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ESTIMATE OF METHANE EMISSIONS FROM RICE FIELDS IN CHINA BY CLIMATE-BASED NET PRIMARY PRODUCTIVITY

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ABSTRACT: Rice fields provide food for over half of the world population but are also an important source of atmospheric CH_4. Using the climate-based GIS empirical model and the meteorological data collected from 600 meteorological stations in China, with county as the basic unit, the net primary productivity (NPP) of rice fields in China in 1990, 1995, 1998, and 2000 were estimated to be in the range from 202.19×10^{12}g C in 1990 to 163.46×10^{12}g C in 2000. From the measured data of the factors affecting CH_4 emission and NPP, the conversion ratio of the NPP into CH_4 emission for the rice fields of China was determined to be 1.8%. Using this ratio and estimated NPP, the CH_4 emissions from rice fields of China in 1990, 1995, 1998, and 2000 were estimated to be 7.24×10^{12}, 6.31×10^{12}, 6.77×10^{12} and 5.85×10^{12}g CH_4, respectively.

KEY WORDS: CH_4 emissions; rice fields; net primary productivity; climatic factor

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1 INTRODUCTION

Irrigated rice fields are characterized by large spatial and temporal variations in CH_4 emission to the atmosphere. Accordingly, there is a great uncertainty in the estimate of CH_4 emissions from rice fields. Great efforts have been made to estimate the CH_4 emissions from rice fields and several approaches have been developed. The representative methods include the IPCC (Intergovernment Panel of Climate Change) region-specific emission factor method and the model calculation method. To improve the calculation accuracy, the IPCC method requires a large number of field observation data. Even so, the IPCC method cannot reflect annual variation of CH_4 emission. Model calculation needs many input parameters, while many of these parameters are very difficult to be acquired. Since the data required are easily acquired, the approach of using the conversion ratio of NPP to CH_4 for estimating CH_4 emissions from irrigated rice fields is generally considered to be a practical and easily popularized one although it overlooks the influences of rice production and management ways and soil properties on the CH_4 emission.

In the exchanges of energy, material and momentum between the ground surface and the atmosphere, the vegetation plays a very important role. The net primary productivity (NPP) is a key variable to characterize the vegetation activities. The NPP of rice plants refers to the total amount of organic matter produced by the photosynthesis in unit time and unit area excluding the photo-assimilates consumed by the autotrophic respiration. Generally speaking, the measurement of the aboveground net primary productivity (ANPP) is relatively easy but accurate measurement of the underground biomass is rather difficult. Almost all the NPP data are obtained by converting ANPP into NPP using the root to shoot ratio (BACHELET *et al*., 1995), while the aboveground biomass does not always keep a stable proportion with the underground parts (MITCHELL, 1984).

At present, the NPP values of terrestrial vegetation are generally estimated by model at national scale or regional scale. According to the implications of vari-

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ous factors for the regulation mechanisms, the existing models can be classified into three types: the climatic statistical model, the process model and the energy use efficiency model (SUN and ZHU, 2000). As for the climatic statistical model, the NPP values can be calculated based on the statistical relationship between the climatic driving factors and the NPP, such as Lieth's Miami model, Thornthwait Memorial model, Chikugo model, and the model of natural vegetation net primary productivity (ZHOU and ZHANG, 1995). As for the process model, the plant productivity is determined based on the principles of the plant physiology and ecology, for example, the Demeter model (FOLEY, 1994). In the energy use efficiency model, the absorption ratio of the photosynthetically active radiation of the vegetation can be determined by the ratio of the vegetation index (VI) to the normalized difference vegetation index (NDVI) extracted from the remote sensing information and therefore the NPP values can be calculated (SUN and ZHU, 2000). The process model requires many input parameters, and for some ecosystems these parameters are very difficult to be acquired. For the energy use efficiency model, the data such as the photosynthetically active radiation and the temperature can be obtained only from the surface observations at meteorological stations. Although the Miami model overlooks the influences of many factors on the NPP, the climatic factors of air temperature and precipitation are easily acquired for running the model. Thus, the Miami model was used to estimate the NPP values of rice fields in this paper. Then, on the basis of the CH_4 emission data measured in rice fields and the estimated NPP across China, a conversion ratio of estimated NPP by the Miami model into CH_4 emission was determined. By using climatic data acquired from 600 meteorological stations in China, the CH_4 emissions from rice fields were estimated at county level, and then summed up to provincial and national level in 1990, 1995, 1998, and 2000.

