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Seasonal Estimates of Methane Emissions from Natural Wetlands in Nakhon Ratchasima, Thailand **

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ABSTRACT

Seasonal methane emissions from natural wetlands in Nakhon Ratchasima province were estimated based on 12-month field works obtained from the actual methane flux measurements at a natural wetland. Methane gas was measured monthly with a static closed chamber technique and later analyzed by a gas chromatography equipped with a flame ionization detector (GC-FID). Results showed that methane fluxes varied widely in the range of 1.9-22.7 mg $m^{-2}day^{-1}$ with the median ± SD of 10.1 ± 5.4 mg $m^{-2}day^{-1}$. Seasonally, the methane fluxes during wet season ranged from 5.2 to 22.7 mg $m^{-2}day^{-1}$ with the median ± SD of 14.1 ± 5.0 mg $m^{-2}day^{-1}$ while the methane fluxes during dry season were between 1.9 and 21.9 mg $m^{-2}day^{-1}$ with the median ± SD of 8.8 ± 5.2 mg $m^{-2}day^{-1}$ .The estimate methane fluxes of the wetland in wet and dry seasons were 1.5-3.1 kg m^{-2} and 0.7-2.9 kg m^{-2}, respectively. The estimated methane emission factor from the natural wetland in the province was 1.7 to 5.7 kg $m^{-2}year^{-1}$ compared to the default methane emission factor from IPCC, 0.0136 kg $m^{-2}year^{-1}$ .When considering global warming potential (GWP) of methane based on 100-year time horizon, the natural wetlands in the province may emit about 15.48 to 52.16 million ton CO_2equivalent a year based on the emission factor derived locally. With the IPCC default emission factor, the methane emission was as low as 0.03 to 0.22 million ton CO_2equivalent a year.

1. INTRODUCTION

Greenhous gases (GHGs) in the atmosphere play key roles on the Earth's climatic systems—without them the Earth's surface temperature could be -18°C [1]–[3]. Three main GHGs are of concern; carbon dioxide, methane, and nitrous oxide, which are emitted in different proportion from various sources.

Methane emissions from natural wetlands have an important role as source and sink of carbon [4]. Regardless of carbon dioxide, methane gas is very important for enhancing the greenhouse effects because it has the global warming potential (GWP) of 28 times with 100-year time horizon [5]. This gas is biologically produced from methanogenesis by methanogenic bacteria in anaerobic [6] or even aerobic environment [7].

Methane emissions from wetlands vary temporally and spatially. Many factors influence the variations, such as, pH (Wang *et al.*, 2009), temperature [9], water table level [10], soil texture [11], salinity [12], [13], organic carbon content [14], and climatic conditions [15]. Several studies showed inconsistent relationship of these factors with methane emissions. Recent report indicated the rising of methane in the atmosphere by 150 percent, from 722 ppb in 1750 to 1,874 ppb in 2020 [16].

To reasonably estimate local methane emission, data on the methane emission factor in the area are essential. The locally specific emission factor undoubtedly gives better emission estimation than some value taken from literatures elsewhere. Lack of site-specific methane emission factor is often substitute by the default emission factor from literatures or international organizations, such as Intergovernmental Panel on Climate Change (IPCC)[17]. In Thailand, previous studies focused on methane emission from rice cultivation [18] and constructed wetlands [19], [20]; only two studies focused on natural wetlands [18], [21]. The latest "Thailand's 2nd National Communication" excluded the GHGs emissions from natural sources [22], possibly from limited data on methane emissions from the natural wetlands in Thailand. Thus, this paper aims to examine the methane emissions based on field measurements in Nakhon Ratchasima province and compare the annual methane emissions calculating from recently developed emissions factor and the default emission factor compiled by IPCC.

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2. METHODS

2.1 Study Area

A natural wetland, named Baan San Kumphaeng reservoir, is located downhill from the Phanom Dong Rak's mountain range in Wang Numkheaw district, Nakhon Ratchasima province (14°23'18" N 101°42'30" E), shown in Figure 1. The small dike had been built, creating a reservoir to ease drought in the area. Soil texture is sandy and contains small pebbles. Lam Prapleng stream discharges water into the reservoir year-round. The stream flow is almost stagnant during dry season with no natural discharge. Average annual rainfall is 1,136 mm. The area of the wetland is about 1.6 km^2. Biologically, the dominant plant species includes water lettuce (*Pistia stratiotes*), cattail (*Typha latifolia*), common frogbit (*Hydrocharis morsus-ranae*), swamp cabbge (*Ipomoea aquatica)*, sunrose willow (*ludwigia adscendens*), and water chestnut (*Eleocharis dulcis*). In wet season, the wetland's edge is dominated by wedelia (*Sphagneticola trilobata*), grass (*Phalaris arundinacea*), and weeds (*e.g. Heliopsis helianthoides*).

