



RESEARCH ARTICLE

10.1002/2016GB005381

Key Points:

- Methane emissions from global rice fields in the 2000s varied from 18.3 to 38.8 Tg CH₄/yr depending on different water schemes
- Expansion of rice cultivation was the key factor causing CH₄ emission increase in the past century
- Intermittent irrigation could reduce half CH₄ emission comparing with continuous flooding

Supporting Information:

- Supporting Information S1

Correspondence to:

H. Tian,
tianhan@auburn.edu

Citation:

Zhang, B., H. Tian, W. Ren, B. Tao, C. Lu, J. Yang, K. Banger, and S. Pan (2016), Methane emissions from global rice fields: Magnitude, spatiotemporal patterns, and environmental controls, *Global Biogeochem. Cycles*, 30, 1246–1263, doi:10.1002/2016GB005381.

Received 28 JAN 2016

Accepted 29 JUL 2016

Accepted article online 8 AUG 2016

Published online 1 SEP 2016

Methane emissions from global rice fields: Magnitude, spatiotemporal patterns, and environmental controls

Bowen Zhang¹, Hanqin Tian¹, Wei Ren^{1,2}, Bo Tao^{1,2}, Chaoqun Lu^{1,3}, Jia Yang¹, Kamaljit Banger^{1,4}, and Shufen Pan¹

¹International Center for Climate and Global Change Research, Auburn University, Auburn, Alabama, USA, ²Department of Plant and Soil Sciences, College of Agriculture, Food, and Environment, University of Kentucky, Lexington, Kentucky, USA, ³Department of Ecology, Evolution, and Organismal Biology, Iowa State University, Ames, Iowa, USA, ⁴Department of Crop Sciences, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA

Abstract Given the importance of the potential positive feedback between methane (CH₄) emissions and climate change, it is critical to accurately estimate the magnitude and spatiotemporal patterns of CH₄ emissions from global rice fields and better understand the underlying determinants governing the emissions. Here we used a coupled biogeochemical model in combination with satellite-derived contemporary inundation area to quantify the magnitude and spatiotemporal variation of CH₄ emissions from global rice fields and attribute the environmental controls of CH₄ emissions during 1901–2010. Our study estimated that CH₄ emissions from global rice fields varied from 18.3 ± 0.1 Tg CH₄/yr (Avg. ± 1 SD) under intermittent irrigation to 38.8 ± 1.0 Tg CH₄/yr under continuous flooding in the 2000s, indicating that the magnitude of CH₄ emissions from global rice fields is largely dependent on different water schemes. Over the past 110 years, our simulated results showed that global CH₄ emissions from rice cultivation increased by 85%. The expansion of rice fields was the dominant factor for the increasing trends of CH₄ emissions, followed by elevated CO₂ concentration, and nitrogen fertilizer use. On the contrary, climate variability had reduced the cumulative CH₄ emissions for most of the years over the study period. Our results imply that CH₄ emissions from global rice fields could be reduced through optimizing irrigation practices. Therefore, the future magnitude of CH₄ emissions from rice fields will be determined by the human demand for rice production as well as the implementation of optimized water management practices.

1. Introduction

Methane (CH₄) emissions from rice cultivation have long been recognized as one of the dominant contributors to anthropogenic greenhouse gas emissions [Ciais *et al.*, 2014; Tian *et al.*, 2016b]. Rice field, a unique human-dominated ecosystem, shares the fundamental set of controls as natural wetlands and meanwhile incorporates different agronomic practices, such as irrigation and fertilizer use [Bridgham *et al.*, 2013]. The net CH₄ flux is determined by both the production from methanogens and the consumption from methanotrophs [Lee *et al.*, 2014; Tian *et al.*, 2010]. Previous studies have shown that the CH₄ emissions from rice fields were influenced by the farming types (irrigated, rainfed, and/or deep water) [Yan *et al.*, 2009], nitrogen fertilizer use [Banger *et al.*, 2012], organic input [Chen *et al.*, 2013; Yan *et al.*, 2009], and rice varieties [Zhang *et al.*, 2014]. In the last 50 years, global rice harvest area increased by 40% due to rice expansion and intensification [Burney *et al.*, 2010; Food and Agriculture Organization of the United Nations Statistics Division (FAOSTAT), 2014], which has greatly increased CH₄ emissions. The rapid increase in CH₄ emissions is expected to continue in the near future due to the increasing demand for food [U.S. Environmental Protection Agency, 2012]. Therefore, it is vital to better understand the current magnitude and spatiotemporal patterns of global CH₄ emissions from rice fields.

Over the last three decades, substantial progress has been made in estimating the CH₄ emissions from rice fields globally; however, large discrepancies exist among various studies in both magnitude, ranging from 25.6 Tg CH₄/yr to 115 Tg CH₄/yr [Aselmann and Crutzen, 1989; Chen and Prinn, 2006; Frankenberg *et al.*, 2005; Yan *et al.*, 2009], and spatial distribution [Monfreda *et al.*, 2008; Xiao *et al.*, 2005] due to multiple environmental factors and complicated agricultural activities involved [Zhang *et al.*, 2011a; Zhang *et al.*, 2011b]. Clearly, it is essential to quantify effects of those influencing factors on CH₄ emissions from rice fields and explore the underlying mechanisms.

Previous studies have illustrated the complicated environmental controls on CH₄ emissions. For example, global warming could increase the rate of root decay, which provides quantitatively important substrates for CH₄ production [Tokida *et al.*, 2011]. On the other hand, rice is very vulnerable to high temperature and a few hours of exposure to overheating could cause complete sterility and poor milling quality [Laborte *et al.*, 2012], which may reduce carbon substrates for CH₄ emissions. Precipitation could influence the water availability of rice fields, especially for the rainfed rice. The shortage of water could greatly reduce the CH₄ emissions. Elevated atmospheric CO₂ concentration may stimulate the CH₄ emissions through providing more methanogen-favored carbon substrate [Dijkstra *et al.*, 2012; van Groenigen *et al.*, 2011]. The effects of nitrogen fertilizer use are complex and can either stimulate or inhibit the CH₄ emissions by influencing the microbial activities [Banger *et al.*, 2012]. Irrigation could change the water status of the soil, which further determines the oxygen availability of the soil and greatly affects the CH₄ producing and oxidizing capability. Elevated ozone concentration could reduce the rice productivity, inhibit the microbial activities, and suppress the belowground carbon processes, which together decrease the CH₄ emissions [Ren *et al.*, 2007; Zheng *et al.*, 2011]. These environmental factors could individually and interactively affect the CH₄ processes. However, how multiple environmental factors together influenced CH₄ emissions from rice fields has not yet been well investigated at the global scale.

Various approaches have been applied to estimate CH₄ emissions from rice fields. Inventory method provides regional-scale estimations of CH₄ emissions from rice fields based on country-specific (or county-specific if applied) statistical data of harvest area, emission factor, and scaling factor [Chen *et al.*, 2013; Chen and Prinn, 2006; Yan *et al.*, 2009; Zhang *et al.*, 2014]. In the top-down approach, atmospheric CH₄ measurements with prior information and transport model are used to estimate the CH₄ emissions. However, both approaches have large limitations when estimating the CH₄ emissions from rice fields. For example, universal emission factors used in inventory methods over large areas without considering the environment heterogeneities limit our ability to predict the feedback between climate change and rice CH₄ emissions. On the other hand, top-down approach is hard to differentiate multiple sources. It has been suggested that transport model itself could lead to 5% to 48% errors [Locatelli *et al.*, 2013]. Meanwhile, reliable estimation of top-down approach may also be constrained by the prior information used, which is usually derived from either inventory estimation or bottom-up estimation [Bergamaschi *et al.*, 2007; Bloom *et al.*, 2010; Frankenberg *et al.*, 2005]. Bottom-up approach, i.e., process-based models which consider multiple environmental factors, land surface heterogeneities, and major pathways of CH₄ processes (e.g., CH₄ production, CH₄ oxidation, and CH₄ transportation), provides spatially explicit estimates of annual CH₄ emissions [Tian *et al.*, 2010]. Meanwhile, it has the capability to quantify the relative contribution of driving factors, such as atmospheric CO₂ concentration, climatic variability, nitrogen enrichment, and cropland management practices, which is vital for policy decisions on climate change mitigation [Bridgham *et al.*, 2013].

Globally, Southeast Asia dominates the CH₄ emissions from rice fields, due to the large rice area occupancy in this region [Yan *et al.*, 2009]. China and India, as the most populous countries in the world, account for 20.0% and 28.5% of the global rice area, respectively [FAOSTAT, 2014]. Approximately 90% of the rice fields are sufficiently irrigated in China, with high spatial-temporal variations in water regimes due to various irrigation strategies in recent decades [Chen *et al.*, 2013]. Over 46% of rice cultivation area is irrigated in India [Banger *et al.*, 2015a; Jain *et al.*, 2000]. Thus, up-to-date information for rice area with accurate water management in those two countries could greatly improve our understanding of global estimation of rice emission.

In this study, we used the Dynamic Land Ecosystem Model version 2.0 (DLEM v2.0) [Tian *et al.*, 2015a] to quantify the effects of multiple environmental factors on the magnitude and spatiotemporal variation of CH₄ emissions from global rice fields during 1901–2010. The specific objectives of this study are (1) to estimate the magnitude of CH₄ emissions from global rice fields by applying different water schemes, (2) to investigate the spatial and temporal variations of CH₄ emissions from rice fields, (3) to quantify the relative contributions of multiple environmental factors to CH₄ emissions from rice fields, and (4) to discuss potential CH₄ mitigation strategies through water regime practices in the rice fields.

