

Rice Agriculture: Factors Controlling Emissions

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1. Introduction

Recent atmospheric measurements indicate that concentrations of greenhouse gases are increasing. Atmospheric methane concentration has increased at about 1% annually to 1.7 ppmV during the last decades (Khalil and Rasmussen, 1987). The resulting effect on global temperature is highly significant because the warming efficiency of methane is up to 30 times that of carbon dioxide (Dickinson and Cicerone, 1986). Data from polar ice cores indicate that tropospheric methane concentrations have increased by a factor of 2-3 over the past 200-300 years (Khalil and Rasmussen, 1989). The increase of methane concentrations in the troposphere correlate closely with global population growth and increased rice production (Figure 1), suggesting a strong link to anthropogenic activities. The total annual global emission of methane is estimated to be 420-620 Tg/yr (Khalil and Rasmussen, 1990), 70-80% of which is of biogenic origin (Bouwman, 1990). Methane emissions from wetland rice agriculture have been estimated up to 170 Tg/yr, which account for approximately 26% of the global anthropogenic methane budget. Flooded ricefields are probably the largest agricultural source of methane, followed by ruminant enteric digestion, biomass burning, and animal wastes (summarized by Bouwman, 1990).

Projected global population levels indicate that the demand for rice will increase by 65% over the next 30 years, from 460 million t/yr today to 760 million t/yr in the year 2020 (IRRI, 1989). The growing demand is most likely to be met by the existing cultivated wetland rice area through intensifying rice production in all rice ecologies, mainly in irrigated and rainfed rice. Coupled with existing rice production technologies, global methane emissions from wetland rice agriculture are likely to increase. Mitigation of methane emissions is needed to

stabilize or even lower atmospheric methane concentrations.

This paper discusses principles and prospects of rice cultivation in view of methane formation, methane fluxes, and mitigation options.

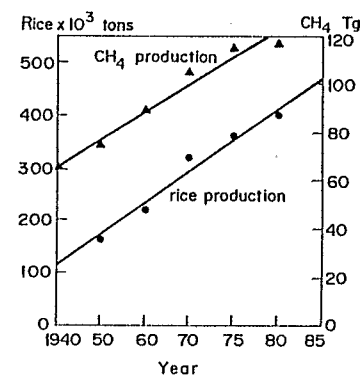


Figure 1. Rice production and methane emission rates.

2. Rice environments

Rice is cultivated under a wider variety of climatic, soil, and hydrological conditions than any other crop. It is grown from the equator to as far as 50°N and 40°S, and from sea level to altitudes of more than 2500 m. The temperature may be as low as 4°C during the seedling stage and as high as 40°C at flowering. Rice is irrigated in arid areas and is grown in rainfed areas with only 500 mm rain/yr. Rice is cultivated as an upland crop and in soils that are submerged more than 1 m. Rice is the only major crop grown on flooded soils.

Rice cultural systems have developed to suit the physical, biological, and socioeconomic conditions of different regions. Because the water regime during the growing season is the most discriminating physical factor, ricelands can be grouped into two main systems: wetlands and uplands. Terms used to differentiate rice cultures are, for example, lowland rice, irrigated rice, rainfed rice, deepwater rice, swamp rice, upland rice, hill rice, dryland rice, and pluvial rice. Many other terms have been evolved in different regions reflecting specific characteristics of and constraints to rice cultivation in these areas. These terms reflect the wide range of agroecologies in which rice is grown and are very reasonable in the context they evolved. But the general use of these terms,

although understandable, is often semantically and technically incorrect (Moormann and Van Breemen, 1978). A comprehensive classification of rice ecologies has been outlined by Neue (1989). He defined three major rice ecologies with a total of seven subecologies by hierarchically applying floodwater source and floodwater depth as diagnostic criteria (Table 1). Further differentiation is done by modifiers related to climate, landform, floodwater regime, soil, and cropping system.

Table 1. Classification of rice ecologies.

Floodwater source	Irrigation		Pluvial, phreatic, surface flow or tidal				
	1-5	5-25	0-25	25-50	50-100	>100	<0
Rice ecologies	-- Irrigated rice --		-- Rainfed rice --			Upland rice	
Subecologies	Shallow	Medium	Shallow	Medium	Deep	Very deep	Upland rice
Land ecosystem	-- Wetland --					Upland	

Rice ecologies are major discriminators for the potential of methane production in ricefields because of their distinct floodwater regimes. The potential of upland rice for methane production is not significant since upland rice is never flooded for a significant period of time. Aerobic soils, including upland rice soils, seem to be important sites for deposition and microbial oxidation of atmospheric CH₄ (Seiler and Conrad, 1987; Cicerone and Oremland, 1988). Irrigated rice has the highest potential to produce CH₄ because flooding and, consequently, anoxic conditions are assured and controlled. The potential for methane production in rainfed rice should vary widely in time and space since floodwater regimes are primarily controlled by rainfall within the watershed. Periods of severe droughts or floods during the growing season are characteristic for rainfed rice. Subecologies are determined by floodwater depth, which likely affects methane fluxes. Emission rates and harvested area of each rice ecology determine the global methane emission. Rice areas harvested in different regions of the world are given in Table 2.

Table 2. Distribution of harvested ricelands (million ha) by rice ecologies (FAO, 1988).

Region	Irrigated	Rain-fed	Deep water	Upland	Total area	Yield (t/ha)	Rough rice production (10 ⁶ ton)
East Asia ^a	34.0	2.8	-	-	36.8	5.4	200.0
Southeast Asia ^b	13.9	13.7	3.75	4.65	36.0	2.9	102.5
South Asia ^c	19.4	20.0	7.3	6.7	53.4	2.0	105.5
Near East ^d	1.25	-	-	-	1.25	3.3	4.1
South/Central Am. Caribbean and USA	2.5	0.5	0.4	5.65	9.05	2.9	26.5
Africa	0.9	1.95	-	2.70	5.5	1.8	9.9
USSR	0.66	-	-	-	0.66	4.1	2.7
Europe	0.42	-	-	-	0.42	5.4	2.3
Oceania	0.12	-	-	-	0.12	6.6	0.79
Australia	0.11	-	-	-	0.11	7.1	0.76
World	73.26	38.95	11.45	19.70	143.4	3.2	455.05

^aChina Taiwan Korea DPR Korea RP Japan; ^bBurma Cambodia Indonesia Laos Malaysia Philippines Thailand Vietnam; ^cBangladesh Bhutan India Nepal Pakistan Sri Lanka; ^dAfghanistan Iran Iraq.

Especially since the 1960s, rice production dramatically increased because of high-yielding rice cultivars, large investments in irrigation schemes, and improved soil, water, and crop management. The developed irrigation schemes and the shorter growth duration of modern cultivars increased the harvested area by allowing 2 to 3 crops per year. However, expansion of residential and industrial areas as well as diversification of crops resulted in only a slight increase in the total harvested area of rice (Figure 2). Though many factors determine the relative contribution of each rice ecology to rice supplies in the future, irrigated areas will continue to dominate rice production. At present, about 50% of the harvested area is in irrigated rice but it contributes about 70% of total production.

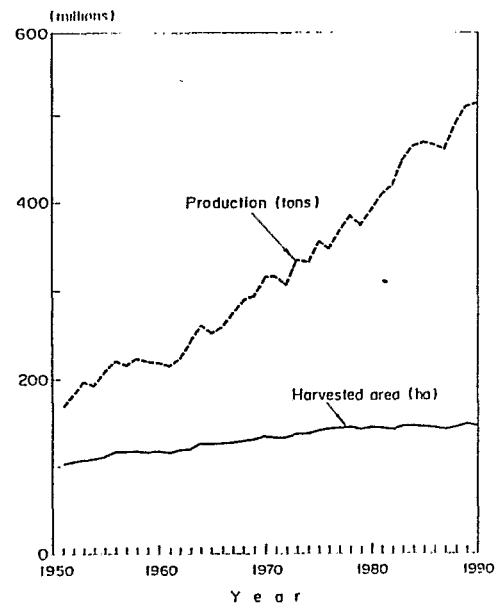


Figure 2. Rough rice production and harvested area (IRRI, 1991)

3. Microbiology of methane emission

3.1 Methanogens. Biogenic methane production is exclusively accomplished by methanogenic bacteria that can metabolize only in strict absence of oxygen and at redox potentials of less than -200 mV. Oxygen causes an irreversible disassociation of the F_{420} -hydrogenase enzyme complex probably due to the lack of protective superoxide dismutase (Schönheit et al., 1981). Methanogens are found in strictly anaerobic environments of freshwater, brackish and marine sediments, hot springs, mid-ocean ridges, decomposing algal mats, heart wood of living trees, intestinal tracts of man and animals (especially the rumen of herbivores), and sewage digesters. In ricefields, methanogenesis occurs in the reduced soil of wetland rice and, possibly, in anoxic water of deepwater rice.

Recent reviews on methanogenic bacteria deal with their biogeochemistry (Oremland and Capone, 1988; Boone, this volume), taxonomy, and ecology (Garcia, 1990).

Table 3. Simplified classification of methanogenic bacteria (adapted from Garcia 1990) and their habitat (Garcia, ORSTOM, personal communication).