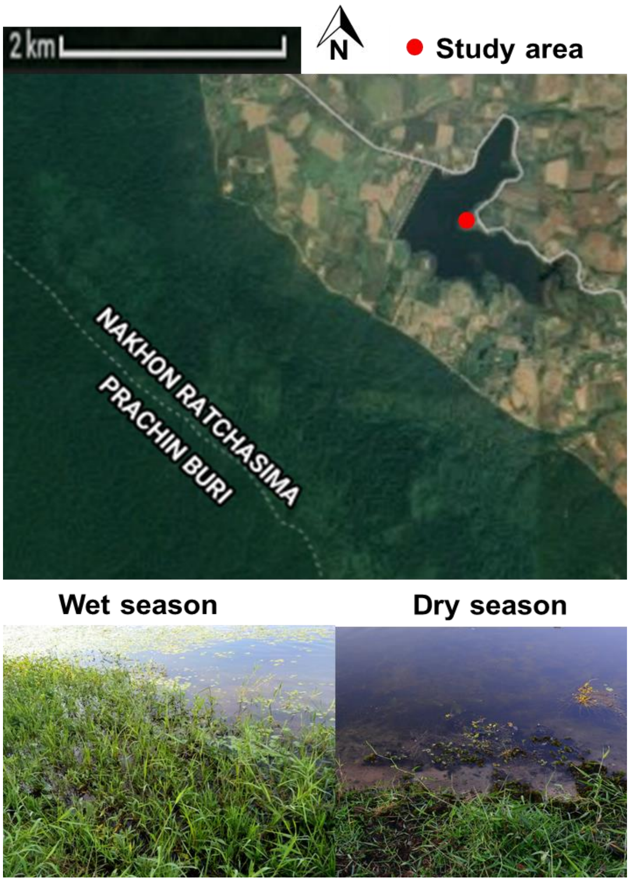

Fig. 1. Study area and appearance during wet and dry seasons.

2.2 Methane Flux Measurements

A static closed rectangular chamber was used for collecting evolved methane gas [23]. The chamber was made from clear acrylics with a dimension of 0.25 m x 0.25 m x 1.20 m (width x length x height). A thermometer was attached inside the chamber to determine the temperature and a small fan was installed to provide uniform mixing of gases in the chamber [24]. A rectangular base was made of aluminum with groove to allow the acrylic chamber fitting inside. A chamber base was firmly inserted in the soil at 0.05 m depth. After two hours, the acrylic chamber was placed in the groove of the aluminum base and water was filled in the groove to prevent any leak. Five replicated chambers were used for methane gas sampling. The gas sampling intervals began at 2, 22, 42, 62, and 82 minutes between 8.30 and 11.00 AM. Gas collection was carried out once a month during December 2018 and November 2019.

Plastic syringes were used to draw the gas from the chambers and transferred into the evacuated glass vials. The vials contained gas samples were kept and stored under 4°C until they were analyzed in our laboratory.

A gas chromatography (Agilent®, Model 7890A, USA), equipped with a flame ionization detector and a stainless steel packed column, was used for quantifying the methane concentrations against the certified 19.5 ppmv standard methane gas (Air Liquid Co. Ltd., Thailand) under the optimum conditions of the GC-FID.

2.3 Methane Flux Determinations

Methane emission rates were calculated based on a linear change of gas concentrations over time, converted to flux rate (mg $m^{-2}day^{-1}$), and corrected for the chamber temperatures [25]. Gas flux rate (mg $m^{-2}day^{-1}$) was calculated by the following Equation (1) at standard temperature and pressure (STP) conditions [19].

$$E = XhM(1440)/RT \tag{1}$$

Where E = emission on the aerial basis (mg $m^{-2}day^{-1}$), X= rate of change in gas concentration (ppmv/min), h= chamber height (m), M = molecular weight of the methane gas (g/mol), 1441 = conversion factor for emission per day, R = universal gas constant (0.0821 atm.L.$K^{-1}mol^{-1}$), and T = absolute temperature (K).