2 DATA AND METHODS

To obtain the NPP values of rice fields and estimate the CH_4 emissions, it is necessary to have the information including the spatial extent of rice fields and climatic conditions. The collected data were processed by using the GIS software such as ARC/INFO and MapInfo. The area data of rice fields, excluding those distributed in Taiwan Province, were collected at county level.

2.1 Distribution of Rice Fields

The Chinese Academy of Agricultural Sciences provided the rice-harvested areas for this study. Because the available data did not make a distinction among early rice, middle rice and late rice in various counties, we calculated their proportions of early rice, middle rice, and late rice harvested areas documented in the *Editorial Board of Chinese Agricultural Yearbooks* (1991, 1996, 1999 and 2001) at provincial level. And then using these proportions we calculated the harvested areas of early rice, middle rice, and late rice in each county. The distribution maps of rice fields in China in 1990, 1995, 1998 and 2000 were developed by connecting the harvested areas of various rice crops with the 1∶1 000 000 Electronic Soil Map of China (provided by SHI Xue-zheng, Institute of Soil Science, Chinese Academy of Sciences).

2.2 NPP Model and CH_4 Emission Model of Rice Fields

2.2.1 Lieth's Miami model

The Lieth's Miami model based on climatically driving factors is recognized as a simplest empirical model and can be conveniently used under the GIS environment. There are the empirical relations between the NPP values (dry matter $g/(m^2 \cdot a)$) calculated by the model and mean annual temperature (T) and annual precipitation (PPT) (BACHELET *et al*., 1995):

$$NPP_T = 3000/(1 + \exp(1.315 - 0.119 \times T)) \quad (1)$$

$$NPP_P = 3000/(1 - \exp(-0.000664 \times PPT)) \quad (2)$$

$$NPP = \mathrm{MIN}\,(NPP_T, NPP_P) \quad (3)$$

where NPP_T is the net primary productivity calculated by mean annual temperature; NPP_P is the net primary productivity calculated by annual precipitation; NPP takes the minimum value between NPP_T and NPP_P.

According to above equations, the NPP values at county level were calculated using the meteorological data from 600 meteorological stations (provided by the National Meteorological Center of China), and then summed up to the provincial and national NPP values.

2.2.2 NPP-CH_4 conversion ratio of rice fields

Taylor *et al*. (1991) calculated the NPP values using Lieth's Miami model, assuming that 5% of NPP was emitted in the form of CH_4. This coincides with the ratio of 3%–7% obtained by ASELMAN and CRUTZEN (1989). BACHELET *et al*. (1995) also assumed that 5% of NPP was converted into CH_4 and then calculated the CH_4 emissions from the rice fields. In this study we used the conversion ratio of 5% of NPP to estimate CH_4 emissions from rice fields in China and found that the CH_4 emissions were overestimated. Then we determined the conversion ratio of NPP into CH_4 through comparing the CH_4 emissions measured across China and estimated NPP, and estimated CH_4 emissions again using the determined ratio.

3 RESULTS

3.1 Estimation of NPP of Rice Plants

Using the climatic data from 600 meteorological stations across China, the NPP values of rice fields in China estimated by Lieth's Miami model were 202.19×10^{12}, 176.88×10^{12}, 190.52×10^{12} and 163.46×10^{12}g C in 1990, 1995, 1998, and 2000, respectively (Table 1). They are approximate to the result of 188.69×10^{12}g C estimated by BACHELET *et al*. (1995) using the empirical relation by NEUE *et al*. (1990).

3.2 CH_4 Emission from Rice Fields Estimated by NPP-CH_4 Conversion Method

TAYLOR *et al*. (1991) estimated CH_4 emissions from rice fields using conversion ratio of 5% of NPP. Using the same conversion ratio, we estimated CH_4 emissions from rice fields in China and got the total CH_4 emissions of 17×10^{12}–20×10^{12}g/a (Table 1) in 1990, 1995, 1998, and 2000, which were much larger than the recent estimate of 7.67×10^{12}g/a by using IPCC method (YAN *et al*., 2003). It indicates that CH_4 emissions from rice fields in China are overestimated by using conversion ratio of 5% of NPP. The conversion ratio is an empirical value and shall be determined by measured CH_4 emission rates. For determining the conversion ratio, we compared CH_4 emissions reported by CAI *et al*. (2000; 2003) and CH_4 emissions from the database with the NPP estimated by Lieth's Miami model. Taking the NPP in 1990 as an example, the mean CH_4 emission rates at 14 sites in 11 provinces (municipalities) obtained by estimated NPP by using NPP-CH_4 conversion ratio of 5% was 2.77 times higher than the rates measured in fields (Fig. 1). When the 1.8% of NPP-CH_4 conver-

