CHAPTER 4

RESULTS AND DISCUSSION

Gas samples from eleven land use types were monthly taken (Table 4.1). From each land use, three replications with four time steps of gas samples were collected. A total of 158 samples per month (including ambient air and standard gas samples) were transported to analyze using the Gas Chromatography (model GC-8A, Shimadzu Co., Inc. Japan) and further calculated into methane flux rate.

The results are presented in four sections, the first three sections cover the quantification of the seasonal variation of methane emission from various land use types in Mae Chaem Watershed (MCW). The last section covers the methane production (source) and consumption (sink) simulation model, which were used to describe the controlling factors and to estimate methane emission.

Table 4.1 Date of sample collection from eleven land use types in MCW, 1999.

Month	Date	Methane Sources	Methane Sinks
January	15		RF1, DF1, OF and PF
	16		F1, F2 and F3
	17		RF2, FC, DF2 and EG
February	14		RF1, DF1, OF and PF
	15		F1, F2 and F3
	16		RF2, FC, DF2 and EG
March	15		RF1, DF1, OF and PF
	16		F1, F2 and F3
	17		RF2, FC, DF2 and EG
April	10		RF1, DF1, OF and PF
	11		F1, F2 and F3
	12		RF2, FC, DF2 and EG
May	17	RF1	DF1, OF and PF
	18		F1, F2 and F3
	19		RF2, FC, DF2 and EG
June	19	RF1	DF1, OF and PF
	20		F1, F2 and F3
	21	RF2	FC, DF2 and EG
July	11	RF2	FC, DF2 and EG
	12	RF1	DF1, OF and PF
	13		F1, F2 and F3
August	16	RF1	DF1, OF and PF
	17		F1, F2 and F3
	18	RF2	FC, DF2 and EG
September	18	RF1	DF1 and OF
	19		PF, F1, F2 and F3
	20	RF2	FC, DF2 and EG
October	8	RF2	FC, DF2 and EG
	9	RF1	DF1, OF and PF
	10		F1, F2 and F3
November	13	RF1	DF1, OF and PF
	14		F1, F2 and F3
	15	RF2	FC, DF2 and EG
December	15		RF1, DF1, OF and PF
	16		F1, F2 and F3
	17	RF2	FC, DF2 and EG

Note; Study site is Mae Chaem watershed, 1999

RF1 =Rice field in Wat Chan

RF2 =Rice field in Charng-Kerng

DF1 =Deciduous forest in Wat Chan

DF2=Deciduous forest in Charng-Kerng

EF =Hill evergreen forest

F1 =One-year fallow

F4 =Four-year fallow

F7 =Seven-year fallow

FC =Field crop area

OF =Orchard field

PF =Pine forest

4.1 Methane Partial Source and Sink

In paddy fields, there were both methane production and consumption occurred, depending on natural and anthoprogenic activities. Rainfed rice field in Wat Chan (RF1) and Charng Kerng (RF2) sub-district was non-flooded soil and good aeration during dry season (January to April) and the soil was submerged in rice growing period. Therefore, the variation of methane emission rates were both negative (consumption) and positive (production) in dry season and rice growing period, respectively (Figure 4.1).

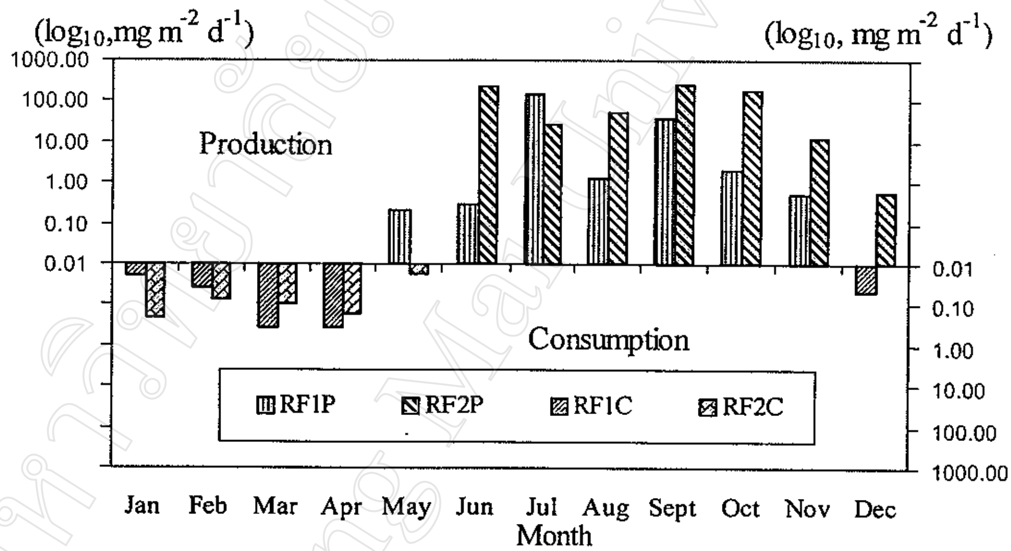

Figure 4.1 Seasonal variation of methane production and consumption in rice field.

Note; Study site was Mae Chaem watershed, 1999

RF1P = methane production from RF1

RF2P = methane production from RF2

RF1C = methane consumption in RF1

RF2C = methane consumption in RF2

4.1.1 Wat Chan Paddy Field (RF1)

Wat Chan rice field (RF1) was methane sink during January to April and December, because the field was not flooded. From May to November, which had been rainy season, rice field was saturated and flooded, therefore it became methane source (Figure 4.1). The methane consumption rate during January to April and December in RF1 ranged from 0.019 to 0.391 mg CH_4 m^{-2} d^{-1}, with an average of 0.171 ± 0.188 mg CH_4 m^{-2} d^{-1}. Whiles emission rate during June to November ranged from 0.212 to 146.312 mg CH_4 m^{-2} d^{-1} with an average of 26.757 ± 54.386 mg CH_4 m^{-2} d^{-1}.

Temperature at the sampling point in the field was also collected. Average air temperature was 28.3 ± 3.2 °C, where as at 5 cm soil depth was 24.9 ± 3.1 °C. Temperature consideration during methane consumption and production period, average air temperature was 29.56 ± 3.31 °C and 27.3 ± 2.95, respectively. Average soil temperature was 25.82 ± 3.35 °C during methane uptake period and 23.8 ± 2.89 in production period.

4.1.2 Charng Kerng Paddy Field (RF2)

Rice field in Charng Kerng sub-district (RF2), only rice crop cultivated during June to November, methane was also produced in this period (June to December). Methane emission rate ranged from 0.576 to 254.035 mg CH_4 m^{-2} d^{-1} with an average of 111.092 ± 112.120 mg CH_4 m^{-2} d^{-1}. The field was fallowed from January to May as grazing field for cattle. Methane consumption rate in this period ranged from 0.018 to 0.218 mg CH_4 m^{-2} d^{-1} with the average of 0.116 ± 0.079 mg CH_4 m^{-2} d^{-1}.

Average air temperature at the sampling point was 33.0 ± 4.9 °C, whiles 32.1 ± 6.3 °C in 5 cm soil depth and it is quite high in summer. During methane uptake period (January to May) the soil temperature was about 37.0 ± 1.24 °C which was similar to the air temperature, 37.9 ± 2.80 °C. In methane producing period, temperature was lower than consumption period. The average soil temperature was 25.63 ± 2.41 °C and 29.54 ± 2.42 °C in the air.

4.2 Methane Sinks

Field crop, forests, orchard field, and fallow cultivation land uses were all absolute methane sinks. The soils were non-flooded all year round even during the rainy season, because the areas are located on high altitudes and steep slope compared to the rice fields. Methanotrophic bacteria activities have been able to run under continue favorable condition.

4.2.1 Deciduous Forest (DF1 and DF2)

Both of deciduous forests, DF1 in Wat Chan and DF2 in Charng Kerng located in a mountainous area on a steep slope land use type. DF1 is rich of undergrowth species while upper species is high density in DF2. Methane consumption in DF1 ranged 0.056 to 0.706 mg CH_4 m^{-2} d^{-1} with an average of 0.259 ± 0.197 mg CH_4 m^{-2} d^{-1} (Figure 4.5). Average air and soil temperature of the site were 29.1 ± 2.8 and 24.2 ± 1.7 °C, respectively. While methane consumption in DF2 ranged from 0.060 to 0.413 mg CH_4 m^{-2} d^{-1} with an average of 0.212 ± 0.146 mg CH_4 m^{-2} d^{-1} (Figure 4.2). The average air and soil temperatures were 27.0 ± 2.4 and 23.3 ± 1.8 °C, respectively.

