Methane emissions from riverine and swampy coastal wetlands: influence of open and macrophyte-infested areas

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Abstract

The atmospheric concentration of methane (CH_4) exerts a strong influence on the global climate. Notably, wetlands are important CH_4 sources, whose emission represents an ecosystem process depending on such wetland characteristics as organic matter, temperature, pH, methanogenesis and CH_4 oxidation, all of which vary on the basis of the type of wetland. Methane fluxes were investigated in a preliminary study in the region, using the chamber method in the open water and macrophyte-infested wetlands of swampy and riverine types in Kilifi, a coastal district in Kenya, Africa. Despite a lack of significant interactions, the macrophyte-infested areas emitted the highest quantity of methane of about 21.96 ± 0.04 mg CH_4 m^{-2} day^{-1}, compared with the water areas that emitted about 19.35 ± 0.05 mg CH_4 m^{-2} day^{-1}. The preliminary CH_4 fluxes measured in this study are below the range reported from previous wetland field experiments in the tropics and temperate regions, indicating the need to conduct a series of similar experiments to produce more precise total estimates in the entire region.

Key words

Coastal Kenya, macrophyte area, methane, open water area, wetland.

INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC (Intergovernmental Panel on Climate Change) 2007), the atmospheric methane concentration has increased by 150% (i.e. increased by 2.5 times) since 1750, accounting for 20% of the total radiative forcing from all the long-lived and globally mixed greenhouse gases. For the overwhelming majority of the IPCC future greenhouse gas scenarios, the methane concentration at the end of this century is projected to be much greater than it is at the present time (Khalil *et al.* 2007).

Natural and cultivated wetlands represent approximately 40% of the sources of atmospheric methane on a global scale, being roughly constant over the past 30 years (Mingkui *et al.* 1998; IPCC (Intergovernmental Panel on Climate Change) 2007). Methane emissions from wetlands involve complex physiological processes of plants and microorganisms, which are regulated by climate and edaphic factors. Notably, the interactions of these processes with heterogeneous environments result in large variations in the methane fluxes, which can change in the time scale of hours (Mingkui *et al.* 1998; Striegl & Michmerhuizen 1998; Huttunen *et al.* 2003; Khalil *et al.* 2007). Wetlands provide a habitat conducive to methanogenic (methane-producing) bacteria that produce methane as a result of their decomposition of organic material (Andreae & Schimel 1989; Mingkui *et al.*

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1998). These bacteria require environments with no oxygen and abundant organic matter, both of which are present in wetland systems. Methanogenic bacteria produce CH_4 when they are obtaining energy in the decomposition process, according to the following reactions:

$$4H_2 + CO_2 \rightarrow 2H_2O + CH_4. \quad (1)$$

$$CH_3COOH \rightarrow CO_2 + CH_4. \quad (2)$$

Some studies also have revealed that some vascular systems in wetland plants might allow diffusion of methane (CH_4) from the sediment into the atmosphere (Butenhoff & Khalil 2007). The nature of the variability of methane fluxes is such that there is a need to improve estimates of wetland emissions and to predict their responses to climate variation by taking into account the ecological and environmental factors controlling the involved processes. Annual total emissions from natural wetlands, for example, were calculated to be 92 Tg (Tg = 1 million tons), with northern wetlands emitting 24 Tg, temperate wetlands emitting 17 Tg and tropical wetlands emitting 51 Tg (Mingkui *et al.* 1998), with these estimates requiring updates from all parts of the globe. Wetlands constitute a significant natural source of atmospheric CH_4, and boreal wetlands have been intensely studied in this context (Chapin *et al.* 2000; Wuebbles & Hayhoe 2002). In most developing countries, however, estimates of such greenhouse gas emissions, as carbon dioxide (CO_2) and CH_4, from different types of wetlands are limited or unknown. Natural tropical wetlands are even more poorly studied, despite their relatively larger contribution to atmospheric methane (Bartlett & Harriss 1993; Milich 1999; Marani & Alvala 2007), with much of the research conducted at low latitudes being limited to the Amazonian floodplain and Florida Everglades (e.g. Bartlett *et al.* 1989; Devol *et al.* 1990), and also being restricted to area-averaged methane flux estimates. This study uses the static chamber method to measure and compare the quantity of methane gas produced from a swampy and a riverine wetland. The results also facilitate estimates of methane emissions from natural wetlands based on methane ebullition and plant-mediated transport.

