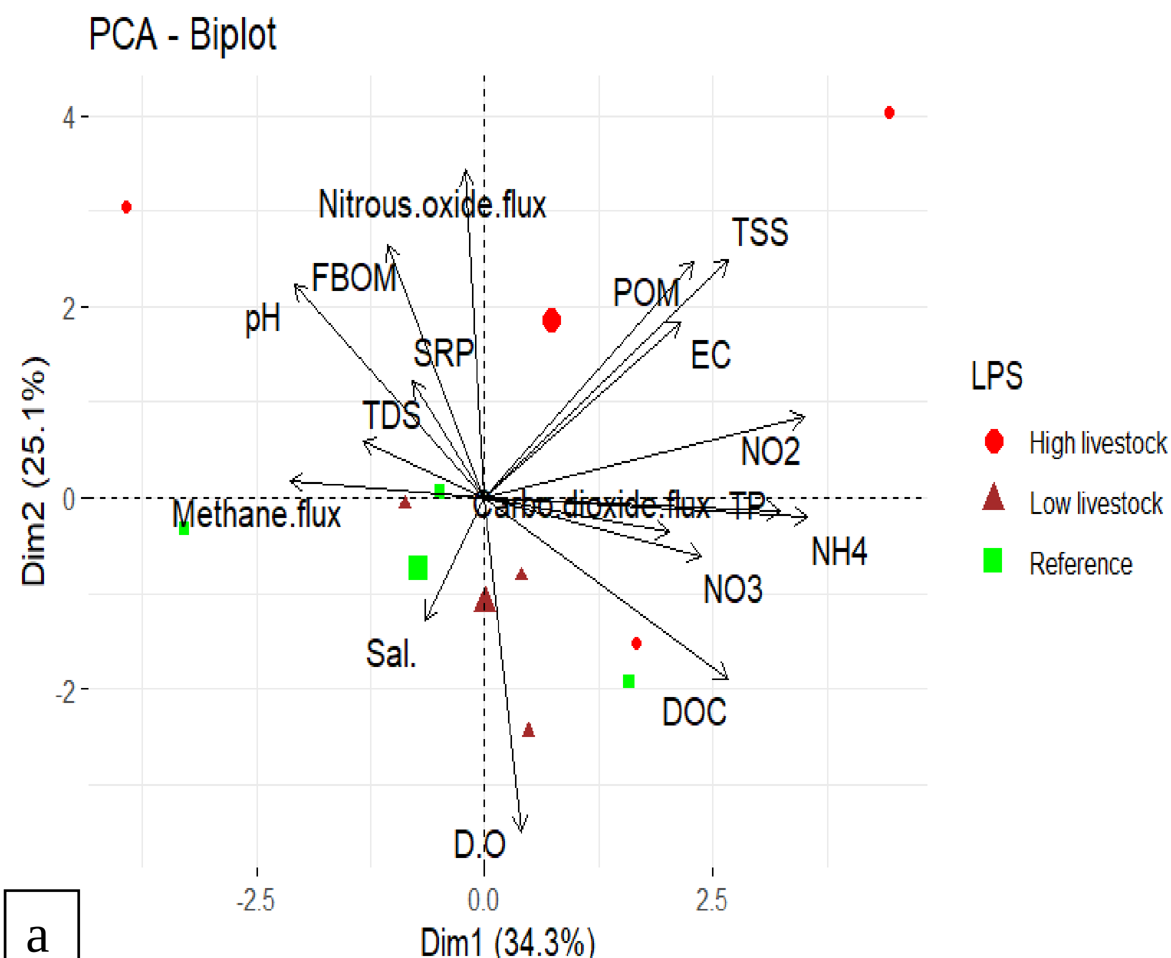
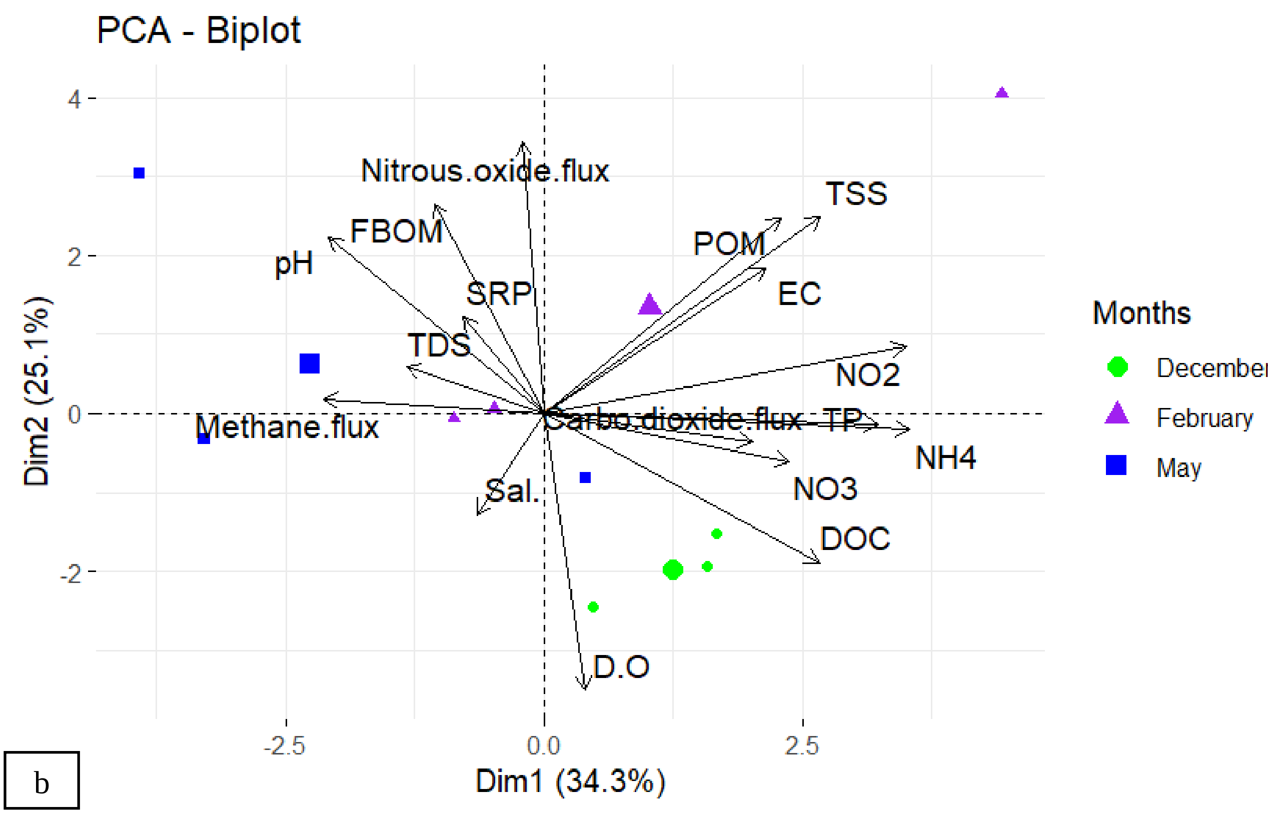
Ammonium (mg/l)	4.3±1.8[a]	5.0±3.7[a]	0.3±0.3[b]	96.89	>0.001*
% FBOM	0.9±1.1[b]	1.2±1.6[ab]	1.8±2.4[a]	5.44	0.005*