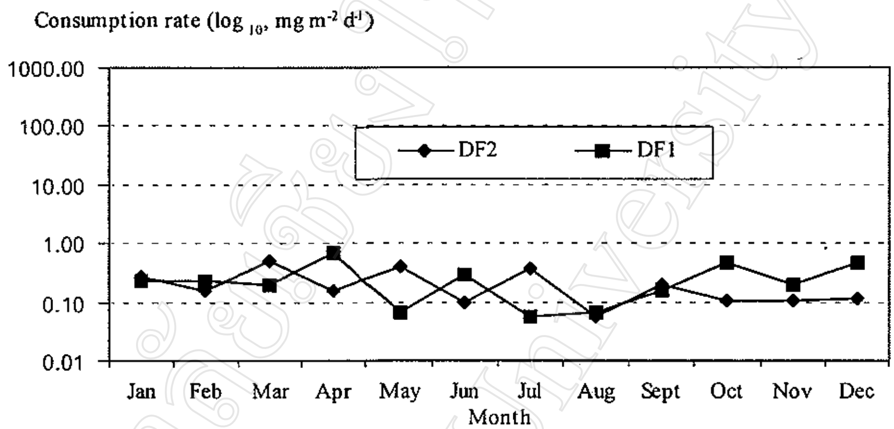

Figure 4.2 Methane consumption rates in deciduous forests.

Note; DF1 = deciduous forest in Wat Chan sub-district

DF2 = deciduous forest in Charng Kerng sub-district

4.2.3 Hill Evergreen Forest (EF)

Hill evergreen forest (EF) was located in Charng Kerng sub-district. The soil color is brown to dark brown and quite fertile. There were many kinds of mushroom growing up during gas samples collection period especially in rainy season. Methane consumption rate in this area varied between 0.011 and 0.481 mg CH_4 m^{-2} d^{-1} with an average of 0.209 $\pm$ 0.152 mg CH_4 m^{-2} d^{-1} (Figure 4.3). Because the area is located on high elevation, causing low temperature. Average soil temperature was 19.8 $\pm$ 1.4 °C and 23.8 $\pm$ 1.5°C for average air temperature.

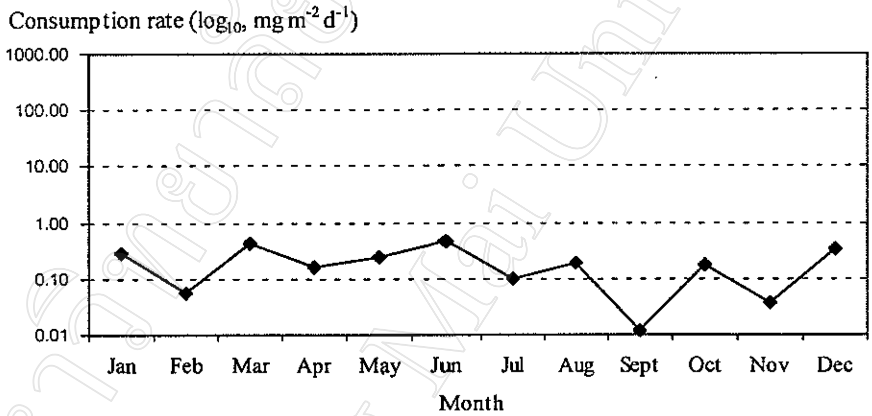

Figure 4.3 Methane consumption rates in hill evergreen forest (EF).

4.2.3 Fallow Fields Cultivation (F1, F4 and F7)

High consumption rates were found in fallow cultivation land uses. Three fallow land uses, which being adjacent to each other, were one-year (F1), four-year (F4) and seven-year fallow (F7). They were located in low sloping area (< 5%). Weed and small shrubs have been fast recovering after fallow both species and growth. Methane uptake rates in these land uses ranged from 0.234 to 0.919, 0.047 to 0.935, and 0.115 to 0.885 mg CH_4 m^{-2} d^{-1} of one-year, four-year and seven-year fallow, with average of 0.567 ± 0.210, 0.495 ± 0.234, and 0.490 ± 0.276 mg CH_4 m^{-2} d^{-1}, respectively (Figure 4.4). These sites consumed methane at the higher rate than other non-wetland soils. The averages air temperature of one-year, four-year and seven-year fallow were 26.9 ± 2.4, 28.5 ± 3.2, and 22.8 ± 2.4°C, respectively. While the average temperatures at 5 cm soil depth were 21.2 ± 2.5, 21.6 ± 2.3 and 20.4 ± 2.1°C, respectively.

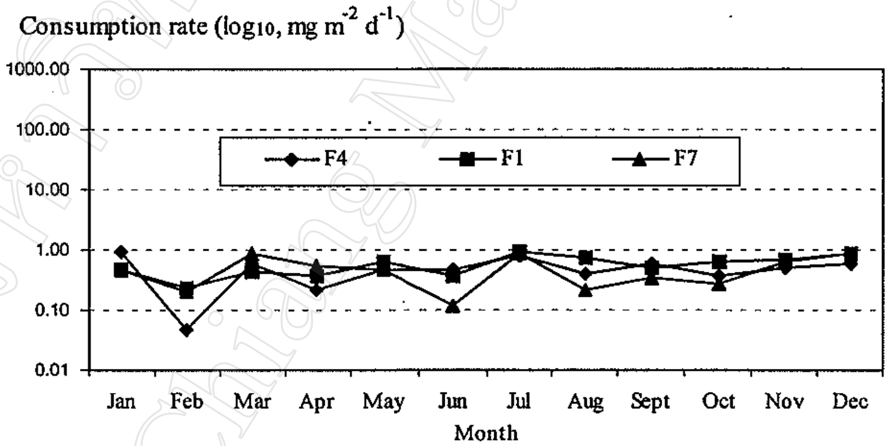

Figure 4.4 Methane consumption rates in fallow field cultivation.

Note: F1= one-year fallow field

F4= four-year fallow field

F7= seven-year fallow field

4.2.4 Field Crop Area (FC)

The area was adjacent to the rice field of Charng Kerng sub-district and situated on a low to medium terrace. It was a methane consumer, with consumption rates ranged from 0.065 to 0.639 mg CH_4 m^{-2} d^{-1} (Figure 4.5). There was high consumption rate in June and October, because land preparation was done in June, which affected on aeration of the soil. While the high consumption rates again occurred in October due to high organic matter degradation rates (Goldman *et al.*, 1995) after maize was harvested in late September then maize biomass was later burned. The average consumption rate was 0.240 ± 0.173 mg CH_4 m^{-2} d^{-1}. The average soil and air temperatures were 29.9 ± 5.5 and 31.1 ± 3.4 °C, respectively.

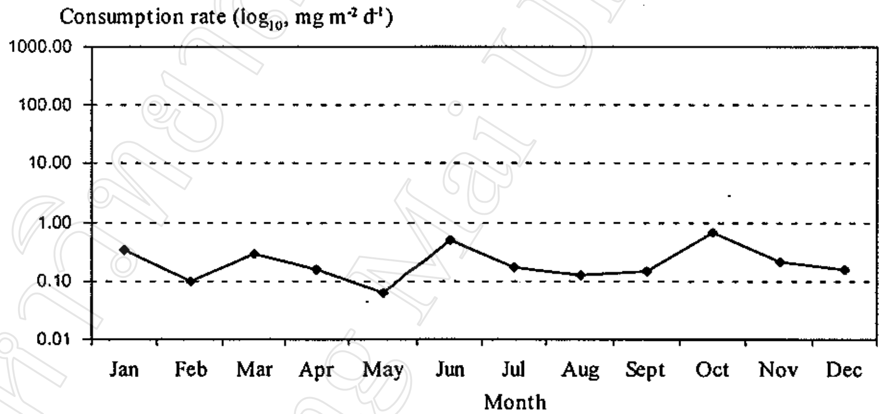

Figure 4.5 Methane consumption rates in field crop area (FC).

4.2.5 Orchard Field (OF)

Orchard field (OF) was located in Wat Chan and adjacent to the rice field (RF1). Temperate fruit trees were planted in the area, with temperate vegetables between fruit trees spacing. Methane consumption rate in the area varied from 0.057 to 0.389 mg CH_4 m^{-2} d^{-1} with an average of 0.234 $\pm$ 0.107 mg CH_4 m^{-2} d^{-1} (Figure 4.6). Average soil and air temperatures at the sampling point were 25.4 $\pm$ 3.5 and 28.0 $\pm$ 2.7 °C, respectively.