MATERIALS AND METHODS

This study was carried out for the 6-month period between October 2008 and March 2009 in swampy and riverine settings, both located in Kilifi District (geographical bearings of 4°40S and 4°40N) of the Kenya coastal

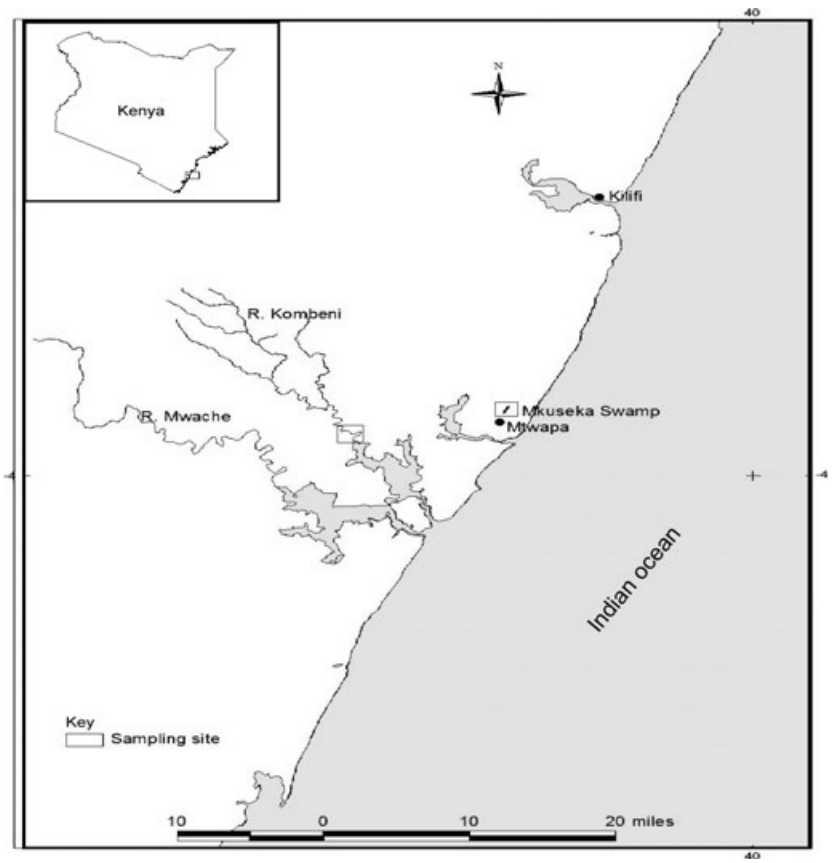

Fig. 1. Swampy (Mkuseko) and riverine (Kombeni) coastal wetlands in Kilifi District of coastal Kenya.

area (Fig. 1). The swampy wetland is a marine wetland consisting of *Cyperus papyrus,* whereas the riverine system is a stream flowing into the Indian Ocean. Kilifi District occupies 67 km of the Kenyan coastline, containing an approximate population of 600 000 inhabitants living in a total area of 4878 km, with an average of 113 persons km^{-2} (KDDP, 2010). The district has two main rainfall seasons annually. The long rains fall from April to June, with a peak in May, while the short rains fall from October to December. The temperatures in the district range between 22.50 and 24.50°C during April, May and June, while the maximum temperatures vary between 26.0 and 30.0°C. The average annual rainfall ranges from 400 mm in the hinterland to 1200 mm in the coastal belt. The coastal belt receives an average annual rainfall of about 900–1100 mm, with a marked decrease in intensity to the north and to the hinterland.