2.4 The Annual Methane Emissions from Natural Wetlands in Nakhon Ratchasima

The methane emissions from natural wetlands in the province were estimated based on Equation (2) [5]:

$$E_m = \Sigma A_w \times EF_w \tag{2}$$

Where E_m = annual methane emission, A_w = total area of wetland, and EF_w = emission factor of wetland.

2.5 Statistical Analysis

Statistical analysis was performed using R with packs "base" and "ggplot2" and Microsoft Excel® for Windows®. Data were tested for normal distribution by Shapiro-Wilk's Test. If the data were normally distributed, one samples t-test was carried out. Otherwise non-parametric Mann-Whitney test was applied. All results were considered statistically significant with 95% confident interval.

3. FINDINGS

3.1 Methane Fluxes

Three hundred and fifteen gas samples were quantified for methane concentrations and the fifty-two fluxes were calculated. Methane fluxes varied from 1.9 to 8,634.9 mg m^{-2} day^{-1}, with the mean ± SD of 467.0 ± 1,544.6 mg $m^{-2}day^{-1}$ and the median of 13.2 mg m^{-2} day^{-1} (n=52). A histogram showed distribution of methane fluxes (Figure 2).

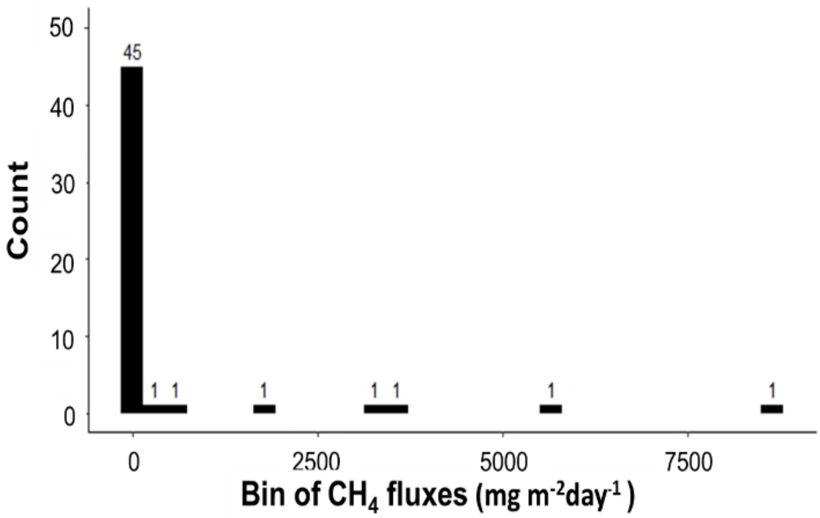

Fig. 2. Histogram of methane fluxes (n=52).

About 87% of methane fluxes grouped between 0 and 150 mg m^{-2} day^{-1}. It was important to note that methane fluxes over the upper fence of 40.7 mg $m^{-2}day^{-1}$ were considered as outliers and thus excluded from statistical analysis.

The total number of monthly gas samples was 41 (n). Wet and dry seasons were classified by the water levels in the wetland and meteorological conditions, observed during the sampling period. Wet season started from mid-June to mid-September (3 months), while dry season started from mid-December to mid-June (7 months). The water levels in the wetland reached the maximum capacity in wet season and the water levels gradually decreased during dry season. The methane fluxes varied in the range of 1.9-22.7 mg $m^{-2}day^{-1}$ with the mean ± SD of 10.6 ± 5.4 mg $m^{-2}day^{-1}$ and the median of 10.1 mg $m^{-2}day^{-1}$. The lowest methane flux was found in December 2018 while the highest methane flux was in July 2019 (Figure 3).