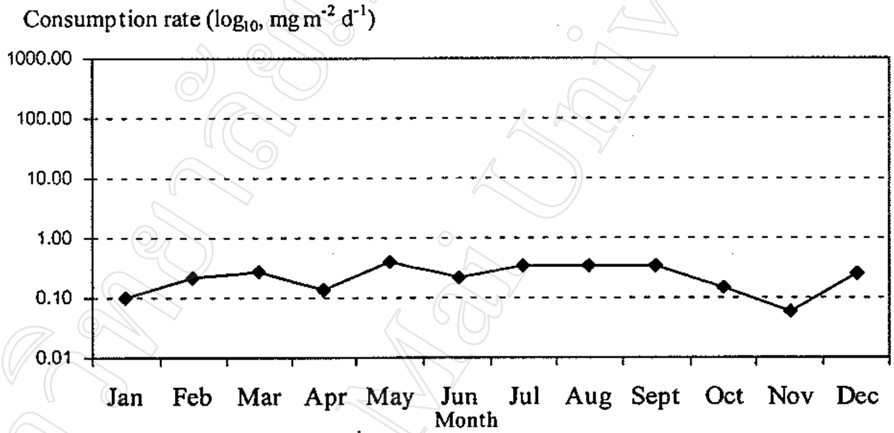

Figure 4.6 Methane consumption rates in orchard field (OF).

4.2.6 Pine Forest (PF)

Pine forest has occupied about 30% of Wat Chan watershed and tend to be stable since 1974 (Sangchyoswat, 1998). A few pine species have been dominant in the area. Methane consumption rate of pine forest in Wat Chan ranged from 0.009 to 0.415 mg CH_4 m^{-2} d^{-1}, with an average of 0.161 ± 0.120 mg CH_4 m^{-2} d^{-1} (Figure 4.7). Average soil and air temperatures were 25.2 ± 3.1 °C and 26.2 ± 2.6 °C, respectively.

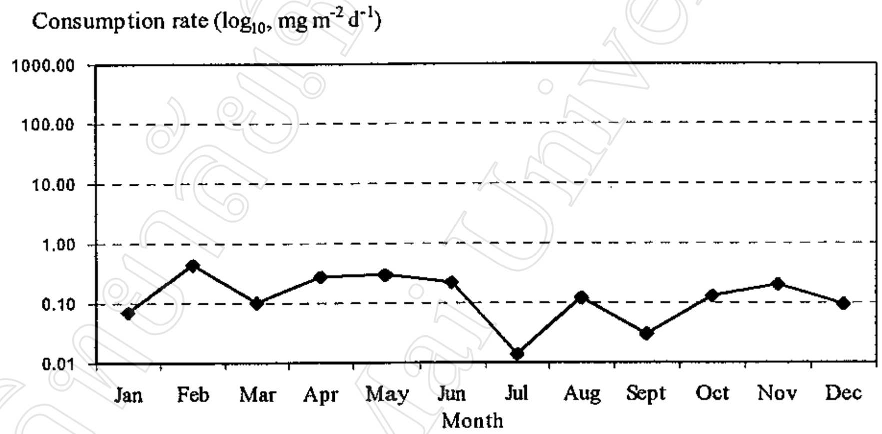

Figure 4.7 Methane consumption rates in pine forest (PF).

This study found that the average emission rate from RF1 and RF2, which were methane sources of MCW were 26.757 ± 54.386 and 111.092 ± 112.120 mg CH_4 m^{-2} d^{-1}, respectively. While the consumption rates in RF1, RF2, DF1, DF2, EF, F1, F4, F7, FC, OF, and PF were 0.171 ± 0.188, 0.116 ± 0.079, 0.259 ± 0.197, 0.212 ± 0.146, 0.209 ± 0.152, 0.567 ± 0.210, 0.495 ± 0.234, 0.490 ± 0.276, 0.240 ± 0.173, 0.234 ± 0.107, and 0.161 ± 0.120 mg CH_4 m^{-2} d^{-1}, respectively (Figure 4.8).

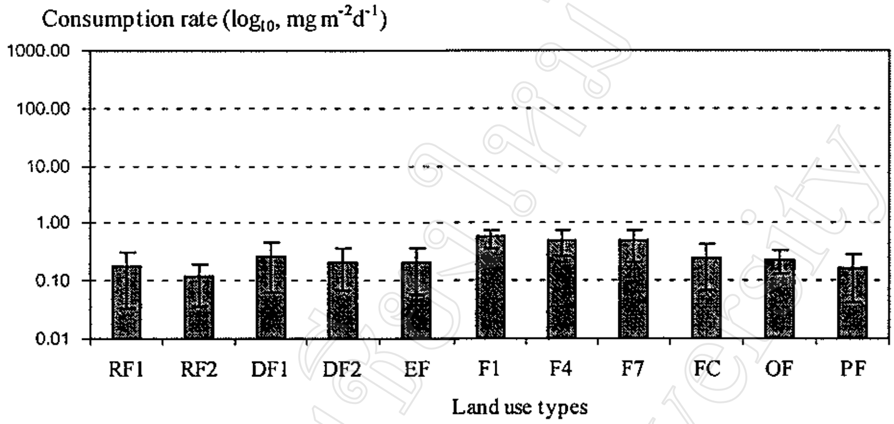

Figure 4.8 Average of methane consumption rates in eleven land uses types.
Note:

RF1	=Rice field in Wat Chan	RF2	=Rice field in Charng-Kerng
DF1	=Deciduous forest in Wat Chan	DF2	=Deciduous forest in Charng-Kerng
EF	=Hill evergreen for	F1	=One-year fallow
F4	=Four-year fallow	F7	=Seven-year fallow
FC	=Field crop area	OF	=Orchard field
PF	=Pine forest		

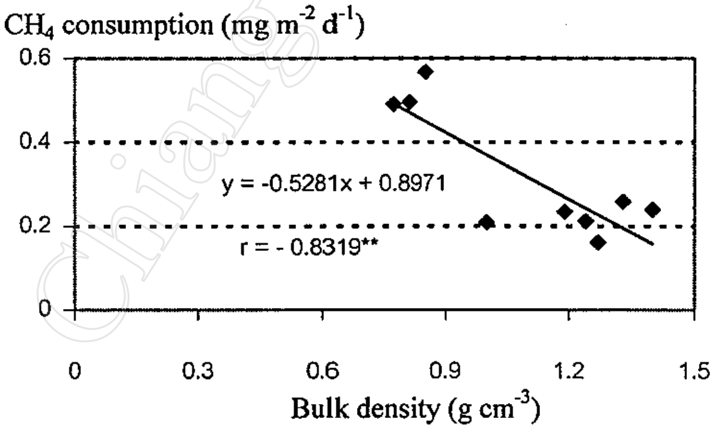

Figure 4.9 Correlation between soil bulk densities and methane consumption rates

Note: ** = significant difference at 1% level

The average methane consumption rates in this study and bulk densities of each land uses from the research namely "C-Stock of Various Land Uses in Mae Chaem Watershed", which was conducted at the same location by Pibool *et al.* (1999, unpublished) were plotted to see their relationship (Figure 4.9). The Figure showed that there was a highly significant negative relationship between bulk density and methane consumption rate. Methane consumption rate will be reduced 0.528 mg CH_4 m^{-2} d^{-1}, when bulk density increases 1 g cm^{-3} ($y = -0.5281x + 0.8971$, and $r = -0.8319^{**}$).

Discussion

Based on methane production and consumption, eleven land uses under this study can be grouped into two categories. The first category is methane partial source and sink, which were rice fields (RF1 and RF2). Among these two rice fields, they differed in term of methane production ability. The causes of difference are, (1) rice varieties, (2) agricultural practices such as water management and fertilizer application, and (3) soil characteristics (Wang *et al.,* 1995).

The second category is the methane consumer, which were forests (DF2, DF2, EF, and PF) and agricultural land use types on non-flooded land area (FC, OF, F1, F4, and F7). The study showed that non-flooded land uses were methane sinks. They acted as methane consumers to reduce methane accumulation in the atmosphere, even the consumption rates found were very small in magnitude compared to the production rates.

The study found that there were high methane consumption rates in fallow land use types as compared to other land uses. The averages of methane consumption rates were 0.567 $\pm$ 0.210, 0.495 $\pm$ 0.234, and 0.490 $\pm$ 0.276 mg CH_4 m^{-2} d^{-1} of one-year, four-year and seven-year fallow, respectively. By visual observation, it was found that (1) the soil surface of fallow fields covered by a thick litter layer compared to other land uses. (2) There was little or no runoff due to the location of these fields were located on a relative flat area, so organic matter was not moved by runoff during the rainy season. Even, evergreen forest and deciduous forest produced high amount of plant biomass, but they were moved by runoff and/or burnt during rainy and/or dry season, respectively, especially in deciduous forest. And (3) the percent sand in soil texture of layer A and B of the three fallow fields was quite high, it implied to indicate a good providing O_2 for methanotropic bacteria activities in the soil. This hypothesis was confirmed by the highly significant difference of the negative relationship between soil bulk density and methane consumption rate. (4) Agricultural management in fallow fields might indirect promote consumption activities in the soils.