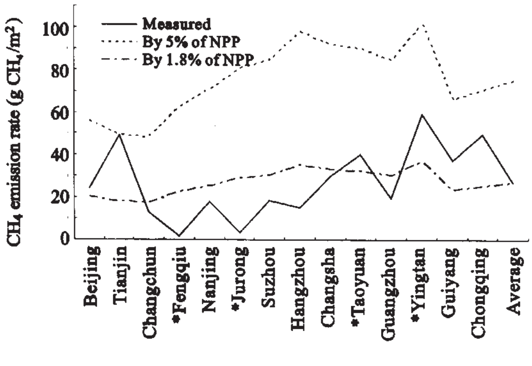
Table1 NPP estimated by Lieth's Miami model and methane emissions from rice fields in China estimated by the NPP-CH_4 conversion ratio of 5%

Province	NPP ($\times10^{12}$g C*)					CH_4 emissions ($\times10^{12}$g CH_4)			
	NEUE**	1990	1995	1998	2000	1990	1995	1998	2000
Beijing	0.263	0.190	0.111	0.112	0.046	0.019	0.011	0.011	0.005
Tianjin	0.317	0.223	0.288	0.227	0.134	0.022	0.029	0.023	0.013
Hebei	0.894	0.843	0.726	0.861	0.505	0.079	0.072	0.073	0.058
Shanxi	0.047	0.038	0.026	0.013	0.012	0.004	0.003	0.001	0.001
Nei Mongol	0.134	0.289	0.266	0.526	0.291	0.026	0.025	0.043	0.028
Liaoning	3.836	0.325	2.610	2.625	2.043	0.031	0.251	0.277	0.197
Jilin	2.474	2.158	2.115	2.353	1.948	0.214	0.210	0.236	0.199
Heilongjiang	2.683	2.938	2.494	3.338	3.085	0.283	0.234	0.324	0.299
Shanghai	1.912	2.138	1.739	1.518	1.345	0.214	0.174	0.152	0.134
Jiangsu	18.278	18.568	14.562	18.651	16.301	1.856	1.453	1.862	1.625
Zhejiang	14.279	16.000	14.251	14.193	10.035	1.581	1.377	1.432	1.017
Anhui	12.896	13.628	10.824	14.856	11.034	1.416	1.074	1.419	1.121
Fujian	7.894	10.383	8.289	8.751	7.701	1.045	0.818	0.878	0.777
Jiangxi	16.348	17.957	17.325	17.604	15.461	1.807	1.698	1.757	1.555
Shandong	0.533	0.828	0.667	0.955	0.720	0.082	0.059	0.093	0.072
Henan	1.787	2.978	3.053	3.852	4.267	0.286	0.234	0.318	0.321
Hubei	17.369	17.806	13.849	14.445	10.984	1.741	1.355	1.421	1.121
Hunan	26.080	25.095	21.865	21.679	20.334	2.529	2.105	2.169	2.037
Guangdong	16.232	15.899	12.992	12.426	12.069	1.600	1.205	1.230	1.202
Guangxi	10.432	12.901	12.574	12.318	10.722	1.291	1.205	1.234	1.091
Hainan	1.113	2.260	2.148	1.926	2.191	0.221	0.213	0.192	0.218
Sichuan	22.518	24.870	20.428	24.293	18.748	2.413	1.939	2.247	1.856
Guizhou	3.372	5.316	6.052	6.049	6.123	0.537	0.601	0.579	0.610
Yunnan	5.050	7.252	6.761	5.647	6.228	0.712	0.644	0.560	0.602
Tibet	–	0.004	0.004	0.005	0.004	0.000	0.000	0.000	0.000
Shaanxi	0.992	1.034	0.640	1.074	0.948	0.083	0.051	0.085	0.070
Gansu	0.022	0.019	0.020	0.020	0.020	0.002	0.002	0.002	0.002
Qinghai	–	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ningxia	0.499	0.142	0.134	0.132	0.091	0.016	0.015	0.015	0.011
Xinjiang	0.433	0.110	0.061	0.073	0.075	0.015	0.007	0.009	0.009
Total	188.69	202.19	176.88	190.52	163.46	20.13	17.06	18.64	16.25

Notes: * The results by the Miami model are expressed in unit of dry matter weight and the dry matter is converted into carbon (C) with the conversion factor 0.5 (SUN and ZHU, 2000)

** These NPP values are the results calculated by BACHELET *et al*. (1995) using the empirical relation by NEUE *et al*. (1990)

sion ratio was used in the calculation, the obtained mean CH_4 emission rate from rice fields was roughly equal to the mean CH_4 emission rate measured at sites. This ratio was much smaller than that of 5% of NPP, which was used by TAYLOR *et al*. (1991).