2. Materials and Methods

2.1. The Dynamic Land Ecosystem Model (DLEM)

In this study, we used the DLEM v2.0, which has the capability to simulate the carbon, water, and nitrogen fluxes and storages within the terrestrial ecosystem, and also the exchanges of greenhouse gases

(CO₂, CH₄, and N₂O) between the terrestrial ecosystems and the atmosphere. Five key components (biophysics, plant physiology, soil biogeochemistry, land use, disturbance and land management, and vegetation dynamics) are interconnected in the model. In brief, the biophysics component simulates the water and energy fluxes within the terrestrial ecosystems and their interactions with the environments. The plant physiology component simulates the key physiological processes, such as photosynthesis, respiration, allocation, and evapotranspiration. The soil biogeochemistry component simulates the processes of decomposition, nitrogen mineralization/immobilization, nitrification/denitrification, fermentation, and some other major biogeochemical processes in the soil including CH₄ production/oxidation and related processes. The land use, disturbance, and land management component simulates the impact of natural and human disturbances on the water and nutrient fluxes and storages in the land ecosystems. The DLEM is able to simulate the exchange of water, carbon, and nitrogen fluxes for both natural and human-dominated ecosystems (such as major crop types, i.e., rice, wheat, and soybean) at daily time step. In this study, we only focus on rice.

The DLEM simulation results have been extensively validated against a large number of field observations and measurements at the site level [Lu and Tian, 2013; Ren et al., 2011; Tao et al., 2013; Tian et al., 2010; Tian et al., 2011]. The DLEM-estimated fluxes and storages of water, carbon, and nutrients are also compared with the estimates from other approaches, such as statistical-based empirical modeling, top-down inversion, or other process-based modeling approaches, at regional, continental, and global scale [Pan et al., 2014a, 2014b; Tian et al., 2015a, 2015b; Yang et al., 2014]. The previous results indicated that the DLEM-Ag is able to realistically simulate the exchange of trace gases, such as CH₄, at different temporal and spatial scales.

2.2. Description of the Agricultural Module in the DLEM

The agricultural module of the DLEM model (DLEM-Ag) incorporates the influences of agronomic practices on crop growth and phenology and other biogeochemical processes [Ren et al., 2012; Ren et al., 2011; Tian et al., 2012]. The DLEM-Ag has the capability to estimate the crop productivity (net primary production) and crop yield. The DLEM-Ag-estimated crop yield has been compared with census data at the provincial level and site-level observations in China [Ren et al., 2012; Tian et al., 2016a], India [Banger et al., 2015b], Africa [Pan et al., 2015], and other regions of the world [Pan et al., 2014b]. Previous studies suggested that the DLEM-Ag could capture both the trend and magnitude of regional responses of crop production to global environmental changes [Tian et al., 2016a].

The main crop categories in each grid were first identified according to the global crop geographic distribution map [Leff et al., 2004] and were then refined based on census data from Food and Agriculture Organization of the United Nations Statistics Division (FAOSTAT). The prescribed crop phenology was derived from large numbers of field observations and remote sensing data (i.e., Moderate Resolution Imaging Spectroradiometer leaf area index (MODIS LAI) and advanced very high resolution radiometer (AVHRR)), which encompassed the onset and development of foliage and also the dynamic of leaf loss [Ren et al., 2012]. Since global 1 km MODIS LAI is only available after the year 2000, we assumed the phenology unchanged before the year 2000. To improve the accuracy of rice distribution in China and India, we further refined the data of land use/land cover and cropping systems by incorporating the data extracted from the Chinese Academy of Agricultural Sciences (<http://www.caas.net.cn>) and multitemporal remote sensing images in China [Liu and Tian, 2010] and high-resolution remote sensing data sets from Resourcesat-1 with historical archives at district and state levels in India [Tian et al., 2014].

In this study, the major agronomic management practices, including rotation, nitrogen fertilizer use, and irrigation, were identified. We considered three major cropping systems, i.e., the single cropping system, double cropping system, and triple cropping system. The rotation types were identified by incorporating the phenological characteristics from multitemporal remote sensing images [Yan et al., 2005]. Multitemporal data refer to a series of temporal data derived from AVHRR. We used the 10 day composited normalized difference vegetation index from AVHRR. Based on 36 time-phase data within a year, we could extract the information for crop growth. We assumed that the cropping systems remain unchanged over the study period. Nitrogen fertilizer use rates for China, India, and the United States were derived from county-level census data [Tian et al., 2012, 2015a; Banger et al., 2015b], while information in other regions were based on Food and Agriculture Organization (FAO) country-level statistical data (<http://faostat3.fao.org/download/E/EF/E>).

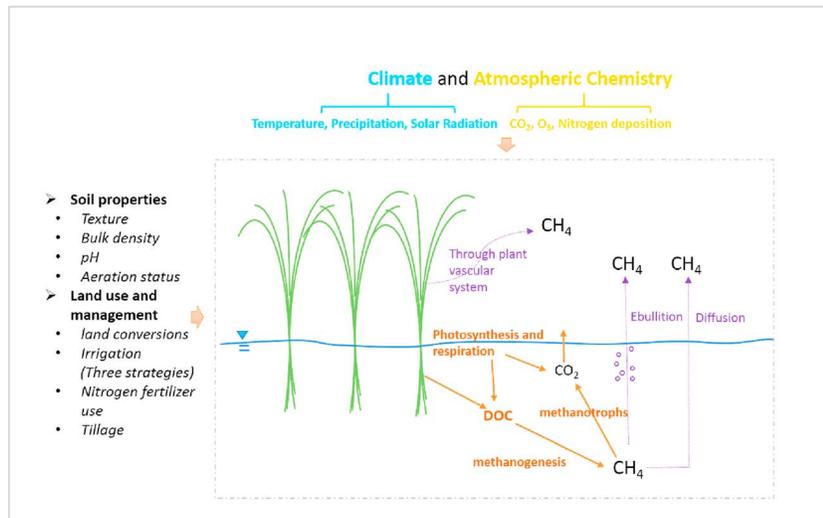


Figure 1. Framework of key biological processes controlling CH_4 fluxes in rice fields, including direct and indirect drivers.

Different from previous studies, we designed three scenarios to depict the potential water management practices based on available data sets and a few assumptions and to determine the impact of water management practices on the rice CH_4 emission. In the Scheme 1 (SC1), we used the dynamic inundation data derived from Global Inundation Extent from Multi-Satellite (GIEMS) observations to determine the water status in the rice fields [Prigent *et al.*, 2012]. GIEMS provides the surface water extent and dynamics at monthly time step during 1993–2007 with a spatial resolution of $0.5^\circ \times 0.5^\circ$ longitude/latitude. Prior to 1993, we used the mean inundation extent derived from the seasonal variation of inundation dynamic for the 15 years (1993–2007). During the model simulation, once the grid cell was identified as rice fields, the inundation status would be checked against Prigent's data. If it was inundated, that grid cell would be irrigated until the soils reach inundation or the CH_4 fluxes would be estimated based on the DLEM-simulated soil moisture status in that grid cell. More details about the representation of soil moisture in the DLEM could be found in the supporting information. We considered SC1 as our best estimate because the dynamic inundation data were derived from multisatellite observation and reflected the irrigation status in the real world to a large extent. In the Scheme 2 (SC2), we used the global data set of monthly irrigated and rainfed rice areas around the year 2000 (MIRCA2000) to determine the irrigation status in the rice fields for the whole study period [Portmann *et al.*, 2010]. In the SC2, the grid cell with rice field would be checked whether it was irrigated or rainfed rice field against Portmann's data. If it was irrigated, or rainfed and at the same time identified as inundation according to Prigent's data, we assumed that its soil water content would reach saturation. Otherwise, the soil moisture status will be calculated based on local climate and soil properties in that grid cell. The application of both Prigent and Portmann's data was to improve the estimation accuracy of irrigation and inundation status from multiple data sources. In the Scheme 3 (SC3), the rice fields were assumed to continuously flood. The differences in monthly inundated areas among the three scenarios of water scheme are presented in Figure S1 in the supporting information. Although the long-term (1901–2010) irrigation data set is not available, the irrigation area could change along with the change in rice-growing area. For instant, the mean inundation extent derived from dynamic inundation data does not change over time, but the rice-growing area could vary year to year according to History Database of the Global Environment (HYDE) data (<http://themasites.pbl.nl/tridion/en/themasites/hyde/landusedata/index-2.html>). Thus, the corresponding irrigation area, which needs to be identified as rice and meanwhile be inundated, could change over the time.

2.3. Description of the CH_4 Module in the DLEM

In the DLEM, the CH_4 -related processes are assumed to only happen in the top 50 cm of soil. DLEM only consider CH_4 produced from dissolved organic carbon (DOC), which is the by-product of the decomposition of litterfall and soil organic matter, and allocation of gross primary production [Tian *et al.*, 2010]. Methane production, oxidation, and transportation from soil pore water to the atmosphere are involved in the

Table 1. Experimental Design ^a

	LCLUC							
	Climate (CLM)	CO ₂	Ozone (O ₃)	Nitrogen Deposition (Ndep)	Land Conversion	Nitrogen Fertilizer (Nfer)	Irrigation	Other Practices
Initial simulation	Averaged (1901–1930)	1900	1900	1900	1900	1900	Averaged GIEMS (1993–2007)	1900
All-combined (SC1)	1901–2010	1901–2010	1901–2010	1901–2010	1901–2010	1901–2010	GIEMS (1993–2007)	1901–2010
All-combined (SC2)	1901–2010	1901–2010	1901–2010	1901–2010	1901–2010	1901–2010	MIRCA2000	1901–2010
All-combined (SC3)	1901–2010	1901–2010	1901–2010	1901–2010	1901–2010	1901–2010	Continuously flooding	1901–2010
Without CLM	Averaged (1901–1930)	1901–2010	1901–2010	1901–2010	1901–2010	1901–2010	GIEMS (1993–2007)	1901–2010
Without CO ₂	1901–2010	1900	1901–2010	1901–2010	1901–2010	1901–2010	GIEMS (1993–2007)	1901–2010
Without O ₃	1901–2010	1901–2010	1900	1901–2010	1901–2010	1901–2010	GIEMS (1993–2007)	1901–2010
Without Ndep	1901–2010	1901–2010	1901–2010	1900	1901–2010	1901–2010	GIEMS (1993–2007)	1901–2010
Without LC	1901–2010	1901–2010	1901–2010	1901–2010	1900	1901–2010	GIEMS (1993–2007)	1901–2010
Without Nfer	1901–2010	1901–2010	1901–2010	1901–2010	1901–2010	1900	GIEMS (1993–2007)	1901–2010

^aCLM, CO₂, O₃, LC, Ndep, and Nfer are abbreviations for climate, atmospheric CO₂ concentration, atmospheric O₃ concentration, land cover change, N deposition, and N fertilization, respectively. The time period indicates that driver data (e.g., climatic data and atmospheric chemistry data) were being used in those periods. In all-combined simulation, the averaged inundation data sets during 1993–2007 were used to represent the inundation extent of rice field before 1993.

calculation of CH₄ exchanges between the rice fields and the atmosphere. The net CH₄ flux between the atmosphere and soil is determined by the following equation:

$$F_{CH_4} = F_P - F_O$$

where F_{CH_4} is the net flux of CH₄ between soil and the atmosphere ($g C m^{-2} d^{-1}$), F_P is the CH₄ production ($g C m^{-2} d^{-1}$), and F_O is the CH₄ oxidation ($g C m^{-2} d^{-1}$).