<u>Methanobacteriales</u>	
Methanobacteriaceae	
<i>Methanobacterium</i>	Various freshwater habitats. Half of the species are thermophilic; few are alkaliphilic.
<i>Methanobrevibacter</i>	Specialized habitats such as trees (Zeikus and Henning, 1975), rumen (Smith and Hungate, 1958), sewage sludge, intestinal tracts of animals (Miller and Wolin, 1985).
<i>Methanosphaera</i>	Feces or digestive tracts of animals (Biavatti et al., 1988).
Methanothermaceae	
<i>Methanothermus</i>	Extreme thermophile from volcanic springs
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<u>Methanococcales</u>	
Methanococcaceae	
<i>Methanococcus</i>	Isolated mostly from marine or coastal environments
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<u>Methanomicrobiales</u>	
Methanomicrobiaceae	
<i>Methanolacinia</i>	Marine sediments.
<i>Methanospirillum</i>	Mesophilic strains from various habitats.
Methanoculleus	
<i>Methanocorpusculum</i>	Sewage sludge lacustrine sediments (Zhao et al., 1989).
<i>Methanomicrobium</i>	
<i>Methanogenium</i>	
Methanoplanaceae	
<i>Methanoplanus</i>	Symbiont of marine ciliate.
Methanosarcinaceae	
<i>Methanosarcina</i>	Freshwater and marine sediments, ricefields, lagoons, anaerobic sewage-sludge digestors, and rumen (Raimbault, 1981).
<hr/>	
Genera not ascribed to a family (mostly isolated from salty biotopes):	
<i>Methanolobus</i> <i>Methanococcoides</i> <i>Methanohalophilus</i> <i>Halomethanococcus</i> <i>Methanohalobium</i> <i>Methanohalobium</i> <i>Methanohalobium</i> <i>Methanohalobium</i> <i>Methanohalobium</i>	

Twenty genera of methane-producing bacteria have been described (Table 3) but only a few, including *Methanobacterium* and *Methanosarcina*, have been isolated from rice soils (Rajagopal et al., 1988). *Methanospirillum* and *Methanocorpusculum*, which were isolated from freshwater sediments, as well as methanogens found as endosymbionts in sapropelic amoeba should also be present in wetland ricefields (Garcia, ORSTOM, personal communication).

The distribution of methanogens in natural environments depends on their adaptation to temperature, pH, and salinity ranges. Most methanogens are mesophilic with temperature optima of 30-40°C. Thermophilic (40-70°C) species account for 20% of the strains (Garcia, 1990) and some extreme thermophilic (up to 97°C) are also known. Most methanogens are neutrophilic with a relatively narrow pH range of 6-8. A few alkaliphilic isolates with optimum growth at pH 8-9 have been reported in the genera *Methanosarcina*, *Methanobacterium* (Blotevogel et al., 1985; Worakit et al., 1986), and *Methanohalophilus* (Mathrani et al., 1988). No acidophilic strains have been reported. A strain isolated from peat tolerated a pH of 3, but its optimum was 6-7 (Williams and Crawford, 1984, 1985).

Methanogens can only metabolize a limited number of simple carbon compounds and hydrogen availability is a key factor for methanogenesis. As summarized by Garcia (1990):

Hydrogenotrophic methanogens (77% of the 68 described species) oxidize H_2 and reduce CO_2 to form methane. According to Conrad et al. (1985), H_2 -dependent methanogenesis in sediments results mostly from H_2 transfer between microbial associations within flocks or consortia.

Methylotrophic methanogens (28% of the species) can use methyl compounds as methanol, methylamines, or dimethylsulfide; 10 species have been identified as obligate methylotrophs.

Acetotrophic methanogens (14% of the species) utilize acetate. The growth of virtually all methanogens is stimulated by acetate and its importance as a methane precursor in sediments has been documented (Cappenberg, 1974; Cappenberg and Prins, 1974; Winfrey and Zeikus, 1977). Sixty percent of the hydrogenotrophic species also use formate. A few species use H_2 to reduce methanol to methane (hydrogeno-methylotrophic methanogens); others form methane in the presence of CO_2 and alcohols as hydrogen donors (alcoholotrophic methanogens). The importance of methanol and methylated

amines as methane precursor in sediments varies with the abundance of decomposing plant materials such as algal mats (King, 1988). Methanol and methylated amines might be abundant in wetland ricefields after fertilizer application has induced the formation of large algal mats.

Methanogenesis in sediments is characterized by a complete degradation of organic matter while in the rumen of ruminants and the intestine of most animals, mineralization is incomplete since intermediate products are absorbed as food. The anaerobic degradation of organic matter to methane in sediments requires the cooperation of several types of bacteria within a substrate chain to provide the simple carbon compounds needed by methanogens. According to Conrad (1989), four types of bacteria are needed: a) hydrolytic and fermenting bacteria, b) H^+ -reducing bacteria, c) homoacetogenic bacteria, and d) methanogenic bacteria. The first group hydrolyzes polymers and ferments the resulting monomers to smaller molecules such as alcohols, short chain fatty acids, H_2 , and CO_2 . Methanogens can immediately convert H_2/CO_2 , formate, acetate, and a few other simple compounds including methanol, methylamines, and dimethylsulfide to CH_4 and CO_2 . Fermentation products such as fatty acids, alcohols, aromates, and others cannot directly be utilized. They are oxidized by obligate H^+ -producing bacteria to acetate and CO_2 . Homoacetogens are very versatile bacteria that can use sugars, alcohols, fatty acids, purines, and aromatic compounds as well as methanol, formate, H_2 , and CO_2 to produce acetate as the sole fermentation product (Dolfing, 1988).

All methanogens use NH_4^+ as a nitrogen source, and a few species are known to fix molecular nitrogen (Belay et al., 1984; Murray and Zinder, 1984).

3.2 *Inhibitors of methane formation.* Mineral terminal electron acceptors like nitrate or sulfate inhibit methanogenesis in sediments by channeling the electron flow to thermodynamically more efficient bacteria like denitrifiers or sulfate reducers (Balderston and Payne, 1976; Ward and Winfrey, 1985). Manganese and iron oxides should have the same effect. Methanogens, sulfate-reducers and homoacetogenic bacteria compete for H_2 produced by fermentative bacteria. Hydrogenotrophic homoacetogens do not significantly compete with methanogens for H_2 in sediments (Lovley and Klug, 1983). Since H_2 concentration is usually very low in such environments (Strayer and Tiedje, 1978), sulfate reducers are able to out-compete hydrogenotrophic methanogens in the presence of sulfate because of their higher affinity for H_2 and faster growth

(Winfrey and Zeikus, 1977; Abram and Nedwell, 1978).

NaCl inhibits pure cultures of methanogens, though high concentrations (about 0.2 M) are required for several strains (Patel and Roth, 1977). In general, adding NaCl to a nonsaline soil inhibits methanogenesis (Koyama et al., 1970). Methanogenesis is inhibited by brackish water (Garcia et al., 1974, De Laune et al., 1983, Holzapfel-Pschorn et al., 1985, Bartlett et al., 1987). Inhibitory effects and interactions with sulfate-reducing bacteria are given as possible reasons (Mitsch and Gosselink, 1986). Competition for H_2 and toxicity of sulfide are the likely mechanisms. However, methanogenesis and sulfate reduction are not mutually exclusive when methane is produced from methanol or methylated amines for which sulfate reducers show little affinity (Oremland et al., 1982; Oremland and Polcin, 1982; Kiene and Visscher, 1987). Methanol is formed during anaerobic decomposition of plant pectins (Schink and Zeikus, 1980). In saline environments, degradation of osmoregulatory compounds such as glycinebetaine produces methylamines (King, 1984). Obligately methylotrophic methanogens constitute about half of the methanogenic population present in salt marsh sediments (Franklin et al., 1988), and methylotrophs are found in rice soils (Rajagopal et al., 1988).

Chemical substances inhibiting methanogenesis have been reviewed by Oremland and Capone (1988). The 2-bromoethane-sulfonic acid (BES), an analog to Coenzyme M, is a specific inhibitor of methanogenesis. Several chlorinated CH_4 analogues such as chloroform and methyl chloride have been identified to inhibit methanogenesis. Chloroform completely suppressed methane production in a paddy soil but did not hamper the turnover of glucose (Krumböck and Conrad, 1991) although evidence for glucose-utilizing H_2 -syntrophic methanogenic bacterial associations has been found in glucose amended paddy soil (Conrad et al., 1989). Substances encountered in ricefields that inhibit methanogenesis and methane oxidation include DDT (McBride and Wolfe, 1971), acetylene (Raimbault, 1975), and nitrapyrin, an inhibitor of nitrification (Salvas and Taylor, 1980). Slow release of acetylene from calcium carbide, encapsulated in fertilizer granules highly reduced methane emission (Bronson and Mosier, 1991).

3.3 Methane-oxidizing bacteria. Methane oxidation may greatly limit the flux of CH_4 to the atmosphere (Bont et al., 1978). Holzapfel-Pschorn et al. (1986) reported that 67% of the CH_4 produced during a rice growing season in

an Italian ricefield was oxidized. Sass et al. (1991) found that 58% was oxidized in a Texas ricefield. Schütz et al. (1989) reported that up to 90% of CH_4 generated at the late growth stage was oxidized.