Several creeks lie across the Kilifi plains, resulting into excellent marine swamps, including the prominent Mkuseko swamp (04°17′ 40.6″S, 034°25′ 51.9″E). River Kombeni (04°19′ 40.2″S, 034°22′ 27.0″E) lies in the slightly undulating terrain, with *C. papyrus* and stunted vegetation. The swampy wetland (Mkuseko), with an area of 30 km^2 and a length of about 7 km, is under the authority of the Kilifi County Council, being used for rice farming and water provision for domestic use, despite being affected by siltation and poor management status. The riverine wetland, known as Kombeni and covering about 8 km, with an area of 35 km^2, is under private ownership, being used by locals in for water provision for washing clothes. It also experiences urban pollution from the town of Mazeras. Both wetland areas exhibit a tropical climate, influenced by northeast and southeast monsoon winds, with a tidal amplitude range of 1–4 m, together with macrophytes (*C. papyrus*) in most parts. The open water area in the riverine wetland covers about 46%, with the rest being covered by *C. papyrus*. The swampy wetland is covered by 54% of the *C. papyrus*, with the remaining area being open water.

Six sampling sites were selected randomly in both wetlands. Three sites represented open water areas, while three represented differences in vegetation cover of the *C. papyrus*-infested areas. The location of the study sites was recorded with a GPS model eTrex Vista® C. Each site was measured *in situ* for water temperature, pH and dissolved oxygen concentration, utilizing a YSI 85 multimeter (APHA 2000; Wetzel & Likens 2000). Sampling for the environmental variables at three sites for each wetland type was conducted from a platform in the centre of each wetland site, with the deepest points of all the three compartments being nearly at a 20–30 cm depth. Undisturbed sediment cores were taken with a Jenkin surface-mud sampler (Ohnstadt & Jones 1982) for measurement of organic matter at a 18–32-cm depth, after the temperature, pH and oxygen concentration were measured. The cores were sliced at the chamber measurement sites and fitted in an Auger Mini Sampling Kit (AMS) soil corer fitted with a plastic pipe (length = 46 cm; diameter = 7 cm). The cores were processed in the laboratory within 2 h after sampling. A plastic liner with holes drilled at 1-cm intervals was used in a Jenkin surface-mud sampler to collect water close to the sediment–water interface. The holes were closed with plastic tape before methane measurements were conducted in the morning hours before 10:00 am once weekly in the open water and macrophyte-infested areas, to eliminate possible disturbances of methane measurements. Standard analyses of percentage organic matter content were performed according to German standards (DEV 1991), involving combustion by determining the loss on ignition, water content and percent dry matter (dm).

For the macrophyte-infested sites, the closed-chamber technique (Schütz & Seiler 1989) was used to monitor the CH_4 plant-mediated transport at all sites. Each chamber consisted of a partially translucent polyethylene cylindrical container 100 cm high with 3-mm-thick walls. Large chambers permit the inclusion of vascular plants, which are an important conduit for methane from the soil in many wetlands (Le Mer & Roger 2001). Because of limited funds, however, the material used did not cover plants taller than 100 cm, which were about 15% of the entire plant population in the wetland. Each chamber was sealed, with foam gaskets and clamps, to a galvanized aluminium collar previously inserted ~10 cm into the soil, thereby establishing a gas-tight seal. A battery-powered fan maintained circulation within each chamber. A 0.48-m^2 floating static chamber was used to measure methane surface fluxes, and the methane concentrations dissolved in water were measured by submerged funnel collectors, all of which were placed at each sampling site (Huttunen *et al.* 2001 and 2003). Gas samples of a 30-mL volume were withdrawn at 30-min intervals through a butyl rubber-5-stopper on the top of the chambers. These were injected into previously evacuated 10-mL serum bottles, establishing a positive pressure. To verify the repeatability of the chamber sampling technique in this study, some gas samples were stored by displacing water from vials. After incubation between 90 and 120 min, each chamber was removed and flushed with air between successive measurements. The aluminium collar was left in place if the next measurement was at the same location. Gas samples were returned to the laboratory and

analysed within 24 h of collection with a Shimadzu GC-14A gas chromatograph.

