A SURVEY OF

LITERATURE ON METHANE EMISSION FROM PADDY FIELDS IN THAILAND

SUBMITTED TO

THE THAILAND RESEACH FUND

PREPARED BY

PIMPAN JERMSAWATDIPONG

LADDAWAN KUNNOOT

NIWAT CHAREONSILP

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Introduction

As world's leading rice producers, Thailand's rice production satisfies Thai and foreign consumers a total of about 6-8 million tons per year. Thailand's sizeable export volume makes her world's leading rice exporters, with major competitors like Vietnam, the United States, Pakistan, China and Myanmar. Vietnam's strategy for expansion of rice production is increased land area and is determined to expand its share in upper quality rice market. At present, the United States is a formidable competitor for Thailand in upper quality rice market, while Vietnam, Pakistan, China and Myanmar compete with Thailand in low quality rice market. Apart from world market competition, Thailand's rice exports are likely to counter trade barrier in the future in the form of environmental measures, in particular, against the alleged emission of methane—greenhouse gas from paddy field. To ensure a fair trade practice, Thailand needs researches about methane emission from paddy fields to support the development of proper positions and decisive counteraction in international trade negotiations. Development in world's rice trade and growing international environmental awareness are concerns provoking comprehensive researches and studies about methane emission in Thailand's paddy field. Thailand needs to administer comprehensive researches and studies to collect data and information about methane emission in the country for a construction of a national account and the development of rice technology with minimum methane emission and without adverse affect on rice output. Prior to forming any research and study project, a national account of methane researches and studies needs to be constructed, many of which are oriented towards the development of technology for increased rice production at minimum methane emission.

The national inventory of greenhouse gas in Thailand with a particular focus on methane gas has been constructed twice. The first inventory was prepared by TDRI/TEI (1992). Methane emission in based year 1990 was 3.42-9.16 Tg per year, closed to the estimate using IPCC (1991) default emission factors (TDRI/TEI, 1992). The second inventory was constructed in 1997 (TEI, 1997) based on IPCC Guidelines 1995 which improved the estimation method by assigning proper weight to methane emission from rice cultivated under intermittent flooding during growing season. The resulted estimate, therefore, suggests emission decreased to 1.8 Tg. When this estimate is compared with the estimate using IPCC (1995)'s default emission factors in conjunction with FAO's world data for rice growing area, the emission of methane was 4.4 Tg. According to the second national inventory, in 1990 Thailand emitted 1.8 million tons of methane from rice cultivation or 65% of total country emission. This value is equivalent to 38 million tons CO_2 or 16.7% of country CO_2 emission, while the contribution from power and transport are about 11% each (TEI, 1997).

Reported in Table 1 are results of other methane researches using different estimation techniques. These estimates suggest different estimating techniques yield significant differences of results. The difference applies even for results estimated using local emission factors measured directly from paddy fields.

There are a number of factors influencing production and level of emission of methane. In Thailand, soil properties were found to clearly influence the differences. Rice is grown in all regions of Thailand, where paddy soils vary largely in their properties. Also variation in rainfalls and air temperature in different parts of the country must also be accounted for the differences in methane level in addition to other factors relating to organic and chemical fertilizer used, rice cultivar, and cultural practice. Examples of variation of methane emission measured in paddy fields in various provinces of Thailand are shown in Fig. 1, which indicates that methane mission levels in some areas are over ten times different.

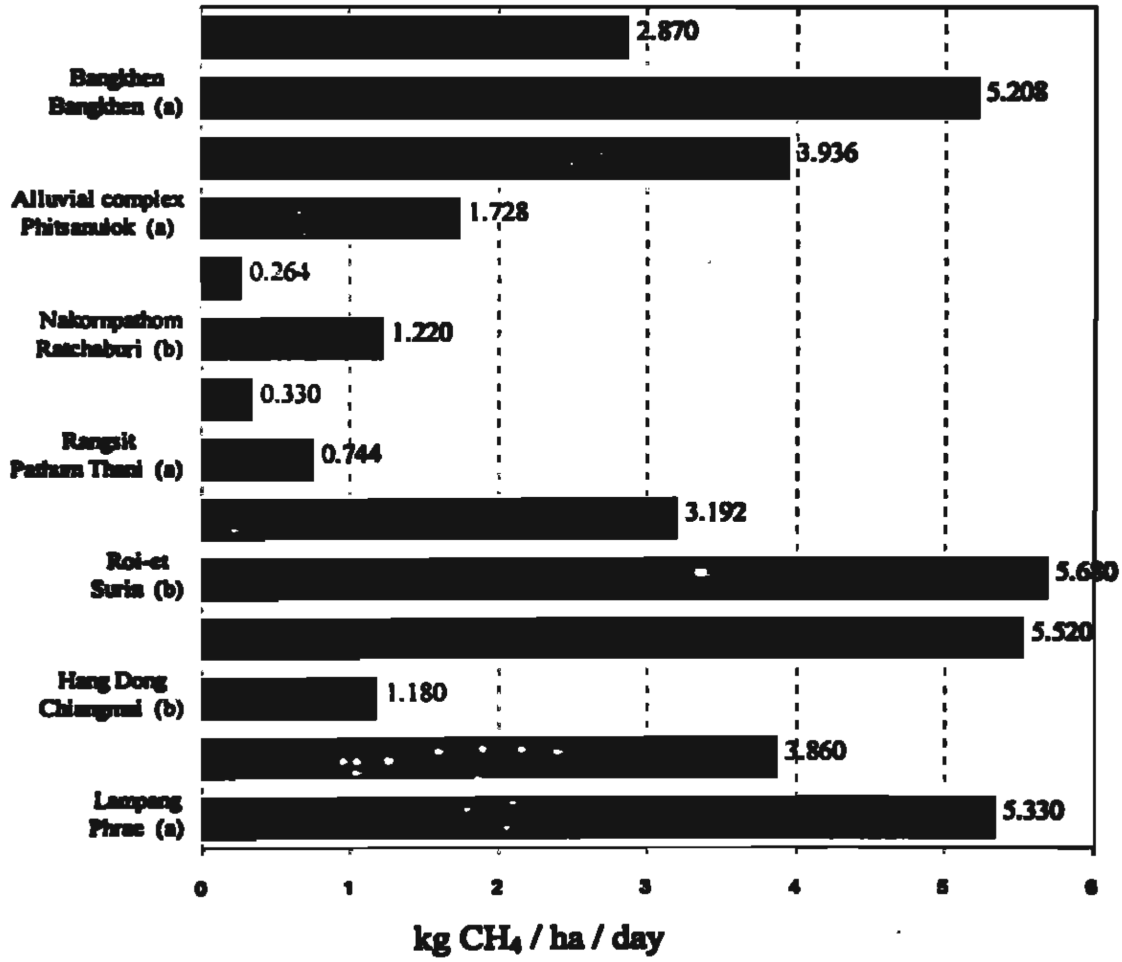
Table 1. Emission of CH_4 from Thailand estimated by various methods.

Evaluation method / Source	Tg CH_4/year
Global emission rate	6.92
Net primary production (Bachelet and Neue ,1993)	4.73
Organic carbon (Bachelet and Neue ,1993)	3.8
Global emission rate + Soil characteristics (Bachelet and Neue ,1993)	4.1
Net primary production + Soil characteristics (Bachelet and Neue ,1993)	2.76
Organic carbon + Soil characteristics (Bachelet and Neue ,1993)	2.24
Towprayoon et al. (1993)	16 (4-40)
Yaki et al.(1992)	0.47-8.77
Sass (1997)	1.8
U.S. Country report on Asia	5.414
ALGAS	1.8
TDRI & TEI (1993), country emission data	3.42 - 9.16
TDRI & TEI (1993), IPCC default values	2.34 - 8.49
TEI (1997), country emission data	1.8
TEI (1997), IPCC default values	4.4

Researches and studies in this subject are currently conducted in many rice growing countries including China, India, Indonesia, Philippines, Korea, the United States, and particularly at IRRI (International Rice Research Institute), but, in Thailand, remain scanty, lack collaboration and are dependent on individual interest. Differences in estimating techniques employed create contradicting picture, and often render results unreliable. For example, Sass (1994)'s research reported the value of 0.47-8.77 Tg per year equivalent to 11.6% of world's methane emission, making

Thailand one of major methane producers, although Thailand's paddy land is only 8% of world's paddy land compared to 22% and 29% for China and India respectively where methane emission of only 38% and 11% of world methane emission respectively was reported.