4.3 Net Methane Emission from Mae Chaem Watershed

More than 120 land use types of Chiang Mai province were classified by the Decision Support System in Agriculture Research Unit (unpublished). Those were regrouped into seven land use types, which were paddy field, field crop, fallow field, deciduous forest, evergreen forest, pine forest, orchard field and others (cities, villages and reservoir). Mae Chaem watershed is a part of Mae Chaem district, a district in Chiang Mai province occupied area of 334,368 hectares. Land use types in the district were also regrouped into 7 types, and shown in the Table 4.2.

Table 4.2 The area and methane production/consumption rate of seven land uses types

Land use types	*Area*	*Emission/Consumption*	
		Emission	Consumption
	ha	*kg ha^{-1} d^{-1}*	
Rice field	5,427	0.6892	0.00144
Field crop	972	-	0.00240
Fallow	29,727	-	0.00517
Deciduous forest	178,281	-	0.00236
Hill evergreen forest	75,411	-	0.00209
Pine forest	42,444	-	0.00161
Others	2,106	-	-
Total	334,368	-	-

Source: Decision Support System in Agricultural Research Unit, Multiple Cropping Center, Chiang Mai University (unpublished).

According to land use classification of Decision Support System in Agriculture Research Unit, there is no horticulture land area in Mae Chaem watershed. It may be grouped as a forest or a field crop area. However, methane consumption rate in orchard field is 0.00234 kg ha^{-1} d^{-1}, which is not significant different with consumption rate in forest or field crop. Methane production and consumption rates of rice field were the average of two rice fields (RF1 and RF2). Similar to methane consumption rates of deciduous forest and fallow field, it was the average of two (DF1 and DF2) and three (F1, F4, and F7) representative fields, respectively.

From the data in the Table 4.2, net methane emission from Mae Chaem watershed was calculated (Table 4.3). In rice field, methane was produced and emitted into the atmosphere from mid of May to November about 195 days and the rest was the consumption period of 170 days.

Table 4.3 Calculation of the net methane emission from seven land use types

Source/Sink	*Duration of P/C*	*P/C Rate*	*Area*	*Total P/C*
	d	*kg ha^{-1} d^{-1}*	*ha*	*kg y^{-1}*
Source (Production)				
Rice field	195	0.68920	5,427	729,356.2
Sink (Consumption)				
Rice field	170	0.00144	5,427	1,328.6
Field crop	365	0.00240	967	847.1
Fallow field	365	0.00517	29,272	55,237.7
Deciduous forest	365	0.00236	178,281	153,571.3
Hill evergreen forest	365	0.00209	75,411	57,527.3
Pine forest	365	0.00161	42,444	24,942.2
Total consumption				293,454.2
Net emission		729,365.2 – 293,454.2	=	435,911.0

Note; P = Production, C = Consumption

The calculation showed that Mae Chaem watershed emitted methane from the rice fields at the rate of 729.4 tonnes per year, while non-flooded soil consumed methane at the rate of 305.2 tonnes per year. Therefore, net methane emission from Mae Chaem watershed was 424.2 tonnes per year.

Discussion

The capacity of methane source (RF1 and RF2) is much higher than sink (DF1, DF2, EF, F1, F4, F7, FC, OF, and PF) even the area is much smaller. However, this study showed that forest and agricultural area could be methane sinks for reducing methane accumulation in the atmosphere. In term of resources management, system approach has to be employed before doing decision making to allocate the limiting resources. Methane source and sink capacity is an important information for policy maker using for long term planning regarding to environmental concern. If there is only methane production data in paddy field, it may bias for agricultural sector. While the rest of area is not interested, which is actually methane consumer. So that methane source and sink research should go together.

From discovered methane production and consumption rates in this study, promotion of methane sink capacity alone may not be enough to reduce the tremendous production rate. Another significant strategy is to reduce methane production in paddy field. Agricultural practices, such as water management and using low methane emission rice variety are high potential to reduce methane production. Water drainage from the paddy field for sometime without effect on rice yield is an efficient practicing to cut out the net methane production. There was an example in Wat Chan rice field during gas samples collection in August. The farmer drained the water out to reduce crabs' damage, consequence to reduce methane production rate from 146.342 mg CH_4 m^{-2} d^{-1} in July to 1.337 mg CH_4 m^{-2} d^{-1} in August. However timing of water management has to be studied as well as water sources. According to aerenchyma and intercellular spaces of rice plant is the main channel of methane movement from production zone into the atmosphere, therefore consideration of this characteristic should be taken into account before improving new rice varieties.

4.4 Modeling of Methane Production and Consumption

Integration of functions from the ORYZA1 and SIMRIW models combined with functions of methane emission from rice field (Cao *et al.,* 1995; Matthews *et al.,* 1999. inpress). The model consists of two sectors, methane production and methane consumption.

4.4.1 Methane Production Sector Model

Methane emission from rice field is an ecosystem process closely couple to rice growth and soil organic matter decomposition (Cao *et al.,* 1995). Therefore this methane production model consists of rice growth model, soil organic matter decomposition process and methane oxidation at rhizosphere before moving upward via rice plant system and emitted into the atmosphere (Figure 4.10).

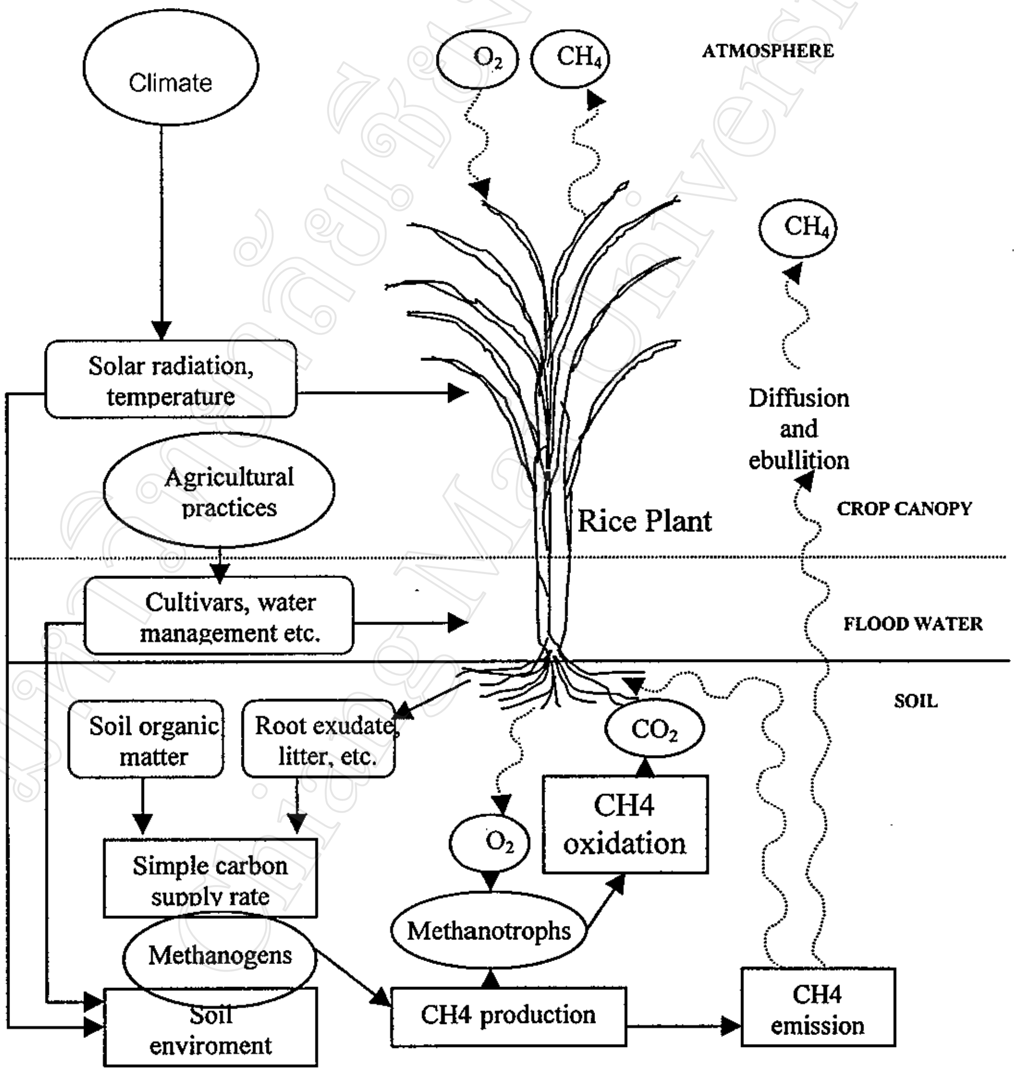

Figure 4.10 Conceptual model of the methane production processes.