The column was maintained at 35°C in the laboratory, with 30 mL min^{-1} of grade-6 helium (Gaspro, Honolulu, HI, USA) used as the carrier gas. The GC was calibrated initially, and after every 10 analysis runs, with a 100 ppm CH_4 standard (Matheson Tri Gas, Montgomeryville, PA, USA). Atmospheric samples (~1.85 ppm) also were run. Methane fluxes were calculated as the difference between the initial and final concentrations in the chambers, adjusted for their volumes, surface coverage and incubation time. The sample calculations were performed in accordance with the technique of Andreae and Schimel (1989), Casper (1992a), Striegl and Michmerhuizen (1998) and Huttunen *et al.* (2001a, 2003), although adjusted to suit the available conditions. Methane fluxes were calculated as the difference between the initial and final concentrations in the chambers, adjusted for their volumes, surface coverage and incubation time. All fluxes are reported in units of milligram of methane per square metre per day. The accuracy of individual CH_4 measurements was determined by withdrawing three replicate samples at the final time point of several experiments. Many measurements also were repeated immediately after flushing the chamber. Other than the sites that were picked randomly, other chambers were deployed simultaneously in different locations to evaluate the effects of vegetation on methane fluxes. On a weekly basis, the chambers were positioned next to each other to determine the repeatability of the measurements, as well as possible small-scale spatial variability in methane emissions.

Gas traps at each sampling site were used to measure CH_4 flux from ebullition. The traps consisted of inverted funnels (0.48 m internal diameter), with a flask screwed to the top. The traps were left *in situ* for 1 week. The flasks were then closed under water with a butyl stopper and transported to the laboratory for analysis of the total volume of the gas collected, and the methane content performed within 4 h. In this scenario, methane was analysed with a Shimadzu GC-14A gas chromatograph equipped with a 1.5-m carboxen columnand fitted with a flame ionization detector. Flow rates were 3.6 L h^{-1} for nitrogen as the carrier gas, and 3 and 30 L h^{-1} for hydrogen and air, respectively, with an oven temperature of 35°C. Samples of the bubble gas were injected via a gas sample valve fitted with a 0.5-mL sample loop. The loop was flushed with at least four times its volume of sample before injection.

The area of the funnel and the rate of change of CH_4 in gas trap fluxes were used to calculate the ebullition fluxes. With the use of the equation of a straight line ($y = kx + m$), the CH_4 concentration was calculated per m^2 area by dividing the value of K (slope of the graphs) by the chamber base area (0.48×0.48 m), to obtain values in k ppm h^{-1} m^{-2}. These values were then multiplied by proportion of 5.0 + 13.2 mL divided by 5.0 mL to compensate for dilution and, therefore, concentration changes in the chamber. The resultants were then multiplied by the volume of the gas in each of the chambers, Using the ideal gas equation, $PV = nRT$ (where P = gas pressure; V = change in gas volume over time; R = gas constant; n = number of moles and T = ideal temperature [T = C + 273.15K]). The number of moles (n) was calculated for each site, using $n = PV/RT$. To calculate methane flux in milligrams, the value of n was multiplied by the molecular weight of methane ($CH_4 = 16.0428 \times 10^3$ g) for either open water or macrophyte-infested areas in mg m^{-2} h^{-1}, being converted to m^{-2} day^{-1}.

The physicochemical parameters and methane flux data were eventually recorded in Microsoft EXCEL spreadsheets and analysed with the STATISTICA software package (Statsoft Inc., 2010, version 8.0). The Levene test of homogeneity of variances was used to assess the departure of the data from homogeneity. One-way ANOVA was employed to determine significant differences in environmental parameters. The monthly and seasonal variations in methane fluxes, as a function of sampling site and sampling dates categories, were determined with factorial ANOVA, with the sites, subsites and months as the fixed effects using General Linear Model. The relationship between physicochemical parameters and methane fluxes was performed utilizing Pearson correlations for the open water and macrophyte-infested sites.