Figure 1. Emission rates of CH4 measured from several paddy fields in Thailand.



Source : (a) Chairoj et al. 1996.

(b) Jermsawatdipong et al. 1994.

(c) Towprayoon, et al. 1993.

Above forms bases for a review of literature about methane emission from paddy field to determine direction for further research and studies conducted in Thailand.

1. Importance of CH_4 to global warming

- The atmospheric methane concentration is steadily increasing at an average the rate of 0.8% per year, although the increasing rates are variable. Khalil and Rasmussen (1994) calculated that 80% of the increase in global atmospheric CH_4 has occurred in this century and that 50% has occurred over the past 40 years. At present the atmospheric concentration of methane is 1.7 ppmv in northern hemisphere to 1.6 ppmv in southern hemisphere (Rasmussen and Khalil, 1986). These levels are roughly 3 times higher than the concentration at 100 years ago (Craig and Chou, 1982). The main increase in atmospheric methane over the past 200 years is probably due to the increase in global emission (70%) of methane and depletion of OH^- by increasing atmospheric CO (Khalil and Rasmussen, 1985). One hundred year time horizon methane has global warming potential of about 24.5 relative to CO_2 and has a life time of 12-17 years. It is estimated to cause approximately 25% of anticipated warming (IPCC, 1995).

The annual emission of methane is estimated to be approximately 550 Tg. Natural wetland occupies approximately 500-600 Mha of the area emit about 115 Tg or 21% of global emission. Agriculture plays an important role in supplying CH_4 to atmosphere (>50% of anthropogenic emission). Flooded rice fields occupy about 148 Mha of area and produce about 475 Mt rice, emit CH_4 annually about 11% of total global emission or 50-60 Tg CH4 yr^{-1}(Table 2). However, the uncertainty values is extremely high, ranges from 20-100 Tg CH_4 yr^{-1}, mainly due to the extreme spatial and temporal variability of fluxes and heterogeneity of soil, water and crop management practices, organic matter amendments and fertilization. At global level, methane production from paddy field was estimated to have doubled, from 34 Tg in 1900 to 70 Tg in 1990 (Khalil and Shearer, 1993). The emission of methane accelerated over the last fifty years (Fig.2), and correlates with increased acreage of paddy land and grain production of the world and of Thailand. In Thailand, paddy land has been extended from 6,000 ha in 1951 to about 100,000 ha in 1991. More important is Thailand's grain production has tripled (Fig. 3).

The main sink for atmospheric methane in troposphere is oxidation via CO to CO_2 by hydroxyl radicals ($OH^·$) in atmosphere (Bouman,1990). Under aerobic condition after drainage practices, paddy soils are able to act as a sink for atmospheric methane. The ability of these soils to absorb CH_4 depends on soil temperature and atmospheric CH_4 concentration (Thurlow et al. 1995). The data for CH_4 uptake from paddy fields has not been sufficiently investigated to estimate global CH_4 uptake. Although Minami et al. (1993) observed that the global terrestrial uptake rate for CH_4 ranged between 7 to 78 Tg CH_4 yr^{-1}, which accounts for less than about one tenth of the emission of the cattle (Minami et al. 1993).

Table 2. Estimated sources of methane from soil and land-use related sources ($Tg\ CH_4\ yr^{-1}$).

Source	Annual emission	% of global source
Soils/sediments		
Wetlands	115 (55- 150)	21
Rice production	60 (20 - 100)	11
Landfills	40 (20 - 70)	7
Termites	20 (10 - 50)	4
Animal wastes	25 (20 - 30)	5
Geological sources	10 (5 - 15)	2
Total soils	270	49
Land-use related sources		
Livestock production (including animal waste)	85 (65 - 100)	15
Biomass burning	40 (20 - 80)	7
Domestic sewage	25 (15 - 80)	5
Total land-use related	150	27
Total soil and land-use related	420	76
Global emission	550	

Source: Prather et al. 1995.

Figure 2. Global emission of CH_4 to atmosphere contributed from paddy fields (Khalil and Shearer, 1993).

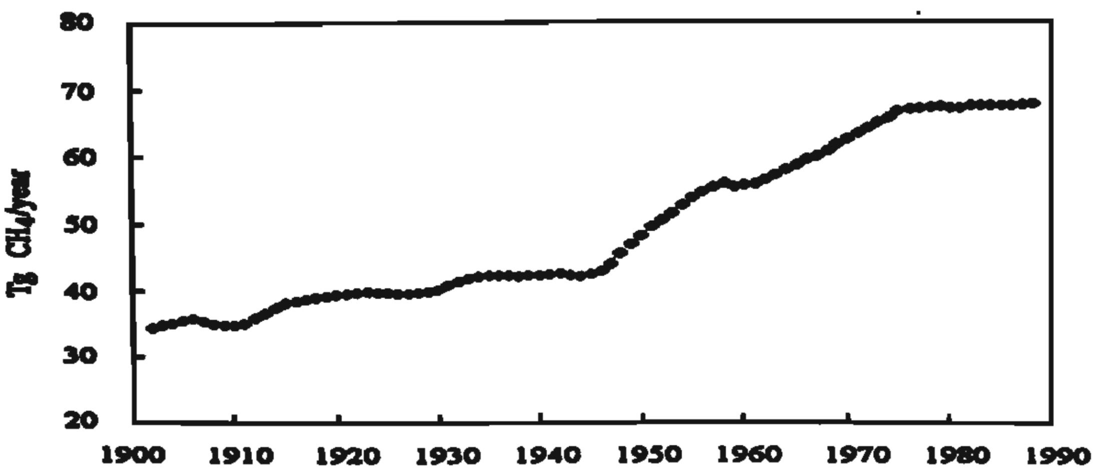
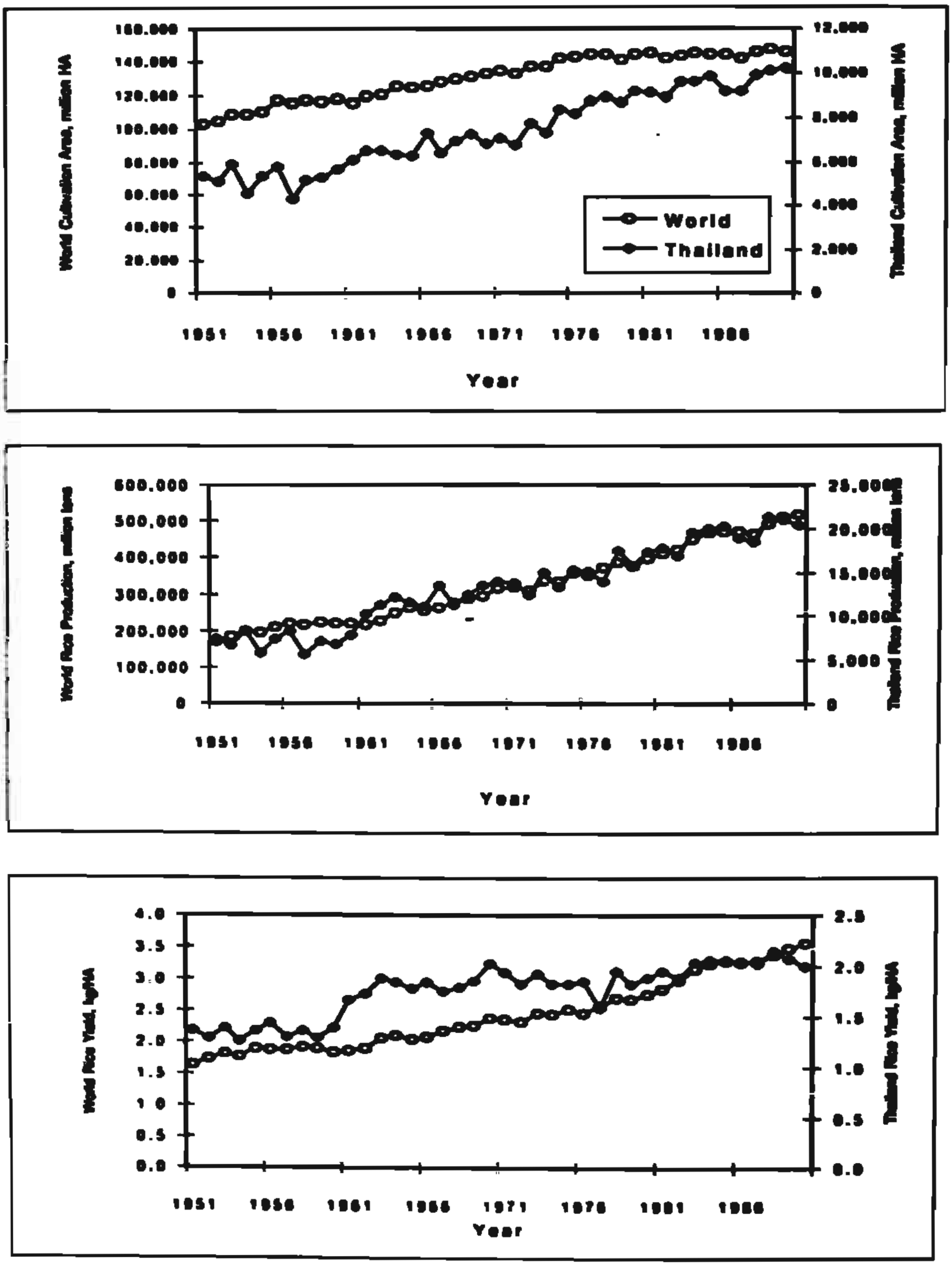


Figure 3. World and Thailand rice cultivation area, production and yield from 1951 to 1990 (World Rice Statistics, 1990).