*Means that do not share a letter are significantly different; Tukey post hoc tests.
*p-values marked with asterisks are significantly different among land-uses at $p < 0.05$.



a



b

Figure 2: PCA biplot for water quality, physio-chemical and greenhouse gas flux variables as affected by seasonality (a) and livestock production systems (b) in Taita-Taveta County, Kenya.

Livestock density strongly influenced the water quality, physio-chemical and greenhouse gas flux variables. The high temperature, total dissolved solids, total phosphate, dissolved organic carbon and ammonium were recorded in high livestock density sites. Though they were not significantly high ($p<0.005$), soluble reactive phosphorus and total suspended solids were also high in high livestock density. The dissolved oxygen was however high in reference sites, characterized by small-scale agricultural activities and shallow rivers. The dry season was characterized by high temperature, total dissolved solids, salinity, and fine benthic organic carbon associated with pick dry season in May. TSS, ammonium, and nitrous oxide fluxes were associated with the early dry season in February. While dissolved oxygen and dissolved organic carbon were associated more with the pick wet season in December.

3.2 Livestock density and seasonal variability of greenhouse gas flux

High methane flux was observed in high livestock density sites (7.3±7.8), compared to the reference (5.3±2.4) sites but did not differ significantly with low livestock density sites. However, nitrous oxide flux was a source in high livestock density sites (3.5±10.9) but remained to be sink in reference and low livestock sites. Carbon dioxide did not differ significantly with the livestock density (Table 2).

Table 2: Means (± SE) variation of methane flux (FluxCH_4.mmol.d.m^2), carbon dioxide flux (FluxCO_2.mmol.d.m^2) and nitrous oxide fluxes (FluxN_2O.umol.d.m^2) in different LPS.

LPS	Reference	Low livestock	High livestock	F-Value	P-Value
Methane flux	5.3±2.4[b]	7.0±3.3[a]	7.3±7.8[a]	5.63	0.004*
Carbon dioxide flux	303.0±181.2[a]	284.3±344.4[a]	275.4±177.5[a]	0.29	0.746
Nitrous oxide flux	-5.8±5.5[b]	-5.1±1.6[b]	3.5±10.9[a]	40.01	>0.001*

*Means that do not share a letter are significantly different; Tukey post hoc tests.
*p-values marked with asterisks are significantly different among land-uses at $p < 0.05$.

The pick rainy season in December recorded higher methane flux (9.1±6.1) compared to the early dry season in February and the peak dry season in May. During the dry season, nitrous oxide maintained a positive trend with the highest flux being recorded during the peak season in May (3.49±10.7) (Table 3).

Table 3: Means (± SE) variation of methane flux (FluxCH_4.mmol.d.m^2), carbon dioxide flux (FluxCO_2.mmol.d.m^2) and nitrous oxide fluxes (FluxN_2O.umol.d.m^2) in different seasons.

Seasonality	December	February	May	F-Value	P-Value
Methane flux	9.1±6.1[a]	5.6±2.7[b]	4.1±2.5[c]	33.57	>0.001*
Carbon dioxide flux	281.1±204.6[a]	247.3±129.0[a]	327.1±239.5[a]	2.65	0.073
Nitrous oxide flux	-7.24±3.1[c]	0.38±8.5[b]3	3.49±10.7[a]	40.97	>0.001*

*Means that do not share a letter are significantly different; Tukey post hoc tests.
*p-values marked with asterisks are significantly different among land-uses at $p < 0.05$.

3.3 Relationships between water quality parameters and greenhouse gas concentrations

The river CO_2 fluxes were positively related to FBOM % and DOC concentrations and negatively related to nitrates, nitrites, DO and ammonium. CH_4 fluxes were also positively related to DOC, and FBOM and negatively related to Ammonium, DO and NO_3-N concentrations. N_2O fluxes were positively related to NO_3-N concentration, and NH_4 and DO. Overall, CO_2 and CH4 fluxes had negative relationships with NO_3-N and ammonium. NO_3-N was the strongest predictor of N_2O, as it contributed up to 90 per cent of increase in N_2O fluxes (Table 4). In addition, the strength of the relationships between Temperature, CO_2 and CH_4 were lowest throughout the seasonality, which was also true for relationships between NO_3-N and N_2O and for DOC and CH_4.

Table 4: Correlation analysis of methane flux ($FluxCH_4.mmol.d.m^2$), carbon dioxide flux ($FluxCO_2.mmol.d.m^2$) and nitrous oxide fluxes ($FluxN_2O.umol.d.m^2$) in different season.

