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Seasonal dynamics of methane emission from wetlands

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Importance of this paper: In spite of its lower concentration (1.7 ppm) in the atmosphere, methane, because of its high impact on climate change, has assumed more importance in recent years due to its ever increasing concentration. Although there are many known sources of methane emission, but natural wetlands are the major contributor to global methane budget. In this study, we tried to find out the seasonal fluctuations in methane fluxes as well as the difference in the methane efflux from the vegetated and unvegetated surfaces of natural and man-made water bodies. It was observed that methane emission was maximum in the summer season, followed by rainy season and the least in the winter season. Many fold more methane efflux from vegetated surface as compared to unvegetated surface of the same wetland underlines the importance of vegetation in methane transport from the rhizosphere to troposphere. It was also noticed that methane efflux from wetland is modulated by a number of edaphic and environmental factors.

Abstract

In view of its impact on the earth's climate, methane despite its low atmospheric concentration, has assumed importance in recent years. Natural wetlands are one of the major sources for methane emission to the atmosphere. This study was carried out to find out the seasonal fluctuation in CH_4 fluxes from water bodies and the difference in the methane efflux from vegetated and unvegetated surfaces of natural and man-made water bodies as well as to investigate the edaphic factors controlling the methane production and emission. The results revealed that there were seasonal fluctuations in methane emission from both the natural and man-made water bodies. Evidently, CH_4 emission from the vegetated surface was many times higher than that from the unvegetated surface of the same water body, indicating the importance of vegetation in methane transport from sediments to atmosphere. Study of several edaphic factors like pH, redox potential, temperature and organic carbon of 10 water bodies, including 5 man-made ponds showed that all these factors largely determined CH_4 production in the sediment as reflected by its emission from water bodies.

Keywords: Wetlands; Methane efflux; Methanogenesis; Aquatic plants; Edaphic factors

1. Introduction

Of all the greenhouse gases present in the atmosphere, methane has assumed considerable significance in recent years due to its impact on the earth's climate and stratospheric ozone chemistry (Jugsujinda et al., 1996). Its tropospheric mixing ratio is at present 1.7 ppmv which has already more than doubled from the pre-industrial concentration of 0.7 ppm within a period of 200 yr (Rasmussen and Khalil, 1984; Pearman et al., 1986). Over the last two decades, its concentration in the troposphere is reportedly increasing at the rate of 1.1% per year which is of serious concern and hence has stimulated more research on the production and transport of methane from wetlands (Blake and Rowland, 1988).

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Natural wetlands constitute one of the major sources of methane emission, releasing between 100 and 200 Tg/yr to the atmosphere (Cicerone and Oremland, 1988; Fung et al., 1991; IPCC, 1992; Lelieveld and Crutzen, 1993). Together with paddy fields, wetlands contribute over 40% of the global CH_4 emission to the atmosphere. In the anoxic sediments of wetlands, methanogenesis occurs in the presence of high level of labile organic material in the absence of alternative inorganic electron acceptors like sulphate (Martens and Berner, 1974).

Plants growing in the wetlands influence both CH_4 production and flux by providing substrates for methanogenesis in the form of root exudates and litter and also by serving as conduit for CH_4 transport from the sediment to the troposphere (Holzapfel-Pschorn and Seiler, 1986; Schutz et al., 1989a, b). Emergent macrophytes in the process of bringing down atmospheric O_2 to their submerged roots generate oxic environment in the sediments which is responsible for CH_4 oxidation by methanotrophs (Holzapfel-Pschorn et al., 1985). Unvegetated sediments are often characterized by large volume of gas bubbles which contain 50–90% methane (Chanton et al., 1989a; Martens and Chanton, 1989). These bubbles are formed because the production of methane tends to raise the sum of the partial pressures of the dissolved gases above the hydrostatic pressure in the sediment.

As the methane production and oxidation in the flooded sediments are the microbiological processes, controlled by several biological, chemical and physical factors (Parashar et al., 1991; Wang et al., 1993a, b; Minami and Neue, 1994; Ramakishanan et al., 1995; Boeckx and Cleemput, 1996), a systematic study was undertaken to measure CH_4 flux from the vegetated and unvegetated surfaces of ten water bodies (natural and man-made) and to investigate the edaphic factors influencing CH_4 efflux.