2. Researches on methane emission from paddy fields

2.1 Factors affecting methane formation

Methane is produced in paddy soils by methanogenic bacteria in highly reduced conditions. After the soil is flooded, O_2 in soil solution is depleted within 2 - 8 hrs, forcing anaerobic microorganisms to use the compounds containing NO_3^-, Mn^{4+}, SO_4^{2-} and CO_2 as substrate which provides energy for their growth. Methane is the end product of this process.

Methane emission not only occurs in paddy soils under submerged condition but also under aerobic condition during drying after submersion. Bianchi et al. (1996) observed peaks of CH_4 emission 1 month after the period of flooding in agricultural soils. This may be due to partial soil aeration occurring in non-uniform soils. Increasing aeration in large soil pores allows degradation of complex polymer organic compounds such as lignin or cellulose to monomers. These monomers diffuses into water saturated zone in small soil pores where oxygen is limited and undergo anaerobic fermentation process resulting methane formation.

2.1.1 Carbon sources:

Three main carbon sources for methanogenic bacteria in flooded rice soil are: (1) the original soil organic matter; (2) the exogenous supply of organic material to the soil and, (3) the leave and root litter and root exudates from growing rice plant. The major substrates providing sources of C and energy for methanogens are H_2+ CO_2, acetate, formate, methylated amines and methanols (Schultz et al., 1989, Knowles, 1993). Studies using C-isotope techniques revealed that the two metabolic pathways of biological CH_4 formation are: (1) CO_2 reduction that utilises hydrogen gas, fatty acids or alcohol as hydrogen donor and (2) transmethylation of acetic acid or methyl alcohol. These are illustrated as follows.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

and

$$CH_3COO^- + H^+ \rightarrow CH4 + CO_2$$

2.1.2 Soil redox potential:

After flooding paddy soils, O_2 in soil solution is consumed rapidly. Reduction of NO^{3-} to NO^{2-}, N_2O and N_2, Mn^{4+} to Mn^{2+} , Fe^{3+} to Fe^{2+}, SO_4^{2-} to S^{2-} and CO_2 to CH_4 occur sequentially in the soil. Redox potential in well aerated soils which ranges from 400 to 600 mV decreases to -300 to -100 mV in most reduced or anaerobic soils. The sequences of inorganic compound reduction (Patrick and Reddy, 1997) and the critical redox potential at which oxidized inorganic compounds begin to undergo reduction in submerged paddy soils (Patrick and DeLaune, 1977) are presented in Fig. 4 and 5. Methane production does not reach appreciable rates until most SO_4^{2-} is removed from soil and water system by sulfate reducing bacteria (Martens and Berner, 1974; Jacobsen et al. 1981). Mascheleyn et al. (1993) and Connell and Patrick (1969) reported that redox potential of -150 mV is critical for CH_4 formation in anaerobic condition. Production of CH_4 is directly related to decreasing values of soil redox potential. The critical redox potential for CH_4 can be reached within 2 weeks if the rice soils contain sufficient energy sources and lows in NO_3^-, Mn^{4+} , Fe^{3+} and SO_4^{2-} content.

Figure 4. Critical redox potential at which oxidized inorganic species begin to undergo reduction in submerged soil (Patrick and DeLaune, 1977)

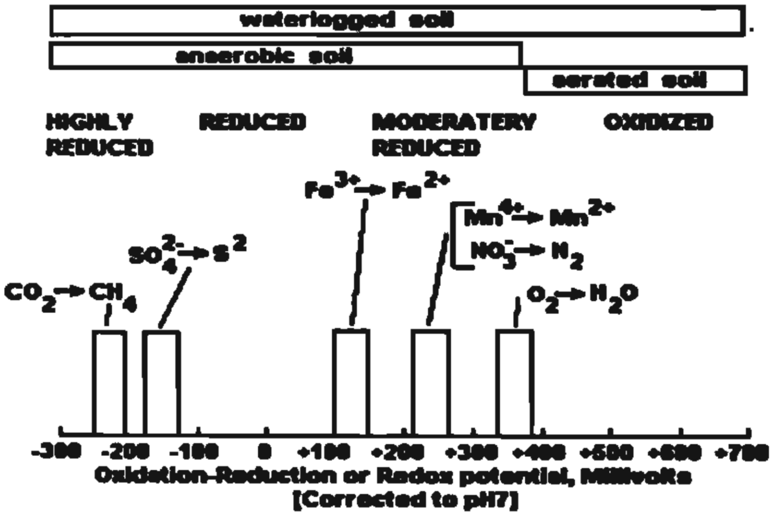
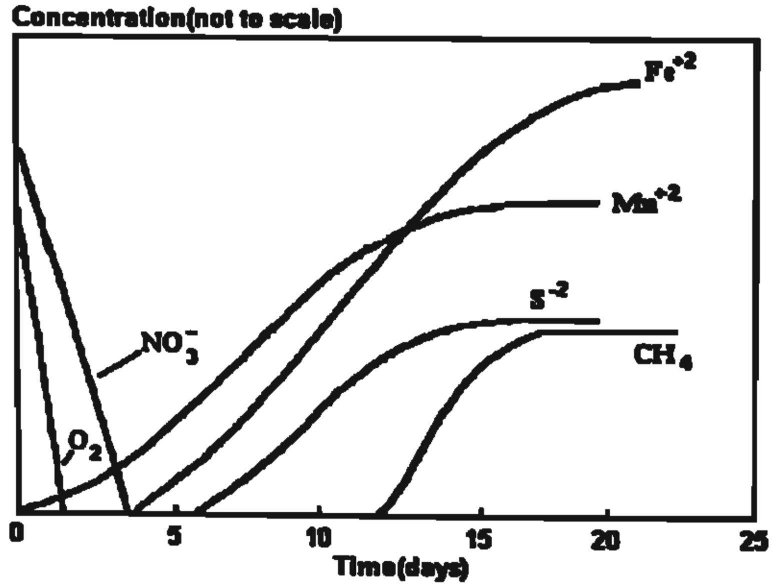


Figure 5. Sequence of reduction of inorganic redox components in soil after flooding (Patrick and Reddy, 1977).



2.1.3 Soil pH:

Most of methanogens grow over a narrow pH range, 6-8 and the optimum pH is 7. The maximum CH_4 production was shown to occur in pH range of 6.9 to 7.1, which is the pH range of most soils. At pH below 5.8 and above 8.8, CH4 production in the soil solution is almost completely inhibited. Only few strains of methanogen are alkaliphilic bacteria which active in optimum pH range of 8.1 to 9.7. Few methanogens grow well under acidic condition. However, the relationship between CH_4 production and dry soil pH is not clear.

Application of organic matters and chemical fertilizer may have some effects on the pH of soil solution, which result in temporary change in CH_4 production. Application of urea changes soil pH. The magnitude of pH after incorporation of chemical fertilizer depends on initial soil pH. Wang et al. (1993) reported the increase in CH_4 formation in acidic soil after addition with urea, but not in alkali and non-acidic soils. urea addition increases soil pH and inhibit CH_4 production. Similar effect to soil pH and CH_4 formation was also observed when organic matter was incorporated into soil (Morgan, 1968). Addition soil with 1% organic matter to acidic soil decrease soil pH and CH_4 production , while addition organic matter to anaerobic alkali soils decrease soil pH but increase CH_4 production.