Note: *Fengqiu (Henan Province), Jurong (Jiangsu Province), Taoyuan (Hunan Province), Yingtan (Jiangxi Province)

Fig. 1 Methane emission rates measured from sites and estimated by the NPP-CH_4 conversion ratios of 5% and 1.8%

Then, we used the ratio of 1.8% of NPP to estimate CH_4 emissions from rice fields at county level and summed up to provincial and national level (Fig. 2). The CH_4 emissions from rice fields in China were estimated to be 7.24×10^{12}, 6.31×10^{12}, 6.77×10^{12} and 5.85×10^{12}g/a in 1990, 1995, 1998, and 2000, respectively, which were very close to 7.67×10^{12}g/a estimated by YAN *et al*. (2003) using IPCC method. These estimated values were also approximate to those calculated by the WinSM and DNDC models (KANG, 2003). HUANG *et al*. (1998) estimated CH_4 emission from China's rice fields (9.66×10^{12}g/a) using a semi-empirical model. But they emphasized that it might be an overestimated value.

The estimated results showed that there existed annual variation of CH_4 emissions from rice fields resulted from the variations of climate and rice harvested areas. The coefficient of variation of estimated CH_4 emission at provincial level ranged from 3.9% in Gansu to 59% in Shanxi. The total CH_4 emission in 1990 was 1.19×10^{12}g larger than that in 2000. Among the provinces, the total emission was the largest in Hunan Province, followed by Sichuan, Jiangsu, and Jiangxi provinces.

4 DISCUSSION

The calculated NPP represents a regional specific mean value, while CH_4 emission was usually measured in a limited space, generally smaller than $1m^2$ in area. Theoretically, because of spatial variation, the CH_4 emission rate measured at special site is not always representative to the regional CH_4 emission rate. Unfortunately, so far there is no approach for directly measuring regional CH_4 emission rate from rice fields. As an alternative approach, we used the site-measured results to approximately represent regional CH_4 emission rates and then determined the conversion ratio of NPP into CH_4. In addition, there are no sufficient CH_4 emission rates measured at different sites in the same year. If we determined the NPP-CH_4 conversion ratio by using the data available in a single year, there would be even larger uncertainties for estimating CH_4 emissions from rice fields. Therefore, we compared the mean emission rates measured at sites in many years and the calculated NPP values in a given year (1990) to determine the conversion ratio.

We used mean CH_4 emission rates measured at 14 sites in 11 provinces and the NPP in 1990 estimated by

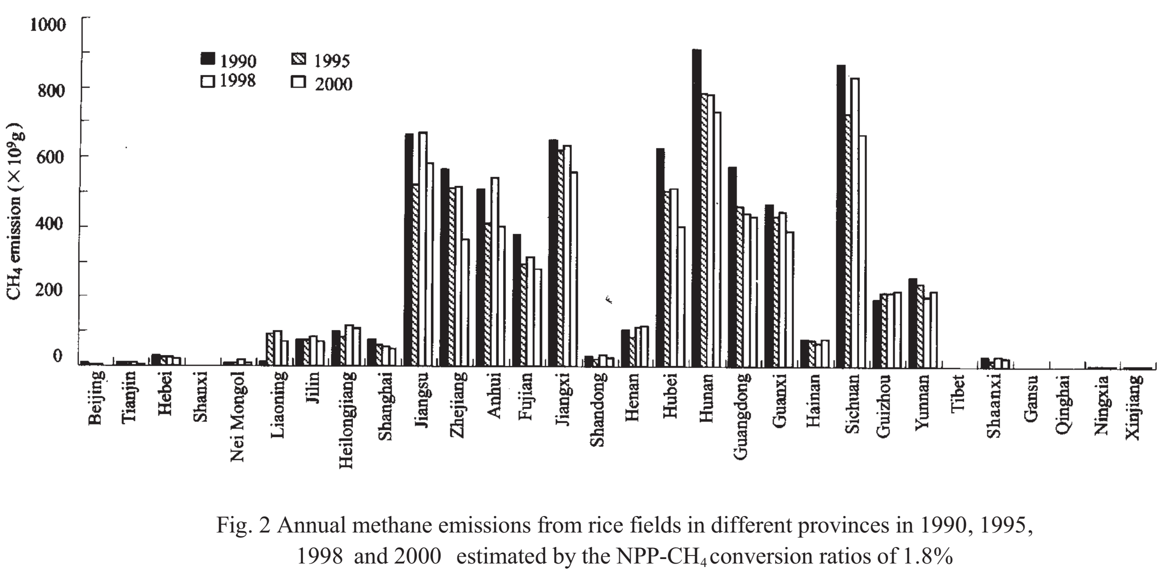


Fig. 2 Annual methane emissions from rice fields in different provinces in 1990, 1995, 1998 and 2000 estimated by the NPP-CH_4 conversion ratios of 1.8%