RESULTS

The measured environmental parameters did not vary temporally or spatially on weekly timescales. Accordingly, the data were pooled according to months. The water temperature between the open water and macrophyte areas significantly varied between the dry and wet seasons ($F = 24.41$; $P = 0.04$), but with no significant ($P > 0.05$) spatial variations (Table 1). As noted with the temperature, there were also temporal significant differences in dissolved oxygen concentrations ($F = 3.51$; $P = 0.04$) and organic matter ($F = 2.11$; $P = 0.03$), with no significant spatial variations ($P > 0.05$) between the open water and macrophyte-infested areas. A relatively neutral pH was recorded in both swampy and riverine wetland systems, despite the macrophyte-infested areas exhibiting lower pH values.

Table 1. Physical characteristics (mean ± SE) of the swampy and riverine ecosystems in Kilifi, Kenya, during the study period

		Swampy		Riverine	
Characteristic/month		Open water	Macrophyte area	Open water	Macrophyte area
Temperature (°C)	October 2008	24.90 ± 1.40	24.70 ± 3.20	26.10 ± 0.70	23.10 ± 0.50
	November 2008	25.70 ± 0.80	24.70 ± 1.30	26.20 ± 1.70	23.30 ± 0.30
	December 2008	25.70 ± 1.40	25.75 ± 3.10	26.20 ± 1.10	24.20 ± 0.80
	January 2009	27.90 ± 0.70	26.70 ± 2.10	27.40 ± 0.80	26.10 ± 0.70
	February 2009	28.30 ± 0.80	26.80 ± 2.80	28.10 ± 0.90	27.40 ± 0.80
	March 2009	28.90 ± 2.10	26.85 ± 1.20	28.80 ± 0.90	28.20 ± 0.90
pH	October 2008	6.70 ± 0.10	6.90 ± 0.50	7.10 ± 0.30	7.20 ± 0.20
	November 2008	7.10 ± 0.20	7.20 ± 0.30	7.10 ± 0.10	7.25 ± 0.30
	December 2008	6.90 ± 0.30	7.10 ± 0.50	6.90 ± 0.10	7.20 ± 0.10
	January 2009	6.80 ± 0.30	6.90 ± 0.10	7.30 ± 0.30	6.90 ± 0.20
	February 2009	7.00 ± 0.10	7.10 ± 0.10	7.00 ± 0.20	6.90 ± 0.10
	March 2009	6.90 ± 0.20	6.90 ± 0.20	7.10 ± 0.20	6.90 ± 0.30
Oxygen (mg L^{-1})	October 2008	6.00 ± 0.20	5.20 ± 0.30	7.10 ± 0.01	5.20 ± 0.20
	November 2008	6.20 ± 0.30	5.30 ± 0.20	7.10 ± 0.11	5.20 ± 0.30
	December 2008	6.28 ± 0.12	5.30 ± 0.15	7.18 ± 0.01	5.50 ± 0.15
	January 2009	6.28 ± 0.18	5.40 ± 0.54	7.20 ± 0.41	5.60 ± 0.19
	February 2009	6.35 ± 0.14	5.60 ± 0.33	7.31 ± 0.17	5.80 ± 0.12
	March 2009	6.40 ± 0.15	5.80 ± 0.28	7.40 ± 0.80	5.84 ± 0.16
Organic matter (%)	October 2008	3.06 ± 0.04	3.73 ± 0.14	2.01 ± 0.06	3.50 ± 0.03
	November 2008	2.96 ± 0.32	3.71 ± 0.11	2.11 ± 0.13	3.42 ± 0.14
	December 2008	3.09 ± 0.14	3.83 ± 0.13	2.21 ± 0.05	3.55 ± 0.01
	January 2009	3.14 ± 0.24	3.88 ± 0.14	2.41 ± 0.09	3.58 ± 0.02
	February 2009	3.16 ± 0.01	3.91 ± 0.07	2.50 ± 0.16	3.61 ± 0.03
	March 2009	3.21 ± 0.24	3.93 ± 0.04	2.53 ± 0.06	3.61 ± 0.01