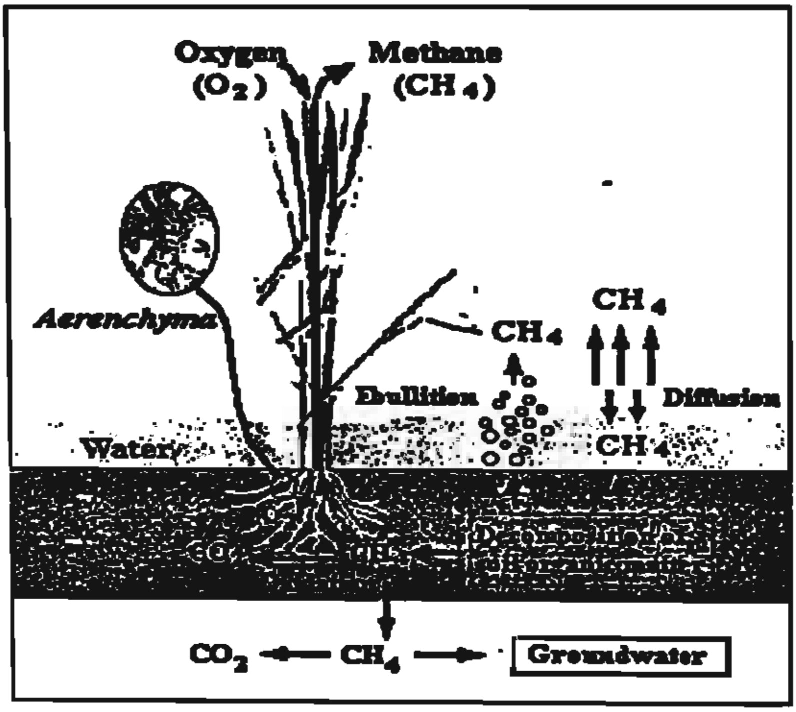
2.1.4 Soil temperature:

Production and emission of methane gas are positively correlated to soil temperature at 0.5 cm depth (Seiler et al. 1984). Tropical soil produces more methane gas than temperate soil (Tsutsuki and Ponnamperuma, 1987). Hozapfel-Pschorn and also found positive relationship between methane gas emission and soil temperature in China. Seiler (1986) reported that methane production increased twice when temperature rose from 20°C to 25°C. Sass et al. (1991a) found that methane production peaks when soil temperature reaches at 37°C. Ninety per cent of methane gas oxidized over soil surface (Holzapfel-Pschorn and Seiler, 1986; Schultz et al., 1989; Sass et al., 1991a). Vogels et al. (1988) found that Methanogen bacteria grow rapidly at 30-40°C. Change in the rate of emission of methane gas between day-time and night-time (diel emission) significantly correlate positively to change in temperature (Schultz et al. 1989).

2.2 Factors affecting CH_4 emission to atmosphere

Methane accumulated in submerged paddy soils is released to atmosphere by (1) diffusion in flooded water, (2) ebullition of entrapped gas and (3) transported through aerenchyma of the rice plant (Fig.6). Seiler et al. (1984) concluded that approximately 95% of total CH_4 released to atmosphere throughout the growing season were through the rice plant gas transport system. Methane may be transported through the aerenchyma either by molecular diffusion or convective flux driven by humidity-induced diffusion (Beckett et al., 1988). Nouchi et al. (1990) looked into the mechanism of CH_4 transport through rice plant and explained that the dissolved CH_4 in soil water surrounding the roots diffuses into the surface water of the roots, and on to the cell wall water of the root cortex, driven by the concentration gradient. Methane is then gasified in the root cortex and transported to the shoots via lysigenous intercellular spaces and aerenchyma and released through the micropores in the leaf sheets at the lower leaf position rather than the stomata in the leaf blade. Some of dissolved CH_4 is transported with percolation water to the subsoil (Kimura et al. 1992, Murase et al. 1993, Yaki and Minami, 1998).

Figure 6. Pathways of CH4 transport in submerged paddy soils.



2.2.1 Rice cultivars :

Production and transport of methane to the atmosphere appear to depend also on rice plant characteristics. Rice plant not only mediate CH_4 to atmosphere but also root exudates and degrading roots are also important carbon sources of CH_4 production at later stage of plant growth. Schultz et al (1989) reported that high emission of CH_4 observed during the reproductive stage of rice might be due to organic root exudates of rice plant and/or decayed root and tillers. The plant characteristics and related factors effecting methane emission from paddy fields follow:

Aerenchyma. Rice plant plays an important role in methane emission. Approximately 90% of methane emitted to atmosphere is conducted through rice plant (Seiler,et al.,1984; Holzapfel-Pschorn et al, 1986, Nouchi et al. 1990, Kludze et al. 1993). Arenchyma is any tissue containing air-filled intercellular spaces or lacunac. Openings of the aerenchyma to the atmosphere are found on leaves and nodes, but not on internodes of stems (Wang, 1995). At later stage of plant growth, major release sites are micropores in the junction of leaf sheath and culm. Methane concentration is highest in aerenchyma below water level and highest emission occurs through the micropores adjacent to the water level. A well developed aerenchyma in leaf sheath, leaf blade, culm and roots provide an effective exchange of gases between O_2 from the atmosphere to the rhizosphere and CH_4 from anaerobic soil to the atmosphere. Oxygen transported to the rhizosphere to serve the dual propose of maintaining aerobic metabolism of roots and microbes and restricting movement of potentially toxic substances such as Fe^{2+} Mn^{2+} and H_2S into plant roots by oxidation. The access of the rhizosphere to O_2 from the atmosphere would enhance the oxidation of CH_4 gas in the rhizosphere and hence reducing its flux into the atmosphere. The flux of gas through aerenchyma depends on concentration gradient of the gas and its diffusion coefficient in the conducting intercellular spaces which vary according to the internal structure of the aerenchyma.

Root exudation: Both quantity and quality of rice root exudate have positively effect on CH_4 production. Exudation rate depends on cultivar type and also on age and physiological stage of the plant. Kludze et al. (1997) found diurnal exudation pattern of all three rice cultivars tested, 2 peaks were observed at 10 and 15 h which coincided with the peaks of CH_4 emission rates. The magnitude of exudation of the cultivars during the growth cycle followed the sequence; flowering > maturity > panicle initiation > seedling stage.

Number of tillers, root mass and rooting patterns: These plant characteristics also influence CH_4 formation and emission. Mariko et al. (1991) found the number of tillers positively correlated to methane emission. This correlation is true only during vegetative stage. A field experiment conducted by Lindau et al. (1995) indicated that semi-dwarf variety emitted an average of 36% less CH_4 than tall variety over both cropping seasons. Measurement conducted by International Rice Research Institute revealed that traditional variety which has more tillers and longer roots, emitted about 30% more CH_4 per day than did the new plant type (IR65597) (Neue et al. 1994). The results of this study suggested that eliminating unproductive tillers in breeding new plant type will result in lower emission of methane. Old tillers responsible for methane emission more than young tillers of the same plant (Kimura, 1992) Sass et al (1990) found biomass of plant above ground level positively correlated to methane emission.

Soil redox potential: Morphological and physiological of rice roots are affected by soil characteristics particularly redox potential. Such change of rice root has been observed to effect gas exchange between anaerobic soil and the atmosphere (Kludze et al. 1993).

2.2.2 Soil preparation and cultivation practices:

Tillage, ploughing, harrowing , weeding, transplanting and fertilizer application cause soil disturbance which may release entrapped CH_4 directly to atmosphere. Such soil disturbance induces entrapped methane to emit from the soil solution to air (Sass et al., 1992). Planting rice by broadcasting dry seeds onto moist soil which reduces flooding time can slow redox potential reduction to the level of CH_4 formation, hence reduce CH_4 methane production. The results of an experiment conducted in Korea confirmed that transplanting with 8 day old seedling emitted highest amount of CH_4, followed by 30 day old seedling, direct seeding on wet soil and direct seeding on dry soil (Ko et al. 1998). Total CH_4 released from the plot with dry direct seeding was 26.9 gm^{-2} while wet direct seeding emited 37.1 gm^{-2}. In the Philippines, Teodula and Bajita (1998) reported direct seeding compared with transplanting reduced emission by 22.5% with continuously flooded conditions.