2. Materials and methods

2.1. Sites

This study was carried out at National Botanical Research Institute, Lucknow, situated in north India (26°45′N; 80°51′E). This region is characterized by three distinct seasons, i.e., winter (October–January), summer (February–May) and rainy (June–September). In the year 1997, the temperature ranged between 10.2°C and 30.6°C in the winter season, between 14.5°C and 44.8°C in the summer season and between 22.7°C and 36.1°C in the rainy season. The average annual relative humidity was recorded 63% and the annual precipitation 970 mm.

Ten water bodies were selected for the CH_4 flux measurement in different seasons, namely Nawabganj lake, Suraj kund, Budha park pond, Motijhil, Bakshi ka Talab, Chinhat lake, NBRI pond, Gomti river, Hussainabad tank and Butler palace pond, out of which five were natural wetlands and remaining were man-made. All these sites were located in Lucknow city and its adjoining areas and were designated as S1, S2, S3, S4, S5, S6, S7, S8, S9 and S10, respectively, in the above sequence for convenience. While a detailed account of types of water bodies, annual range of water level, flowing conditions, vegetation type and its density has been given in Table 1, a seasonal floristic compo-

Table 1
Wetland characteristics

Sites	Water bodies	Type of water bodies	Flowing/stagnant water	Annual range of water level (m)	Vegetation type[a]	Vegetation density
S1	Nawab Ganj Lake	Natural	Stagnant	0.3–1	EM, RS, FF	Sparse (throughout)
S2	Suraj Kund	Man-made	Stagnant	3–4	FF	Sparse
S3	Buddha Park Pond	Man-made	Stagnant	2–2.5	UN	Rare
S4	Motijhil	Natural	Stagnant	2–3	RS, EM	Dense (littoral zone)
S5	Bakshi Ka Talab	Man-made	Stagnant	0–2	FF, EM	Dense (fully covered zone)
S6	Chinhat Lake	Natural	Stagnant	2–3	FF, EM	Sparse
S7	NBRI Pond	Man-made	Stagnant	3–4.5	FF	Sparse
S8	Gomti River	Natural	Flowing	4–6	RS	Dense (littoral zone)
S9	Hussainabad Tank	Man-made	Stagnant	3–4	FF	Dense (fully covered zone)
S10	Butler Palace Pond	Natural	Stagnant	2–3	FF, EM	Dense

[a] EM – emergent; SR – rooted in sediment; FF – free floating; UN – unvegetated.

Table 2
Floristic composition (mainly higher aquatic plants) of natural and man-made water bodies and percentage vegetation cover in different seasons

Sites	Winter season (October–January)	Summer season (February–May)	Rainy season (June–September)	Vegetation cover (%)
Nawabganj Lake	1,3,4,5,7,8,9,12,14, 15,16	7,8,11,16,20 (water available only in pockets)	4,5,6,7,8,9,14,16, 20,21	40–50
Suraj Kund	1,5,8,16	1,8,16,21	8,16,21	10–50
Buddha Park Pond	5,8	Fresh water added	5,12,21	5–10
Motijhil	2,4,6,7,16	4,6,7,16	6,7,16	30–50
Bakshi Ka Talab	1,3,8	Dried	20,21	60–100
Chinhat Lake	1,3,6,7,13,16,18	4,6,7,20	6,7,10,18,20	20–30
NBRI Garden Pond	11,12,20	5,11,12	11,12	50–60
Gomti River	2,4,6,8,10,17	4,6,7,10,20,17	6,7,10,17	10–30
Hussainabad Tank	7,8,16	7,8,16	5,11,20	70–100
Butler Palace Pond	4,7,8,16	4,8,16,20	4,8,16,20	40–100

1. *Azolla pinnata*, 2. *Bacopa monnieri*, 3. *Ceratophyllum demersum*, 4. *Eichhornia crassipes*, 5. *Hydrilla verticillata*, 6. *Ipomoea aquatica*, 7. *Jussieua repens*, 8. *Lemna minor*, 9. *Limnanthemum cristatum*, 10. *Marselia minuta*, 11. *Nelumbo nucifera*, 12. *Nymphaea alba*, 13. *Pistia stratiotes*, 14. *Potamogeton pectinatus*, 15. *Schoenoplectus subalatus*, 16. *Spirodela polyrrhiza*, 17. *Typha latifolia*, 18. *Trapa natans*, 19. *Vallisneria spiralis*, 20. *Zannichellia palustris*, 21. Algal mats.

sition, mainly of higher aquatic plants and the percent vegetation cover in different wetlands are presented in Table 2.