Methane can be oxidized by aerobic and anaerobic bacteria. Several reviews have been published on methane-oxidizing bacteria and aerobic methane oxidation (Whittenbury et al., 1970 a,b; Higgins et al., 1981; Anthony, 1982; Crawford and Hanson, 1984). Aerobic methane-oxidizing (methanotrophic) bacteria constitute a group of eubacteria that grow only on methane or carbon compounds lacking carbon-carbon bonds such as methanol, formate, and methylated amines. One species (*Methylobacterium organophilum*) can also grow on more complex organic compounds in combination with methane (Patt et al., 1974). All aerobic methanotrophs sequentially oxidize CH_4 to CO_2 via methanol, formaldehyde, and formate. Oxygen is essential for the growth of methane-oxidizing bacteria, but the required partial pressure may be low (Cicerone and Oremland, 1988), especially when methanotrophs fix nitrogen (Murrell and Dalton, 1983) or grow with nitrate as a nitrogen source (Toukdarian and Lidstrom, 1984). Aerobic methanotrophs, which require both methane and oxygen, are most active in ricefields at the interface of aerobic and anaerobic environments (floodwater-soil interface, rice rhizosphere).

Anaerobic oxidation of methane is poorly understood but appears to be an important methane sink in sulfate-containing environments, such as marine sediments or anoxic water (Alperin and Reeburgh, 1984; Iversen et al., 1987). The process has also been reported to occur in freshwater systems (Panganiban et al., 1979).

4. Flooded rice soils as site for methane emission

In general, flooded rice soils provide an optimum environment for methane production and emission, especially in the tropics. Flooding a soil causes the essential low redox potential and anaerobic decomposition of organic matter and stabilizes the soil pH near neutral. In the tropics, the temperature of the reduced puddled layer becomes optimal for methanogenesis. Rice plants highly enhance the emission of methane. Variations in methane fluxes from rice paddies are caused by variations in soil properties, crop management, and related growth of rice.

4.1 *Rice soils.* Neue (1989) characterized a typical soil profile of a flooded rice soil during the middle of a growing season as follows:

<u>Horizon</u>	<u>Description</u>
Ofw	A layer of standing water that becomes the habitat of bacteria, phytoplankton, macrophytes (submerged and floating weeds), zooplankton, and aquatic invertebrates and vertebrates. The chemical status of the floodwater depends on the water source, soil, nature, and biomass of aquatic fauna and flora, cultural practices, and rice growth. The pH of the standing water is determined by the alkalinity of the water source, soil pH, algal activity, and fertilization. Because of the growth of algae and aquatic weeds, the pH and oxygen content undergo marked diel fluctuations. During daytime, the pH may increase up to 11 and the standing water becomes oversaturated with O ₂ due to photosynthesis of the aquatic biomass. Standing water stabilizes the soil water regime, moderates the soil temperature regime, prevents soil erosion, and enhances C and N supply.
Apox	The floodwater-soil interface that receives sufficient O ₂ from the floodwater to maintain a pE + pH above the range where NH ₄ ⁺ becomes the most stable form of N. The thickness of the layer may range from several mm to several cm depending on pedoturbation by soil fauna and the percolation rate of water.
Apg	The reduced puddled layer is characterized by the absence of free O ₂ in the soil solution and a pE + pH low enough to reduce iron oxides.
Apx	This layer has increased bulk density, high mechanical strength, and low permeability. It is frequently referred to as plow pan or traffic pan.
B	The characteristics of the B horizon depend highly on water regime. In epiaquic moisture regimes the horizon generally remains oxidized, and mottling occurs along cracks and in wide pores. In aquic moisture regimes, the whole horizon or at least the interior of soil peds remain reduced during most years.

The chemistry and biology of rice soils have frequently been reviewed (Ponnamperuma, 1972, 1981, 1984a, 1985; Patrick and Reddy, 1978; De Datta, 1981; Watanabe and Roger, 1985; Yu, 1985; Patrick et al., 1985; Roger et al., 1987; Neue, 1988).

The duration and pattern of flooding and saturation are important criteria for methane formation. Saturation can be caused by groundwater (aquic moisture regime) or surface water (epiaquic moisture regime). Flooding an air-dried cultivated soil drastically changes the hydrosphere, atmosphere, and biosphere of that soil. Flooding highly limits diffusion of air into the soil. The O₂ supply cannot meet the demand of aerobic organisms, and facultative and anaerobic organisms proliferate using oxidized soil substrates as electron acceptors in their respiration. Consequently, the redox potential falls sharply according to a sequence predicted by thermodynamics and CO₂ and HCO₃⁻ concentrations increase to very high levels. As a result, the soil pH of acid soils increases while that of sodic and calcareous soils decreases, stabilizing between 6.5 and 7.2. Flooding and puddling render most soils an ideal growth medium for rice by supplying abundant water, buffering soil pH near neutral, enhancing N₂ fixation, and increasing diffusion rates, mass flow, and availability of most nutrients. In less favorable soils, flooding may result in toxicities of Fe, H₂S, or organic acids, or deficiencies of Zn or S.

The anaerobic fermentation produces an array of organic substances, many of them transitory and not found in aerobic soils. The major gaseous end products are CO₂, H₂S, and CH₄. The description of the paddy soil profile clearly indicates that methane formation mainly takes place in the reduced Apg horizon. In aquic moisture regimes, the B horizon may also become a source of methane. But in general carbon contents of B horizons are low and their organic matter is less degradable. In epiaquic moisture regimes, methane oxidation may predominate in the B horizon. The same holds true for the Apox layer. Harrison and Aiyer (1913) established early on that all methane diffusing into the aerobic surface layer is oxidized. This was reconfirmed by Bont et al. (1978). They found that 10 ml of a suspension of rice soil oxidized 2 ml of methane within 24 hours when incubated aerobically. Methane may also be oxidized in shallow floodwater since it is often oversaturated with O₂ due to assimilation of the aquatic flora.

In deepwater ricefields, the deeper layers of the floodwater may also become anoxic during the crop cycle (Whitton and Rother, 1988), permitting methanogenesis from the large quantity of organic material available from rice culms, nodal roots, and dead aquatic biomass.

4.2 *Temperature regimes of rice soils.* Rice is grown under widely differing temperature regimes. The temperature of flooded soils at planting may range from 15°C in northern latitudes to 40°C in equatorial wetlands. Rice physiologists have studied extensively the effects of air and water temperature on rice growth characteristics (Matsushima et al., 1964 a,b; Yoshida, 1981), but there is only little information on the temperature regimes of flooded rice soils and their effects on the chemistry of the soils (Kondo, 1952; Cho and Ponnampereuma, 1971; Gupta, 1974; Sharma and De Datta, 1985). Seasonal and diel temperature changes likely influence methane formation and emission. Holzapfel-Pschorn and Seiler (1986) reported a marked influence of soil temperature on the methane flux with doubling of emission rates when temperature increased from 20 to 25°C. Diel variation of methane emission is correlated with temperature fluctuation (Schütz et al., 1989).

Most isolates of methanogenic bacteria are mesophilic with temperature optima of 30 to 40°C (Acharya, 1935; Vogels et al., 1988). Psychrophilic acetate-utilizing methanogens with a temperature optimum below 20°C seem to occur in acidic peat, which generally shows substantial rates of methane production (Svensson, 1984). The temperature optimum for the production of methanogenic substrates by fermenting bacteria may not concur with the optimum for methanogenesis. In subtropical regions or at high altitudes, the accumulation of intermediate metabolites may reach toxic levels, especially early in the rice-growing season, because of low temperatures. Specific drainage techniques with increased percolation rates and/or intermittent aeration periods are practiced to remedy such accumulations. In tropical lowlands, high temperature throughout the growing seasons stimulates degradation and methane production.

In flooded conditions, soil temperature varies in response to the meteorological regime acting upon the atmosphere-floodwater and floodwater-soil interfaces. The changing properties of soil and floodwater (i.e., temporal changes in reflectivity, heat capacity, thermal conductivity, incoming water temperature, and water flow) as well as vegetation interact with these external influences. Hackman (1979) reported that floodwater temperatures are above minimum air temperature but below maximum air temperature if daily amplitudes of air temperature are high, while water temperatures are above maximum air temperatures if daily fluctuations are low. Neuc (1988) reported that floodwater temperature in Philippine ricefields always exceeded ambient air temperature and

showed lower daily fluctuations. The temperature of the puddled layer closely followed the temperature of the floodwater and decreased with depth. The annual mean soil temperature at 2:00 p.m. was 33°C at 7 cm depth, its daily maximum equaled or exceeded the maximum air temperature on most days.