The DLEM considers CH₄ production from DOC, which is a function of environmental factors including soil pH, temperature, and soil moisture content (Figure 1).

$$CH_{4prod} = V_{prod, max} * \frac{[DOC]}{[DOC] + km_{prod}} * f(T_{soil}) * f(pH) * f_{prod}(vwc)$$

where $V_{prod, max}$ is the maximum rate of CH₄ production ($g C m^{-3} d^{-1}$), [DOC] is the concentration of DOC ($g C m^{-3}$), km_{prod} is the half-saturation coefficient of CH₄ production ($g C m^{-3}$), $f(T_{soil})$ is a multiplier that describes the effect of soil temperature on CH₄ production and oxidation, $f(pH)$ is a multiplier that describes the effect of soil pH on CH₄ production and oxidation, and $f_{prod}(vwc)$ is a multiplier that describes the effect of soil moisture on CH₄ production and oxidation.

Three pathways are considered in the DLEM for CH₄ oxidation: (1) atmospheric CH₄ oxidation, (2) CH₄ oxidation in the soil pore water, and (3) CH₄ oxidation during plant-mediated transport. In this model, ebullition, diffusion, and plant-mediated transport are considered as three pathways by which CH₄ can be transported from soil pore water to the atmosphere. More detailed information about the features of the CH₄ module in the DLEM can be found in Tian *et al.* [2010]. CH₄ module in the DLEM has already been validated at regional scales, such as West Siberian Lowland and Sanjiang Plain [Bohn *et al.*, 2015; Song *et al.*, 2013], at country level, such as China [Ren *et al.*, 2011], and Canada [Miller *et al.*, 2014], at continental level, such as North America [Tian *et al.*, 2010], and at global level [Melton *et al.*, 2013; Tian *et al.*, 2015b; Wania *et al.*, 2013].

2.4. Other Input Data

Several sets of georeferenced and time series input data are compiled to drive the DLEM model, including (1) daily climate data (maximum, minimum, and mean air temperature, precipitation, relative humidity, and downward shortwave radiation), (2) atmospheric chemical components (atmospheric CO₂ concentration, AOT40 O₃ index, and nitrogen deposition), (3) soil

Table 2. The Major Parameters for Simulating the CH₄ Emission From Rice Field in the DLEM

Parameter	Value	Observed Range	Location	Reference
Maximum rate of CH ₄ production (g C/m ³ /d)	0.65	0.51–1.82	China	<i>Chen et al.</i> [1993] and <i>Wassmann et al.</i> [1993]
		0.65–0.73	India	<i>Mitra et al.</i> [1999]
		0.64–1.14	Indonesia	<i>Nugroho et al.</i> [1994]
		0.28–0.59	Japan	<i>Yagi and Minami</i> [1990]
		0.43–1.16	Thailand	<i>Yagi and Minami</i> [1990]
		0.64–0.85	USA	<i>Lindau et al.</i> [1991] and <i>Sass et al.</i> [1992]
Half-saturation coefficient of CH ₄ production (g C/m ³)	2	1.68–9.8		<i>Law et al.</i> [1993] and <i>Lokshina et al.</i> [2001]
Maximum rate of CH ₄ oxidation (g C/m ³ /d)	0.2	0.18		<i>Wang et al.</i> [1997]
Half-saturation coefficient of CH ₄ oxidation (g C/m ³)	10	4.8–81.1	India	<i>Dubey</i> [2003] and <i>Dubey et al.</i> [2002]

properties (soil texture, soil pH, and bulk density), (4) land use and land cover data, and (5) agricultural management practices (irrigation, nitrogen fertilizer use, and rotation etc.) and other ancillary data, such as river network and topographic data. More specifically, daily climate variables during 1901–2010 were derived from Climate Research Unit-National Center for Environmental Prediction 6-hourly climate data sets (http://dods.extra.cea.fr/store/p529viov/cruncep/V4_1901_2012/readme.htm). Atmospheric CO₂ concentration data were obtained from a spline fit of the Law Dome before 1959 (<http://cdiac.ornl.gov/ftp/trends/co2/law-dome.smoothed.yr20>) and from NOAA (<http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html>) during 1959–2010. Monthly atmospheric ozone concentration was represented by AOT40 [*Felzer et al.*, 2005] and further interpolated to daily data [*Ren et al.*, 2007]. Atmospheric nitrogen deposition data were obtained from North American Carbon Program Multi-scale Synthesis and Terrestrial Model Intercomparison Project [*Wei et al.*, 2014]. The basic soil physical and chemical properties, such as soil texture, bulk density, and soil pH, were obtained from the Harmonized World Soil Database [*Wieder et al.*, 2014]. Cropland distribution was derived from the 5 arc min resolution HYDE v3.1 data and aggregated to half-degree [*Goldewijk et al.*, 2011]. Inundation data from multisatellite observations were obtained from global Wetland Extent and Wetland CH₄ Intercomparison of Models Project [*Prigent et al.*, 2012]. Further details of other input data can be found in the previous publications [*Ren et al.*, 2011; *Tian et al.*, 2015b; *Xu et al.*, 2010; *Yang et al.*, 2014].

2.5. Experimental Design

To determine the spatial and temporal patterns of CH₄ emissions and quantify the relative contribution of multiple environmental factors, we conducted 10 simulations in total (Table 1). The model was first run to reach the equilibrium state and get the initial condition for the spin-up and transient simulations. In the equilibrium run, all the input data in 1900 were used to drive the model except climate data and inundation data. For climate data, we used long-term mean climate data during 1901–1930. For inundation data, we derived the seasonal variation patterns from 15 year (1993–2007) mean inundation extent. After the equilibrium run, the model was run another 900 years for the spin-up with detrend climate data from 1901 to 2010. The spin-up was to smooth the transition from the equilibrium state to the transient run. The transient runs for all-combined simulation were to get the estimation of CH₄ fluxes by considering all the natural and anthropogenic changes during 1901–2010 (*S*_{all-combined}). We conducted six simulations to quantify the effects of individual environmental factors (*S*_{single}), such as climate, atmospheric chemistry, land cover change, and land management practices on the CH₄ fluxes. For example, for the experiment without climate considered, we let all other input data change

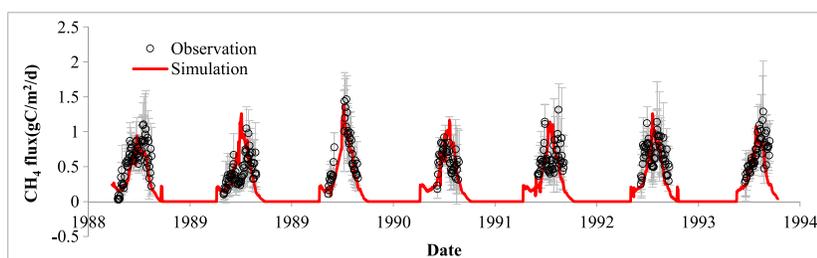


Figure 2. Evaluation of DLEM-estimated daily CH₄ emissions against observed data at Tuzu, Sichuan, China. Note: $n = 365$, $Modelled = 0.8475 * Observed$, $R^2 = 2878$, $p < 0.0001$ [*Khalil et al.*, 1998].