The methane fluxes during wet season ranged from 5.2 to 22.7 mg $m^{-2}day^{-1}$ with the median ± SD of 14.1 ± 5.0 mg m^{-2} day^{-1} (n=14) while methane fluxes during dry season were between 1.9 and 21.9 mg $m^{-2}day^{-1}$ with the median ± SD of 8.8 ± 5.2 mg $m^{-2}day^{-1}$ (n=31). The methane fluxes from the natural wetland seemed to increase from the beginning of dry season in 2018 to February 2019. From mid-December 2018 to February 2019, increasing in temperature from 25.0 to 29.0°C may cause the methane producing microbes at the lower soil layers to become active leading to more methane production [26], [27]. The decreasing of methane fluxes in March 2019 may attribute by the lower water levels causing more oxic conditions in the lower soil layers, less favorable conditions for active microbial activity [28], [29]. These conditions may cause the lower rate of methane fluxes. After February, the methane fluxes increased continuously and peaked in April 2019. This dry period had slightly higher temperatures, in the range of 29.0-31.0°C, than the previous period with the lower water level. The methane fluxes decreased about 1.7 times from April when entered the wet season in mid-June 2019. During this period, the level of water in wetland remained near the lowest capacity of water storage. The gradually increase in methane fluxes potentially resulted from more available substrates with higher water level that methane producing microbes consume while they degrade organic matters. During wet season, the water from the stream continuously discharged into the wetland. The water level of the wetland increased and reached the maximum storage capacity in July 2019. Additionally, the rainstorm from July to August 2019 led more water input into the wetland. The wetland, during this period, had high median methane fluxes with the number of 14.1 mg m^{-2} day^{-1}. The flooded conditions of the wetland provided the ideal conditions for methanogenesis. The organic matters increased as a result of decomposed grass, thus more substrate for methanogenesis [4], [30].

Many studies indicated that methane fluxes varied temporally and spatially. When comparing the results to those of previous studies, shown in Table 1, it can point out that large difference of methane fluxes potentially originated from spatiotemporal variation.

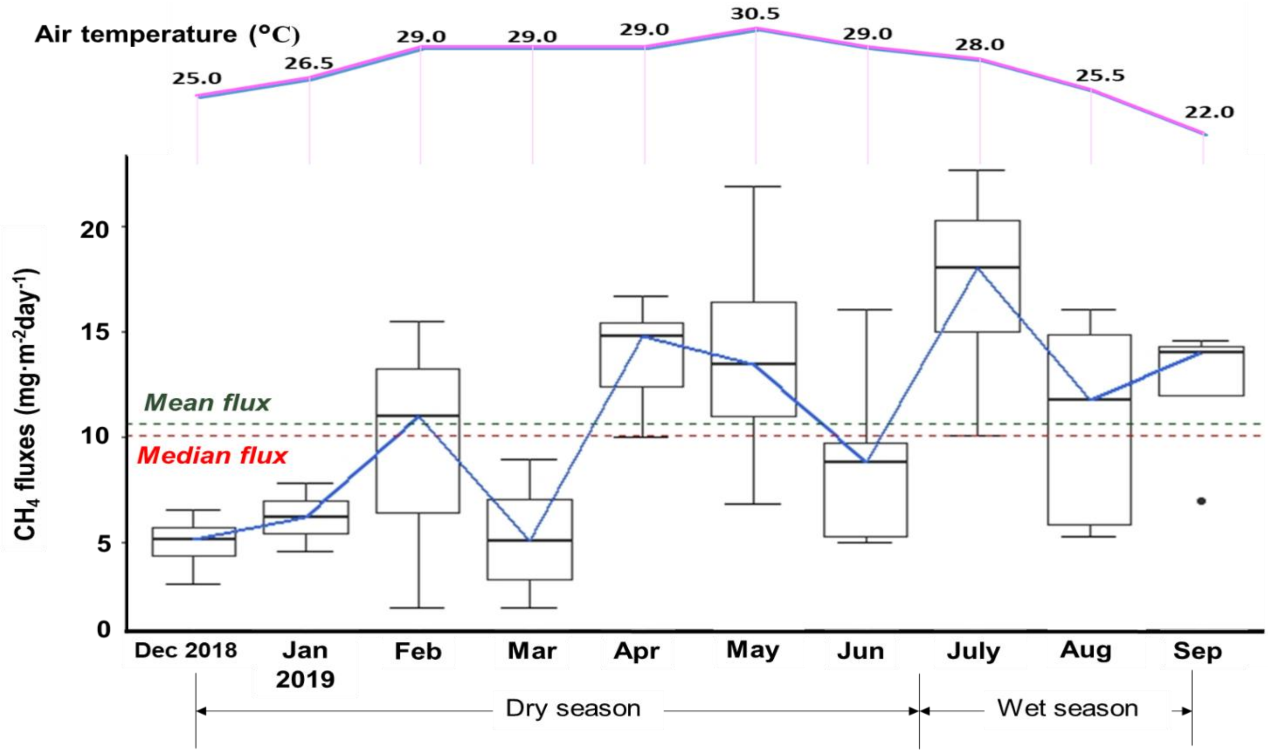

Fig. 3. Time-series Box-Winkler plot of seasonal methane fluxes from the natural wetland (n=41).