2.2. Methane flux measurement

To measure CH_4 emission from the water surface, a floating device was used which was made up of a steel cylinder. Around the rim of the cylinder, a rubber tube was fixed, which on being inflated, keeps the device floating on the water surface. A battery operated pump with the capacity 1.5 l/min was fixed atop to circulate the air inside the cylinder. At the intervals of 0, 15 and 30 min, the air samples were collected in the sampling tubes and brought to the laboratory for analysis on a Gas Chromatograph (14B Shimadzu, Japan), using FID detector and molecular sieve column (5 Å). The operating conditions were column temp. 90°C, detector temp. 120°C and injection temp. 120°C. Methane peak was detected at retention time 3.6 min at 0 attenuation. Methane flux was measured from both vegetated and unvegetated surfaces thrice in a season and values were averaged to determine methane efflux in a season. The measurement of methane fluxes from the different wetlands was carried out throughout the year in 1997 in all the three seasons, i.e., winter, summer and rainy.

As regard the edaphic factors, organic C was determined following Wakley and Black method (Piper, 1966), while soil pH and redox potential were measured with an pH/Eh meter (Orion, model 290 A, USA), following the standard techniques as outlined by Piper (1966). The soil temperature was measured at the depth 0.5 cm at the time of flux measurement.

3. Results

The investigation on methane efflux from water bodies revealed that the methane emission rate was many times higher in the natural wetlands than in man-made ones. Out of 10 water bodies, the highest emitter of CH_4 (67.72 mg/m^2/h) was Gomti (site S8) – a natural water body and the lowest emitter (1.53 mg/m^2/h) was Hussainabad tank (site S9) – a man-made pond. While the CH_4 efflux ranged between 7.3 and 67.72 mg/m^2/h from vegetated surface in natural wetlands, it varied between 1.53 and 3.07 mg/m^2/h in man-made water bodies (Fig. 1). However, from the unvegetated surface, the CH_4 emission was drastically reduced in both natural and man-made water bodies as compared to vegetated surface. In summer season, the CH_4 efflux was reduced from 67.72 mg/m^2/h from the vegetated surface to 3.84 mg/m^2/h from the unvegetated surface at site S8, from 45.48 to 1.87 mg/ m^2/h at S4 and from 9.2 to 0.48 mg/m^2/h at S6 (Fig. 2). This indicated the importance of the vegetation in the CH_4 transport from the sediment to troposphere.

Measurement of CH_4 flux in different seasons indicated that there was seasonal dynamics in CH_4 emission from water bodies. Except at sites S2, S4 and S9, where minimum CH_4 efflux was recorded in the rainy season, the CH_4 emission was maximum in summer season and minimum in winter season in all water bodies. At the site S8, in comparison to other sites, CH_4 flux was maximum in all three seasons, the emission rate being maximum of 67.72 mg/ m^2/h in summer season, followed by rainy season (28.83 mg/m^2/h) and least (14.92 mg/m^2/h) in the winter season from the vegetated surface (Fig. 1). In a man-made tank at site S3, the CH_4 emission rate was