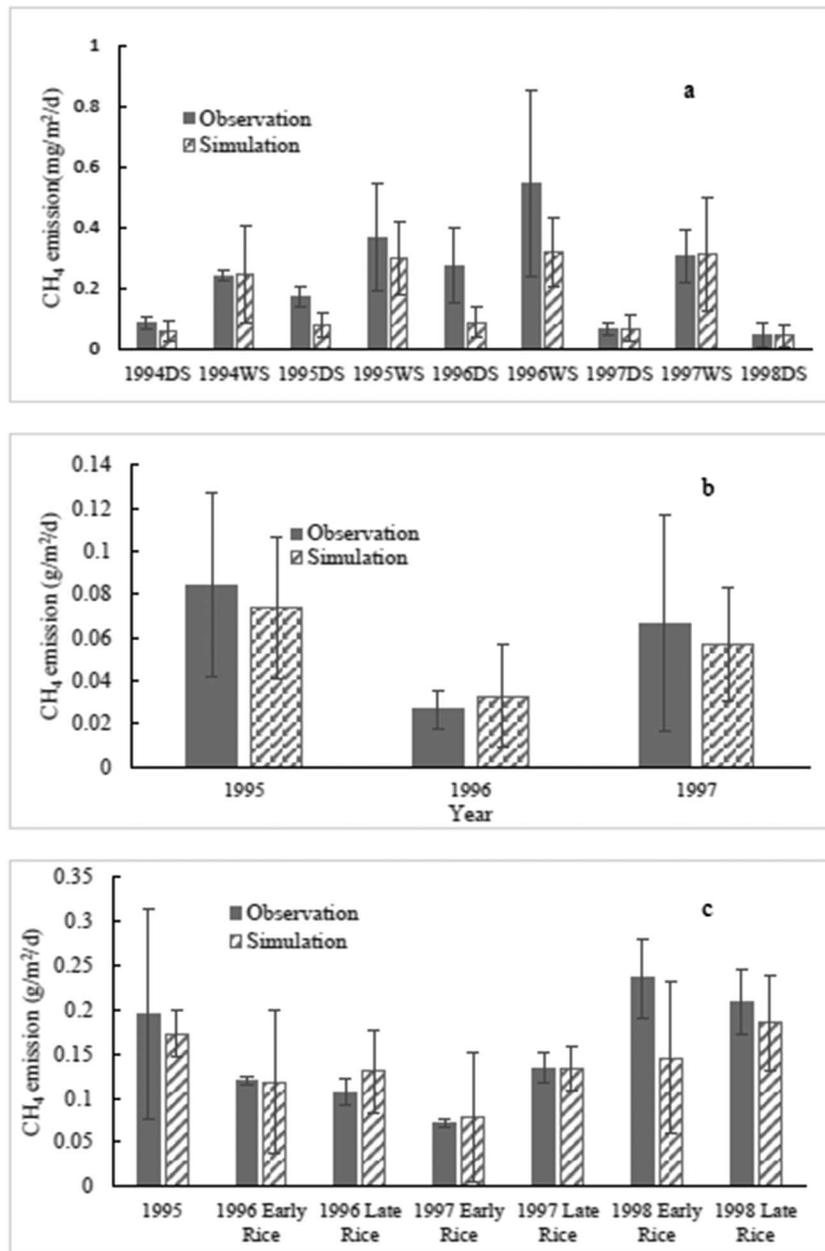


Figure 3. Evaluation of DLEM-estimated seasonal CH₄ emissions against observed data at multiple sites. *Note:* (a) CH₄ emissions at PhilRice Central Experiment Station in Maligaya, Muñoz, Nueva Ecija, Philippines (15.6725°N, 120.8906°E) [Corton *et al.*, 2000] (DS and WS are abbreviations for dry season and wet season); (b) CH₄ emissions at the experimental farm of the Institute of Crop Breeding and Cultivation, Beijing, China (39.9611°N, 116.3681°E) [Wang *et al.*, 2000b]; (c) CH₄ emissions at the experimental farm of the China National Rice Research Institute in Hangzhou, China (30.2700°N, 120.1597°E) [Lu *et al.*, 2000]. The error bars indicate the standard deviation.

with time except climatic data, which was kept at the level of 1901. Then the effect of climate on the CH₄ fluxes was determined by $S_{\text{all-combined}}$ versus $S_{\text{single(climate)}}$.

2.6. Model Evaluation Against Field Observations at Site Level

The key parameters for the CH₄-related processes are derived from field observations (Table 2). In this study, we further evaluated the DLEM performance of the CH₄ emissions from rice fields at 31 observation sites (Figure 2 and Table S1 in the supporting information). The comparisons of the DLEM-estimated CH₄ with site-level observations indicate that the DLEM can capture the daily and seasonal patterns of CH₄ emissions (Figures 2–4). In

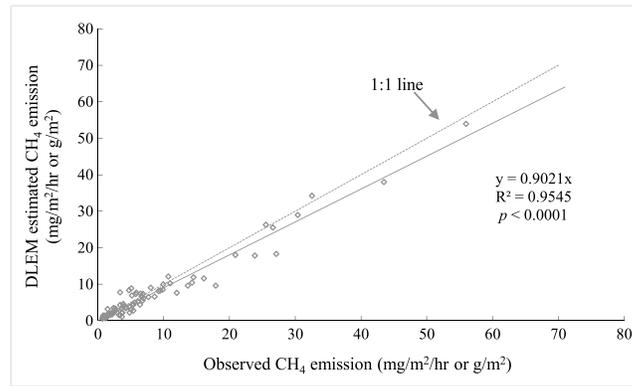


Figure 4. Comparison of DLEM-estimated CH₄ emissions from rice field with observed data at 31 sites Note: $n = 31$, Modeled = $0.9021 \times$ Observed, $R^2 = 0.9545$, $p < 0.0001$ (More detailed information could be found in Table S1). There are six sites in India [Adhya et al., 2000; Bharati et al., 2000; Debnath et al., 1996; Ghosh et al., 2003; Gupta et al., 1994; Pathak et al., 2003; Satpathy et al., 1998; Singh et al., 1996], 14 sites in China [Cai et al., 2000; Chen et al., 1995; Lin et al., 2000; Tao, 1998; Wang et al., 2000a; Wassmann et al., 1996; Wassmann et al., 1993; Xu et al., 2004], six sites in Japan [Goto et al., 2004; Inubushi et al., 2003; Kumagai et al., 2000; Matsumoto et al., 2002; Yagi and Minami, 1990; Yagi et al., 1996], three sites in Indonesia [Setyanto et al., 2000; Subadiyasa et al., 1997], and two sites in Thailand [Chareonsilp et al., 2000; Jermasawadipong et al., 1994].

general, the DLEM estimations showed a good agreement with the field observations ($n = 31$; slope = 0.9021; $R^2 = 0.9545$; $p < 0.0001$) (Figure 4). The big differences of CH₄ emissions between the observations and the DLEM-estimations at PhilRice Central Experimental Station in Maligaya during 1996 were probably caused by the commence use of organic amendments in that year at the experimental site. The addition of organic amendments could provide the rich substrate for the methanogens which greatly stimulate the CH₄ emissions in that year. Thus, the observed CH₄ emissions during the dry and wet seasons in 1996 were obviously higher than the other years (Figure 3a). Compared with the dry season, the amount of CH₄ emissions during the wet season were much greater at PhilRice Central Experimental Station and the DLEM was able to capture the seasonal

variation of CH₄ emissions. For the double rice cropping system, the DLEM-estimated CH₄ emissions were comparable with the observations during the 5 year experiment in southeast China [Lu et al., 2000].

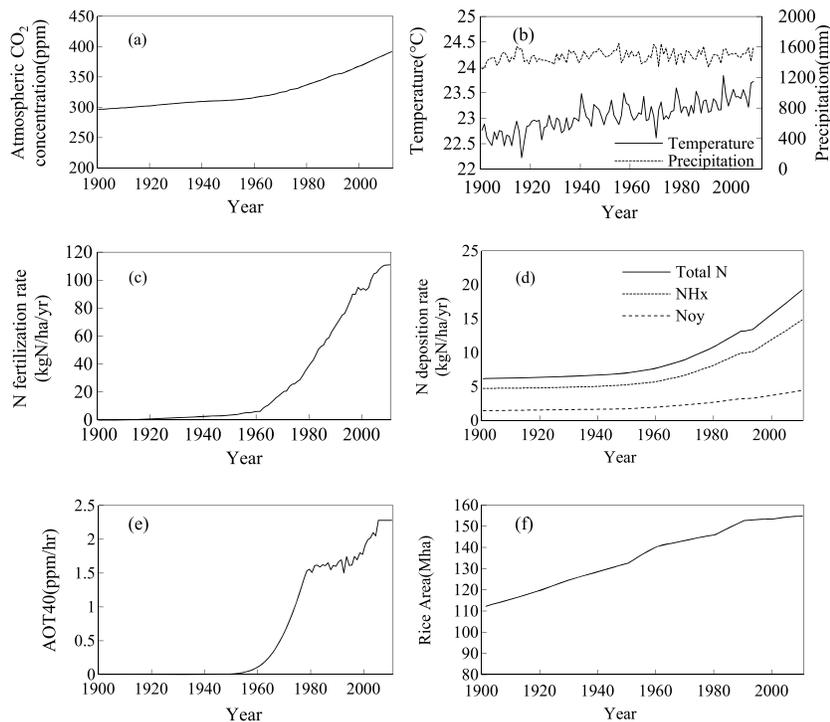


Figure 5. Multiple environmental changes over global rice fields. (a) Annual atmospheric CO₂ concentration. (b) Annual mean temperature and precipitation. (c) Nitrogen fertilizer use. (d) Nitrogen deposition. (e). AOT40 (note that AOT40 is a cumulative O₃ index, the accumulated hourly O₃ dose over a threshold of 40 ppb in ppb per hour). (f) Rice area.

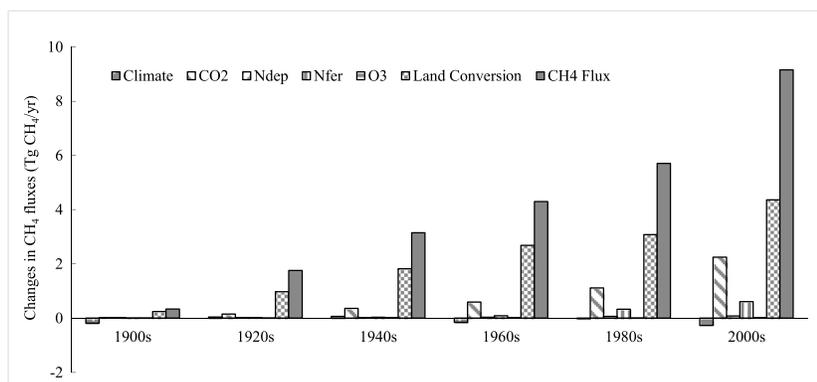


Figure 6. Relative contributions of land conversion, O₃, nitrogen fertilizer use, nitrogen deposition, atmospheric CO₂ concentration, and climate to decadal changes in CH₄ fluxes from global rice fields during 1901–2010.

3. Results

3.1. Multiple Environmental Changes in the Global Rice Field During 1901–2010

During 1901–2010, global rice fields increased at a rate of 0.43 Mha/yr and meanwhile experienced substantial environmental changes (Figure 5). Atmospheric CO₂ concentration steadily increased from 296.4 ppm to 391.9 ppm. At the same time, both precipitation and temperature showed large interannual variations in overall significant increasing trends of 6.2 mm/decade and 0.075°C/decade ($p < 0.01$). AOT40 increased rapidly since the 1950s, with the largest increase occurred in Asia. Rice fields received more amount of nitrogen through fertilizer use than deposition. The amount of nitrogen through atmospheric deposition was around one fifth of the amount of fertilizer use in the 2000s. Both nitrogen fertilizer use and deposition increased slowly before the 1960s and then enhanced dramatically afterward, at an overall increasing trend of 1 and 0.12 kg N/ha/yr, respectively.