Rice growth

This simulation model is based on known relationship between rice-weather process and a simplified rice growth module. The model was developed by a rational simplification of physiological and physical processes of the growth of a rice crop. Assumptions of the model are no limitation of soil nutrient, no damages of insects and diseases. The model began with development of leaf area index (LAI) by using temperature sum (t_s) function. The temperature sum was calculated from Growing Degree Days (GDD, Ritchei and NeSmith, 1995), beginning at transplanting date;

$$GDD = \sum_{i=1}^{n} (\overline{Ta} - Tb) \qquad (4.1)$$

Where; Ta = daily mean air temperature

Tb = is the base temperature at which development stop (9 °C)

n = the number of days of temperature observation used in the summation.

$$\text{LAI} = 0.015*\text{EXP}(.003*t_S) \qquad (4.2)$$

Development of leaf area index consisted of initial LAI (m^2 of leaf m^{-2} of ground), an exponential of relative growth rate of leaf area multiplied by temperature sum (Kropff *et al.*, 1995). Initial leaf area index used in the model was 0.015 m^2 leaf m^{-2} ground, because most of rice leaves were cut before transplanting. Relative growth rate of leaf area was the growth of leaf per a degree day $(^{o}Cd)^{-1}$. It varied from variety to variety. This research used 0.003 $(^{o}Cd)^{-1}$. Function of LAI was to absorb Photosynthesis Active Radiation (PAR). Amount of absorbed radiation (S_s) was defined by this equation (Horie *et al.*, 1995);

$$S_s = S_o(1-r-(1-r_o)\text{EXP}(-(1-m)k(\text{LAI}))) \qquad (4.3)$$

Where;

S_o = the daily incident solar radiation (MJ m^{-2} d^{-1})

r = reflectance of canopy

r_o = reflectance of bare soil (0.1)

m = 0.25 (empirical constant)

k = 0.6 (empirical constant)

$$r = r_f - (r_f - r_o)\text{EXP}(-\text{LAI}/2) \qquad (4.4)$$

r_f = the reflectance when the ground surface is completely covered by the vegetation

Daily incident solar radiation (MJ m^{-2} d^{-1}) used in this model was calculated from a function of latitude and day of the year (Van Keulen and Wolf, 1986). The location of rice field in Wat Chan sub-district was located at latitude 19° 4′ 15.5″ N. The model calculated LAI, daily incidence solar radiation, then the absorbed radiation followed. Radiation used efficiency of rice was about 1.95 g MJ^{-1} (Matthews *et al.*, 1995), therefore dry matter production could be simulated on a daily basis.

Methane Production

As mentioned in Chapter 2, three sources of organic carbon provided for methane producing are (1) soil organic matter, (2) exogenous supply of organic material and (3) root and leave litter and root exudate. The fraction of carbon transferred to the root of annual crop ranges from 35 to 60% of total growth rate (Cao *et al.*, 1995). This model used a value of 35% of traditional rice growth. Soil organic matter of Wat Chan's rice field was 3.85% or equal to 0.6618 kg m^{-2} (calculated from plough soil layer). Carbon fraction of soil organic matter was 0.4449 (TEI, 1997). Organic materials were assumed to be partition into Pool I (easily decomposable material, e.g., sugar, protein, and carbohydrate) 75% and Pool II (Slowly decomposable material, e.g., recalcitrant, and lignin material) 25% (Cao *et al.*, 1995). Non-methane producer microorganisms firstly use the organic materials then the microbial biomass was directed into Pool I (60%) and Pool II (40%). First order decay rate of Pool I was 43.84 unit per 1000 unit per day, while Pool II was 0.44 unit per 1000 unit per day. Yield efficiency (a part of carbon being degraded that incorporated into microbial tissue) was 0.4 and 0.3 for Pool I and Pool II, respectively.

This model used a part of carbon from daily rice growth and soil organic matter to predict methane production under controlling factors. Factors used in this model were soil pH, air temperature, water depth, redox potential and the maximum fraction of the carbon substrate to be converted to methane (P_m). The equation of methane production rate (MPR, mg CH_4 m^{-2} d^{-1}) was developed (Cao *et al.,* 1995) as follows;

$$MPR = 16 * ((P_m * SCSR * FCs)/12) \qquad (4.5)$$

Where; SCSR was the simple carbon supply rate from root exudate and soil organic carbon. FCs were the functions of soil pH, Eh, water depth, and air temperature. And P_m used was 0.47. Atomic weight of C and CH_4 was 12 and 16 respectively. The product was divided by 12 and multiplied by 16 to convert atomic weight of carbon to methane.

Methane Oxidation at Rice Rhizosphere

Some of methane was oxidized at rice rhizosphere by methanotrops before emitting into the atmosphere. About 40 to 90% of the methane produced during rice growing season was consumed. Rates of methane oxidation depended on the availability of O_2 in the soil. Methane oxidation was simulated as a function of rice growth and development, which influenced by aerenchyma in the rice stem. Increase of aerenchyma cell consequently increased in O_2 flux from the atmosphere into rhizosphere and methane oxidation was increase together with rice growth development. Methane oxidation rate (mg CH_4 m^{-2} d^{-1}) in rice rhizosphere was calculated by the following equation (Cao *et al.,* 1995).

Methane Oxidation = MPR (0.4+(0.5(Rice growth/RDMm))) (4.6)

Where; MPR is methane production rate and 0.40, 0.50 is constant. Rice growth is the product of equation 4.3 multiplied by radiation use efficiency. RDMm is the maximum dry matter accumulated in the end of rice growing season, which is 933,320 mg m^{-2}.

The methane production simulation model (Figure 3.10) is able to simulate methane production rate, methane oxidation rate in rice rhizosphere. So that, the methane emissions rate from rice field can be accounted by subtracting the oxidation rate from the production rate.

This simulation model was constructed using Stella program. The model used two sources of carbon to simulate methane production, soil organic matter and rice root exudate. Methane production process was controlled by four significant controlling factors, redox potential (Eh), pH, water depth in rice field, and air temperature. Primary methane product from the process was partly oxidized by methanotrophic bacteria at rice rhizosphere before emitting into the atmosphere. Methane emission was simulated day by day under given carbon sources and environmental factors.

4.4.2 Methane Consumption Sector Model

This model simulated methane consumption rate of non-flooded soils by using the methane oxidation equations suggested by of Matthews *et al.* (1999). Four affecting factors were added into the equation, which were soil pH, air temperature, soil moisture, and soil organic matter (Figure 4.11). The model could be used to estimate methane consumption in rice field during dry season. The methane consumption rate (mg CH_4 m^{-2} d^{-1}) was simulated with the following equation;

$$MCR = CH_4 \times \frac{CH_4}{(0.33 + CH_4)} \times \frac{O_2}{(0.44 + O_2)} \times FCs \qquad (4.7)$$

Where MCR is methane consumption rate, CH_4 is ambient methane supply rate (1.2 mg C $m^{-2} s^{-1}$) and O_2 is atmospheric quantity of oxygen supply rate (2.48 x 10^5 mg $m^{-2} s^{-1}$). While 0.33 and 0.44 are constant values (Matthews *et al.,* 1999). FCs is affecting factors as already mentioned.

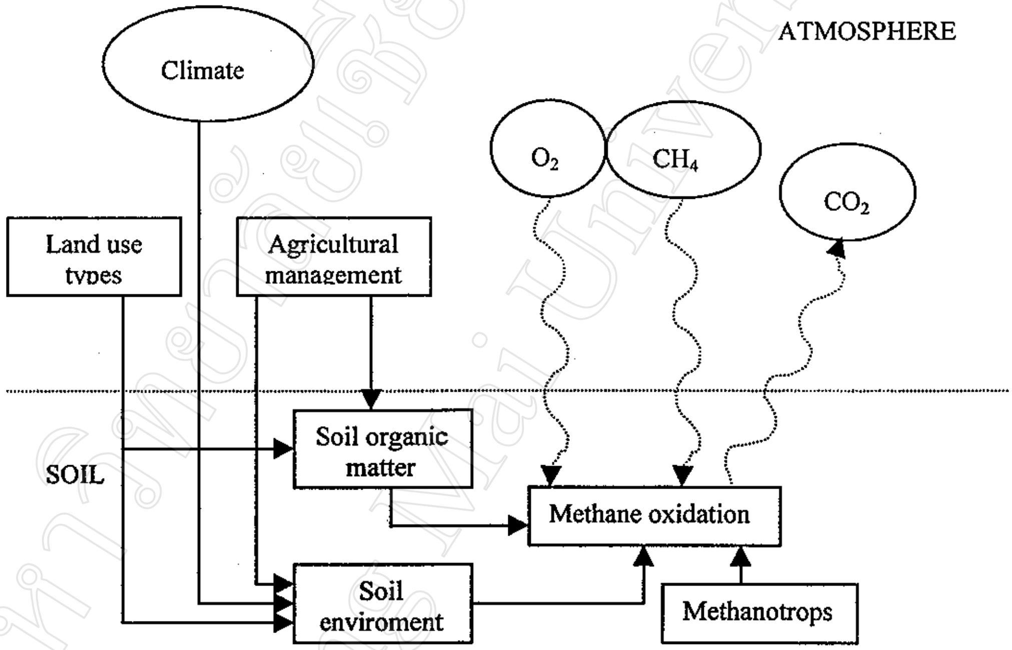

Figure 4.11 Conceptual model of the methane consumption processes
Note; The arrow lines represent material flows.