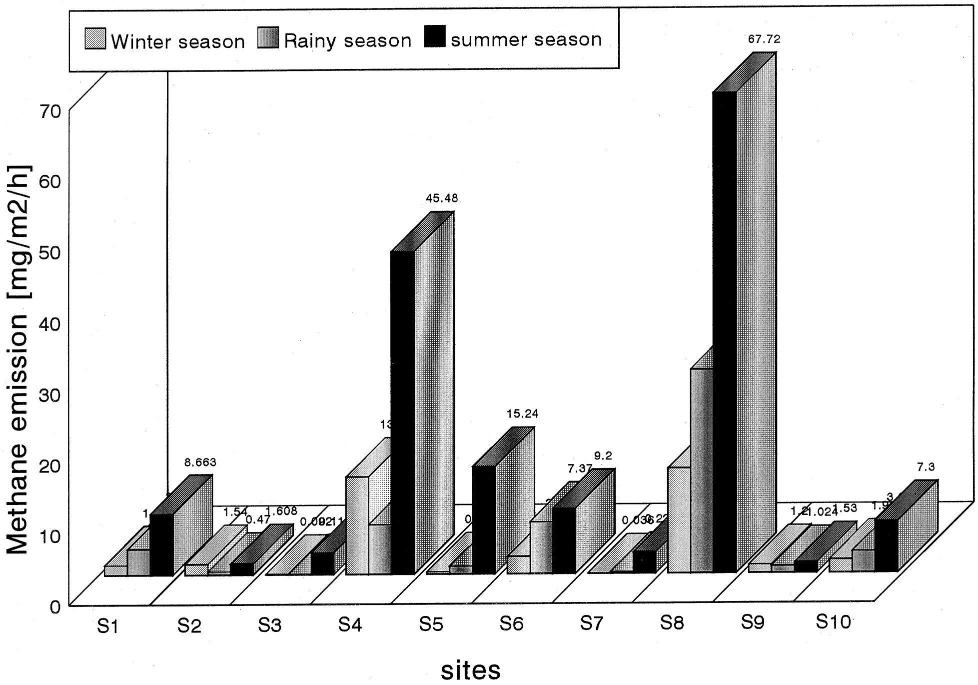

Fig. 1. Methane efflux from the vegetated surface of different water bodies (mean of three measurements).

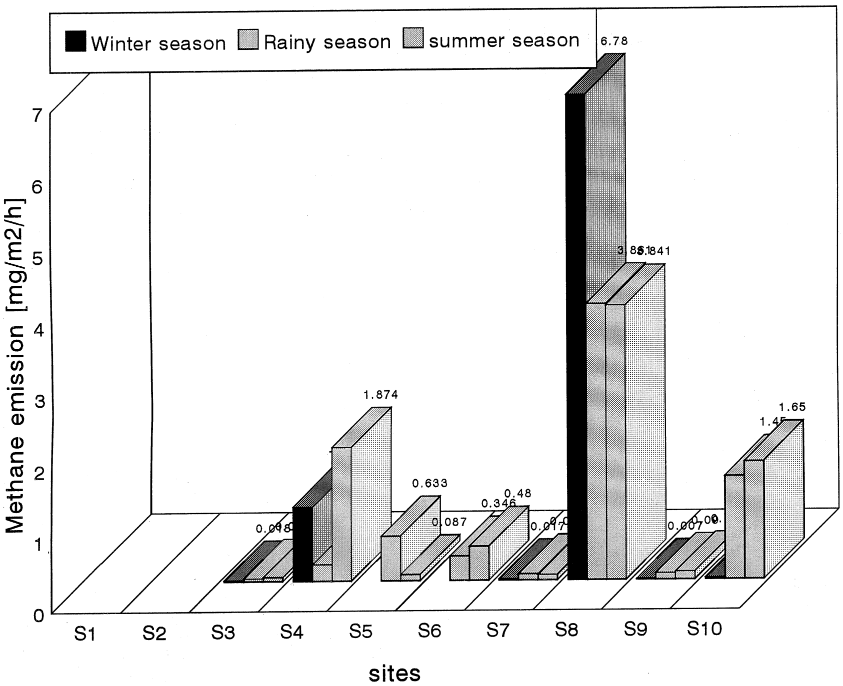

Fig. 2. Methane emission from the unvegetated surface of different water bodies (mean of three measurements).

recorded 3.07 mg/m^2/h in the summer season, 0.11 mg/m^2/h in the rainy season and 0.09 mg/m^2/h in the winter season.