Table 1. Methane emissions from some wetland.

Country	Climate	Wetland type	Flux (mg/m^{-2}/day)	Authors	Year
Thailand	Tropical	Natural reservoir	10.6 ± 5.4 (mean ± SD)	This study	2019
Thailand	Tropical	Mangrove area	0.19 (cold), 0.27 (summer), 0.52 (rainy); (mean)	[21]	2005
Thailand	Tropical	Freshwater marsh	7.1-29.7 (mean ± SD)	[18]	2001
Brazil	Tropical	Lake/reservoir	13.8 (mean)	[31]	2006
France	Tropical	reservoir	44.8 (mean)	[32]	2006
India	Tropical	reservoir	116.6 (mean)	[33]	2015
U.K.	Temperate	Natural pond	1.0-22.5 (range)	[34]	2000
U.S.	Temperate	reservoir	4.4 (mean)	[35]	2004
Finland	Boreal	reservoir	33.6 (mean)	[36]	2003
Canada	Boreal	reservoir	27.36 (mean)	[37], [38]	2005
China	Subtropical	Lake	0.06-5.5 (range)	[39]	2005
China	Subtropical	Meadow	270.5 ± 271.0 (mean ± SD)* 71.8 ± 40.1 (mean ± SD)**	[40]	2018
Australia	Subtropical	reservoir	93.5 (mean)	[41]	2013
China	Subtropical	reservoir	5.12 (mean)	[38]	2013
Taiwan	Subtropical	reservoir	4.8 (mean)	[42]	2013

Note: * = wetland was dominated by *Carex cinerascens*
** = wetland was dominated by *Artemisia selengensis*

Data from Thailand in Table 1 showed range of the methane flux. Khemjaroen (2001) used the measurement for 4 months, February to May, while this study and Lekphet *et al.* (2005) were observed throughout the year. Discrepancies on the methane fluxes may come from various factors such as different area, time, and even specific properties of the wetlands. On the other hand, the results from Lekphet *et al.* (2005) may indicate that the methane fluxes fluctuated seasonally [21].

In China, the methane fluxes were largely different between two different plants dominated in a wetland [40].

Similarly, spatial dynamics of methane fluxes can be observed from various wetlands in China [38]-[40].

Additionally, methane flux variation could be attributed to the difference in climate zone of a wetland (Table 1) that affected the balance between methane production and methane reduction, thus spatiotemporal of methane emissions.

3.2 Seasonal Estimates of Methane Emissions

According to the official records for season classification, the time span of the dry season was 204 days and 161 days for the wet season. Seasonal estimates of methane emissions from the natural wetland were shown in Table 2. Despite dry season covered more months (Figure 2), the methane emissions during dry season were lower compared to the wet season due to high methane fluxes during wet season.

Table 2. Seasonal estimates of methane emissions.

Period	Day	Methane emissions ($kg\ m^2\ period^{-1}$)		
		lower	upper	median
Wet season	161	1.5	3.1	2.3
Dry season	204	0.7	2.9	1.8
Annual	365	1.7	5.7	3.7

3.3 Estimating the Methane Emissions from the Natural Wetlands in Nakhon Ratchasima

The approximate area of natural wetlands was calculated from a geospatial database. The area of natural wetlands in Nakhon Ratchasima province was about 298.7 km^2. The methane emission factor of the natural wetland in this study was 1.7 to 5.7 kg $m^{-2}year^{-1}$ (Table 2) while the methane emission factor of the natural wetland from IPCC (mean ± SD) was 0.0037-0.0235 kg $m^{-2}year^{-1}$. When considering 100-year time horizon, the natural wetlands in the province emitted about 15.48 to 52.16 million ton CO_2equivalent $year^{-1}$ based on our locally derived emission factor while estimation using the IPCC default emission factor yielded 0.03 to 0.22 million ton CO_2equivalent $year^{-1}$ (Figure 4).

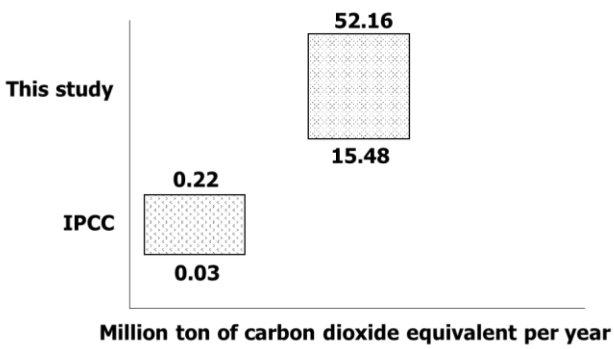

Fig. 4. Estimated methane emissions in Nakhon Ratchasima by two different emission factors.