A Stella program was used to simulate methane consumption in non-flooded areas. Atmospheric concentration of O_2 and CH_4, and soil organic matter were inputs of the model. Methane consumption controlling factors included, soil moisture content, soil pH, and air temperature.

4.4.3 Simulation Results

Weather and soil data sets were used to construct the models. The data sets in the methane production model were the data of Wat Chan and Charng Kerng sub-district, which constructed as a representative of rice field in Mae Chaem watershed. In case of non-flooded soil, methane consumption in DF1, F1, F4, F7, OF, and PF were simulated by using the same weather data of production model, but soil data set varied from site to site. The data sets and function of affecting factors were shown in the Appendices. Function of affecting factors such as pH, Eh, temperature, soil moisture, and soil organic matter were developed base on function and optimum condition defined by Cao *et al.* (1995) and Bender and Corad (1995).

Simulation Results of Methane Partial Source and Sink

Methane consumption occurred in dry season from January to mid May and December. The consumption rates ranged from 0.001 to 0.802 mg CH_4 m^{-2} d^{-1} with an average of 0.178 $\pm$ 0.220 mg CH_4 m^{-2} d^{-1}, while the average actual measurement was 0.144 mg CH_4 m^{-2} d^{-1}. Methane was produced during rice growing season from mid of May to November. Variation pattern of methane production was similar to growth rate of rice. Methane emission rate ranged from 0.432 to 246.798 mg CH_4 m^{-2} d^{-1}. The peak of emission rate occurred in flowering stage (Figure 4.12). The average emission was 59.702 $\pm$ 54.705 mg CH_4 m^{-2} d^{-1} compared to 68.925 mg CH_4 m^{-2} d^{-1} of observed value.

In term of seasonal variation of methane emission, observed and simulated seems to be valid (Figure 4.12). Evaluation of the model by plotting graph one to one line (Figure 4.13; Figure 4.14) found that methane consumption rates from the model were lower than measurement, while the overall agreement of observed and simulated of methane production tends to be good.

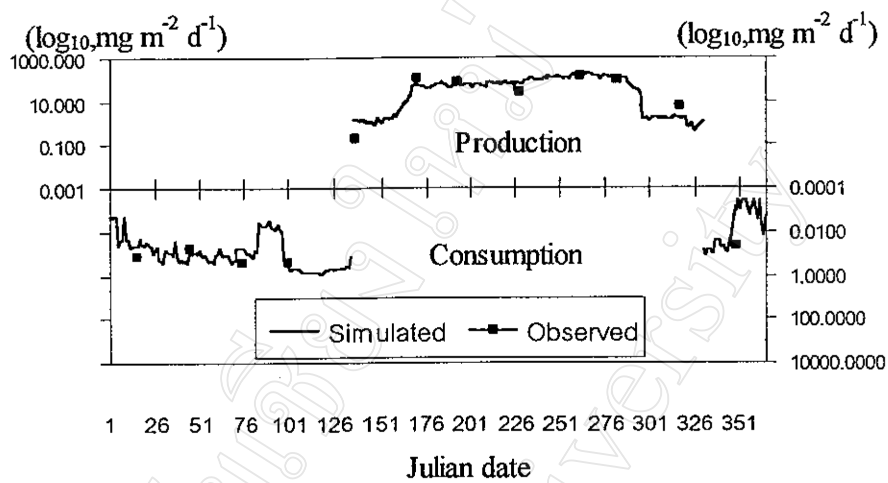

Figure 4.12 Simulated and observed methane production and consumption in rice field.

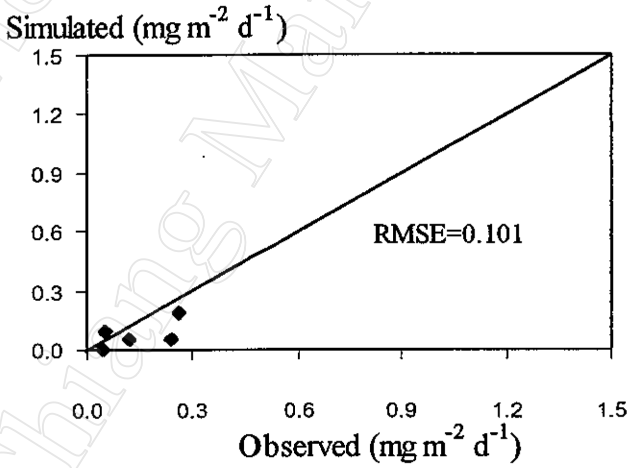

Figure 4.13 Comparison of observed and simulated methane consumption in rice field.

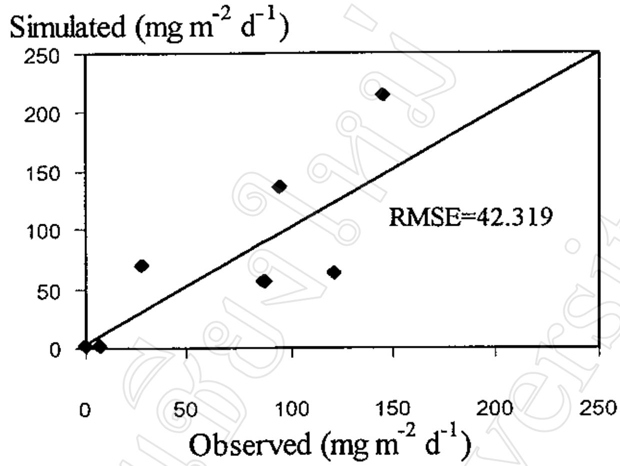

Figure 4.14 Comparison of observed and simulated methane production in rice field.

Simulation Results of Methane Sink

Methane Consumption in Deciduous Forest (DF1)

The percentage of organic matter of the area was quite high compared to the others (3.98), soil pH used in the model is 6.6. The results of simulation ranged from 0.0002 to 0.958 with an average of 0.295 $\pm$ 0.231 mg CH_4 m^{-2} d^{-1}. While the observed ranges from 0.056 to 0.706 and the average was 0.259 $\pm$ 197 mg CH_4 m^{-2} d^{-1} (Figure 4.15). Both agreements of seasonal variation pattern, and simulated and observed value were acceptable. However, some of simulated values were varied from the observed values (Figure 4.16).

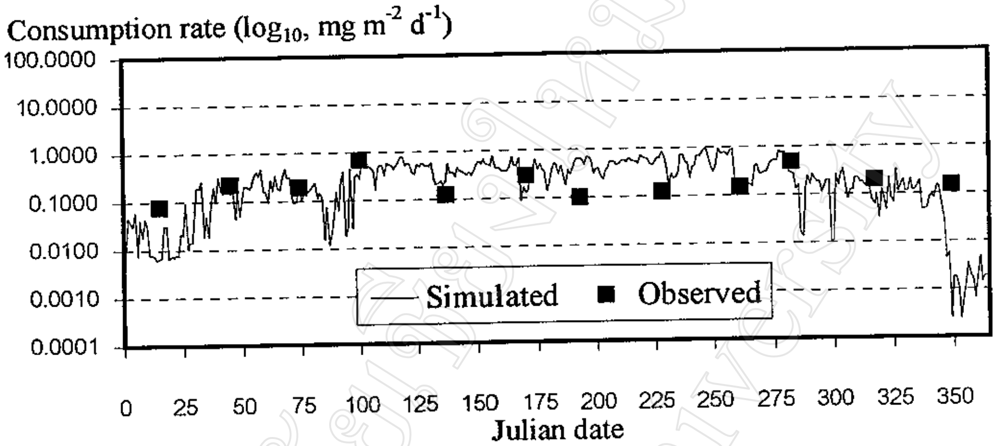

Figure 4.15 Simulated and observed methane consumption in deciduous forest (DF1).

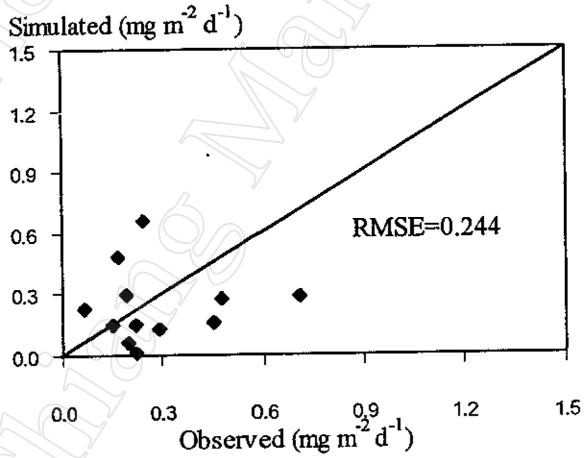

Figure 4.16 Comparison of observed and simulated methane consumption in deciduous forest (DF1).