3.2. Temporal Changes in Global CH₄ Emissions

In this study, we quantified the CH₄ emissions from global rice fields during 1901–2010. For the SC1, we determined the inundation status in the rice fields based on multisatellite observations, the estimated CH₄ emissions increased from 10.4 ± 0.2 Tg CH₄/yr (Avg. ± 1 SD, same hereafter) in the 1900s to 19.2 ± 1.9 Tg CH₄/yr in the 2000s with a significant increasing trend (0.1 Tg CH₄/yr, $p < 0.01$) (Figure 6). The dynamic inundation data only cover 1993 to 2007; hence, the estimate of CH₄ emissions during this period was 20.5 ± 1.4 Tg CH₄/yr. For the SC2, the DLEM-estimated CH₄ emissions were 18.3 ± 0.1 Tg CH₄/yr when soil moisture was determined by one-phase monthly irrigation/rainfed maps. For the SC3, we assumed that the rice fields were continuously flooded, and the DLEM-estimated CH₄ emissions were 38.8 ± 1.0 Tg CH₄/yr during the 2000s. Compared with the SC1 and the SC2, continuously flooding could double the CH₄ emissions from the global rice fields.

For the intra-annual variation, the DLEM estimation showed that CH₄ emissions increased from early February and reached a peak emission during July to August, which was partly due to the larger area of rice planted and

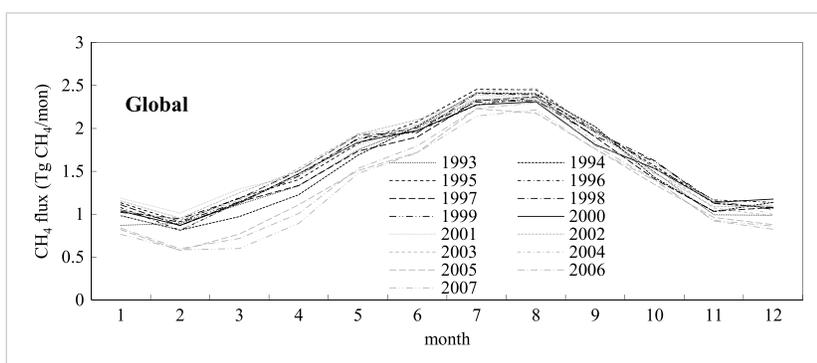


Figure 7. Estimated monthly CH₄ emissions from global rice fields during 1993–2007 (Tg CH₄/mon).

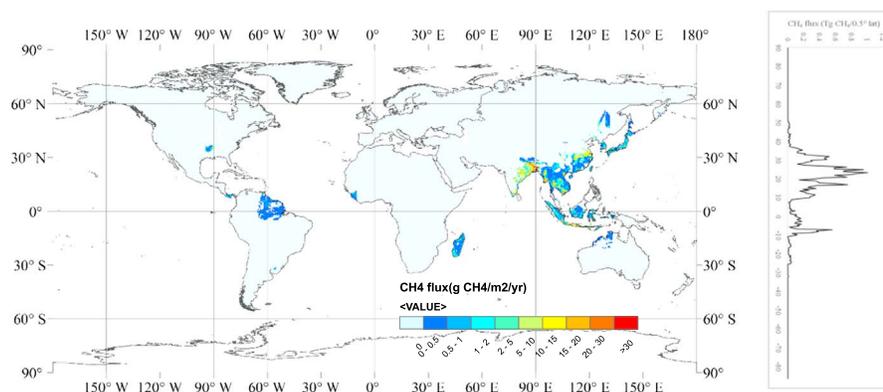


Figure 8. Spatial distribution of estimated mean annual CH₄ emissions from global rice fields during 1993–2007.

the high rates of CH₄ emissions during this time period, and then leveled off from September (Figure 7). The seasonal contribution of the CH₄ emissions varied at different continents. In Asia, the estimated CH₄ emissions in spring, summer, autumn, and winter contributed 22%, 38%, 25%, and 15% of the annual emission, respectively. In North America, the CH₄ emissions in spring, summer, autumn, and winter contributed 28%, 32%, 21%, and 19% of the annual emission, respectively. The DLEM-estimated CH₄ emissions during the growing and nongrowing season accounted for 76% and 24% of the annual emission, respectively.

3.3. Spatial Patterns of Global CH₄ Emissions

When investigating CH₄ emissions in the SC1 along the latitudinal gradient, our results showed that the estimated CH₄ emission from rice fields peaked (1 Tg CH₄/0.5 latitude) at around 21°N–22°N and 23°N–24°N, mainly due to the distribution of large rice fields in subtropical and tropical Asia (Figure 8). Further analysis suggested that tropical region (30°N–30°S) contributed 85% of the estimated global rice emission, followed by northern midlatitude (30°N–60°N) and southern midlatitude (30°S–60°S). From the continental perspective, Asia was the primary emitter, which contributed around 94% of the total rice emissions. Country-level analysis showed that India and China were two biggest contributors to the global rice emissions. The DLEM-estimated rice CH₄ emissions were around 4.99 ± 0.36 Tg CH₄/yr in India and 3.61 ± 0.16 Tg CH₄/yr in China, which accounted for 24% and 18% of the estimated CH₄ emissions from global rice fields, respectively.

3.4. Relative Contributions of Multiple Environmental Factors

Through factorial simulation experiments, we further quantified the relative contribution of environmental factors to the cumulative rice emission. Our simulations indicated that land conversion from natural vegetation to rice fields played the dominant role in the increase of the rice emissions, which was around 49.44% (4.36 Tg CH₄/yr) of the total increase in global CH₄ emissions from rice fields (Figure 6).

Elevated atmospheric CO₂ concentration induced an increase of 2.25 Tg CH₄/yr in estimated CH₄ emissions from the 1900s to the 2010s, which roughly accounts for 25.52% of the total increase in global CH₄ emissions from rice fields. Both nitrogen fertilizer use and nitrogen deposition had a positive influence on the CH₄ emissions (Figures 5c and 5d). In the 2000s, nitrogen fertilizer use and deposition increased the CH₄ emissions by 0.61 and 0.08 Tg CH₄/yr, respectively (Figure 6). Elevated O₃ concentration had a minor influence on the global rice emissions over time compared with other factors. On the contrary, climate decreased the CH₄ emissions for most of the years over the study period. Particularly, in the 2000s, the warmest decade compared with all the previous decades in the instrumental record [Intergovernmental Panel on Climate Change (IPCC), 2013], which induced a reduction of 0.27 Tg CH₄/yr in the CH₄ emission (Figure 6).

4. Discussion

4.1. Comparison With Other Studies

Over the last two decades, due to the increasing number of field measurements, the availability of remote sensing observations, and the improved understanding of mechanisms responsible for the CH₄ emissions in rice fields, the accuracy of the estimated rice emissions has been improved and the magnitude of the

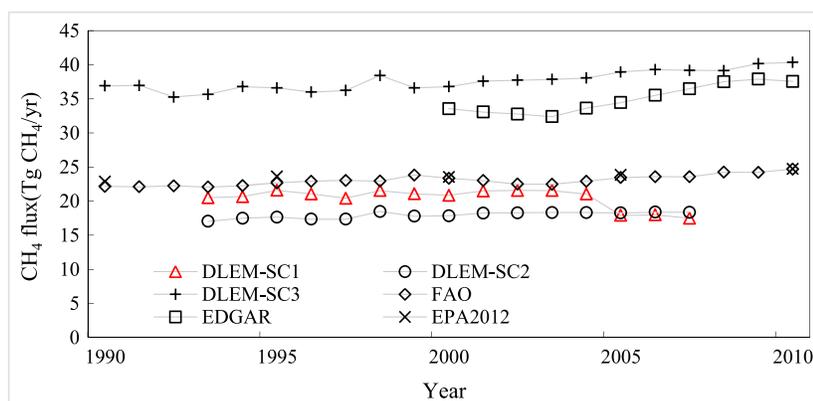


Figure 9. Comparison of temporal variation in estimated CH_4 emissions from global rice fields among three scenarios of water regime scheme (DLEM-SC1, DLEM-SC2, and DLEM-SC3) and three previous estimates (FAO, EDGAR, and EPA2012).

estimated rice emissions turned out a downward trend in previous studies [Chen and Prinn, 2006]. In this study, the DLEM-estimated CH_4 emissions from rice fields were 18.3 ± 0.1 – 38.8 ± 1.0 Tg CH_4/yr during the 2000s by applying different water schemes. The assumption of continuous flooding for the rice fields may overestimate the CH_4 emissions. Here we compared our results with the studies from recent 10 years at both global and country levels. In general, the estimations from top-down approaches (44–115 Tg CH_4/yr) [Bergamaschi et al., 2007; Bloom et al., 2010; Chen and Prinn, 2006; Spahni et al., 2011] were much higher than those from both inventory (25.6–41.7 Tg CH_4/yr) [Yan et al., 2009] and bottom-up (24.8–44.9 Tg CH_4/yr) approaches [Ito and Inatomi, 2012; Spahni et al., 2011], which was probably due to the higher estimation of prior information of either rice field distribution or the estimated CH_4 emissions being used in top-down studies [Bergamaschi et al., 2007; Bloom et al., 2010; Chen and Prinn, 2006] (Table. S2). To the best of our understanding, our study incorporated the “state-of-the-art” information from multisatellite observations-derived inundation data and inventory-based, monthly irrigated rice area to determine the water status in the rice fields and narrow down the current estimation of CH_4 emissions from rice field. Most of the previous ecosystem models treated rice as one type of wetland and applied the same schemes to calculate the CH_4 fluxes. Due to the consideration of the noninundation status in the rice fields, the estimated annual CH_4 emissions were largely reduced.