There were generally no significant methane flux emissions between the macrophyte-infested areas ($F = 35.01$; $P = 0.06$), compared with the open water areas during the sampling period (Table 2 and Fig. 2), with a difference of about 1–2% in favour of the macrophyte-infested areas. Further, the swampy wetland had slightly high methane fluxes compared with the riverine wetland, with no significant ($F = 23.42$; $P = 0.08$) variations. The macrophyte-infested areas in the swampy wetland emitted the highest average quantity of methane, being about 21.96 ± 0.04 mg CH_4 m^{-2} day^{-1}, while the open water area emitted 19.35 ± 0.05 mg CH_4 m^{-2} day^{-1}. The vegetated area in the riverine type also exhibited the highest average CH_4 fluxes of about 19.56 ± 0.06 mg CH_4 m^{-2} day^{-1}, compared to the open water areas that emitted about 16.04 ± 0.05 mg CH_4 m^{-2} day^{-1}.

No significant temporal variations were observed for the CH_4 fluxes ($F = 15.37$; $P = 0.07$), or the CH_4 ebullition ($F = 8.28$; $P = 0.06$) (Fig. 2). Notably, the dry period (from January 2009 to March 2009) exhibited slightly higher methane fluxes, compared with the short rainy period during October 2008–December 2008.

A strong, significant positive correlation between temperature (macrophyte site: $r^2 = 0.83$; $P = 0.04$; open water: $r^2 = 0.77$; $P = 0.03$) and dissolved oxygen concentrations (macrophyte site: $r^2 = 0.75$; $P = 0.03$; open water: $r^2 = 0.78$; $P = 0.02$) was found, with methane fluxes (for combined ebullition and diffusion) occurring in both types of wetlands. In addition, a strong, significant positive correlation ($r^2 = 0.73$; $P = 0.04$) was observed between organic matter and methane fluxes (for combined ebullition and diffusion) in the macrophyte-infested areas, although an insignificant positive correlation ($r^2 = 0.63$; $P = 0.06$) was recorded in the open water area.

DISCUSSION

The insignificant ($P > 0.05$) higher quantity of methane in macrophyte areas in the swampy and riverine wetlands could be attributed to the availability of plant litter

Table 2. Monthly methane emissions (mean ± SE mg CH_4 m^{-2} day^{-1}) from a swampy and riverine wetland in both open water and macrophyte-infested areas, October 2008–March 2009