Floodwater transmits short-wave radiation to the soil while reducing the upward escape of emitted long-wave radiation. Thus, a "greenhouse effect" is produced, heating floodwater and soil. Diel temperature amplitudes of the floodwater are highly moderated because of the high heat capacity of water and because evaporation of water consumes energy from the floodwater but not directly from the soil. The high thermal conductivity of flooded and puddled soils, in which the bulk densities may be reduced to only 0.2-0.5 g/cm³, enhances the downward conduction to the dense layer. Dissolved and suspended particles and aquatic biomass in the floodwater change the absorption of radiation, and depth of floodwater changes the heat capacity. The temperature of both floodwater and soils may rise above 40°C in unplanted soils with muddy floodwater of shallow depth. Floodwater temperature is lowered by canopy shading, flow of water, and through rainfall. In ricefields where floodwater has been drained for transplanting or seeding, soil temperatures may reach 50°C in the top centimeter because of increased heat absorption and reduced heat capacity, thermal conductivity, evaporation, and ventilation.

Aselmann and Crutzen (1990) computed monthly distributions of global methane emissions from linearly temperature-dependent methane fluxes in the range from 300 to 1000 mg/m² per day for temperatures from 20 to 30°C and constant emission of 300 mg/m² per day for temperatures below 20°C. Emissions of methane in the northern hemisphere reveal low monthly values (1.5 - 3 Tg) in December to April and a bell-shaped distribution between May and November with a clear peak of about 16 Tg in August. The southern hemisphere reveals highest emission rates (up to 2 Tg) in the months of February and March. The largest sources were computed between 20 and 30°N (South China, North India, Pakistan, Bangladesh, North Myanmar) with 37.6 Tg/yr, followed by 10 to 20°N (South India, South Myanmar, Thailand, Cambodia, Laos, Vietnam, North and Central Philippines, Brunei, Kalimantan) with 22 Tg/yr, 30 to 40°N (Central China, Japan, Korea) with 8 Tg/yr, 0 to 10°S with 6.5 Tg/yr (most of Indonesia) and 0-10°N (Sri Lanka, Malaysia, South Philippines, Brunei, Kalimantan) with 5 Tg/yr. Though rice ecologies have not been discriminated explicitly, the

computed distribution of emission rates clearly reflects the importance of irrigated rice ecologies since double- and triple-cropped areas account for a major part of irrigated rice.

4.3 Organic matter accumulation and decomposition. Readily mineralizable organic matter derived from primary production or organic amendments are the main source for methane formation in wetland rice soils. The net primary production of wetland rice soils (Table 4) can be deduced from yield statistics and estimates of aquatic biomass and weed growth during fallow periods.

In 1988, worldwide wetland rice production was 477 million tons (t), of which upland rice contributed about 28 million t. Based on a shoot/grain ratio of 3/2 (Ponnamperuma, 1984b) and a root/shoot ratio of 0.17 (Yoshida, 1981; Watanabe and Roger, 1985), the total dry matter production of wetland rice amounts to 1123 million t. Adding 74 million t dry matter of aquatic biomass [600 kg/ha season (Roger and Watanabe, 1984; Watanabe and Roger, 1985)] and 200 million t of weed dry matter [2 t/ha during fallow periods (Buresh and De Datta, 1991)] amounts to a total dry matter production of 1512 million t or 1500 g/m² per yr.

Table 4. Annual net primary production in wetland ricefields.

Source	Dry Weight	Returned to soil	
		%	(million t/yr)
Wetland rough rice	449	--	--
Wetland rice straw ^a	674	15	101
Wetland rice roots ^b	115	100	115
Aquatic biomass (algae/weeds)	74	100	74
Fallow weeds	200	50	100
TOTAL	1512	26	390

^a Shoot:grain ratio = 1.50; ^b Root:shoot ratio = 0.17

It is assumed that, on an average, 15% of the straw, 50% of the weeds, and all roots and aquatic biomass amounting to 390 million t dry matter or 156 million t carbon are returned to the soil. If a maximum of 30% of the returned carbon

is transformed to methane as found by Neue (1985) in studies with ¹⁴C-labeled straw in soils prone to methane formation, 60 Tg of methane would be globally produced in wetland ricelands annually. The input of degradable organic carbon is likely higher due to organic amendments. Reliable data on amounts of organic manures added are lacking. Based on long-term yield trials in the Philippines, a relation among soil C content, N fertilizer rates, and rice grain yields was established. The optimum C content in puddled and flooded soils was found to be 2 - 2.5%, corresponding to 0.20 - 0.25% total nitrogen (Neue, 1985; Smith et al., 1987). Since almost 90% of the tropical soils studied by Kawaguchi and Kyuma (1977) had less than the optimum total nitrogen content, moderate organic amendments seem to be essential to sustain or increase soil fertility and rice yields. In some instances, the returned net primary production of organic matter seems to be sufficient.

The rate and pattern of organic matter addition and decomposition control the rate and pattern of methane formation. Anaerobic fermentation produces an array of organic substances, many of them transitory and not found in well-aerated soils. Ponnamperuma (1984a) listed various gases, hydrocarbons, alcohols, carbonyls, volatile fatty acids, nonvolatile fatty acids, phenolic acids, and volatile S compounds. Methanogens constitute the last step in the electron transfer chain generated by the anaerobic degradation of organic matter. Submergence of soils retards initial decomposition of rice straw in the field only slightly compared with upland soils (Neue and Scharpenseel, 1987; Neue, 1988). The rate of decomposition decreases with soil depth (Neue, 1985). Decomposition of the remaining, more resistant metabolites and residues is similar, with half-lives of about 2 years in all soils and water regimes if the following conditions for flooded soils are met:

- soil is intensively puddled each cropping season;
- soil temperature of the puddled layer is 30-35°C;
- neutral pH;
- low soil bulk density and wide soil/water ratio;
- shallow floodwater;
- high and balanced nutrient supply;
- no long-lasting accumulation of organic acids;
- permanent supply of energy-rich photosynthetic aquatic and benthic biomass;

- high diversity of micro- and macroorganisms that provide successive fermentation down to CO_2 , CH_4 , H_2 , and NH_3 ;
- supply of O_2 into the reduced layer by rice root excretion and oligochaete population; and
- diel oversaturation of the floodwater with O_2 due to photosynthetic aquatic biomass enhancing the aeration function of oligochaetes.

Decomposition and, accordingly, methane production are retarded in wetland rice soils with low and imbalanced nutrient supply, high bulk density, and low biological diversity and activity, as demonstrated in the Aeric Paleaquult of Northeast Thailand (Snitwongse et al., 1988). If the biological activity is restricted to bacteria, as in laboratory experiments, the decomposition of rice straw in flooded soils is highly retarded (Capistrano, 1988). Only 7-18% of the incorporated straw was decomposed after 100 days following the order San Manuel clay loam (pH 6.6) > Maahas clay loam (pH 5.5) > Louisiana clay (pH 4.9). These results clearly demonstrate the high limitations of laboratory incubation studies.

In calcareous and alkaline soils, methane production may occur within hours after flooding an air-dried soil, while in acid soils it may take weeks before methane is formed (Figure 3). In very acid soils, methane may not be formed at any time. The formation of methane is preceded by the production of volatile acids. Short-term H_2 evolution immediately follows the disappearance of O_2 after flooding. Thereafter, CO_2 production increases, and finally, with decreasing CO_2 , CH_4 formation increases (Takai et al., 1956; Neue and Scharpenseel, 1984). The addition of organic substrates enhances the fermentation process. With increasing temperature up to 35°C , decomposition starts earlier and is more vigorous in every case. At high temperatures, the formation of CO_2 and CH_4 occurs earlier and is stronger (Yamane and Sato, 1961). The period of occurrence and the amount of the gaseous products and volatile acids depend largely on temperature and reducing conditions.

The ratio of CO_2 to CH_4 formation is controlled by the fermentation chain and the ratio of the oxidizing capacity (amount of reducible O_2 , NO_3^- , Mn(IV) , and Fe(III)) to the reducing capacity (Takai, 1961). The actual capacity is highly influenced by O_2 diffusion from the atmosphere, floodwater, and plant roots; the soil bulk density (soil-water ratio); and fertilization. Less CH_4 and higher

accumulation of volatile acids are found in soils with higher bulk density (lower soil:water ratio). Digging tubificidae (earthworms) in the top soil decrease methane formation but increase methane emission by enhancing fluxes of gases.

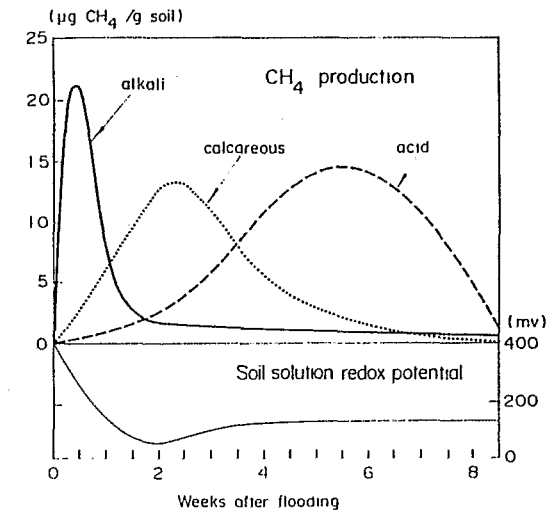


Figure 3. Methane formation in alkaline, calcareous, and acid soils.