2.3 Soil properties that affect CH_4 emission:

IRRI measured methane production from paddy soils in the Philippines and grouped the soils into five categories according to their potential to produce CH_4 and found strong relationship between CH_4 production and the content of organic carbon in soils. Neue et al. (1993) indicated that the production of CH_4 is more or less depending on substrate such as hydrogen and acetate rather than change in pH or Eh in soil. If other factors in soil are reduced, total carbon is correlated with CH_4 production (Neue and Roger, 1993).

For soils with equivalent amount of total carbon, sandy soils showed higher CH_4 emission because the large pore size distribution enhances ebullition and diffusion process. Less CH_4 formation is observed in clayey textured soil. This may be due to the formation of organo-mineral complexes which protects organic compounds from being degraded. High bulk density soil associates with slow degradation of organic carbon, slow change in pH and Eh, and, therefore, slow methane production (Neue and Sass, 1993; Neue et al, 1993).

Degradation of organic matter in soil will rapidly reduce Eh in soil. In soil with high composition of organic matter, Eh will reduce by –200 or –300 mv in 2 weeks after flooded (Ponnamperuma, 1972). Methane gas is generated when Eh in soil reduces more than –150 mv (Patrick and Reddy, 1978). Methanogens grow and function their activities well in soil with pH 6-8. Only some forms of micrcbial favour pH 8-9, e.g., Methanosarcina, Methanobacterium and Methanohalophilus (Blotevogel et al., 1985; Worakit et al., 1986; Mathrani et al., 1988). Nevertheless, no research suggests what form of Methanogen favors soil with acid pH. Wang et al. (1993) found peak of methane gas production in soil with pH ranges 6.9-7.1, and no methane is produced at lower pH than 5.75 and higher pH than 8.75. Parashar et al. (1991) reported methane production peaks in soil with pH 8.2. Nevertheless, pH level favorable to methane gas production differs slightly in different soils depending on level of carbon in soil. In alkaline soil, methane gas is produced as soon as one hour after flooded, while it may take over a week in acid soil. In high acid soil, no methane gas will be produced (Neue and Sass, 1993).

Kimura (1992) estimated methane emissions from Japanese and Thai paddy soils based on soil chemical properties. The total carbon mineralization of a soil was converted to CO_2/CH_4 ratio in relation to free iron content and reduction capacity data of the soil. The total carbon mineralization was estimated from anaerobic nitrogen mineralization. using the ratio of 10.8. Ammonium nitrogen mineralization in paddy soils was related to total nitrogen content in soil, amount of cation exchange capacity

(CEC), amount of exchangeable Ca and free iron content. He showed the average potential CH_4 flux per unit area of soils from the central plains and north-eastern, northern and southern regions of Thailand to be 124, 51, 47 and 81 kg CH_4/ha, respectively. These values did not include the contribution of organic debris, such as plant roots, to methane production during plant growth, and hence were lower than comparable figures derived in other reports.

2.4 Organic amendments that affect CH_4 emission:

The rate and pattern of organic matter application and fate of decomposition are the determining factors of CH_4 production in paddy soils. Easily degradable crop residues, fallow weeds and soil organic matter are the major sources of initial CH_4 production during cropping season. At later stage of crop growth, root exudates and decaying roots and aquatic biomass seem to be more important.

Addition of organic matter in saturated soil enhances methane gas production (Schultz et al., 1989; Yagi and Minami, 1990; Sass et al., 1991b). Experiments conducted in IRRI show that incorporation rice straw or green manure with urea fertilizer increases CH_4 emission than fertilization with urea only. Also, experiments conducted in China found CH_4 emission increased over 100% when green manure was applied in extra with chemical fertilizer (Wangfang and Wei, 1998). Jain et al. (1998) reported incorporation paddy soil with high C/N ratio organic materials, green manure caused CH_4 emission higher than azolla and farm yard manure, respectively. Wang et al. (1992)'s experiment suggested CH_4 production correlates with addition of rice straw in soil. The effect of fresh rice straw on CH_4 emission is very powerful, even in the plots with phosphogypsum addition failed to decrease CH_4 emission (Teodula et al. 1998). This stimulatory effect was noticed even and under nonflooded conditions (Sethunathan et al, 1998). But application farm yard manure and rice straw to paddy fields under rainfed conditions in Indonesia did not significantly emit CH_4 (Makarim and Setyanto, 1998). Addition with low C/N ratio organic fertilizer, such as rice straw compost, chicken manure, cow manure and biogas slurry, was found significantly decreased CH_4 emission (Yagi and Minami, 1990,Teodula et al. 1998, Wangfang and Wei; 1998). Pig manure seems to cause more CH_4 formation than other type of animal manure (Zengyuan et al. 1998).

2.5 Mineral fertilization that affect CH_4 emission:

Rice cultivation generally applies nitrogen fertilizer, particularly, in the form of urea. Application of mineral fertilizer in rice field changes soil solution in various aspects, e.g., soil pH change influences microbial population and activities, and influences plant activities, increasing root litter and exudation, and influencing emission of methane gas. There are many studies of influences of chemical fertilizer application, particularly nitrogen fertilizer, on methane gas emission, but their findings differ. The difference can be explained in terms of difference in soil properties, particularly in terms of soil pH, which strongly influences microbial activities, thus, suggesting requirement for more detail studies. Nevertheless, it can be assured that fertilizer application to increase rice piant and a root increases methane gas emission (Neue and Sass, 1993). Schultz et al. (1989) concluded that types, method and rate of fertilization clearly influence methane gas emission. Lindau et al. (1991) reported increase in urea fertilization increases methane gas emission. Ammonium fertilization helps arrest oxidization of methane in soil, which causes emission of methane gas to rise (Conrad and Rothfuss, 1991). Kimura et al. (1992) applied threè types of nitrogen fertilizer to compare methane gas emission, and found rate of methane gas emission ranking from urea > ammonium chloride > ammonium sulfate. Urea has strongest influence on methane emission may be explained by more extensive microbial activities, increase in root litter and root exudation, which changes soil pH in short effect. Wang et al., (1992) concluded their laboratory study on rate of methane gas production by incubation that urea fertilization has no effect on methane gas production; nitrate fertilization clearly reduces rate of methane production; and nitrate fertilization also reduces rate of methane production. Cicerone and Shetter (1981)'s study found five times increase in methane gas emission as ammonium nitrate fertilization was applied. Other researchers, e.g., Schultz et al., (1989); Yagi and Minami, (1990); Sass et al., (1990), Buendia et al (1998) found CH_4 emission decreases significantly as ammonium sulfate fertilization was applied. Lindau et al., (1993) found sodium sulfate has more influence on methane gas emission than ammonium sulfate.

Nitrogen fertilizer NH_4NO_3 reduces methane emission more than $(NH_4)_2SO_4$ and urea (Lindau et al., 1990). This may be explained that NO_3 tends to buffer soil Eh, slowing CH4 production (Patrick and DeLaune, 1977). Application of NH_4NO_3 into highly reduced soil in the laboratory increased Eh from –200 mv to +200 mv, higher than the critical value for CH_4 production.

Moreover, method of fertilization is quite important. Schultz et al. (1989) found emission of methane gas decreases only 42% of control level when fertilizer was incorporated at 20 cm depth and can reduce to 91% as ammonium sulfate was applied on soil surface. Makarim and Setyanto (1998) reported deep placement of table urea reduced CH_4 emission by 20% compared with prilled urea.

2.6 Microbiological processes:

Methanogenic bacteria are ones which does not need oxygen. These bacteria may die or seize to grow in oxygen environment (Knowles, 1993). About 20 genus of methane producing bacteria are reported, but those clearly classified include Methanobaterium and Methanosarcina which found in paddy soil (Rajagopal et al., 1988). Methanospillum and Methanocorpusculum are found in fresh water sediments (Neue and Sass, 1993).

Using 4 different substrate for growth of methanogenus shows the diversity of the population in the rice fields in the Philippines (Joulian et al., 1998).

Using methylfluoride as methane inhibitor in field investigation showed that methanotrophic bacteria can consume more than 90% of the methane potentially available (Oremland and Culbertson, 1992).

At present, very little information of nature and potential of both methanogen and methanotropic bacteria in paddy soils are available.

2.7 Oxidation of methane in the rice fields:

Some of CH4 is oxidized to CO_2 by aerobic methanotropic bacteria in aerobic part of submerged soils, such as in the thin oxidized layer at surface soil-water interface and in the rhizosphere (Whittenbury et al, 1970a-b; Anthony, 1982; Higgins et al, 1981; Crawford and Hanson, 1984). Sink of methane by microbial uptake is approximately 15-45 Tg CH4 yr^{-1}(Bouman, 1998). Oxidation of CH4 in the rhizosphere is considered as an important sink within soil. Approximately 90% of methane produced in soils is oxidized in the rhizosphere and at the soil surface-water interface (Holzapfel-Pschorn et al, 1985; Schultz et al, 1989; Frenzel et al, 1992). Conrad and Rothfuss (1991) reported that CH4 oxidation in the soil surface consumed about 80% of the potential diffusive flux.