The difference of the estimated methane emissions showed that locally derived emission factor gave 241-454 times higher estimate than the IPCC emission factor. It was possible that the default emission factor was a global average (IPCC, 2014) and methane emissions vary temporally and spatially [43]–[45].

4. CONCLUSION AND RECOMMENDATION

The methane fluxes from a natural wetland in Nakhon Ratchasima varied widely, 1.9–22.7 mg $m^{-2}day^{-1}$ with the mean ± SD of 10.6 ± 5.4 mg $m^{-2}day^{-1}$. The methane fluxes during wet season had the mean ± SD of 13.2 ± 5.0 mg m^{-2} day^{-1} and 10.3 ± 5.8 mg $m^{-2}day^{-1}$ in dry season. Annual methane emission rate from a natural wetland in Nakhon Ratchasima during December 2018 to November 2019 ranged between 2,015 and 6,169 mg $m^{-2}year^{-1}$ with the mean of 4,092 mg $m^{-2}year^{-1}$. Estimate of methane emissions from the natural wetlands in Nakhon Ratchasima was 601,880,500 to 1,842,680,300 kg $year^{-1}$. Estimate of methane emissions from the natural wetlands with the IPCC emission factor led to much lower emissions.

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REFERENCES

[1] Fourier J.B.J., 1824. General Remarks on the Temperature of the Terrestrial Globe and the Planetary Spaces, Translation from the French by Burgess,E., 1837, American Journal of Science, Vol 32, pp. 1-20. *Paris - Crochard*, vol. 27, *Annals of Chemistry and Physics* 27: 136–167.

[2] Stephens G.L and S. A Tjemkes, 1993. Water Vapour and Its Role in the Earth's Greenhouse. *Aust. J. Phys.* 46(1): 149. doi: 10.1071/PH930149.

[3] Tyndall J., 1862. On the Absorption and Radiation of Heat by Gaseous Matter. Second Memoir. *Philosophical Transactions of the Royal Society of London* 152: 59–98.

[4] Laanbroek , 2010. Methane emission from natural wetlands: interplay between emergent macrophytes and soil microbial processes. A mini-review. *Ann Bot* 105(1: 141–153. doi: 10.1093/aob/mcp201.

[5] Myhre G. *et al.*, 2013. Anthropogenic and Natural Radiative Forcing. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[6] Fenchel T., Blackburn T.H., and King G.M., 2012. Bacterial Biogeochemistry. Third edition. Academic Press, Elsevier Ltd

[7] Repeta D.J., Ferrón S., Sosa O.A., and Johansson C.G., 2016. Marine methane paradox explained by bacterial degradation of dissolved organic matter. *Nature Geoscience* 9: 884–887.

[8] Wang Z., Delaune R., Patrick Jr. W.H., and Masscheleyn P.H., 2009. Soil Redox and pH effects on methane production in a flooded rice soil. *Soil Science Society of America Journal - SSSAJ* 57: 382–385. doi:10.2136/sssaj1993.03615995005700020016x.

[9] Butterbach-Bahl K., Baggs E.M., Dannenmann M., Kiese R., and Zechmeister-Boltenstern S., 2013. Nitrous oxide emissions from soils: how well do we understand the processes and their controls?. *Royal Society Publishing*, *Soil Science* : 1–13. doi: https://doi.org/10.1098/rstb.2013.0122.

[10] Bubier J., Moore T., and Roulet N. 1993. Methane emissions from wetlands in the Midboreal region of Northern Ontario, Canada. *Ecology* 74: 2240–2254. doi: 10.2307/1939577.

[11] Brye K.R., Roger C.W., Smartt A.D., and Norman R.J., 2013. Soil texture on methane emissions from direct-seeded, delayed-flood rice production in Arkansas. *Lippincott Williams & Wilkins* 178(10): 519–529. doi: 10.1097/SS.0000000000000020.

[12] B. Kaesler and P. Schönheit, "The role of sodium ions in methanogenesis. Formaldehyde oxidation to CO_2 and $2H_2$ in methanogenic bacteria is coupled with primary electrogenic Na^+ translocation at a stoichiometry of 2-3 Na^+/CO_2," *European journal of biochemistry / FEBS*, vol. 184, pp. 223–32, Oct. 1989, doi: 10.1111/j.1432-1033.1989.tb15010.x.