Consecutive addition of organic substrates through plant growth and photosynthetic biomass production in the floodwater maintain the fermentation chain. The low specific activity of CH_4 produced after adding ^{14}C -labeled rice straw in field experiments (IRRI, 1981) was caused by degradation of newly produced photosynthetic biomass and root exudates. In permanently flooded soils, methane is only produced in significant amounts after soil-borne production or addition of readily mineralizable organic substrates. Humification of organic matter in wetland rice soils is less than that in aerobic soils. Humus of seasonal flooded soils has lower H_2 and N contents, its degree of unsaturation and its content of carboxyl and phenolic groups is lower, but its alcoholic and methoxyl groups are higher (Kuwatsuka et al., 1978; Tsutsuki and Kuwatsuka, 1978; Tsutsuki and Kumada, 1980). Humification indices in flooded soils, given as the ratio of nonhumified and humified materials (Sequi et al., 1986), are high (low humification) in topsoils and decrease with depth. Very acid rice soils have more humified materials.

Submergence is often equated with retarded decomposition and accumulation of organic matter. But wetland rice soils in the tropics fall into wet soils with high temperature in all seasons that show rapid mineralization and weak humification (Bonneau, 1982; Neue and Scharpenseel, 1987), both of which favor methane formation.

4.4 Redox potential. The supply of biodegradable carbon and the activity of the edaphon are the key to most of the characteristic biochemical and chemical processes in flooded soils (Neue, 1988). These processes include soil reduction and associated electrochemical changes; N immobilization and fixation; production of an array of organic compounds, especially organic acids; and release of NH_4^+ , CO_2 , H_2S , and CH_4 . Since methane is produced only by strictly anaerobic bacteria (methanogens), a sufficient low redox potential is required.

The magnitude of reduction is determined by the amount of easily degradable organic substrates; their rate of decomposition; and the amounts and kinds of reducible nitrates, iron and manganese oxides, sulfates, and organic compounds. A rapid initial decrease of Eh after flooding in most soils is caused by high decomposition rates of organic substrates and a low buffer of nitrates and Mn oxides. The most important redox buffer systems in rice soils are Fe(III) oxyhydroxides/Fe(II) and organic compounds stabilizing the Eh somewhat between +100 and -100 mV in most soil solutions. Measurements in the bulk soil may reveal Eh values as low as -300 mV because of direct contact with reduced surfaces of soil particles. The most important interacting chemical changes after flooding an air-dried acid soil are shown in Figure 4a,b.

Although the reduction of flooded soils proceeds stepwise in a thermodynamic sequence (Ponnamperuma, 1972; Patrick and Reddy, 1978), the given oxidation-reduction systems are only partially applicable to field conditions.

The mineral phases present in soils are not pure and often unknown, and a large portion of reduced Fe^{2+} and Mn^{2+} ions are held at ion exchange sites (Tsuchiya et al., 1986). Changes in pH and activities of reactants and resultants can also alter the order of redox reactions. As a consequence, reduction potentials of a given redox reaction span a fairly wide range not only because of variations at microsites. Nevertheless, redox potentials of the bulk soil (corrected to pH 7) of at least -50 mV are needed for the formation of CH_4 .

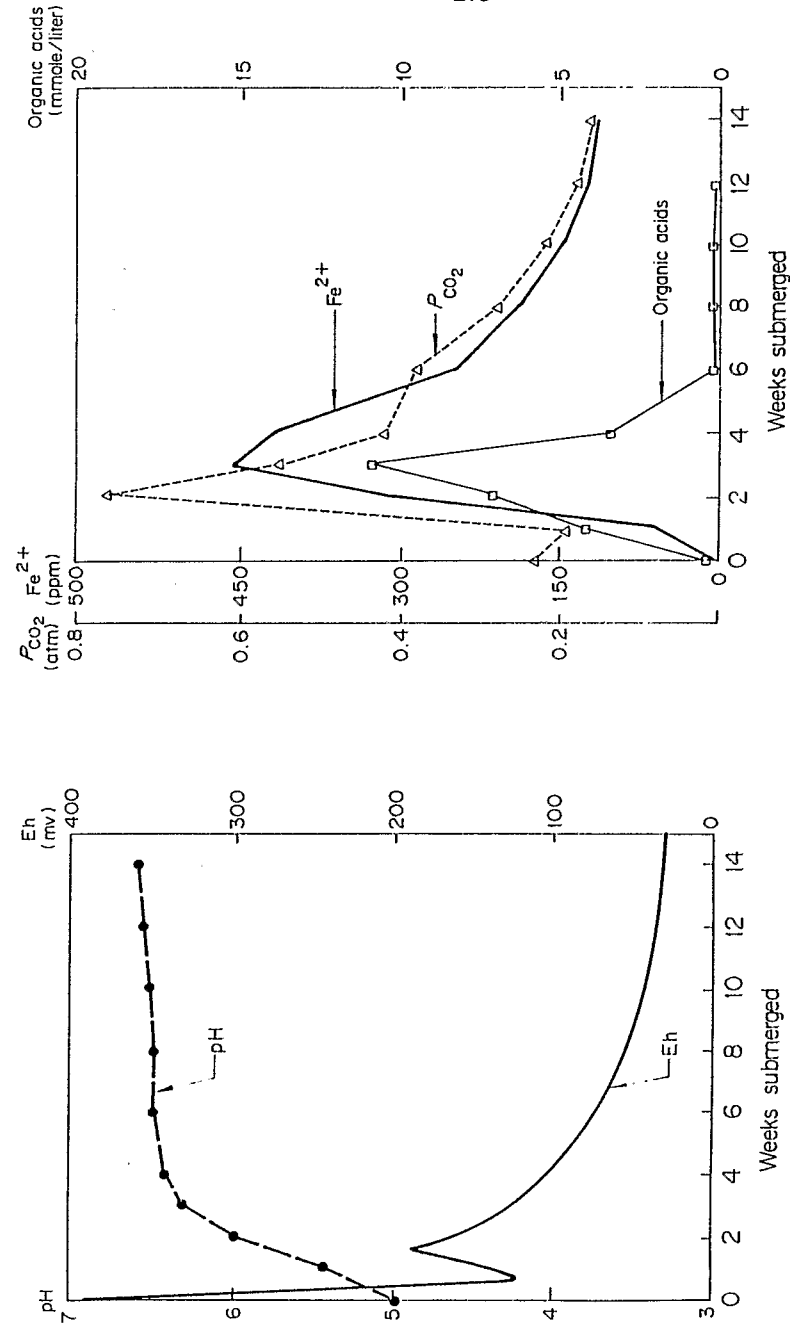


Figure 4a. Kinetics of pH and Eh in the soil solution of a flooded Ultisol at 30°C (adapted from Ponnamperuma, 1985).

Figure 4b. Kinetics of P_{CO_2} , water-soluble Fe^{2+} , and organic acids in the soil solution of a flooded Ultisol at 30°C (adapted from Ponnamperuma, 1985).

Chemical reactions that are favored thermodynamically are not necessarily favored kinetically. The lack of effective coupling and the slowness of redox reactions mean that catalysis is required if equilibrium is to be attained. In soils, the catalysis of redox reactions is mediated by microbial organisms. Equilibrium is dependent entirely on the growth and ecological behavior of the soil microbial population and the degree to which the reagents and products can diffuse and mix. Soil organisms are important with regard to kinetic aspects of redox by affecting the rate of a redox reaction but not its standard free energy change (Sposito, 1981).

Soils low in active iron with high organic matter may attain Eh values of -200 to -300 mV within 2 weeks after submergence (Ponnamperuma, 1972). In soils high in both iron and organic matter, the Eh may rapidly fall to -50 mV and then slowly decline over weeks and level off. Soils where the redox potential is controlled by a ferritic, ferruginous, or oxidic mineralogy and/or the soil reaction is strong acidic or allic are less prone to methane formation (Neue et al., 1990).

4.5 Partial pressure of CO_2 . The partial pressure of CO_2 directly influences CH_4 production since CO_2 is a carbon source for methane. It also affects CH_4 production indirectly because the accumulation of CO_2 coupled with the formation of HCO_3^- buffers the pH near neutral in all flooded soils.

The increase in pH of acid soils is initially brought about by soil reduction of Fe-oxyhydroxides. The pH decrease of sodic and calcareous soil and the final regulation of the pH rise in acid soils are the result of CO_2 accumulation. The pH values at steady state of flooded alkaline, calcareous, and acid soils are highly sensitive to the partial pressure of CO_2 . Carbon dioxide that accumulates in large amounts profoundly influences the chemical equilibria of almost all divalent cations (Ca^{2+} , Mg^{2+} , Fe^{2+} , Mn^{2+} , Zn^{2+}) in flooded soils as well as methane formation. Parashar et al. (1990) found the highest emission rates of CH_4 at a pH of 8.2. Acharya (1935) reported that the preliminary stage of acid formation is more tolerant to pH reactions, but gas formation is greatly impeded outside the range of pH 7.5 - 8.

Table 5. Coefficient of correlation between soil characteristics and the number of methanogenic bacteria/methane production potential (calculated from data from 29 soils given by Garcia et al., 1974).