The process of CH4 oxidation sequentially follows methane – Methanol – Formadehyde – Formate – Carbon dioxide. Oxidation of methane also occurs biologically in anaerobic environment at the less reduced sites in submerged soil. Production of electron acceptors, such as NO_3^-, $Mn^{4+}$and SO_4^{2-} along with anaerobic respiration process provide energy for methane oxidising microorganisms. Association of sulfate reduction with anaerobic methane oxidation has been reported (Murase and Kimura, 1994a and 1994b). Cultivation practices and nitrogen fertilization has been shown to reduce the effectiveness of this soil to sink . Instead, this enhances more emission to atmosphere. Percolation water contributes CH4 oxidation by increasing the thickness of aerobic layer at the soil surface. The net methane emission is the sum of the amount of methane production (in anaerobic zone) and consumption (in aerobic zone).

2.8 Modeling CH4 emission from paddy fields :

Although, there are quite a number of factors influenced CH_4 methane production in paddy fields. Several attempts have been proposed to develop models for CH_4 emission. Bodegom (1998) used mechanistic model to explain CH_4 emission in paddy field of the USA. Sass et al. (1998) successfully developed a model to assess CH_4 emission in paddy field for diverse rice varieties with various factors effecting CH_4 emission such as soil properties, soil temperatures, amounts of organic matter added to soil. Similar studies have also been conducted in the U.K. (Cao et al., 1996), and in China (Zaiju and Mingxing, 1996). Kimura et al. (1992) estimated CH_4 emission from paddy fields using soil chemical properties. In Thailand, study of these issues has only recently been initiated for rice growing areas of the northern region.

3. Possible Mitigation options of CH4 emission from rice fields :

The following review of studies about methane emission from paddy field in various countries helps us discover good technique to decrease methane production in paddy field.

3.1 Water management :

Reduction of CH4 production in paddy fields can be achieved by aeration of paddy fields. Multiple soil aeration for few days at 3, 6 and 9 weeks after initial flooding can reduced methane emission by 88% and did not effect crop yield but required 2.7 times more water than normal irrigation (Sass et al. 1992). A single short time soil aeration during mid-tillering or late tillering stage can decreased CH4 emission more than 50% compared with continuous flooding (Kimura, 1992., Sass et al., 1992, Javellana et al., 1995, Wang et al., 1996., Wangfang et al., 1996). The effect of soil aeration on reduction of CH4 emission is confirmed by series of experiments conducted in Asia, such as an experiment conducted in the Philippines demonstrated that a single mid-season drainage reduced CH4 emission from direct seeding by 55.4% while transplanting by 16.7% when compared with continuous flooding (Corton and Bajita, 1998). The results of these experiments are presented in Appendix 2 and 3.

Draining out flooded water to allow soil aeration is unrealistic in some areas. Water supplied through irrigation is uncertain, and cannot be assured at a time irrigation is needed. Moreover, irrigation involves economic costs and careful use is recommended. In general, irrigation requirements varies with cultivation methods (transplanting, wet direct seeding, minimum tillage or dry direct seeding), rice cultivars, soil types, and other environment. Generally, soil preparation for seedling bed, transplanting and wet direct seeding plots, required significant amount of irrigation water, about 330-440 mm. However, water use for rice cultivation can be reduced as being shown by an experiment that flooding paddy through out cropping season is unnecessary. Paddy soil can be flooded and unflooded alternately to keep soil moisture not lower than 85% of AWC (available water capacity) without affecting rice yield. Thus, CH4 emission can be minimized by applying alternate soil aeration and flooding technique. In addition, leaving paddy soil unflooded and naturally dried up help improve efficiency of irrigation.

Subsurface drainage of paddy soil to help reduce emission of CH4 involves investment for an installation of drainage system. Percolation of soil water to subsoil increase O_2 in the surface soil layer, resulting increasing of Eh values and oxidation of CH4 in the soil and also remove organic soluble compounds and CH4 with leaching water to the subsoil or groundwater. Methane transported with groundwater may be released to atmosphere at other site (Kimura, 1992). In paddy soils where percolation rate is 4 mm per day may decrease CH4 emission by 58% (Inubushi et al, 1992).

3.2 Organic matter amendment :

Therefore, incorporation with organic matter rich in easily decomposable carbon such as green manure, fresh rice straw and farmyard manure in flooded soil must be minimized. Prefermentation of farm residues and animal wastes or compost is preferable. Biogas slurry incorporation in paddy soil with urea decreased CH4 emission about 50% compared with farm manure without any significant reduction in grain yield (Goutam Debnath et al. 1996).

3.3 Inorganic fertilizer amendment:

Nitrogen is normally deficit plant nutrient in flooded rice fields. Application of different type of nitrogen fertilizer to paddy soils effects both nitrous oxide and methane formation. Addition of sulfate containing nitrogen fertilizer instead of urea suppresses CH_4 production significantly, particularly ammonium sulfate fertilizer ($(NH_4)_2SO_4$) (Lindau et al. 1993). However, contradicting results were observed when fertilized rice fields with or other sulfate containing fertilizers. Emission of CH_4 either increased (Cicerone and Shetter, 1981), or stayed constant (Wassmann et al., 1993) or decreased (Schultz et al., 1989), due to difference in substrate availability at the measurement sites. Competition between sulfate reducing bacteria and methanogens occurs simultaneously depending on the concentration of the substrate in the soil solution. If substrate for sulfate reducing bacteria is insufficient, CH_4 formation is not restricted. A minimum sulfate concentration is required for sulfate reducers to outcompete methanogens. Loveday and Klug (1983) found the outcompete of methanogens by sulfate reducing bacteria in soil solution with SO_4^{2-} as low as 60 μM. Higher addition of $(NH_4)_2SO_4$ to soil would suppress CH4 formation.

Competition between methanogens and sulfate reducing bacteria in rice fields not only occurs with $(NH_4)_2SO_4$ application but also with soil types, such as saline soil with high sulfate content and acid sulfate soils. Amendment soil with gypsum ($CaSO_4.H_2O$) in sodic soil also results in lower CH_4 formation. Denier and Neue (1994) observed 55-70% reduction in CH_4 emission from soil amended with 6.66 tons.per ha gypsum. Sulfate containing fertilizer is recommended for paddy soils with high content of iron.

3.4 Cultural practices :

Land preparation, transplanting rice seedling, weeding and fertilizer application in the flooded paddy fields cause soil disturbance which release entrapped CH4 to the atmosphere. Such practice should be minimized. Planting by direct seeding (broadcasting pregerminated seed on saturated soil) which is presently encouraged by the government not only cause less entrapped methane release during cropping period but also requires less labor and water than transplanting in irrigated paddies. But entrapped methane may be released during land preparation for direct seeding that ploughing and harrowing must be done several times under flooded condition until the soils become good puddle and leveling.

Dry direct seeding method (broadcasting dry seed on moist paddy filed) is presently increasing in popularity. Harvesting area for dry direct seeding in Thailand increased remarkably from 13.6% to 23.7% of the total area for major rice production in 1989 to 1991, while the area for transplanting decreased from 74 to 65%. This planting method is not only reduced the release of entrapped methane and shortening the period of methane formation but also increase water use efficiency.

3.5 Rice cultivars :

Production and transport of CH4 to the atmosphere appear to depend on rice plant characteristics, both capacity for conducting CH4 and root exudates and degrading roots are important source of organic carbon, especially at the later stage of plant growth. These findings suggest that the selection of existing rice cultivars and/or breeding new cultivars with low exudation could offer an important methane mitigation options.

3.6 Methane production inhibitors :

Chemical compounds inhibiting CH4 production are being under investigation. Some of the effective chemicals are sulfate compounds such as calcium sulfate or gypsum, phosphogypsum, ammonium sulfate and sodium sulfate (Lindau et al. 1993). In studies the slow release of acetylene from calcium carbide, encapsulated in fertilizer granules highly reduced CH4 emission (Bronson and Mosier, 1991). The main limitation of the use of these inhibitors is the cost and availability. At present, the cost gypsum in Thailand is almost the same as ammonium sulfate.