Production of methane in the sediment of water bodies is regulated by several edaphic factors among which, soil pH, organic carbon, redox potential and

Table 3
Seasonal changes in redox potential (Eh) and pH of the sediments of different sites

Sites	Summer season		Rainy season		Winter season	
	Eh (mV)	pH	Eh (mV)	pH	Eh (mV)	pH
S1	−59.50	7.43 ± 0.04	−70.60	7.50 ± 0.02	−237.0	7.73 ± 0.03
	7.28		1.75		5.93	
S2	NA[a]	7.33 ± 0.03	NA	7.97 ± 0.32	NA	8.23 ± 0.02
S3	NA	7.67 ± 0.02	NA	7.85 ± 0.56	NA	7.97 ± 0.01
S4	−192.4	7.35 ± 0.05	−167.3	8.03 ± 0.01	−90.70	7.46 ± 0.01
	7.79		3.40		6.04	
S5	−173.1	6.97 ± 0.04	−147.8	7.37 ± 0.02	−117.6	7.55 ± 0.09
	4.39		5.54		3.30	
S6	−174.9	6.49 ± 0.03	−223.9	7.04 ± 0.02	−66.00	6.86 ± 0.03
	7.87		8.70		7.05	
S7	NA	7.99 ± 0.06	NA	8.54 ± 0.08	NA	8.68 ± 0.03
S8	−147.0	7.13 ± 0.02	−200.3	7.74 ± 0.05	−206.7	7.88 ± 0.04
	5.56		2.23		7.37	
S9	NA	7.07 ± 0.04	NA	7.64 ± 0.04	NA	8.54 ± 0.04
S10	−239.6	6.97 ± 0.03	−209.7	7.27 ± 0.03	−169.8	7.49 ± 0.11
	3.81		6.05		3.26	

[a] NA = not available.

temperature are the most important. It is evident from the Table 3 that there was no specific pattern of sediment reduction with the season. Among the natural water bodies, the sediment was most reduced with a redox potential value of −240 mv at site S10 in the summer season and the least reduced is the sediment of site S6 with a value −66 mv in the winter season. Like wise, the sediments of sites S4, S5 and S10 were also −maximally reduced in the summer season and least in the winter season, while those of S6 and S8 were most reduced in the rainy season and least in the winter. However, the redox potential of the sediments of all man-made water bodies could not be measured in vivo as the sediments were deep seated, beyond our reach.

As regards the soil pH, it was observed that soil pH of most of the water bodies remained neutral with slight variations on either side in the different seasons, varying between 6.5 and 7.5 (Table 3). However, the soil pH of 3 man-made water bodies namely S2, S7 and S9 were recorded alkaline in the winter season with values 8.23, 8.67 and 8.54, respectively. Only at site S7, the soil pH was recorded alkaline in all the seasons with values ranging between 7.99 and 8.67.

Not much variation with season in soil pH clearly indicates that pH is a stable chemical characteristic which does not get changed with the season. However, redox potential (Eh) of the sediment varied widely from a minimum of −239.6 (site 10) to a maximum of −59.50 (site 1) as shown in Table 3. A wide variation in the sediment Eh in different seasons shows a correlation with the water regime and the sediment temperature which changes with the season.

The soil organic carbon differed significantly in the different water bodies. While it was highest at the site S8 (0.95%), the lowest was recorded at S3 (0.3%) in the summer season (Table 4). There was no specific trend of variation in organic carbon in relation to different seasons. However, it was clear that the organic carbon contents of the sediments of natural wetlands were higher than the man-made water bodies. Out of 10 water bodies, 5 recorded maximum organic carbon in the summer season, 2 in the rainy season and the remaining 3 in the winter season. The sediment temperature was recorded maximum in the summer season and minimum in the winter season in all the water bodies (Table 4). In the summer season, the sediment temperature ranged between 35°C and 38°C, in the rainy season, between 29°C and 34°C and in the winter season, between 15°C and 19°C.