	Range	Mean	log no. of methanogens per g of soil	log methane production potential ^a
Clay (%)	2.8-66	28	- 0.488**	- 0.524 **
Silt (%)	7.9-58	23	- 0.227	- 0.145
Sand (%)	1.7-82	37	+ 0.491**	+ 0.486 **
ECs (dS/m)	0.04-5.3	0.95	- 0.543**	- 0.384 *
pH (7 d after flooding[DAF])	3.4-6.8	5.4	+ 0.589**	+ 0.522 **
Eh [7 (DAF) (mV)]	+400-135	+116	- 0.661**	- 0.646 **
Carbon content (%)	0.4-9.0	2.1	- 0.067	- 0.071
Total nitrogen (%)	0.04-0.31	0.12	+ 0.044	+ 0.192
C/N	9.9-29	17	- 0.299	- 0.400 *
S-SO ₄ ²⁻ [zero day] (mg/kg)	53-1690	380	- 0.437*	- 0.265
N-NO ₃ ⁻ [zero day] (mg/kg)	0-41.8	2.7	- 0.235	+ 0.005
Cl ⁻ [zero day] meq/100g)	0-42.9	7.1	- 0.496**	- 0.358
No. of denitrifiers (log 10 No./g)	1.7-5.4	3.9	+ 0.305	+ 0.153
Denitrification potential ^b	40->1500	> 370	- 0.637**	- 0.509 **
No. of sulfate-reducing bacteria (log 10 No./g)	1.8-5.9	3.4	- 0.144	- 0.071
Sulfate-reducing index ^c	0-5	2.2	- 0.257	- 0.227
Rice growth index ^d	0-7.8	3.3	+ 0.321	+ 0.473 **

^a Methane produced during anaerobic incubation of soil at 37°C during 8 to 12 days after flooding;

^b Denitrification of 100 mg/kg N-NO₃ (KNO₃) at 30°C;

^c Percentage of dead rice plants in standardized conditions of growth favoring sulphatoreduction;

^d Weight of grain produced in pot experiment.

* and ** = significant at 1% and 5% levels, respectively.

Up to 2.6 t CO₂/ha is produced in the puddled layer during the first few weeks of flooding (IRRI, 1964). After the addition of organic substrates, the partial pressure of CO₂ in a flooded soil may reach a peak of almost 100 kPa (Ponnamperuma, 1985; Neue and Bloom, 1989). Typical values in flooded soils range from 5 to 20 kPa (Kundu, 1987; Patra, 1987). Carbon dioxide concentrations greater than 15 kPa retard root development, leading to wilting and reduced nutrient uptake (Dent, 1986).

At soil temperatures found in flooded tropical soils, CO₂ and CH₄ formation occur sooner and in larger amounts than in cooler climates (Tsutsuki and Ponnamperuma, 1987). The amount of CH₄ found in the soil solution and in gas bubbles of flooded soils may be up to 3 times higher than that of CO₂ after the initial stage of flooding (Martin et al., 1983). The change in favor of CH₄ is likely caused by assimilation of CO₂ and precipitation of carbonates rather than reduction of CO₂ to CH₄, but the controlling processes still need elucidation. According to Takai (1970), the bulk of CH₄ is formed through decarboxylation of acetic acid, which would result in a 1:1 ratio of CO₂ and CH₄ formation.

4.6 *Correlations between soil properties and methane formation.* Neue et al. (1990) identified four crucial parameters for high methane production in wetland rice soils into four crucial parameters aside from carbon supply and water regime: temperature, texture and mineralogy, Eh/pH buffer, and salinity. He suggested that soils are not prone to high methane production if one or more of the following soil characteristics following limits of Soil Taxonomy (USDA, 1975) are met:

- EC > 4 dS/m while flooded,
- acidic or allic reaction,
- ferritic, gibbsitic, ferruginous, or oxidic mineralogy,
- > 40% of kaolinitic or halloysitic clays,
- < 18% clay in the fine earth fraction if the water regime is epiaquic, and
- drought-prone during cultivation period.

Soils comprising these features are Oxisols, most of the Ultisols, and some of the Aridisols, Entisols, and Inceptisols. Rice soils that are prone to methane production mainly belong to the orders of Entisols, Inceptisols, Alfisols, Vertisols, and Mollisols. Correlations between methane formation and physicochemical

features (Tables 5 and 6), calculated from data of 29 soils given by Garcia et al. (1974), support this concept.

Table 6. Correlation between the number of methanogenic bacteria/methane production potential and pH/Eh at different days after flooding (DAF)(calculated from data of 29 soils given by Garcia et al., 1974).

	DAF methanogens	Log no. of production potential	Log methane potential	
pH	0	+	0.112	+ 0.030
	7	+	0.589**	+ 0.522**
	14	+	0.411*	+ 0.293
	21	+	0.541**	+ 0.385*
	28	+	0.539**	+ 0.268
Eh	0	-	0.107	- 0.197
	7	-	0.661**	- 0.646**
	14	-	0.438*	- 0.361*
	21	-	0.443**	- 0.303
	28	-	0.380*	- 0.097

* and ** = significant at 1% and 5% levels respectively.

Methane production potential is negatively correlated with Eh, ECs, chloride content, sulfate content, and C-N ratio but positively correlated with pH. The pH/Eh values 1 week after flooding, the denitrification potential, and the rice growth index show higher correlations. The high negative correlation with the clay content and positive correlation with the sand content indicate dominance of kaolinitic clays, and/or effect of the large number of salt affected mangrove soils in the sample. Considering only the 11 non-saline soils results in a highly significant correlation between soil carbon as well as soil nitrogen content and methane production potential but not with the number of methanogenic bacteria. This shows that the carbon content influences the activity but not necessarily the density of methanogenic bacteria. In the sample of non-saline soils there is no correlation between methane production potential and clay as well as sand. The positive correlation between methane production and the rice growth index, measured as rice grain yield, clearly indicates that increasing rice production enhances methane formation. Since the rice growth index is also an index for soil fertility of rice soils, it is evident that improving wetland soil

fertility combined with current cropping technologies increases methane production and likely methane emission.

5. Rice cultivars and methane emission

Rice plants play an important role in the flux of methane. Up to 90% of the methane released from the rice soil to the atmosphere is emitted via the rice plant (Bont et al., 1978; Seiler, 1984; Holzappel-Pschorn et al., 1986). The aerenchyma and intracellular space of rice plants mediate the transport of CH_4 from the reduced soil to the atmosphere (Raimbault et al., 1977). However, up to 80% of the methane produced is apparently oxidized in the rhizosphere (Holzappel-Pschorn et al., 1985) and the oxidized soil floodwater interface (Figure 5).

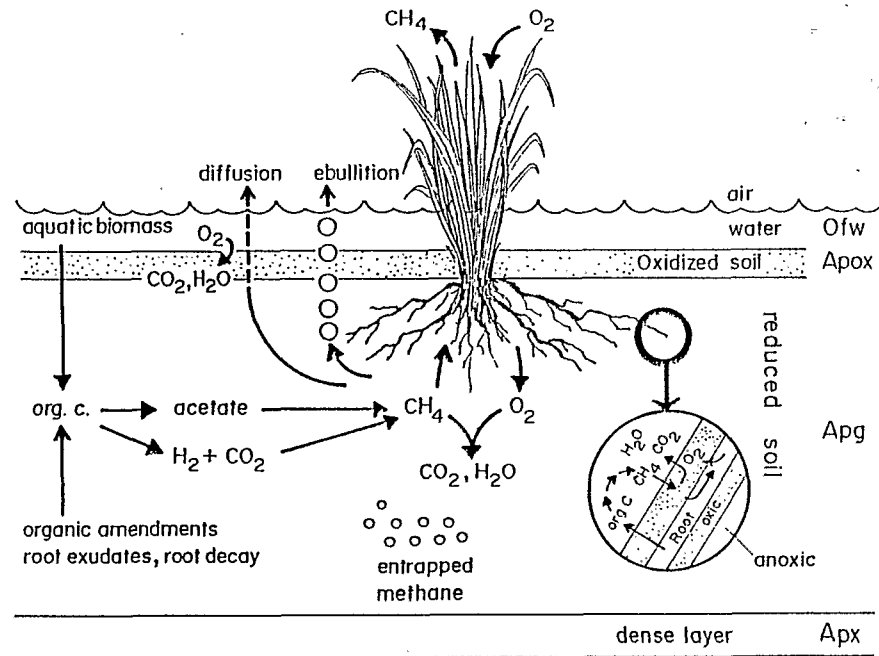


Figure 5. Schematic of production, reoxidation, and emission of CH_4 in a paddy field. (Modified from Schütz et al., 1989.)