Methane Consumption in One-year Fallow (F1)

Organic matter and soil pH of the area were 0.265% and 6.8, respectively. The simulated consumption rates from the model ranged from 0.0075 to 1.383 with an average of 0.566 ± 0.271 mg CH_4 m^{-2} d^{-1} compared to 0.567 ± 0.209 mg CH_4 m^{-2} d^{-1} of the observed value (Figure 4.17). Generally, the agreement between simulated and observed value was good (Figure 4.18).

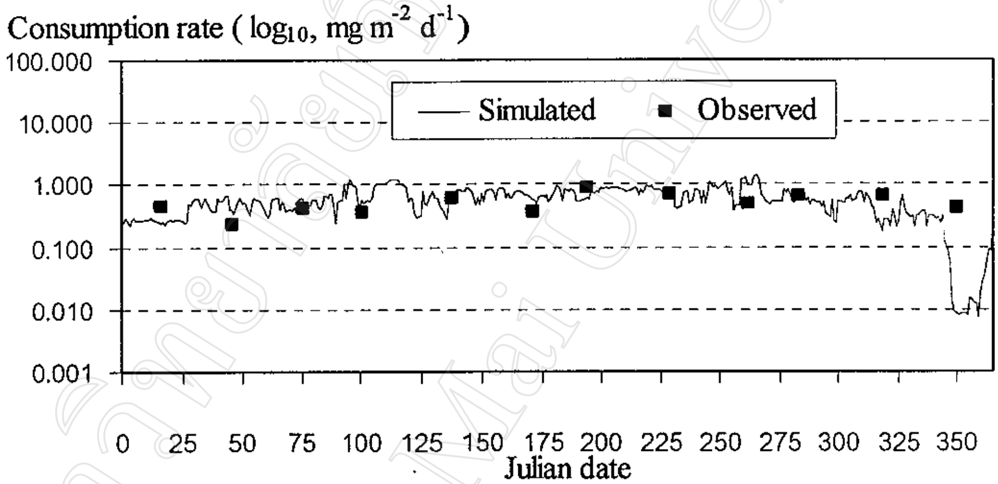

Figure 4.17 Simulated and observed methane consumption in one-year fallow (F1).

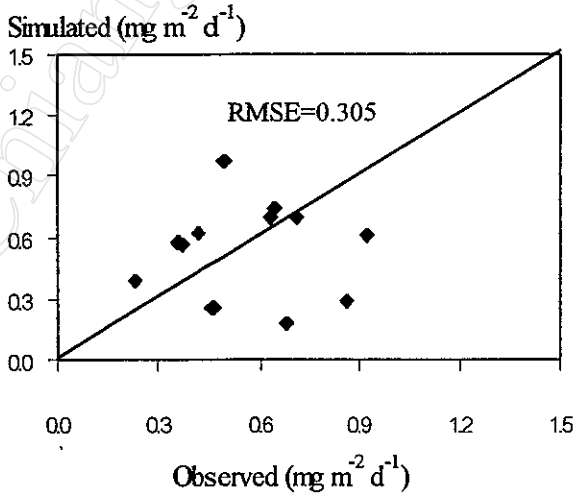

Figure 4.18 Comparison of observed and simulated methane consumption in one-year fallow (F1).

Methane Consumption in Four-year Fallow (F4)

The percentage of organic matter and pH of the area used in the model are 0.345% and 6.8. The simulation results ranged from 0.0083 to 1.518 with an average of 0.621 ± 0.298 mg CH_4 m^{-2} d^{-1}. The observed values ranged from 0.047 to 0.935, with an average of 0.495 mg CH_4 m^{-2} d^{-1} (Figure 4.19). The agreement between observed and simulated value tended to be good (Figure 4.20). The model needs to be adjusted for more accurate prediction, because most of simulated values are higher than observed.

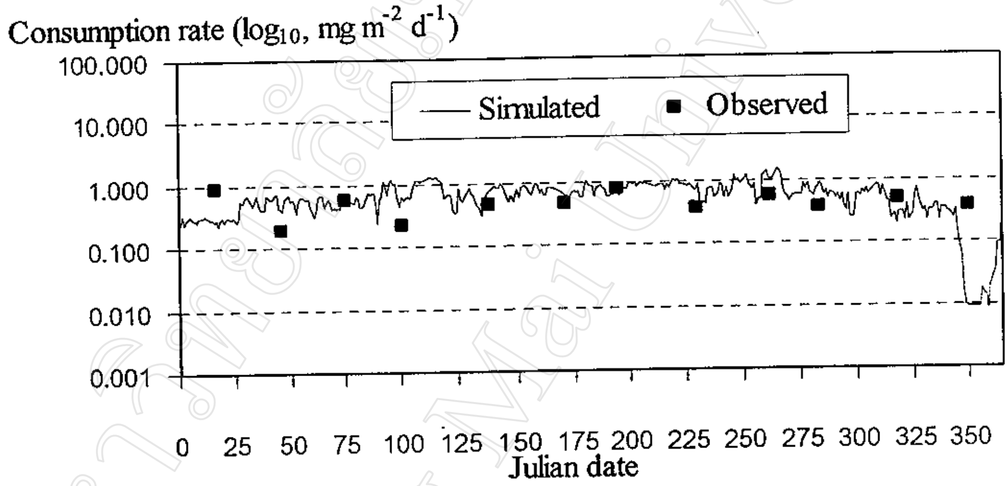

Figure 4.19 Simulated and observed methane consumption in four-year fallow (F4).

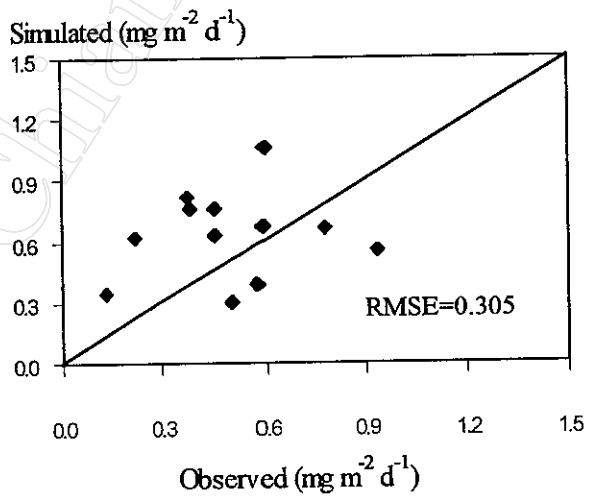

Figure 4.20 Comparison of observed and simulated methane consumption in four-year fallow (F4).

Methane Consumption in Seven-year Fallow (F7)

The pH and percentage of organic matter of the area used in the model were 6.8 and 0.307%. The simulated methane consumption rates ranged from 0.0079 to 1.454 with an average of 0.595 ± 0.285 mg CH_4 m^{-2} d^{-1}. While the observed ranged from 0.120 to 0.885 and the average was 0.490 ± 276 mg CH_4 m^{-2} d^{-1} (Figure 4.21). The seasonal variation of methane consumption of observed and simulated values seemed to be a good relation. However, the model adjustment is necessary to be done to reduce the gap between two values (Figure 4.22).

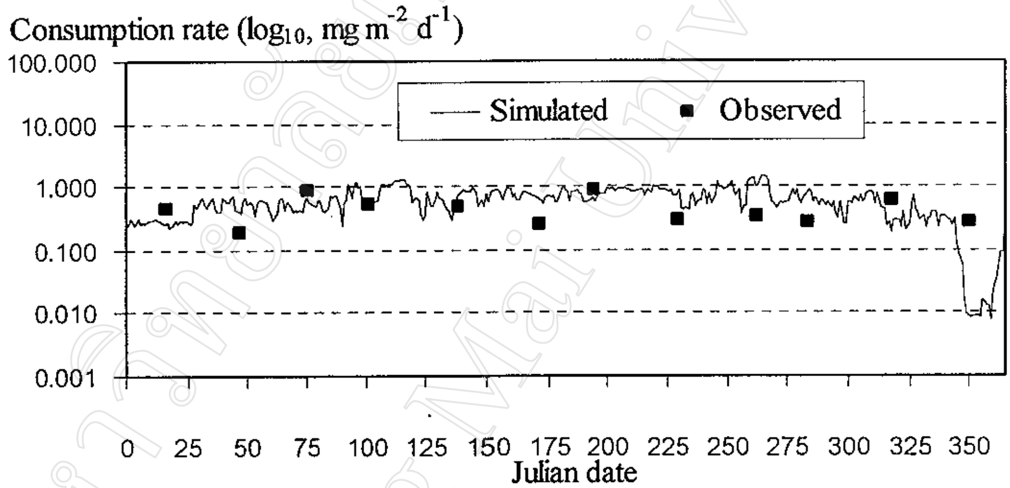

Figure 4.21 Simulated and observed methane consumption in seven-year fallow (F7).