[13] Müller V., Blaut M., and Gottschalk G., 1987. Generation of a transmembrane gradient of Na^+ in Methanosarcina barkeri. *European journal of biochemistry / FEBS* 162: 461. doi: 10.1111/j.1432-1033.1987.tb10624.x.

[14] Annisa W., Maas A., Purwanto B.P., and Widada J., 2014. Effect of organic matter level on methane emission in acid sulfate soil from Belandean, South Kalimantan. *Asian Research Publishing Network (ARPN)* 9(4): 146–151.

[15] Boon P.I. and A. Mitchell. 1995. Methanogenesis in the sediments of an Australian freshwater wetland: Comparison with aerobic decay, and factors controlling methanogenesis. *FEMS Microbiology Ecology* 18(3): 175–190. doi: 10.1016/0168-6496(95)00053-5.

[16] Dlugokencky E., NOAA/GML. Carbon cycle greenhouse gases, Trends in CH_4. Retrieved from the World Wide Web: *www.esrl.noaa.gov/gmd/ccgg/trends_ch4/.*

[17] IPCC, *2013*. Supplement to the 2006 IPCC Guidlines for National Greenhouse Gas Inventories: Wetland. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). IPCC, Switzerland, 2014.

[18] Khemjaroen K., 2001. Methane emissions from natural and man-made wetlands: A comparative study on freshwater marsh, paddy field, and shrimp farm in Bansang district. *Master Thesis of Environmental Management*, Mahidol University, Bangkok, Thailand, 2001.

[19] Chuersuwan S., Suwanwaree P., and Chuersuwan N., 2014. Estimating greenhouse gas fluxes from constructed wetlands used for water quality improvement. *Songklanakarin Journal of Science and Technology* 36: 367–373.

[20] Kaewgamtong N., 2002. Methane Emission form Constructed Wetland. *Master Thesis*. King Mongut's University of Technology Thonburi, Bangkok, Thailand.

[21] Lekphet S., Adsavakulchai S., and Nitisoravut S., 2005. Etimating methane emissions from mangrove area in Ranong province, Thailand. *Songklanakarin Journal of Science and Technology* 27(1): 153–163.

[22] Office of Natural Resources and Environmental Policy and Planning, 2017. Thailand's Second National Communication under the United Nations Framework Convention on Climate Change - OD Mekong Datahub. *Open Development Mekong*. Retrieved from the World Wide Web: https://data.opendevelopmentmekong.net/dataset/09817b4f-380c-4bed-83bb-bf22c809496b.

[23] Hutchinson G.L. and A.R. Mosier. 1981. Improved soil cover method for field measurement of nitrous oxide fluxes. *Soil Science Society of America Journal* 45(2): 311–316. doi: 10.2136/sssaj1981.03615995004500020017x.

[24] Collier S.M., Ruark M.D., Oates L.G., Jokela W.E., and Dell C.J., 2014. Measurement of greenhouse gas flux from agricultural soils using static chambers. *J Vis Exp* (90). doi: 10.3791/52110.

[25] Healy M.G., Devine C.M., and Murphy R. 1996. Microbial production of biosurfactants. *Resources, Conservation and Recycling* 18(1–4): 41–57. doi: 10.1016/S0921-3449(96)01167-6.

[26] Dise N.B., 1992. Winter fluxes of methane from Minnesota peatlands. *Biogeochemistry* 17(2): 71–83. doi: 10.1007/BF00002641.

[27] King G.M. and A.P.S. Adamsen. 1992. Effects of temperature on methane consumption in a forest Soil and in pure cultures of the Methanotroph *Methylomonas rubra*. *Appl Environ Microbiol* 58(9): 2758–2763.

[28] Castro M.S., Steudler P.A., Melillo J.M., Aber J.D., and Bowden R.D., 1995. Factors controlling atmospheric methane consumption by temperate forest soils. *Global Biogeochemical Cycles* 9(1): 1–10. doi: 10.1029/94GB02651.

[29] Moore T.R. and M. Dalva. 1993. The influence of temperature and water table position on carbon dioxide and methane emissions from laboratory columns of peatland soils. *Journal of Soil Science* 44(4):651–664. doi: 10.1111/j.1365-2389.1993.tb02330.x.