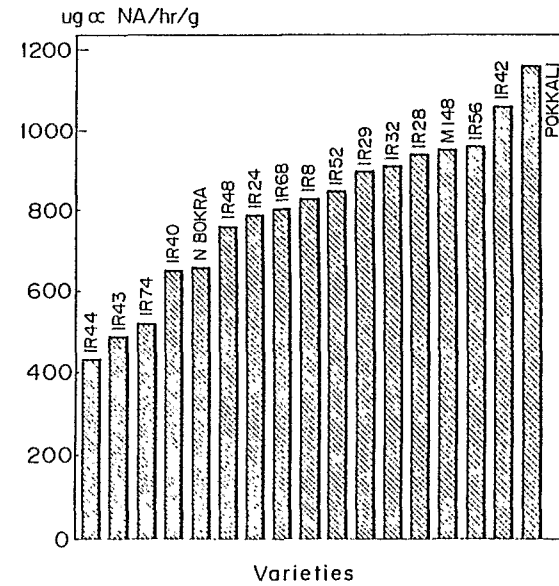


Figure 6. Root oxidizing power of selected rices.

The aerenchyma of rice plants acts as a chimney but the transport mechanisms still have to be elucidated. The well-developed air spaces in leaf blades, leaf sheath, culm and roots provide an efficient gas exchange between the atmosphere and the anaerobic soil. Atmospheric O_2 is supplied via the aerenchyma to the roots for respiration. Oxygen diffusion from rice roots seems to constitute an important part of the root-oxidizing power aside from enzymatic oxidation due to hydrogen peroxide production. Because of the abundance of methane-oxidizing bacteria present in the rhizosphere, its potential for methane oxidation is very high. At tillering, Bont et al. (1978) counted in the rhizosphere 10 times more methane-oxidizing bacteria than in the bulk anaerobic soil and 1/3 more than in the oxidized soil-water interface. They found significant increases in CH_4 emission from cultivar IR36 when suppressing CH_4 oxidation with acetylene at the soil-water interface. However, acetylene had only a small effect on emission rates when applied to the rhizosphere. Bont et al. (1978) concluded that the utilization of O_2 by reduced substances and microbial activity other than methanotrophs in the root-soil interfacial region exceeds the supply of O_2 by the root. Consequently, the aerobic zone surrounding the root is too thin to get the

diffusing CH_4 oxidized or the rhizosphere is, for the most part, anaerobic. Rice plants may not only mediate the flux of CH_4 , they enhance biological activities in soils and their root exudates and degrading roots may be an important source of CH_4 formation. Sass et al. (1991) found that spatial variability of methane production coincided with spatial distribution of roots in wetland ricefields.

Large cultivar differences in root oxidation power (Figure 6) and in emission rates (Parashar et al., 1990) open up the possibility of breeding rices that emit less methane. The inheritance of underlying traits has still to be elucidated.

6. Agronomic practices affecting CH_4 production.

Various rice culture systems have been developed to suit the physical, biological, and socioeconomic conditions of different regions and environments. Little is known about the effect of agronomic practices on methane fluxes in wetland ricefields.

6.1 Water control. Water control (irrigation and drainage) is one of the most important factors in rice production. In many ricefields, crops suffer from either too much or too little water because of rainfall pattern and topography.

During the monsoonal rainy season in tropical Asia, ricefields are naturally flooded. Excess water is a serious constraint in river, lacustrine, and coastal floodplains. Bunding (raising levees around the field) of ricefields and terracing and levelling of sloping land considerably change the water regime of that land. The overall effect is that uncontrolled runoff of water is minimized and more water, whether from natural sources or from irrigation is retained on or in the soil. Bunding and leveling of ricefields is a perfect measure of erosion control and allows efficient water harvesting and water conservation.

The following parameters of floodwater regimes are important for rice growth and should affect methane fluxes as well:

- duration and depth of flooding,
- regularity of flooding as determined by climatic relief and regime of rivers, and
- degree and pattern to which flooding is controlled by irrigation, flood protection, and drainage.

Single ricefields may have two distinct flooding regimes in a given year, especially in pronounced wet-dry monsoonal climates. Ricefields may be naturally shallow to moderately deep flooded during the rainy season and dry out or become shallow flooded by irrigation water during the dry season.

Floodwater control is the prerequisite for most technology changes in rice cultivation. Floodwater and soil water regime primarily determine methanogenesis and will likely be key issues for reducing methane fluxes. Aerating wetland soils to reduce methane fluxes without hampering rice production is a tempting mitigation technology.

But water stress at any growth stage may reduce yield. Moisture stress of 50 kPa (slightly above field capacity) may reduce grain yield to 20-25% of the yield of continually flooded treatments (De Datta, 1981). The rice plant is most sensitive to water deficit during the reproductive stage causing a high percentage of sterility (Yoshida, 1981). Water deficits during the vegetative stage may reduce plant height, tiller number, and leaf area that may also highly reduce yields if plants do not recover before flowering. The duration of a moisture stress is more important than the growth stage at which the stress occurred.

Short aeration periods at the end of the tillering stage and just before heading may improve wetland rice yields (Wang Zhaoqian, 1986) but only if it is followed by flooding. Intermittent irrigation or keeping soils only saturated considerably lowers rice yields (Borrell et al., 1991). Intermittent drying periods or percolation rates of up to 35 mm/day are associated with maximum rice yields in subtropical China and Japan (Wang Zhaoqian, 1986; Iwata et al., 1986). Percolation rates significantly increase yields only above production levels of 6 t/ha (Honya, 1966). Permanent year-round flooding or saturation, which may favor methane production, increases gleying and reduces soil fertility (Li Shi-jun and Li Xue-yuan, 1981), except in acid sulfate soils and some iron toxic soils. Although yields in a triple rice cropping system at IRRI have slightly declined over the past 22 years (Greenland, 1985), there is little evidence that high percolation rates, intermittent drying, or dry fallow periods are needed for high rice yields in most tropical wetland soils. The magnitude of aeration (oxidation) needed is likely dependent and interlinked with decomposition pattern and accumulation of organic and inorganic toxins, and nutrient imbalances involving Fe, Mn, Zn, S, and P (Neue, 1988, 1989). Much more information is needed to understand these interrelationships.

The high water demand for wetland rice becomes a constraint in areas and seasons of limited water resources. Wetland rice requires, on an average, 1240 mm of water (Yoshida, 1981), while upland crops may need less than half (Maesschalck et al., 1985). No methane is produced when upland crops are cultivated on riceland in seasons in which the land is naturally not flooded. This is commonly practiced in areas of limited water resources, especially since modern rice cultivars with short growth duration are available leaving sufficient water in the soil for a following upland crop. If water supply is assured, shifts to upland crops, which would reduce methane emission, are highly dependent on socioeconomic conditions.

6.2 *Land preparation.* Tillage operations vary according to water availability, soil texture, topography, rice culture, and resources available. Kawaguchi and Kyuma (1977) found that 40% of the tropical rice soils they studied had at least 45% clay. Soils with such high clay content have a poor structure and are hard when dry. Since hand- and animal- powered tillage are still common in most Asian countries and the principal form of mechanization is only the 10-15 hp tiller (hand tractor), wet tillage is the preferred land preparation. Wet tillage comprises land soaking until the soil is saturated, then plowing, puddling and harrowing. One third of the total water required for a rice crop is needed for the wet field preparation. Two weeks are required to prepare the field for transplanting.

According to De Datta (1981), the advantages of wet tillage are:

- improved weed control;
 - ease of transplanting;
 - establishment of reduced soil condition which improves soil fertility and fertilizer management;
 - reduced draft requirement;
 - reduced water percolation;
 - reliability of monsoon rains by the time land preparation is completed;
- and
- higher fertilizer efficiency, especially for N fertilizer.

Flooding and puddling a soil provide an ideal growth medium for rice by supplying abundant water, buffering soil pH near neutral, enhancing N fixation

and carbon supply, and increasing diffusion rates, mass flow, and availability of most nutrients. Standing water stabilizes the soil moisture regime, moderates soil temperature, and prevents soil erosion.

When initial crop growth at early monsoonal rainfall becomes essential because of subsequent floods, as in deepwater rice ecosystems, tillage and seeding are done in dry soils. Less than 200 mm of rainfall for the planting month leads to dryland preparation and seeding. Labor constraints associated with seedbed preparation, land preparation, and transplanting may also force farmers in other rainfed rice ecosystems to dryland tillage and seeding to ensure timely crop establishment. In most rice-growing countries where large power units can be employed because of available capital (as in the United States, Australia, most of Latin America, and Europe), dryland tillage is commonly practiced. In the United States and Australia rice is mostly also sown in dry soil, which is flooded after crop establishment. Upland rielands are never flooded and tillage is, of course, the same as for other upland crops.

Information on the effect of land preparation on methane fluxes is lacking. Dryland tillage and dry seeding shorten the anaerobic phase and may slow down the decrease of the redox potential resulting in delayed and likely lower methane production. Minimum or zero tillage should have similar effects. However, these land preparation and seeding techniques require likely new rice cultural types, higher fertilizer rates, higher powered tillage implements, and alternative seeding and weeding techniques.

6.3 *Seeding and transplanting.* Transplanted rice is the major practice of rice culture in most of tropical Asia. Direct seeding of pregerminated rice in wet prepared soils becomes popular in areas with good water control and if manpower is lacking or becoming expensive. Pregerminated seeds are mostly broadcast onto puddled fields without standing water (saturated soil moisture) and the field is flooded after crop establishment. The crop duration (vegetative phase) is shorter in direct seeded rice, avoiding delay due to seedbed preparation, transplanting, and reduced initial growth because of the transplanting shock. Weed control in broadcast seeded rice and possible moisture stresses because of insufficient water control are the main obstacles in direct wet seeded rice. The yield potential for direct wet seeded rice is similar to that of transplanted rice (De Datta, 1981).