For the contemporary period (1990–2010), FAO (<http://faostat3.fao.org/home/E>), Emission Database for Global Atmospheric Research (EDGAR) (http://edgar.jrc.ec.europa.eu/part_CH4.php), and Environmental Protection Agency (<http://epa.gov/climatechange/ghgemissions/gases/ch4.html>) provided time series estimation of CH_4 emissions from rice fields. The magnitudes of DLEM-simulated CH_4 emissions were comparable with other estimations; however, the interannual variation in CH_4 emissions was diverging from each other. For FAO estimation, there is no significant interannual variation. For EDGAR, the estimated CH_4 emissions decreased 33.6 Tg CH_4/yr from 2000 to 2004 and then started to increase afterward until 2010 (37.6 Tg CH_4/yr) (Figure 9), which may be attributed to the similar trend in harvest area during the 2000s [FAOSTAT, 2014]. It is worth noting that the increase of CH_4 emission after 2007 may also contribute to the resumption of atmospheric CH_4 concentration increase. For the DLEM-estimated CH_4 fluxes, the annual variation is determined by both the spatial and temporal variations of inundation status and environmental heterogeneity in the rice fields. In the SC1, DLEM-estimated CH_4 emissions showed a great reduction after 2004, which may be caused by climatic change (Figure 9). Further analysis indicated that South and Southeast Asia contributed over 85% of the reduced CH_4 fluxes. At the country level, India and Indonesia played a major contribution. Previous studies suggested that severe drought happened in Northeast India during the summer monsoon in 2006 [Bergamaschi et al., 2007], which may reduce the CH_4 emissions. In Indonesia, the monthly mean temperature in February and March during 2005–2007 was 0.73°C and 0.43°C lower than that during 1993–2004. And the mean temperature from October to March was 0.22°C lower during 2005–2007 compared with that during 1993–2004. In most areas of Indonesia, the rice planting season starts from October to March, with the highest rainfall from December to March. The lower temperature could reduce the microbial activities, which further reduce the CH_4 emissions.

DLEM-simulated intra-annual variations in CH₄ fluxes showed consistent patterns with the column-averaged CH₄ mixing ratio from atmospheric inversion estimation [Bergamaschi *et al.*, 2007]. The estimated CH₄ emissions during winter also contributed a small portion of the total amount emitted annually. At the global scale, the estimated CH₄ emissions during the non-growing season accounted for almost one fifth of the annual emission, which was within the range estimated by Weller *et al.* [2016]. In the United States and China, some of the rice fields during the nongrowing season are still being flooded in order to provide the habitat for waterfowl and migratory birds [Wood *et al.*, 2010], which may lead to CH₄ emissions.

Most country-level analyses of CH₄ emissions from rice cultivation were inventory-based (Table S2). Previous estimation of rice emission in China ranged from 5.2 to 11.4 Tg CH₄/yr as estimated by inventory studies [Chen *et al.*, 2013; *Second National Communication on Climate Change of The People's Republic of China*, 2012; Yan *et al.*, 2009; Zhang and Chen, 2014; Zhang *et al.*, 2014] and ranged from 4.1 to 7.5 Tg CH₄/yr in bottom-up estimations [Kai *et al.*, 2010; Wang *et al.*, 2008; Zhang *et al.*, 2011a]. The DLEM-estimated rice emissions were around 3.2–5.6 Tg CH₄/yr. The differences among studies were probably caused by various water regimes being used. During the last two decades, China has already improved water management and fertilizer use in the rice fields. Intermittent drainage together with other water management practices has been applied to a large portion of rice fields over China, and field observations also confirmed that water-saving management could largely reduce or even cease the CH₄ emissions [Chen *et al.*, 2013]. In India, 55% of the rice field was irrigated and the rest were either rainfed upland or lowland rice field [Bhatia *et al.*, 2013]. By applying the Intergovernmental Panel on Climate Change 2006 guidelines, estimated CH₄ emissions from rice cultivation in India were around 3.4 to 6.1 Tg CH₄/yr [Bhatia *et al.*, 2013; Garg *et al.*, 2011; Yan *et al.*, 2009], which is similar to the DLEM estimation (4.99 Tg CH₄/yr).

4.2. Climate Effects on CH₄ Emissions

Our simulated results showed that over the study period, climate variability/change had reduced CH₄ emissions from rice field. Both China and India experienced global warming [Jain and Kumar, 2012; Li *et al.*, 2010], which changed the availability of soil moisture content and carbon substrate, and further affected the CH₄ emissions from rice fields [Laborte *et al.*, 2012; Tokida *et al.*, 2011]. Precipitation is another key climatic factor which governed the CH₄ emissions, especially in Southeast Asia, such as Indonesia, Myanmar, and Thailand, where 40%, 79%, and 35% of the rice area were under rainfed, respectively [Redfern *et al.*, 2012]. The reduction in precipitation or shifting in timing and magnitude of rainfall event may cause crop failure, which could further reduce CH₄ emissions from the rice fields.

4.3. Effects of Land Use and Water Use on CH₄ Emissions

Land cover and land use change, including land conversion, irrigation, and nitrogen fertilizer use, had significant impacts on the CH₄ emissions. Our input data indicate that the rice cultivation area between the 1900s and the 2000s increased by around 38%, which was partially supported by the global rice harvest area derived from census data (1964–2010) from FAO and U.S. Department of Agriculture. The expansion of rice cultivation is the primary factor that led to an increase in rice CH₄ emission. Water management regimes, like different irrigation practices, could effectively mitigate CH₄ emissions, which are well documented in Asian countries [Corton *et al.*, 2000]. Intermittent irrigation could reduce CH₄ emissions by 22–80% as compared with continuous flooding [Jain *et al.*, 2000; Lu *et al.*, 2000; Wang *et al.*, 2000b; Wassmann *et al.*, 2000].

Previous study suggested that the improved water use efficiency and the rapid rise in chemical fertilizer use were the dominant contributor of the reduced CH₄ emission between 1980 and 2005 [Kai *et al.*, 2011], which was partially contradictory to our results. In Kai *et al.* [2011], they attributed the change of CH₄ growth rate since 1980 to the reduction of CH₄ emission from the rice field by assuming that there was no significant change in both wetland area in the northern hemisphere and CH₄ emission from global wetlands. However, Prigent's data revealed that the global inundation extent decreased dramatically, at the rate of 67,700 km²/yr during January 1993 to mid-2000 [Prigent *et al.*, 2012]. In addition, the DLEM-estimated CH₄ emission from wetland showed an overall decreasing trend from 1993 to 2007 (unpublished data), which was supported by the inversion model of atmospheric transport and chemistry [Bousquet *et al.*, 2006; Pison *et al.*, 2013]. Meanwhile, Kai *et al.* [2011] suggested that the use of inorganic fertilizer could reduce the CH₄ emission in rice fields partly due to the displacement of organic amendments. However, in their empirical-based model, they just simply incorporated the mechanisms that the use of inorganic fertilizer decreased

the CH₄ emission in rice fields without considering the organic amendments, ignoring complex effects of nitrogen fertilizer use on both CH₄ production and oxidation processes [Banger *et al.*, 2012]. Liu and Greaver [2009] demonstrated that in the anaerobic agricultural system, CH₄ emissions increase by 0.008 ± 0.004 kg/ha/yr per 1 kg N/ha/yr fertilizer use. Banger *et al.* [2012] analyzed 155 data pairs in rice fields and 64% of them showed CH₄ emissions increase in response to nitrogen fertilizer application. In our study, nitrogen fertilizer use could promote the crop production, which provided higher litter input, root biomass, and root exudation for the carbon substrate of methanogens and stimulated the CH₄ production. At the same time, it could accelerate water transpiration in N-limited area, lowered soil water content given a certain amount of rainfall, and thus increased CH₄ oxidation while depressing its production [Lu and Tian, 2013]. Our study agreed with Kai *et al.* [2011] that the improved water management could reduce the CH₄ emissions in rice field.

4.4. Effects of Other Atmospheric Chemistry Components

In our study, atmospheric CO₂ concentration enrichment has induced an increase of 2.25 Tg CH₄/yr in CH₄ emissions from global rice fields from the 1900s to the 2010s (Figure 6). Elevated CO₂ could stimulate belowground carbon production, which may provide more substrate for methanogens activity [Allen *et al.*, 2003; Jackson *et al.*, 2009; Pregitzer *et al.*, 2008; Zak *et al.*, 2000]. Field observation confirmed that under free-air CO₂ enrichment experiment, CH₄ production from the rice fields was significantly greater than that under ambient conditions [Dijkstra *et al.*, 2012; Inubushi *et al.*, 2003]. Chen *et al.* [2013] found the increasing trend of CH₄ emissions from the rice fields in China as a result of elevated atmospheric CO₂ concentration. Meta-data analysis for the effect of elevated CO₂ on CH₄ emissions revealed that CO₂ enrichment could stimulate CH₄ by 43.4% in the rice fields [van Groenigen *et al.*, 2011]. Under the future climate scenarios, atmospheric CO₂ concentrations are expected to continue increase, which may further stimulate the CH₄ emission in the rice fields [IPCC, 2013].

During 1901–2010, global nitrogen deposition enhanced at an increasing rate of 0.12 kg N/ha/yr. Nitrogen addition could promote crop growth and provide more carbon substrate for the microbial activity and hence stimulates CH₄ emission. In the 2000s, nitrogen deposition increased the CH₄ emissions by 0.08 Tg CH₄/yr (Figure 6). The level of tropospheric ozone as indicated by AOT40 has significantly increased especially after the 1990s in China and India [Ren *et al.*, 2007], which reduced the CH₄ emissions [Bhatia *et al.*, 2011; Zheng *et al.*, 2011]. At a global level, however, this study showed that tropospheric ozone pollution had a minor influence on rice CH₄ emission compared with other factors.