Period	Type	Subtype	CH_4 flux	CH_4 ebullition
Month	Site	Subsite	Mean ± SE	Mean ± SE
October	Swamp	Open water	19.20 ± 0.00	8.4 ± 0.91
2008	Swamp	Macrophyte	21.60 ± 0.00	8.87 ± 1.06
	Riverine	Open water	16.08 ± 0.00	7.32 ± 0.87
	Riverine	Macrophyte	19.68 ± 0.00	8.96 ± 1.06
November	Swamp	Open water	19.61 ± 0.07	8.12 ± 1.10
2008	Swamp	Macrophyte	22.05 ± 0.03	8.27 ± 0.96
	Riverine	Open water	16.11 ± 0.03	6.04 ± 0.69
	Riverine	Macrophyte	19.37 ± 0.07	7.10 ± 0.88
December	Swamp	Open water	19.30 ± 0.10	7.25 ± 0.58
2008	Swamp	Macrophyte	21.81 ± 0.03	8.18 ± 0.64
	Riverine	Open water	16.29 ± 0.03	6.45 ± 0.44
	Riverine	Macrophyte	19.13 ± 0.17	7.58 ± 0.53
January	Swamp	Open water	19.82 ± 0.10	9.51 ± 0.63
2009	Swamp	Macrophyte	21.78 ± 0.12	10.42 ± 0.63
	Riverine	Open water	15.98 ± 0.10	7.91 ± 0.52
	Riverine	Macrophyte	20.16 ± 0.00	10.36 ± 0.56
February	Swamp	Open water	19.16 ± 0.03	9.75 ± 0.66
2009	Swamp	Macrophyte	22.32 ± 0.00	11.36 ± 0.77
	Riverine	Open water	15.50 ± 0.14	7.89 ± 0.56
	Riverine	Macrophyte	19.92 ± 0.00	9.60 ± 0.75
March	Swamp	Open water	19.03 ± 0.07	7.99 ± 0.31
2009	Swamp	Macrophyte	22.29 ± 0.03	9.35 ± 0.33
	Riverine	Open water	16.29 ± 0.03	6.83 ± 0.24
	Riverine	Macrophyte	19.20 ± 0.00	8.51 ± 0.48
All groups			19.25 ± 0.17	8.42 ± 0.17

(organic matter) in both areas that stimulates CH_4 production under extreme anoxic condition (Mingkui *et al.* 1998), and possibly increased methane transport from soil via plants (Heilman & Carlton 2001). Andreae and Schimel (1989) reported that stimulation of CH_4 is because of enhanced fermentative production of CH_4 precursors, which could explain the slightly high methane fluxes in swampy wetlands, compared with the riverine wetlands, which is consistent with our measurements. The litter of swampy wetlands is less affected by water velocity, thereby providing substrate for bacterial action (Mingkui *et al.* 1998). The rate of CH_4 production is limited by the availability of substrate from plant primary production and soil organic matter decomposition, and regulated by climatic and edaphic factors such as temperature and pH (Conrad 1989; Valentine *et al.* 1994; Mingkui *et al.* 1998), as noted in this study, although insignificant pH variations were observed.

There were insignificant seasonal variations in the CH_4 fluxes, although the dry season exhibited high methane fluxes, possibly attributable to changes in temperature and increased accumulation of organic matter (Table 1), thereby exhibiting slightly high methane fluxes during the dry season. The differences in water levels in both the dry and wet seasons were minimal, raising the possibility that increased methane oxidation by methanotrophs could not partly compensate for variation in methane production owing to minimal changes in water table level during both the dry and the wet seasons. The population dynamics of both methanogens and methanotrophs subject to rapid water table fluctuations, however, might also obscure any correspondence between that water table level and net methane emission. Further studies in wetland systems are necessary to investigate this hypothesis. The oversaturation of the relatively insoluble methane (saturation in freshwater is about 1.6 mmol L^{-1} at 20°C; Yamamoto *et al.* 1976), followed by the formation of so-called gas bags in the sediment, might have been the prerequisite for ebullition losses to the atmosphere (Casper *et al.* 2000b). The static chamber method was employed in this study to counter wind-induced fluctuations. Mays *et al.* (2009) recorded large variability in the measured day-to-day CH_4 emissions fluxes, as well as in the relative CH_4 and CO_2 fluxes, being attributed to the use of aircraft-based measurements of methane fluxes. Mays *et al.* (2009) used long horizontal transects flown perpendicular to the wind downwind of the city, in which methane emissions were calculated using the wind speed and the difference between the concentration in the plume and the background concentration.