[30] Macdonald J.A., Fowler D., Hargreaves K.J., Skiba U., Leith I.D., and Murray M.B. 1998. Methane emission rates from a northern wetland; response to temperature, water table and transport.

Atmospheric Environment 32(19): 3219–3227. doi: 10.1016/S1352-2310(97)00464-0.

[31] dos Santos M.A., Rosa L.P., Sikar B., Sikar E., and dos Santos E.O., 2006. Gross greenhouse gas fluxes from hydro-power reservoir compared to thermo-power plants. *Energy Policy* 34(4): 481–488.

[32] Guérin F. *et al.*, 2006. Methane and carbon dioxide emissions from tropical reservoirs: Significance of downstream rivers. *Geophysical Research Letters* 33(21). doi: 10.1029/2006GL027929.

[33] Bansal S., Chakraborty M., Katyal D., and Garg J., 2015. Methane flux from a subtropical reservoir located in the floodplains of river Yamuna, India. *Applied Ecology and Environmental Research* 13. doi: 10.15666/aeer/1302_597613.

[34] Casper P., Maberly S.C., Hall G.H, and Finlay B.J., 2000. Fluxes of methane and carbon dioxide from a small productive lake to the atmosphere. *Biogeochemistry* 49(1): 1–19. doi: 10.1023/A:1006269900174.

[35] Soumis N., Duchemin É., Canuel R., and Lucotte M., 2004. Greenhouse gas emissions from reservoirs of the western United States. *Global Biogeochemical Cycles* 18(3) 2004. doi: 10.1029/2003GB002197.

[36] Huttunen J.T. *et al.*, 2003. Fluxes of methane, carbon dioxide and nitrous oxide in boreal lakes and potential anthropogenic effects on the aquatic greenhouse gas emissions. *Chemosphere* 52(3): 609–621. doi: 10.1016/S0045-6535(03)00243-1.

[37] Tremblay A., Therrien J., Hamlin B., Wichmann E., and LeDrew L.J., 2005. GHG Emissions from Boreal Reservoirs and Natural Aquatic Ecosystems. In *Greenhouse Gas Emissions — Fluxes and Processes: Hydroelectric Reservoirs and Natural Environments*, A. Tremblay, L. Varfalvy, C. Roehm, and M. Garneau, Eds. Berlin, Heidelberg: Springer: 209–232.

[38] Zhao Y., Wu B.F., and Zeng Y., 2013. Spatial and temporal patterns of greenhouse gas emissions from Three Gorges Reservoir of China. *Biogeosciences* 10(2): 1219–1230. doi: https://doi.org/10.5194/bg-10-1219-2013.

[39] Xing Y., Xie P., Yang H., Ni L., Wang Y., and Rong K., 2005. Methane and carbon dioxide fluxes from a shallow hypereutrophic subtropical Lake in China. *Atmospheric Environment* 39(30): 5532–5540. doi: 10.1016/j.atmosenv.2005.06.010.

[40] Liu S., Chen Y., and Liu J., 2019. Methane emissions from the littoral zone of Poyang lake during drawdown periods. *Journal of Freshwater Ecology* 34(1): 37–48. doi: 10.1080/02705060.2018.1537941.

[41] Sturm K., Yuan Z., Gibbes B., Werner U., and Grinham A., 2014. Methane and nitrous oxide sources and emissions in a subtropical freshwater reservoir, South East Queensland, Australia. *Biogeosciences* 11(18):5245–5258. doi: https://doi.org/10.5194/bg-11-5245-2014.

[42] Wang Y.-H., Huang H.-H., Chu C.-P., and Chuag Y.-J., 2013. A preliminary survey of greenhouse gas emission from three reservoirs in Taiwan. *Sustainable Environment Research* 23: 215–225.

[43] Singh S.N., Kulshreshtha K., and Agnihotri S., 2000. Seasonal dynamics of methane emission from wetlands. *Chemosphere - Global Change Science* 2: 39–46. doi: 10.1016/S1465-9972(99)00046-X.

[44] Wassmann R. *et al.*, 1994. Temporal Patterns of Methane Emissions from Wetland Rice Fields Treated Different Modes of N Application. *Journal of Geophysical Research* 991: 16457–16462. doi: 10.1029/94JD00017.

[45] Wilson J.O., Crill P.M., Bartlett K.B., Sebacher D.I., Harriss R.C., and Sass R.L., 1989. Seasonal variation of methane emissions from a temperate swamp. *Biogeochemistry* 8(1): 55–71. doi: 10.1007/BF02180167.