The advantages of transplanting rice seedlings are:

- lower seed requirement (increased tillering),
- save seed establishment (control of pests and fertilization),
- variable schedule of field establishment is possible without risk,
- less requirements for floodwater control, and
- tolerance to biotic and abiotic stresses increases with seedling age.

Methane fluxes should vary between direct seeded and transplanted rice because

- crop duration is shorter in direct seeded rice,
- soil surface is aerated for 7-14 days after land preparation in direct seeded rice,
- growth pattern and canopy development differ, and
- transplanting causes additional soil disturbances.

6.4 Fertilization. The most deficient nutrient for high wetland rice yields is nitrogen, followed by P, K, and Zn. The choice of nitrogen source depends on the method and time of application. Most farmers apply nitrogen fertilizer in two or three parts. The first part is applied during final land preparation or shortly after planting and the remainder as topdressing at later growth stages, especially at the early panicle stage. The most common source of N-fertilizer in wetland rice is urea followed by ammonium-containing fertilizers like ammonium sulfate. The source of nitrogen used as topdressing at later growth stages is less critical because of rapid uptake. In general, K and P are basically applied during the final land preparation. Potassium chloride is the principal fertilizer source of K and superphosphate is the primary source of P fertilizer. On acid rice soils, phosphate rock may be applied. Zn may be added by seed treatments, dipping seedling roots in ZnO solution, or broadcasting Zn salts at the time Zn deficiency symptoms occur.

Studies on fertilizer use and crop management to minimize nitrogen losses (up to 60% due to volatilization of NH_3 , nitrification denitrification) and to increase the efficiency of fertilizer have recently been reviewed (De Datta, 1981; De Datta and Patrick, 1986; De Datta, 1987). For basal application, ammonium-containing or ammonium producing (urea) N fertilizer are recommended (De Datta, 1981) to minimize denitrification losses. To reduce volatilization losses incorporation or deep placement of N fertilizer has to be done without standing

water at final harrowing. Broadcasting basal N-fertilizer into floodwater results in extensive N losses (as ammonia) to the atmosphere due to high pH values as a result of the algal assimilation or alkaline irrigation water (Fillery and Vlek, 1986).

Reports on the influence of the mineral fertilizer application (source, mode, and rate) on CH_4 production and emission are inconsistent. The complex interrelationships of fertilization on the biochemistry (CH_4 production and oxidation) of flooded soils and on plant growth (plant-mediated emission) still have to be elucidated. Increasing the number of tiller/m² and enhancing root growth in methane enriched soil layers through fertilization will obviously increase methane emission. As discussed above, encapsulating methane inhibitors in fertilizer seems to be very promising.

It is evident that organic amendments of flooded soils increase CH_4 production and emission (Schütz et al., 1989) by lowering the Eh and providing carbon sources. Addition of plant residues accelerate and intensify Eh and pH changes (Katyal, 1977). The effect of vetch, which has a narrow C-N ratio, is greater than that of rice straw (Yu, 1985). Changes are more pronounced when organic substrates are added to soils low in organic matter (Nagarajah et al., 1989). Increasing the soil bulk density of flooded soils retards organic matter decomposition, increases the concentration and residue time of organic acids, and reduces the speed of Eh and pH changes as well as methane formation.

Though organic amendments are propagated to sustain soil resources, actual application of organic substrates into wetland ricefields seems on the decline (see Figure 7). In China the production of green manure increased sharply after 1960 and peaked sometime in the 1970s (13.2 million ha), followed by a steep decline to only 6.6 million ha in 1987 (Stone, 1990). In Japan, the decline of green manure cultivation started already in the 1950s. According to Kanazawa (1984), the total addition of organic substrates to ricefields in Japan decreased from 6 t/ha in 1965 to 2.7 t/ha in 1980.

Based on the content of readily mineralizable carbon, humified substrates like compost should produce less methane per unit carbon while rice straw or green manures likely produce more. Application of compost did not remarkably enhance methane emission while application of rice straw significantly increased methane emission irrespective of soil type (Yagi and Minami, 1990). Sound technologies have to consider both maintaining or increasing soil fertility and

reducing methane emission. In a sustainable wetland rice system, it may be advisable to minimize rather than to maximize organic soil amendments.

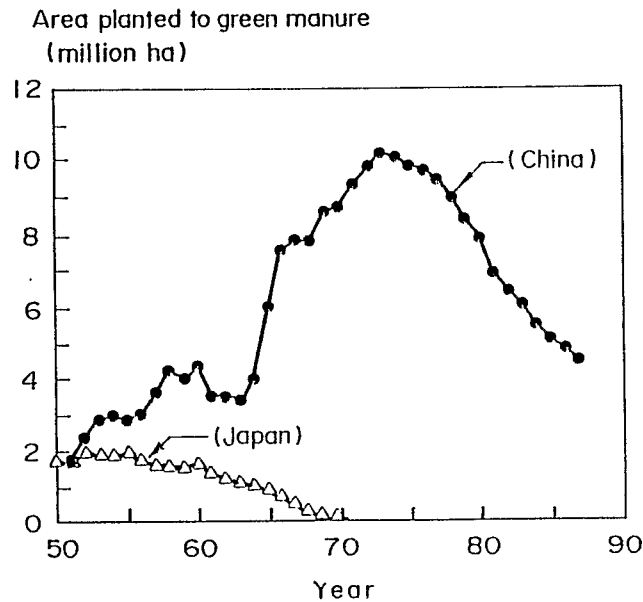


Figure 7. Area planted to green manure in China (1952-1987) (Stone, 1990) and in Japan (Watanabe, 1984).

6.5 Pest control. Control of pests in wetland rice ranges from varietal resistance through cultural control, biological control, and chemical control. Application of pesticides to the floodwater, soil surface, or into the soil may have significant effects on methane fluxes, especially if it adversely affects the aquatic and soil flora and fauna. Many cultural control measures, such as cropping pattern, crop residue management, tillage, water, fertility, weeding, or plant spacing and population, affect pests in rice but should affect methane fluxes at the same time. For example, the mechanical disturbance of the soil during weeding (2-3 times per season by hand or small implements) increases the release of gases trapped in the soil. Weeds become an additional source of methane since they are commonly returned to the reduced soil. On the other hand, aquatic weeds may provide a more efficient pathway for CH_4 to the atmosphere than rice plants, as indicated by Holzapfel-Pschorn et al. (1986).

7. Summary

Ricefields provide ideal environments for methanogenesis, especially irrigated ricefields in the tropics, because of anaerobic conditions at neutral pH, optimum temperature, and high easily degradable C inputs. Rice plants favor methane fluxes by supplying carbon and acting as chimney. The high C input in rice soils due to a high primary production both by the crop and the photosynthetic aquatic biomass and organic amendments favor methane emission from ricefields.

Irrigated rice ecologies seem to be the major source for increased global methane emissions from ricefields. The assured water supply and control, the intensive soil preparation, and the resultant improved growth of rice, mediating the methane flux to the atmosphere, favor methane production and emission. Methane emissions should be much lower and highly variable in space and time in rainfed rice because of drought periods during the growing season and the poorer growth of rice. In deepwater rice, methane production may be high but related emission rates are unknown. Upland rice is believed not to be a source of methane emission because upland rice is never flooded for a significant period of time.

Global extrapolations of emission rates are still highly uncertain and tentative. Accounting for variations of emission rates due to climate, soil properties, duration and pattern of flooding, organic amendments, fertilization and rice growth reveals that most published extrapolations are too high. Adjusting a basic emission rate of $0.5 \text{ g m}^{-2} \text{ day}^{-1}$ according to rice ecologies or soil types results in global emission rates of about 40 Tg year^{-1} (Neue, 1992; Bachelet and Neue, 1993). But reported measurements of CH_4 fluxes in rice fields do not account for ebullition induced by soil disturbance due to wet tillage, transplanting, fertilization, weeding, pest control and harvest. A large proportion of soil entrapped methane that may account for up to 90% of the methane generated and is oxidized in undisturbed rice fields likely escapes to the atmosphere during these cultural practices. Therefore, the global CH_4 emission rate from rice fields is likely higher than 40 Tg year^{-1} .

Methane from ricefields may contribute up to one third of the global anthropogenic methane emission, and mitigation technologies are required to stabilize atmospheric methane concentration in the long term. Possible mitigation technologies include reducing C inputs of easily degradable carbon, increasing

soil and plant-mediated methane oxidation, reducing emission pathways through the selection and breeding of rice cultivars, and preventing or reducing methane formation through intermittent aeration, sources and mode of fertilizer, and application of chemical inhibitors. The most effective mitigation technology would be to shift from wetland rice to upland cropping whenever possible.

However, technologies that will be accepted by farmers have to be not only environmentally but also socio-economically sound. Because of the limited existing knowledge and the complexity of any methane-mitigating technology, a comprehensive interdisciplinary research approach of various biological and social sciences and common sense are needed to develop and implement feasible technologies.

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