4.5. Uncertainties and Future Research Need

Our estimation of CH₄ emissions from rice cultivation must be used with caution because of much uncertainty resulting from input data, model structure, and parameters. Estimate uncertainties may be resulted from the inaccurate spatial distribution of rice cultivation and agronomic practices being applied. In this study, we have incorporated the map of global crop geographic distribution with regional agricultural census data derived from FAOSTAT along with the multiple rotation types to generate the distribution of rice fields; however, there are still discrepancies among various rice distribution maps due to the differences in georeferenced resolution as well as the lack of information on rice cultivation over some regions of the world. In addition, we applied different irrigation schemes to determine the impact of irrigation on the CH₄ emission from global rice fields. In the SC1, we identified the inundation status of rice cultivation by using the observation from multisatellites, which only covers from 1993 to 2007. This may bring large uncertainties to the estimated CH₄ emission from other years. Besides, the satellite data sets may underestimate some small paddy field (few hectares) [Prigent *et al.*, 2007], which could result in the underestimation of CH₄ emission. The DLEM inexplicitly addressed CH₄ emission associated with the crop residues through model parameterization. However, DLEM used time-invariant parameter to estimate the amount of crop residue returning to the field, which could introduce some uncertainties. More explicit, representation of such processes is needed to reduce the uncertainties.

Several additional issues have been identified for advancing our research in the future, including (1) improving spatial resolution of input data and subgrid heterogeneity for driving the model and (2) improving model representation of additional processes that regulate the CH₄ emission in rice field. Finer-resolution data are needed for future model application at multiple spatial scales, which will serve to make more realistic

assumptions based on conditions that are truly happening in the real world [Pan *et al.*, 2014a]. In this study, all the data sets have a spatial resolution of $0.5^\circ \times 0.5^\circ$ longitude/latitude. However, in reality, the water regimes might be highly variable at the local scale, such as field to field variation or variation within field. The current assumption of homogeneous water regimes applied in each individual grid needs to be improved by considering the subgrid variability in water regimes.

In addition, the model representations of rice varieties and iron reduction/oxidation are needed to better estimate CH_4 emission in rice field. Rice variety is a key factor to regulate the CH_4 fluxes [Zhang *et al.*, 2014]. Different types of rice could provide various amounts of root-derived carbon and also differ in structures which regulate the pathway to diffuse the oxygen flux to the soil and transport CH_4 to the atmosphere. At the same time, the improvement in rice varieties over time could contribute to the variation of CH_4 emission. For example, modern rice varieties often shorten vegetation periods and meanwhile may adapt to multiple environmental changes, such as extreme climate, which directly and indirectly regulate the total CH_4 emissions. Other critical factors, such as iron reduction/oxidation processes [Van Bodegom *et al.*, 2002], were missing in the current version of the DLEM. These factors or local practices are very important in regulating the CH_4 emission but have a large spatial and temporal variabilities, which are very difficult to collect at the large scale [Van Bodegom *et al.*, 2002]. This limitation of data over a large scale makes it impossible to incorporate such information and processes into the model for a global level estimation at the current stage of study.

5. Conclusion

Given the importance of the CH_4 emissions from the global rice fields, it is vital to provide robust estimation before developing climate mitigation strategies. Rice fields serve about half of the world population. The production and management practices for the rice fields affect food security, water scarcity, and the feedback to climate change. It can be anticipated that to meet the demand of boost population, rice cultivation area is expected to increase, which could result in more CH_4 emissions. Despite some remaining uncertainties, our process-based modeling study provides the state-of-the-art estimate on the magnitude and spatial-temporal variability of CH_4 emissions from global rice field. Our results suggest that CH_4 emissions from global rice field varied from 18.3 ± 0.1 to 38.8 ± 1.0 Tg CH_4/yr during the 2000s depending on different water management practices. The estimated CH_4 emission from the global rice field under continuous flooding could be reduced by more than 50% if intermittent irrigation would be applied. The optimized irrigation strategies could have potentials to attenuate the water scarcity, and meanwhile reduce the CH_4 emissions. Thus, more works need to be done to determine the optimum level of water content to simultaneously reduce CH_4 emissions as well as achieve sustainable rice production.

Acknowledgments

This study has been supported by the NASA Interdisciplinary Science Program (NNX10AU06G, NNX11AD47G, and NNG04GM39C), the NASA Land Cover/Land Use Change Program (NNX08AL73G and NNX14AD94G), the NASA Carbon Monitoring System Program (NNX14AO73G), and the National Science Foundation (1243232 and 1243220). We acknowledge Prigent Catherine for providing the dynamic inundation extent data sets and Felix Portmann for providing the MIRCA2000 data sets. We thank associated editor and two anonymous referees for their constructive comments and suggestions to improve the manuscript. All input data and output files used in this manuscript are available from the author upon request (tianhan@auburn.edu).

References

- Adhya, T., S. Mishra, A. Rath, K. Bharati, S. Mohanty, B. Ramakrishnan, V. Rao, and N. Sethunathan (2000), Methane efflux from rice-based cropping systems under humid tropical conditions of eastern India, *Agric. Ecosyst. Environ.*, *79*(1), 85–90.
- Allen, L. H., S. L. Albrecht, W. Colon-Guasp, S. A. Covell, J. T. Baker, D. Y. Pan, and K. J. Boote (2003), Methane emissions of rice increased by elevated carbon dioxide and temperature, *J. Environ. Qual.*, *32*(6), 1978–1991.
- Aselmann, I., and P. J. Crutzen (1989), Global distribution of natural fresh-water wetlands and rice paddies, their net primary productivity, seasonality and possible methane emissions, *J. Atmos. Chem.*, *8*(4), 307–358.
- Banger, K., H. Q. Tian, and C. Q. Lu (2012), Do nitrogen fertilizers stimulate or inhibit methane emissions from rice fields?, *Global Change Biol.*, *18*(10), 3259–3267.
- Banger, K., H. Q. Tian, B. W. Zhang, C. Q. Lu, W. Ren, and B. Tao (2015a), Biosphere-atmosphere exchange of methane in India as influenced by multiple environmental changes during 1901–2010, *Atmos. Environ.*, 192–200.
- Banger, K., H. Q. Tian, B. Tao, W. Ren, S. F. Pan, S. R. S. Dangal, and J. Yang (2015b), Terrestrial net primary productivity in India during 1901–2010: Contributions from multiple environmental changes, *Clim. Change*, *132*(4), 575–588.
- Bergamaschi, P., et al. (2007), Satellite cartography of atmospheric methane from SCIAMACHY on board ENVISAT: 2. Evaluation based on inverse model simulations, *J. Geophys. Res.*, *112*, D02304, doi:10.1029/2006JD007268.
- Bharati, K., S. R. Mohanty, D. P. Singh, V. R. Rao, and T. K. Adhya (2000), Influence of incorporation or dual cropping of Azolla on methane emission from a flooded alluvial soil planted to rice in eastern India, *Agric. Ecosyst. Environ.*, *79*(1), 73–83.
- Bhatia, A., A. Ghosh, V. Kumar, R. Tomer, S. D. Singh, and H. Pathak (2011), Effect of elevated tropospheric ozone on methane and nitrous oxide emission from rice soil in north India, *Agric. Ecosyst. Environ.*, *144*(1), 21–28.
- Bhatia, A., N. Jain, and H. Pathak (2013), Methane and nitrous oxide emissions from Indian rice paddies, agricultural soils and crop residue burning, *Greenhouse Gases*, *3*(3), 196–211.
- Bloom, A. A., P. I. Palmer, A. Fraser, D. S. Reay, and C. Frankenberg (2010), Large-scale controls of methanogenesis inferred from methane and gravity spaceborne data, *Science*, *327*(5963), 322–325.
- Bohn, T. J., et al. (2015), WETCHIMP-WSL: Intercomparison of wetland methane emissions models over West Siberia, *Biogeosciences*, *12*(11), 3321–3349.