Using methylfluoride as methane inhibitor in field investigation showed that methanotrophic bacteria can consume more than 90% of the methane potentially available (Oremland and Culbertson, 1992) In an experiment, addition of nitrification inhibitor dicyandiamide at the rate 3 kg/ha was found to reduce methane production (Adhya, et al. 1998). Experiments conducted in India by Sethunathan et al.(1998) showed carbamate insecticide, carbofuran and organochlorine insecticide, hexachlorocyclohexane applied to paddy fields appeared to be inhibitory to CH_4 emission. 3.7 Crop rotation systems :

3.7 Crop rotation systems :

Neue et al. (1991) suggest that rotation rice crop with other upland crops is a feasible option to reduce total CH_4 emission and increase production as well as income particularly in the intensive rice production areas. Production of rice in areas where irrigation available all year round is generally increased by growing rice 2 times per year or 5 times per 2 years in the central region of Thailand. Neue et al. (1991) recommended to decrease CH_4 emission by growing other upland crops as rotation crops before or after one or two crops of rice. Various upland crops which can be grown in the paddy before rice cultivation are baby corn, mungbean, cowpeas and after rice cultivation are soybean, corn, cowpea, chicken bean and mungbean. The sequences of cropping rotation applicable for any region should be investigated. Fore example, an experiments conducted in Korea show that planting alfalfa in winter before rice significantly increases more CH_4 emission than wheat or fallow (Xu and Cai,1998).

4. Impacts of CH_4 emission from paddy fields on socio-economics

There are a few studies of this impact of CH_4 emission and mitigation option on the aspect of socio-economics. Various mitigation technologies employed to reduce CH_4 emission may have various affects on farmers. Mitigation technology used may affect rice productivity and labor cost. These affects should be studied to modified mitigation techniques that most suit an area. For example, area with low fertility that can not avoid using organic fertilizer in rice cultivation, a study to find type of organic fertilizer and application method that would give least CH_4 emission is needed. For irrigation area and area with ample of water, an appropriate water management, cropping rotation, mineral fertilization and CH_4 emission inhibitors may be possible for mitigating CH_4 emission, depending on the cost of land leveling, type of irrigation system and chemical compounds, and most of all must be practicable by farmers.

Status of research conducted in Thailand

Research about methane production in paddy field in Thailand remains inadequate although research in such area began several years back. Findings of these researches are as follows.

1. Research findings: Methane emission rates measured in paddy field in Thailand are summarized in **Table 3**. Shown in this **Table** are values for methane emission rate in various paddy areas with diverse influences, including types of soils, addition of organic matters, chemical fertilizer, and rice varieties.

Large variation was observed in emission of methane from different paddy fields in Thailand. The true effect of soil property on CH_4 production was not adequately investigated. Jermsawatdipong et al. (1994), Yaki et al. (1994) and Chareonsilp et al. (1998) found emission of CH_4 from Roi-et soil series, a sandy textured soils, emitted much higher than the mean emission rates from other countries, while emission rate from Rangsit soil series (an acid sulfate soil) was relatively low. The emission of CH4 from paddy fields increases in the order of low humic gley soils (Roi-et soil series) > fresh water alluvial soil (Nakornpathom soil series) > acid sulfate soil (Rangsit soil series). Jermsawatdipong et al. (1994) explained that the high production of CH_4 in Roi-et sandy soils may be due to low in the content of electron donors, Mn^{4+} and Fe^{3+}, causing rapid decrease in soil redox potential to the level that enhance CH_4 production. The very low CH_4 emission measured from Rangsit soil was attributed to the acid sulfate properties, the low pH and active consumption of hydrogen by sulfate reducing bacteria which may suppress the CH_4 production. Chareonsilp et al (1998) compared emission of CH_4 from 6 paddy soils by incubation method and reported that soils pH ranged between 6-7 emitted high amount of CH_4.

Table 3. Methane emission rates from various experiment conducted in Thailand.

Location	Soil series	Range of CH4 flux, mg/m²/hr	Seasonal total g/m²	Experimental treatment	Cropping condition	Reference
Ayutthaya	NAV	3.3 – 7.9	13 – 20	CU, OM, WM	F	Siriratpiriya et al., 1995
Ayutthaya			5		P	Charoensilp et al. 1998
Bang Khen		4.3 - 21.7	16 – 55	SE	F	Minami, 1994; Yaki et al., 1994
Chai Nat		1.6	4		F	Minami, 1994; Yaki et al., 1994
Chiangmai	Hang Dong	3.7 - 5.5	9 – 13	MF, OM	F	Jermsawatdipong et al., 1994.
Chiangmai	Hang Dong	9.0 - 9.5	20 – 21	CU	F	Siriratpiriya, et al., 1995
Chiangmai	Hang Dong	10.4 -16.1	25 – 40	SE	F	Minami, 1994; Yaki et al., 1994
Khlong Luang		3.8	8		F	Minami, 1994; Yaki et al., 1994
Khon Kaen		23	76		F	Minami, 1994; Yaki et al., 1994
Nakornpathom		9.4 - 12	25 – 32	SE	F	Tawprayoon et al., 1991.
Pathumthani	Rangsit	1.9 - 4.6	5 –11	MF, OM	F	Jermsawatdipong, et al., 1994.
Pathumthani	Rangsit		16		P	Charoensilp, et al. 1998
Phitsanulok		6.6 - 7.2	17 – 18	SE	F	Katoh et al., 1995
Phrae		16.6 - 22.2	51 – 69	SE	F	Minami, 1994; Yaki et al., 1994
Ratchaburi	Nakorn pathom	3.2 - 42.5	9 – 117	MF, OM	F	Jermsawatdipong, et al., 1994
Surin	Roi-et	15 - 24.5	41 – 66	MF, OM	F	Jermsawatdipong, et al., 1994
Surin	Roi-et	13.3	41		F	Minami, 1994; Yaki et al., 1994
Suphanburi		19.5 - 32.2	51 – 75	SE	F	Minami, 1994; Yaki et al., 1994

Experimental treatment; CU-cultivars, MF-fertilizer, OM-organic matter, SE-seasons(early and late rice or dry and rainy season) Cropping condition ; F - field , P – pot

NAV – not available

Source: modified from IPCC, 1995.

Addition of organic matters in paddy field is an important issue. Such practice increases rice yield and is essential for infertile soil, such as sandy soil, acid sulfate soil and saline soil. Addition of organic matters to infertile soil increases plant nutrients and improves soil physical properties. Several long term experiments have been conducted in unfertile soils to improve soil productivity by addition of organic matters, including type of organic materials, method of addition, optimum rate for improved paddy yield and optimum combination with chemical fertilizer. In Thailand, organic matter generally applied to paddy soils, are dry rice straw, green manure, compost and farmyard manure, all of them contributes to CH_4 production. Incorporated green manure (*Sesbania rostrata*) prior to transplanting in fresh water alluvial soils in Ratchaburi Province and addition of dry rice straw to acid sulfate soil (Rangsit soil series) in Pathumthani Province were found to produce high emission of CH_4. Moreover, addition of manure and green manure in combination with chemical fertilizer in low fertile soil (Roi-et soil series) in Ubol Rachathani at government recommended low application rate contributes less CH_4 emission than addition of chemical fertilizer at high rate, but addition of green manure results in higher grain yield (**Table 4**). Rice straw incorporated after harvest did not effect CH_4 emission from paddy field cultivated in the following crop year in sandy soil of the north-eastern region of Thailand as easily decomposable organic compounds were completely decomposed (**Table 5**). This practice is currently being tested as a mean to reduce bulk density of fine sandy textured soil, making transplanting more easier.

Table 4. Methane emission from Roi-et soil with different government recommended rate of mineral fertilizer application and organic fertilizers.

Fertilizer treatment	Seasonal emission g/m2	Average emission rate G/m2/d	Grain yield kg/ha	$KgCH_4$/ kg grain yield
Check	41.1	0.324	2,267	0.181
High rate	57.3	0.451	2,509	0.228
Low rate+Farm yard manure	49.3	0.388	2,521	0.196
Low rate+Green manure	41.1	0.324	2,873	0.143

The most common strategy to increase rice production in problem and infertile soil, coarse textured soil, saline soil, is to combine chemical fertilizer with organic fertilizers, particularly, green manure. Recommendation by Land Development Department after conducting series of long term experiments that coarse textured saline soil should be incorporated with organic matter such as manure, green manure, compost, and hull at the rate of 2 tons per rai at soil preparation stage. Any types of organic fertilizer incorporation resulted indifferent in terms of grain yield output and green manure seems to be the most preferable. Although, at present, no reports are found about the effect of salt concentration in soil solution in paddy soil in Thailand on activities of methanorganics, but addition of organic matters to soil at a high rate, particularly easily decomposable type, are likely to enhance CH_4 production. Thus, comprehensive studies are needed to determine types and methods of organic matter incorporation for minimum CH_4 production in paddy field.