	December			February			May		
	CH_4 flux	CO_2 flux	N_2O flux	CH_4 flux	CO_2 flux	N_2O flux	CH_4 flux	CO_2 flux	N_2O flux
Temp	-0.435	-0.468	0.505	-0.517	-0.527	-0.064	-0.403	-0.409	-0.047
EC	-4.110	-0.339	0.405	-0.091	-0.075	-0.236	-0.189	-0.220	-0.577
TDS	-1.520	-0.146	0.149	0.365	0.410	-0.207	-0.029	-0.002	-0.052
Sal.	-0.098	-0.177	0.172	-0.142	-0.137	0.329	-0.140	-0.138	-0.014
D.O	0.165	0.214	-0.277	0.156	0.180	-0.255	0.354	0.372	-0.063
pH	-0.200	-0.342	0.366	-0.169	-0.166	-0.020	0.073	-0.060	-0.071
TSS	0.176	0.075	0.030	0.001	-0.009	0.059	0.231	0.499	-0.184
POM	0.184	0.058	0.031	-0.068	-0.080	0.078	0.212	0.558	-0.218
TP	-0.278	-0.328	0.362	-0.215	-0.266	0.236	0.434	0.295	-0.289
DOC	0.951	0.917	-0.916	0.923	0.966	-0.551	0.443	0.787	-0.347
Nitrites	-0.652	-0.771	0.781	-0.383	-0.485	0.977	-0.601	-0.555	0.722
Nitrates	-0.476	-0.573	0.587	-0.501	-0.616	0.960	-0.462	-0.564	0.713
SRP	-0.106	-0.117	0.094	0.141	0.177	-0.230	-0.198	-0.199	0.052
Ammonium	-0.681	-0.796	0.814	-0.746	-0.772	0.802	-0.500	-0.411	0.558
% FBOM	0.972	0.981	-0.936	0.965	0.977	-0.417	0.965	0.922	-0.505

4.0 Discussion

4.1 Livestock production system and seasonal variability in carbon stock, and water quality variables

Both livestock density and season played significant roles in influencing water quality, dissolved organic carbon and fine benthic organic matter in the study. Changes in water quality across different livestock density sites were indicated by decreasing DO levels, increasing temperature, conductivity, nutrients and TSS (Table 1). The higher mean temperature in the high livestock density sites can be attributed to open canopy cover along the riparian zones, while the lower mean temperature at reference sites was due to dense vegetation cover. Vegetation cover on river margins limits solar radiation reaching the water thus reducing fluctuations in water temperature in reference sites (Bacca et al., 2023; Sitati, Raburu, Yegon, & Masese, 2021). The lower conductivity recorded in reference sites than other site categories can be attributed to the fact that rivers with little disturbance along the riparian have less amount of iron concentration. On the contrary, higher conductivity was recorded in high livestock density sites due to high nutrients from livestock watering activities as a result of eroded river bank, and loadings from dung, and urine (Ricky Mwanake et al., 2020). However, during the pick of the wet season in December, conductivity was high probably due to runoff from the adjacent riparian areas to the rivers.

The high levels of nitrates in reference sites could be attributed to nitrogenous fertilizers used in farmlands used for maize and bananas production. Increase in dissolved fractions of nitrogen and electrical conductivity are indicators of disturbance that have been attributed to change in livestock and agricultural activities as the river channel meander from highlands to the low land area of the study sites. High levels of ammonium in high livestock density watering points are attributed to runoff from the riparian grazing fields and urine from livestock that finds pools within the river channels. The dissolved organic carbon and fine benthic organic matter had significant differences among livestock density and seasonality. The high DOC in high livestock density sites was attributed to defection, trampling, and urine from livestock that increases labile carbon in the water while during the pick wet season in December, high DOC was attributed to runoff from the adjacent agropastoral field. The inverse relationship of fine benthic organic matter in soil and dissolved organic matter was attributed to decomposition rate, and presence of dissolved oxygen.

4.2 Livestock density and seasonal variability of greenhouse gas flux

In agreement with findings from other studies on African rivers, the Taita-Taveta agropastoral rivers are net source of greenhouse gas emissions to the atmosphere (Borges et al., 2019; RM Mwanake et al., 2019; Ricky Mwanake et al., 2020; R. M. Mwanake et al., 2022; Qin et al., 2020) contributing ~ 0.38 Gg CO_2 eq yr^{-1}. Generally, the spatial and temporal variation of CO_2, CH_4, and fluxes in this study were linked to livestock density and seasonality in rivers. Temporal changes in greenhouse gas concentrations and fluxes were related to the balance between instream processing, which dominated during the dry season in February and June s, and increased external supply and high evasion rates, which dominated high livestock density sites. During the dry period, the different gases acted differently with respect to super-saturation or under-saturation. During the high pick rainy period in December, CH_4 fluxes increased significantly, indicating that increased supply from external sources could offset the reduction in instream production rates. Catchment characteristics such as the dominant grazing zones stream size influenced the spatial variability in greenhouse gas fluxes. High livestock density watering points along the rivers, which were characterized by higher temperatures and higher nutrient and organic matter concentrations than reference rivers, favored instream production of the greenhouse gases resulting in higher fluxes, while reference streams with better sediment–water and land–water connectivity also exhibited higher fluxes.