The values for the rates of CH_4 emissions predicted by this study from wetlands were below the range reported from wetland field experiments in the tropics (e.g. Bartlett & Harriss 1993) or temperate regions (e.g. Andreae & Schimel 1989; Devol *et al.* 1990; Fontan *et al.* 1992), a scenario that could be attributed to the wetland surface that was consistently better drained, perhaps because of higher soil permeability and its proximity to the outlet (Indian ocean). It also could be attributed to the use of small-height chambers that would not permit the inclusion of all tall plants (which accounted for about 15% of the entire plant community in the wetland), which are an important conduit for methane from many wetland soils (Yamamoto *et al.* 1976; Casper *et al.* 2000b; Le Mer & Roger 2001). Nevertheless, the overall results from a series of wetlands within the Kenyan coastal

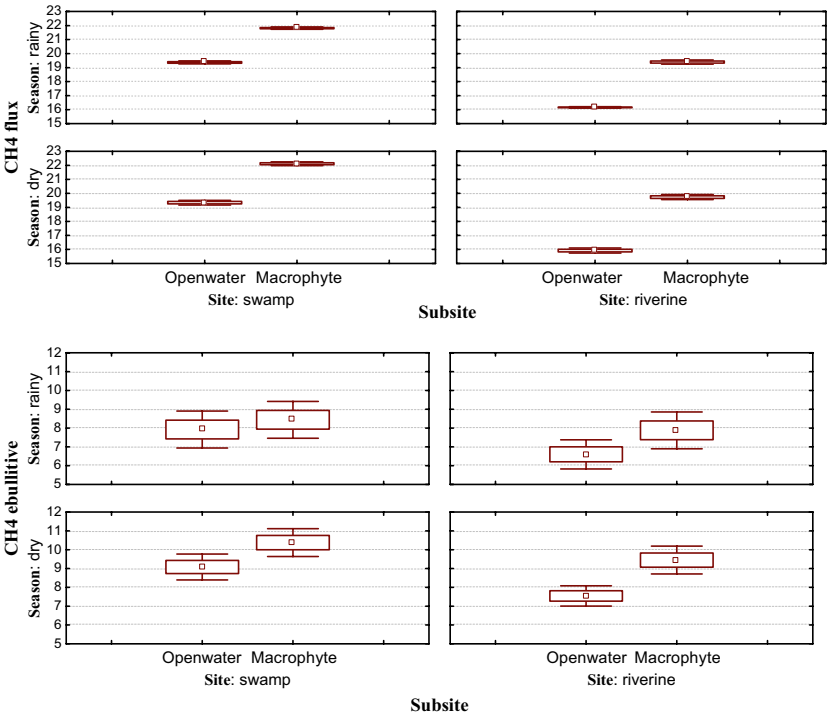

Fig. 2. Methane emissions as CH_4 fluxes and ebullitive emissions (mean ± SE mg CH_4 m^{-2} day^{-1}) from a swampy and riverine wetland in both open water and macrophyte-infested areas, based on the short rainy season (October–December 2008) and dry season (January 2009–March 2009).

region for methane measurements was hampered by financial limitations, although it could have provided the total estimates for the entire region. Considering the average emissions from the swamp and riverine wetlands by conducting this study in other parts of the coast region would allow estimation of regional methane fluxes. Similar measurements using eddy correlation methods in regional-scale investigations in the region suggest values in the range of 10–50 mg CH_4 m^{-2} day^{-1} (Ritter *et al.* 1991; Fan *et al.* 1992), which are within the ranges of this study.

In conclusion, methane gas emission from wetlands could be a function of the structure of the ecosystem, microbial communities within them (methanogenic bacteria), and the availability of organic substrates and electron acceptors. The emissions in this study were controlled primarily by temperature, based on the wetland type in both water and sediments, and the slight differences could have been influenced by organic matter, dissolved oxygen concentration and seasonal effect. These variables require further detailed study, however, to ascertain the level of their influence on the wetland sites. Despite a lack of significant interactions, macrophyte-infested sites emitted slightly high methane fluxes (difference of 1–2%), compared with the open water areas. Furthermore, there is a need for more research and extensive study to improve estimates of CH_4 emissions from all wetland types and predict their responses to climate change and to elucidate the role of tidal changes not investigated in this study, especially in the developing countries. This would facilitate our bridging the knowledge gaps on the precise methane fluxes in all the tropical wetland ecological niches of the world.

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