4. Discussion

Among 10 water bodies studied, the highest CH_4 emission rate was recorded in Gomti river (site S8) in all three seasons and the lowest in Hussainabad tank (site S9). The reasons for wide differences in CH_4 efflux between these two water bodies are many. Firstly, the site S8 is the natural wetland while S9 is the man-made pond with the cemented bottom. As a result, sediment of S9 was very limited to host methanogenic bacteria responsible for CH_4 production. On the other hand, the bed of the S8 had enough sediment and remained inundated in all the seasons to be in the reduced state to favour methanogenesis process. Secondly, organic wastes in the form of sewage and industrial effluents are discharged daily at several points in the Gomti river which might serve as substrates for methanogenic bac-

Table 4
Seasonal variations in organic carbon (O.C.) and temperature of the sediments of different sites

Sites	Summer season		Rainy season		Winter season	
	O.C. (%)	Temperature	O.C. (%)	Temperature	O.C. (%)	Temperature
S1	0.59	37 ± 0.14	0.50	34 ± 0.31	0.54	15 ± 0.33
	0.03		0.03		0.01	
S2	0.45	35 ± 0.16	0.54	32 ± 0.29	0.51	18 ± 0.28
	0.03		0.04		0.01	
S3	0.30	36 ± 0.10	0.39	30 ± 0.17	0.38	18 ± 0.41
	0.02		0.01		0.03	
S4	0.69	35 ± 0.21	0.48	29 ± 0.35	0.83	16 ± 0.26
	0.04		0.03		0.02	
S5	0.89	38 ± 0.15	0.84	32 ± 0.41	0.55	19 ± 0.19
	0.03		0.02		0.02	
S6	0.90	35 ± 0.23	0.82	33 ± 0.24	0.83	17 ± 0.18
	0.02		0.03		0.04	
S7	0.36	36 ± 0.19	0.24	30 ± 0.19	0.35	19 ± 0.18
	0.03		0.03		0.02	
S8	0.95	38 ± 0.25	0.86	33 ± 0.23	0.75	18 ± 0.31
	0.04		0.01		0.01	
S9	0.50	35 ± 0.41	0.52	32 ± 0.17	0.64	18 ± 0.34
	0.03		0.02		0.02	
S10	0.52	37 ± 0.36	0.56	30 ± 0.22	0.79	16 ± 0.19
	0.02		0.01		0.03	

teria in the process of fermentive decomposition. Thirdly, many higher aquatic plants like, *Bacopa monnieri* L., *Eichhornia crassipes* Mart., *Jussieua repens* L., *Zannichellia palustris* L., etc., were growing profusely in the river water which helped in the CH_4 transport from the sediment to troposphere. However, the site S9 had only floating plants such as, *Spirodela polyrrhiza* L. and *Lemna minor* L. which might not effectively transport CH_4 as did the rooted macrophytes.

Among the natural wetlands, next to Gomti river was the Motijhil (site S4) in methane emission. Like Gomti river, Motijhil is a rain fed lake but used to receive municipal and industrial waste round the year. As the result, it never dried up and kept the sediment in the reduced state to favour methanogenesis. Besides it had plants like *Bacopa monnieri, Eichhornia crassipes*, *Ipomoea aquatica* and *Jussieua repens* growing in the littoral region which helped in the methane transport. Although, Nawabganj lake (site S1) is also a natural wetland and had many aquatic plants, but still the CH_4 emission rate was very low as compared to other water bodies. The reason for low emission might be the lower water depth and the intermittent drying up of the lake which drastically reduced the methane formation in the oxic conditions. The same was the case with Chinhat lake (site S6) and Butler Palace Pond (Site S10). Both of them are the natural wetlands but did not produce much methane. Besides, vegetation in these water bodies was mainly free floating which transports less methane to the atmosphere than the sediment rooted plants (Table 2). All the man-made ponds either had clear water or usually dried up in the summer season or had floating aquatic flora like *Lemna minor* and *Spirodela polyrrhiza* which lack connection with the sediment and so transport less CH_4 to the troposphere.

A wide difference in the methane efflux from the vegetated and unvegetated surface of the water bodies clearly indicates that the vegetation had an important role in the CH_4 transport from the sediment to the rhizosphere. Moreover, sediment-rooted aquatic plants have well developed aerenchyma to serve as conduit pipe for the supply of atmospheric O_2 from upward to downward as well as for CH_4 transportation from downward to upward (Neue and Sass, 1994). Aquatic plants not only transport methane through aerenchyma to the atmosphere, but also influence the CH_4 fluxes; firstly, by providing root exudates or root autolysis products to the anaerobic food chain and ultimately to methanogenic bacteria for CH_4 production. Secondly, through the O_2 transport to the rhizosphere, they provide oxic environment for the consumption of CH_4 (Rovira and Davey, 1974; Holzapfel-Pschorn et al., 1985).