4.3 Relationships between water quality parameters and greenhouse gas concentrations

In this study, CH_4 flux increased with increase in livestock density which is in agreement with other studies (RM Mwanake et al., 2019; Ntinyari & Gweyi-Onyango, 2021; Wangari et al., 2022). This was attributed to higher rates of sediment methanogenesis, as evidenced by low NO_3-N and high DOC that observed at the same time and the strong negative relationship between CH_4, NO_2, NH_4 and NO_3 concentration and the positive relationship with DOC and FBOM. During the longer residence times created in pick rainfall season in December, low gas transfer rates together with the consumption of oxygen and nitrate as terminal electron acceptors and the increased mineralization of organic carbon appears to have provided suitable conditions for methanogenesis. Similar conditions were also related to increased methanogenesis in stream sediments in a global review of riverine methane dynamics (Gachibu, 2019). These conditions were evident in the high livestock sites, which are characterized by deeper pools with slower moving water as well as additional input of organic matter from manure. Comparable seasonal trends of high CH_4 concentrations in the high discharge periods have also been reported in other studies such as Mwanake et al., (2020), attributed to external source of greenhouse gases from the riparian zone.

The seasonal trends of CO2 fluxes in our study were linked to changes in seasonal patterns of organic carbon (DOC and FBOM%), and livestock density observations which agree well with other studies (Allan et al., 2021; Masese, Salcedo-Borda, Gettel, Irvine, & McClain, 2017; Swart, Oleynik, Martinez-Garcia, Haug, & Sigman, 2021). Our data show that increased organic carbon concentration and low gas evasion rates in high livestock density watering points may have favored an increase in microbial heterotrophic production of CO_2, sustaining high fluxes. This finding is supported by the positive relationship of CO2 fluxes with DOC concentration and FBOM%, and the strong negative relationship with nitrates, nitrites, and ammonium while weak negative relationship with DO. Mwanake et al. (2022) in their study of estimates of greenhouse gases emissions in Mara river basin in Kenya associated CO_2 concentrations in the dry season to in situ microbial production processes and the reduction of the gas transfer velocity under low discharge conditions.

During the dry season in February and May, urine concentration, and dung with high NO_3-N and low pH seemed to support N_2O production processes and subsequent N_2O supersaturation, similar to previous riverine studies that linked high NO_3-N concentrations in streams to N_2O supersaturation. This is supported by high positive correlation of nitrates, ammonium, and nitrites. The negative relationship between Nitrous oxide fluxes with dissolved organic carbon and fine benthic organic carbon supports nitrification process as the source of N_2O. On the other hand, low nitrates in reference sites were characterized by lower N_2O negative fluxes. The positive relationship between N_2O fluxes, and ammonium, nitrates, nitrites, and negative relationship with DOC concentration and FBOM%, supports compete nitrification process during the rainy season that results in negative fluxes in livestock, and reference sites.

Conclusion

High livestock density prays an important role in greenhouse gas emissions as the system seem to dominate, with fluxes a function of both nutrients loading, and trampling. The effect of land livestock density at watering points is particularly evident within seasonal variations, when relationships with water quality variables (DO, DOC, and NO_3-N) and FBOM suggested in situ greenhouse gas production. Specifically, high livestock density sites had positives N_2O emissions and an increase in CH_4 emissions than reference sites. Given that livestock density is a major factor increasing the source strengths of streams and rivers for greenhouse gases in the study region, having high livestock density in open system accessing watering points and riparian zones for grazing is likely global greenhouse gas emissions. Future research should include the contribution of dry riverbeds in the area to greenhouse gas emissions, which are likely an important but understudied source of nitrous oxide, methane and carbon dioxide in savannah river basins.

Declaration of Conflicting Interest

The Author declares no conflicting interests

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