Table 5. Methane emission from paddy fields as affected by mineral fertilizer application and incorporation rice straw after harvesting of previous crop.

Fertilizer Treatment	Seasonal CH_4 emission, g/m^2		Rice Yield, kg/ha	
	No OM/1	With OM/2	No OM/1	With OM/2
Check	24.6	21.3	1,378	1,501
Low rate	37.5	33.3	2,038	2,017
High rate	42.2	48.6	2,463	2,456

/1 no rice straw incorporation after harvest

/2 with rice straw incorporation after harvest

Moreover, popular practice of farmers in the central region is to burn rice straw by fire after harvest, a practice which not only kills insects and plant diseases, but also neutralizes soil acidity and for convenience in soil preparation. Charoensilp et al. (1998) have shown, for deep water rice cultivation, that incorporation of rice straw burning caused lowest CH_4 emission when compared with rice straw compost and dry rice straw incorporation while no significant effect was observed on grain yield (Table 6).

Fertilization of paddy soil was found to affect level of methane emission. Study in sandy soil of the north eastern region found fertilization of sandy paddy soil of Roi-et series at the recommended high rate increases methane emission by 30% as compared with the recommended low rate (Table 5). Further more, Table 7 shows addition of ammonium sulfate ($(NH_4)_2SO_4$) as top dressing fertilizer decreases CH_4 emission compared to addition of urea. Fertilization with mixed straight fertilizers (urea or ammonium sulfate and triple super phosphate) resulted in lower methane emission from paddy field than fertilization with commercial grade compound granulation fertilizer. Incorporation of ammonium sulfate with basal fertilizer uses as top dressing fertilizer can decrease methane emission even further (unpublished data).

Table 6. Methane emission and yield of deep water rice as affected by straw management.

Year/ Season	Treatment	CH_4 emission, Kg CH_4/ha	Yield T/ha
1994ws	Straw burned	182	3.1
	Chemical fertilizer	178	3.0
	Check	175	3.4
1995ws	Straw burned	10	2.9
	Chemical fertilizer	12	3.6
	Straw incorporate	18	2.8
1996ws	Straw burned	72	2.9
	Straw incorporate	630	3.6
	Zero tillage+mulching	146	2.8
1997ws	Straw burned	65	1.3
	Straw compost	147	1.2
	Zero tillage+mulching	101	1.2

Table 7. Methane emission from paddy fields as affected by mineral fertilization.

Fertilizer Treatment		Mean emission Rate, $g/m^2/d$	
Basal	Top dressing	With rice straw	No Rice straw
Commercial compound fertilizer	Urea	0.297	0.1927
Commercial compound fertilizer	AS[/1]	0.2777	0.1180
Mixed straight fertilizer (TSP[/2]+Urea)	Urea	0.3060	0.16267
Mixed straight fertilizer (TSP+Urea)	AS	0.357	0.1430
Mixed straight fertilizer (TSP+AS)	AS	0.212	0.1110

[/1] ammonium sulfate; [/2] triple super phosphate

Rigorous study focussing on relationship between rice varieties and methane emission in Thailand remains unfounded. Rice cultivars of photosensitive type remains popular for Thailand's major rice cultivation. Over eighty per cent of rice planted consisted of local varieties, RD6 and KDL105. Non-photosensitive varieties, such as Chainat and Suphanburi are popular for second rice. There are two new interesting aromatic rice varieties, recently released by Rice Research Institute, Department of Agriculture, Ministry of Agriculture and Cooperative. These varieties are non-photosensitive, Chao Hom Klong Luang 1 (HKLG1) and Chao Hom Supanburi (HSPR), thus appropriated for planting in both major and second rice cultivation. The yield and quality of these new rice varieties are satisfactory commercially and now increasing in cultivation area.

Rates of CH4 emission by diverse rice varieties are shown in **Table 8**. In field experiment by Chareonsilp, et al.(1998), three high yield varieties were found to produce indifferent methane levels. In pot experiment by Jermsawatdipong (unpublished data), high yield--non-photo sensitive--hybrid rice varieties--RD21 and RD23 were found to produce more methane than high yield--photo sensitive--hybrid rice varieties. The photo-sensitive PT60 and KDL105 varieties were found to produce more methane than other varieties. However, these findings should be cohfirmed by further field test.

Table 8. Methane emission rate of various rice cultivars in Thailand.

Crop cultivar	Emission rate	References
Non-photosensitive type :		
RD7[/1]	12.4	Jermsawatdipong (unpublished)
RD21[/1]	16.5	Jermsawatdipong (unpublished)
RD23[/1]	14.9	Jermsawatdipong (unpublished)
RD25[/1]	10.7	Jermsawatdipong (unpublished)
IR72[/2]	93.2	Chareonsilp, et al.1998
Poe-Thong[/2]	42	Chareonsilp, et al.1998
SPR1[/2]	43	Chareonsilp, et al.1998
SPR60[/2]	44	Chareonsilp, et al.1998
Photosensitive type:		
Ply-Ngarm[/2] (deep water rice)	50.4	Chareonsilp, et al.1998
RD27[/1]	7.5	Jermsawatdipong (unpublished)
PT60[/1]	14.6	Jermsawatdipong (unpublished)
KDL105[/1]	11.2	Jermsawatdipong (unpublished)
LPT123[/1]	9.2	Jermsawatdipong (unpublished)

[/1] Pot experiment, emission rate is in mg CH4 /d

[/2] Field experiment, emission rate is in mg CH4 /m2/d

Although, CH_4 emission from paddy fields can be substantially reduced by water management, duration and timing of soil aeration, only one experiment was conducted in the central region in 1998 (Jermsawatdipong, unpublished). She found multiple soil aeration at day 30 and 45 after sowing germinated seed is more effective in reducing CH_4 emission (30-40%) than single aeration at day 40 (18%) (Table 9). The results of various experiments conducted oversea also suggest that aeration of paddy soils can be one of the promising options in reducing CH_4 emission which can be adopted to extend in the irrigated area for mitigation strategies.

Table 9 Methane emission from paddy fields under different water regimes in Nakornpathom, Thailand.

Water Regime	Mean emission rate, (g/m2/d)	
	Normal	+Rice straw
Continuous flooding	1.08	1.73
Drainage at day 30 and 45 after planting	0.76	0.97
Natural dry at day 30 after planting	0.88	1.24
Natural dry at day 30 and 45 after planting	0.63	1.20
Long period natural dry at day 30 after planting	0.71	0.76

There is no report about relationship between soil micro-organism and methane production in Thailand. Study of this relationship is crucial for reducing methane production in paddy field.

2. Method of measurement : Most studies of methane production in paddy field apply static closed chamber technique with manual sampling. However, methane emission varies greatly depending on time of day and stage of growth. Therefore, times of collecting samples are crucial. Weaknesses of studies in Thailand are inconsistent sampling method. For example, Siriratpiriya et al (1996) 's only 4 samples per season could hint some doubt if the data are reliable. Analyses of data collected continually by automatic sampling system in four countries suggest sampling must be more frequent at time of high variation, including from planting to panicle initiation stage, from flowering to harvesting period, and sampling time at 6.00 am, 12.00 p.m. and 18.00 p.m. The more warranted practice is to obtain samples at seven day interval for the whole period of vegetative growth stage, and sampling of 1-2 times per day at about 9 am and 3 p.m., at which time samples are likely to show values closed to whole day average.

International Rice Research Institute designed apparatus with instruction manual for measuring methane in paddy field. The apparatus consists of 1) base module of 60x60 cm made of galvanized iron and installed permanently in paddy fields, 2) cover module made of clear plexiglass equipped with small electric fan and sampling port, 3) extension model made of clear plexiglass. The cover module is placed on to the base module only when taking gas sample. The detail drawing of the chamber is presented in Appendix 11. Algas project (A Study of Least Cost Abatement Strategy for Asia), a project initiated by Asian Development Bank, has adopted this method as a standard method and has organized training workshops with participants from Asian countries (Thailand, Republic of Korea, India, Indonesia, Philippines, China, Myanmar, Vietnam).