Lieth's Miami model to determine the NPP-CH_4 conversion ratio and got the averaged value of 1.8% (Fig. 1). This ratio was in the range of 1.7%–3%, which was calculated by DENIER VAN DER GON (2000). HUANG *et al*. (1997) used 1.2%–5.4% of NPP-CH_4 conversion ratio to calculate the CH_4 emissions from rice fields. The CH_4 emissions of over 17×10^{12}g/a from rice fields in China were overestimated by using the NPP-CH_4 conversion ratio of 5% (TAYLOR *et al*. 1991) because they were much larger than 7.67×10^{12}g/a estimated by IPCC method (YAN *et al*., 2003). The NPP of 188.69×10^{12}g C estimated by BACHELET *et al*. (1995) was comparable to our estimated values from 163.46×10^{12} to 202.19g C in China. Obviously, the overestimate was resulted from the NPP-CH_4 conversion ratio rather than from the NPP estimate. Since the estimated CH_4 emissions by using the NPP-CH_4 conversion ratio of 1.8% was comparable to that estimated by IPCC method, the ratio of 1.8% was applicable to estimate CH_4 emission from rice fields in China.

Lieth's Miami model only considers the correlation between the air temperature and precipitation and the net primary productivity of natural vegetation. In fact, the NPP of natural vegetation can also be affected by other environmental factors. In the calculation of the NPP of rice fields, this model improperly assumed that the responses of rice plant to the precipitation and temperature are the same as natural vegetation. Actually, rice plant is not growing all the year round but seasonal, generally between April and November. Hence, the use of annual temperature and precipitation in the calculation is irrational. In addition, in the calculation of the NPP by the Miami model the annual precipitation was used, as a matter of fact, rice production in China mostly relies on the irrigation and the precipitation has a little influence on rice growing period. However, Miami model as a simplest one can rapidly figure out the NPP value of vegetation as connected with GIS.

Although there are many shortages that using NPP conversion method to estimate CH_4 emission from rice fields, at national level, the estimated CH_4 emissions in Chinese rice fields is comparable to that recent estimated value by using IPCC method (YAN *et al*., 2003), if the conversion ratio of 1.8% rather than 5% (TAYLOR *et al*., 1991) is used. The data needed for estimating CH_4 emission by using the NPP-CH_4 conversion method are easily accessible. The method provides a general concept that at national level, about 1.8% of NPP of rice crop converts into CH_4 emitting into the atmosphere. Furthermore, the method reflects the influence of variation of most important climate parameters (temperature and precipitation) on CH_4 emission, although their mechanisms need to be explored. Therefore, the NPP conversion method is an effective approach to estimate CH_4 emissions from rice fields at regional and global level.

5 CONCLUSIONS

In this paper the CH_4 emission rates measured at 14 sites in 11 provinces were compared with the estimated rates by using the NPP-CH_4 conversion ratio of 5% and the later was 2.77 times larger than the mean values measured at sites, on average. Furthermore, the total CH_4 emissions from rice fields estimated by the NPP-CH_4 conversion ratio of 5% was over 17×10^{12}g/a in 1990, 1995, 1998, and 2000, being much larger than that estimated by IPCC method. These indicated that the ratio of 5% overestimated the NPP-CH_4 conversion ratio. By using the NPP-CH_4 conversion ratio of 1.8%, the estimated CH_4 emissions from rice fields in China were 7.24×10^{12}, 6.31×10^{12}, 6.77×10^{12} and 5.85×10^{12}g in 1990, 1995, 1998, and 2000, respectively, comparable to that estimated by IPCC method. Therefore, on the national scale, about 1.8% rather than 5% of NPP of rice crop was converted into CH_4 emitting into the atmosphere. The NPP-CH_4 conversion ratio method provides an effective approach for estimating CH_4 emissions from rice fields on regional and global scale and reflecting the effect of climate variation on the annual variation of CH_4 emissions from rice fields.

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