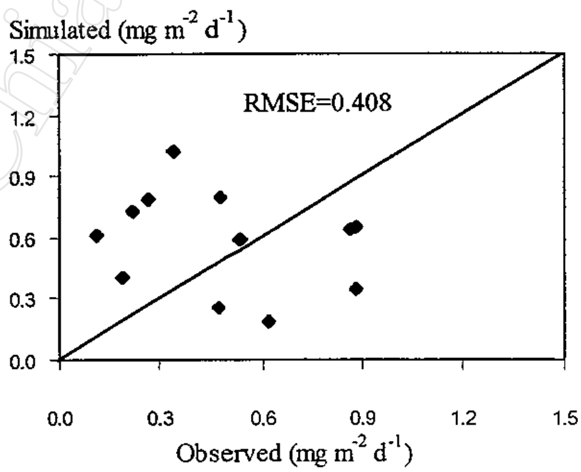

Figure 4.22 Comparison of observed and simulated methane consumption in seven-year fallow (F7).

Methane Consumption in Orchard Field (OF)

Soil pH and soil organic matter used to construct the model were 5.6 and 6.14%, respectively. The results of the model was that the consumption rates ranged from 0.002 to 0.577 mg CH_4 m^{-2} d^{-1} with an average of 0.240 ± 0.115 mg CH_4 m^{-2} d^{-1}. While the observed was 0.234 ± 0.107 mg CH_4 m^{-2} d^{-1} (Figure 4.23). Methane consumption rates from both simulation and measurement seemed to be a very good agreement (Figure 4.24).

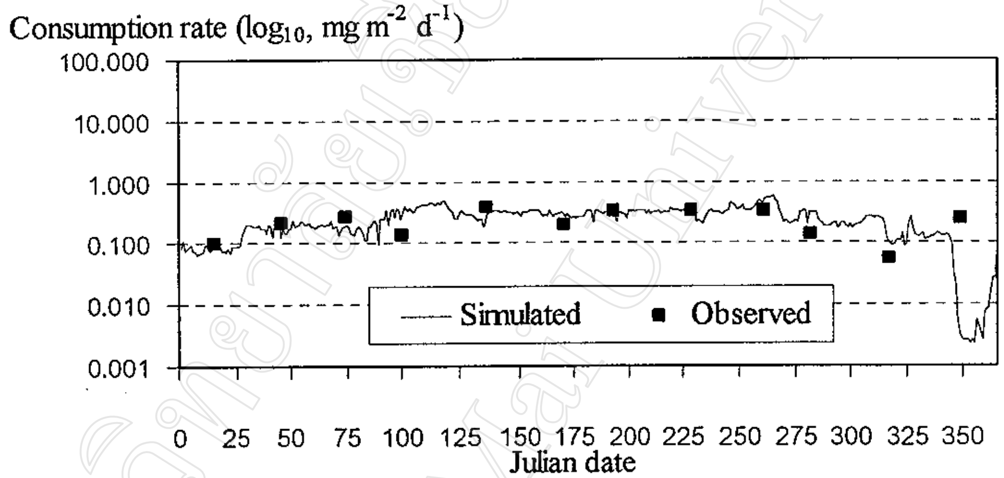

Figure 4.23 Simulated and observed methane consumption in orchard field (OF).

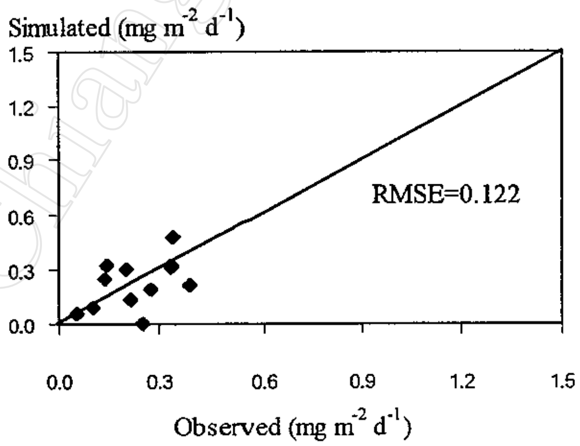

Figure 4.24 Comparison of observed and simulated methane consumption in orchard field (OF).

Methane Consumption in Pine Forest (PF)

The percentage of organic matter and pH of the area were 0.265% and 6.8. The results of simulation ranged from 0.0002 to 0.630 with an average of 0.194 ± 0.152 mg CH_4 m^{-2} d^{-1}. While the observed ranged from 0.009 to 0.415 and the average was 0.161 ± 120 mg CH_4 m^{-2} d^{-1} (Figure 4.25). The overall agreement of simulated values and observed value seemed to be good and acceptable (Figure 4.26).

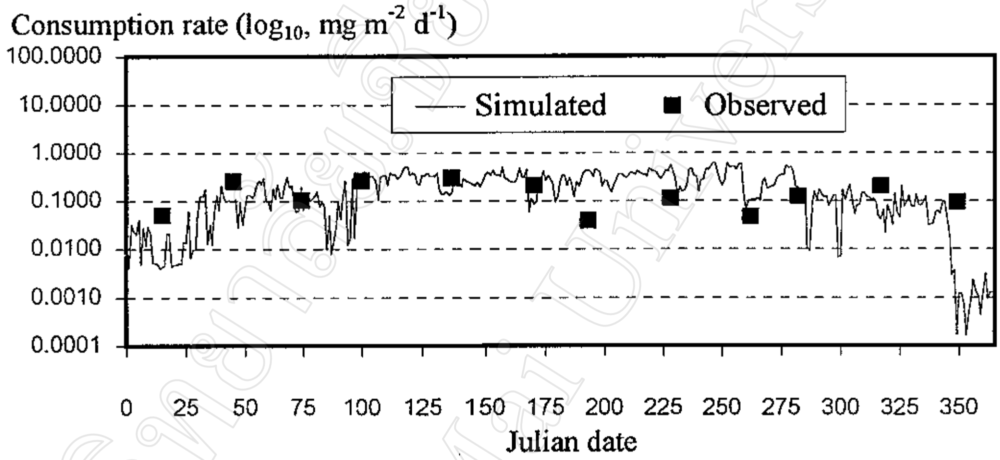

Figure 4.25 Simulated and observed methane consumption in pine forest (PF)

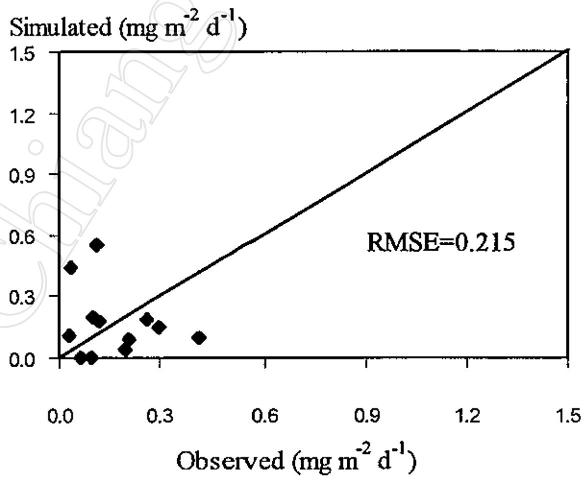

Figure 4.26 Comparison of observed and simulated methane consumption in pine forest (PF)

Discussion

These methane production and consumption simulation models were constructed and integrated functions used in ORZA1 and SIMRIW models with some functions of methane emission from rice field of Cao *et al.* (1995) and Matthews *et al.* (1999). The simulated seasonal variation of methane production and consumption values tended to be similar to observed values. Overall agreement between observed and simulated values seemed to be good. However, the model have to be more developed for more precision estimation.

Methane production model was constructed from various sources of function of controlling factors. Therefore, those factors have to be readjusted under real environment. For example, growth function of rice used in the model is the function of high yielding variety, which is much different to local rice variety. In this model, there is a fraction of root exudate providing carbon for methane production, while there is no biomass of leaf decomposition rate. It needs to be added.

Methane consumption model was developed from methane oxidation function of Matthews *et al.* (1999), which is a function of methane oxidation at rice rhizosphere. It was developed by providing additional atmospheric CH_4 concentration, ambient O_2, and given physical environment such as soil organic matter, soil pH, soil moisture, and air temperature. This is a very simple methane consumption model and constructed by a few functions, therefore the model need to be more developed and tested.