In the unvegetated areas, methane is transported to the atmosphere from the sediments mainly through two processes: molecular diffusion across the sediment–water interface and bubble ebullition. These processes account for the low fluxes of methane from the unvegetated surface of the same water bodies (Chanton et al., 1989a; Kelley et al., 1990). Seasonal fluctuation in CH_4 emission from water bodies might be the function of various edaphic factors like soil type, moisture regime, temperature, organic carbon, pH, redox potential and the sulphate and nitrate levels (Wang et al., 1993a, b; Minami and Neue, 1994; Ramakishanan et al., 1995).

With regard to seasonal changes in the methane emission from the wetlands, it was apparent that maximum CH_4 efflux was recorded in the summer season, followed by rainy season and the least in the winter season in most of the water bodies, indicating that CH_4 production is mainly a temperature dependent process. In this study, the Q10 value was found to be 3, based on the temperature difference between the summer and the winter season. This value is very close to Q10 values of 2.5–3.5 for CH_4 production reported by Conrad (1989) and 3 by Khalil et al. (1991).

Soil pH is an important factor affecting the methane production in the sediment of water bodies, because methanogenic bacteria are pH-sensitive and grow at a relatively narrow pH range of 6–8. However, acidophilic strains have been reported from acidic peat bogs and alkaliphilic species from alkaline regions with optimum growth at pH 8–9 (Williams and Crawford, 1984; Worakit et al., 1986). In this study, the soil pH ranged between 6.5 and 8.6 in different water bodies in different seasons. Hence, the soil was thought to be favourable for the optimum growth of methanogenic bacteria. It is, therefore, suggested that soil pH did not affect CH_4 production and hence might not be responsible for low or high fluxes of CH_4 from different water bodies.

Methane is the end product of anaerobic decomposition of organic matter in the soil. Therefore, an exogenous supply of organic C had direct bearing on CH_4 production in the waterlogged soils (Yagi and Minami, 1991). Methane production rates have been reported to be linearly correlated with water soluble carbon in the soil or with readily mineralizable carbon in both field and laboratory conditions (Jugsjinda et al., 1998; Yagi and Minami, 1990; Van Cleemput et al., 1991). In this study also, it was observed that higher was the organic carbon content in the sediment, the higher was the methane efflux from water bodies. In the natural wetlands, the organic C content was higher than in the man-made ponds in all the three seasons which might have stimulated CH_4 production in the soils. However, site S6 which had 0.90% organic carbon in the soil did not show more CH_4 efflux as compared to S4 containing only 0.69% organic C. This clearly indicates that not only the organic C but also the composition of organic matter determines the rate of CH_4 production (Yagi and Minami, 1991). A fair relationship between organic carbon and methane efflux was found in this study.

Redox potential is a measure of oxidation–reduction status of the soil. Wetlands are characterized by the lack of sufficient oxygen in the soil atmosphere to act as the sole electron acceptor for microbial, plant and animal respiration (Reddy and Patrick, 1984). A redox potential of -150 mv was reported to be essential for the action of methanogenic bacteria for CH_4 production (Connel and Patrick, 1969). It was observed in this study that the redox potential of the sediment was reduced below 150 mV to favour methanogenesis in the natural wetlands which might have resulted in higher fluxes of methane.

Soil temperature had a positive relationship with CH_4 production as reported by Seiler et al. (1984). However, in the field studies, the positive correlation between soil temperature and CH_4 emission was not always observed because of several other limiting factors. In this study, CH_4 efflux was maximum in the summer season, followed by rainy season and least in the winter season, in most water bodies, showing a positive correlation between soil temperature and methane efflux.

It may be concluded from the above observations that there are several edaphic factors like soil pH, organic carbon, redox potential and temperature which largely determine the CH_4 production and emission. However, in the field studies, it becomes difficult to find a correlation between CH_4 emission and one of the edaphic characters because of many other limiting factors. Since a major amount of CH_4 produced in the sediment is transported through the aquatic plants, its emission does not entirely depend on the rate of production but on the presence of vegetation also, as it was observed that CH_4 efflux from the vegetated surface was many times more than that from the unvegetated surface of the same wetland.

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