- Bousquet, P., et al. (2006), Contribution of anthropogenic and natural sources to atmospheric methane variability, *Nature*, *443*(7110), 439–443.
- Bridgman, S. D., H. Cadillo-Quiroz, J. K. Keller, and Q. L. Zhuang (2013), Methane emissions from wetlands: Biogeochemical, microbial, and modeling perspectives from local to global scales, *Global Change Biol.*, *19*(5), 1325–1346.
- Burney, J. A., S. J. Davis, and D. B. Lobell (2010), Greenhouse gas mitigation by agricultural intensification, *Proc. Natl. Acad. Sci. U.S.A.*, *107*(26), 12,052–12,057.
- Cai, Z., H. Tsuruta, and K. Minami (2000), Methane emission from rice fields in China: Measurements and influencing factors, *J. Geophys. Res.*, *105*(D13), 17,231–17,242, doi:10.1029/2000JD900014.
- Chareonsilp, N., C. Buddhaboon, P. Promnart, R. Wassmann, and R. Lantin (2000), Methane emission from deepwater rice fields in Thailand, in *Methane Emissions From Major Rice Ecosystems in Asia*, edited by R. Wassmann, R. S. Lantin, and Heinz-Ulrich Neue, pp. 121–130, Kluwer Acad., Dordrecht, Netherlands.
- Chen, G., G. Huang, B. Huang, J. Wu, K. Yu, H. Xu, H. Xie, and Z. Wang (1995), CH₄ and N₂O emission from a rice field and effect of Azolla and fertilization on them, *Chin. J. Appl. Ecol.*, *6*, 378–382.
- Chen, H., et al. (2013), Methane emissions from rice paddies natural wetlands, lakes in China: Synthesis new estimate, *Global Change Biol.*, *19*(1), 19–32.
- Chen, Y. H., and R. G. Prinn (2006), Estimation of atmospheric methane emissions between 1996 and 2001 using a three-dimensional global chemical transport model, *J. Geophys. Res.*, *111*, D10307, doi:10.1029/2005JD006058.
- Chen, Z. L., D. B. Li, K. S. Shao, and B. J. Wang (1993), Features of CH₄ emission from rice paddy fields in Beijing and Nanjing, *Chemosphere*, *26*(1-4), 239–245.
- Ciais, P., et al. (2014), Carbon and other biogeochemical cycles, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker et al., pp. 465–570, Cambridge Univ. Press, Cambridge.
- Corton, T. M., J. B. Bajita, F. S. Grospe, R. R. Pamplona, C. A. Assis, R. Wassmann, R. S. Lantin, and L. V. Buendia (2000), Methane emission from irrigated and intensively managed rice fields in Central Luzon (Philippines), *Nutr. Cycling Agroecosyst.*, *58*(1-3), 37–53.
- Debnath, G., M. Jain, S. Kumar, K. Sarkar, and S. K. Sinha (1996), Methane emissions from rice fields amended with biogas slurry and farm yard manure, *Clim. Change*, *33*(1), 97–109.
- Dijkstra, F. A., S. A. Prior, G. B. Runion, H. A. Torbert, H. Tian, C. Lu, and R. T. Venterea (2012), Effects of elevated carbon dioxide and increased temperature on methane and nitrous oxide fluxes: Evidence from field experiments, *Front. Ecol. Environ.*, *10*(10), 520–527.
- Dubey, S. K. (2003), Spatio-kinetic variation of methane oxidizing bacteria in paddy soil at mid-tillering: Effect of N-fertilizers, *Nutr. Cycling Agroecosyst.*, *65*(1), 53–59.
- Dubey, S. K., A. S. K. Sinha, and J. S. Singh (2002), Differential inhibition of CH₄ oxidation in bare, bulk and rhizosphere soils of dryland rice field by nitrogen fertilizers, *Basic Appl. Ecol.*, *3*(4), 347–355.
- FAOSTAT (2014), Food and Agriculture Organization of the United Nations Statistics Division.
- Felzer, B., J. Reilly, J. Melillo, D. Kicklighter, M. Sarofim, C. Wang, R. Prinn, and Q. Zhuang (2005), Future effects of ozone on carbon sequestration and climate change policy using a global biogeochemical model, *Clim. Change*, *73*(3), 345–373.
- Frankenberg, C., J. F. Meirink, M. van Weele, U. Platt, and T. Wagner (2005), Assessing methane emissions from global space-borne observations, *Science*, *308*(5724), 1010–1014.
- Garg, A., B. Kankal, and P. R. Shukla (2011), Methane emissions in India: Sub-regional and sectoral trends, *Atmos. Environ.*, *45*(28), 4922–4929.
- Ghosh, S., D. Majumdar, and M. C. Jain (2003), Methane and nitrous oxide emissions from an irrigated rice of North India, *Chemosphere*, *51*(3), 181–195.
- Goldewijk, K. K., A. Beusen, G. van Drecht, and M. de Vos (2011), The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years, *Global Ecol. Biogeogr.*, *20*(1), 73–86.
- Goto, E., Y. Miyamori, S. Hasegawa, and O. Inatsu (2004), Reduction effects of accelerating rice straw decomposition and water management on methane emission from paddy fields in a cold district [of Japan], *Jpn. J. Soil Sci. Plant Nutr.*, *75*, 191–201.
- Gupta, M., S. Verma, D. Parashar, and P. K. Gupta (1994), Temporal variation of methane emission from rice paddy fields of Gujarat, *Indian J. Radio Space Phys.*, *23*(4), 265–268.
- Intergovernmental Panel on Climate Change (IPCC) (2013), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker et al., 1535 pp., Cambridge Univ. Press, Cambridge, U. K., and New York.
- Inubushi, K., W. Cheng, S. Aonuma, M. M. Hoque, K. Kobayashi, S. Miura, H. Y. Kim, and M. Okada (2003), Effects of free-air CO₂ enrichment (FACE) on CH₄ emission from a rice paddy field, *Global Change Biol.*, *9*(10), 1458–1464.
- Ito, A., and M. Inatomi (2012), Use of a process-based model for assessing the methane budgets of global terrestrial ecosystems and evaluation of uncertainty, *Biogeosciences*, *9*(2), 759–773.
- Jackson, R. B., C. W. Cook, J. S. Pippen, and S. M. Palmer (2009), Increased belowground biomass and soil CO₂ fluxes after a decade of carbon dioxide enrichment in a warm-temperate forest, *Ecology*, *90*(12), 3352–3366.
- Jain, M. C., S. Kumar, R. Wassmann, S. Mitra, S. D. Singh, J. P. Singh, R. Singh, A. K. Yadav, and S. Gupta (2000), Methane emissions from irrigated rice fields in northern India (New Delhi), *Nutr. Cycling Agroecosyst.*, *58*(1-3), 75–83.
- Jain, S. K., and V. Kumar (2012), Trend analysis of rainfall and temperature data for India, *Curr. Sci. India*, *102*(1), 37–49.
- Jernsawatdipong, P., J. Murase, P. Prabuddham, Y. Hasathon, N. Khomthong, K. Naklang, A. Watanabe, H. Haraguchi, and M. Kimura (1994), Methane emission from plots with differences in fertilizer application in Thai paddy fields, *Soil Sci. Plant Nutr.*, *40*(1), 63–71.
- Kai, F. M., S. C. Tyler, and J. T. Randerson (2010), Modeling methane emissions from rice agriculture in China during 1961–2007, *J. Integr. Environ. Sci.*, *7*, 49–60.
- Kai, F. M., S. C. Tyler, J. T. Randerson, and D. R. Blake (2011), Reduced methane growth rate explained by decreased Northern Hemisphere microbial sources, *Nature*, *476*(7359), 194–197.
- Khalil, M., R. Rasmussen, M. J. Shearer, R. Dalluge, L. Ren, and C.-L. Duan (1998), Measurements of methane emissions from rice fields in China, *J. Geophys. Res.*, *103*(D19), 25,181–25,210, doi:10.1029/97JD02611.
- Kumagai, K., Y. Konno, and M. Togashi (2000), Effect of water management and rice plant growth on methane emission from rice paddy fields in a cold district of Japan, *Jpn. J. Soil Sci. Plant Nutr.*, *69*, 333–339.
- Laborte, A., A. Nelson, K. Jagadish, J. Aunario, A. Sparks, C. Ye, and E. Redoña (2012), Rice feels the heat, *Rice Today*, *11*, 30–31.
- Law, V., N. Johnson, A. Oyefodun, and S. Bhattacharya (1993), Modeling methane emissions from rice soils, *Environ. Soft.*, *8*(4), 197–207.
- Lee, H. J., S. Y. Kim, P. J. Kim, E. L. Madsen, and C. O. Jeon (2014), Methane emission and dynamics of methanotrophic and methanogenic communities in a flooded rice field ecosystem, *Fems Microbiol. Ecol.*, *88*(1), 195–212.

- Leff, B., N. Ramankutty, and J. A. Foley (2004), Geographic distribution of major crops across the world, *Global Biogeochem. Cycles*, *18*, GB1009, doi:10.1029/2003GB002108.
- Li, Q. X., W. J. Dong, W. Li, X. R. Gao, P. Jones, J. Kennedy, and D. Parker (2010), Assessment of the uncertainties in temperature change in China during the last century, *Chin. Sci. Bull.*, *55*(19), 1974–1982.
- Lin, K., Y. Xiang, D. Jiang, Q. Hu, Z. Li, D. Du, and Z. Tao (2000), Methane emission flux from paddy fields in its control in Hubei, *Agro-environ. Prot.*, *19*, 257–270.
- Lindau, C., P. Bollich, R. Delaune, W. Patrick Jr., and V. Law (1991), Effect of urea fertilizer and environmental factors on CH₄ emissions from a Louisiana, USA rice field, *Plant Soil*, *136*(2), 195–203.
- Liu, L. L., and T. L. Greaver (2009), A review of nitrogen enrichment effects on three biogenic GHGs: The CO₂ sink may be largely offset by stimulated N₂O and CH₄ emission, *Ecol. Lett.*, *12*, 1103–1117.
- Liu, M. L., and H. Q. Tian (2010), China's land cover and land use change from 1700 to 2005: Estimations from high-resolution satellite data and historical archives, *Global Biogeochem. Cycles*, *24*, GB3003, doi:10.1029/2009GB003687.
- Locatelli, R., et al. (2013), Impact of transport model errors on the global and regional methane emissions estimated by inverse modelling, *Atmos. Chem. Phys.*, *13*(19), 9917–9937.
- Lokshina, L. Y., V. A. Vavilin, R. H. Kettunen, J. A. Rintala, C. Holliger, and A. N. Nozhevnikova (2001), Evaluation of kinetic coefficients using integrated Monod and Haldane models for low-temperature acetoclastic methanogenesis, *Water Res.*, *35*(12), 2913–2922.
- Lu, C. Q., and H. Q. Tian (2013), Net greenhouse gas balance in response to nitrogen enrichment: Perspectives from a coupled biogeochemical model, *Global Change Biol.*, *19*(2), 571–588.
- Lu, W. F., W. Chen, B. W. Duan, W. M. Guo, Y. Lu, R. S. Lantin, R. Wassmann, and H. U. Neue (2000), Methane emissions and mitigation options in irrigated rice fields in southeast China, *Nutr. Cycling Agroecosyst.*, *58*(1–3), 65–73.
- Matsumoto, J., Y. Minamiyama, S. Akahori, and K. Takahashi (2002), Suppression of methane emission from paddy field supplemented with organic matter, *Jpn. J. Soil Sci. Plant Nutr.*, *73*, 315–318.
- Melton, J. R., et al. (2013), Present state of global wetland extent and wetland methane modelling: Conclusions from a model inter-comparison project (WETCHIMP), *Biogeosciences*, *10*(2), 753–788.
- Miller, S. M., et al. (2014), Observational constraints on the distribution, seasonality, and environmental predictors of North American boreal methane emissions, *Global Biogeochem. Cycles*, *28*, 146–160, doi:10.1002/2013GB004580.
- Mitra, S., M. C. Jain, S. Kumar, S. K. Bandyopadhyay, and N. Kalra (1999), Effect of rice cultivars on methane emission, *Agric. Ecosyst. Environ.*, *73*(3), 177–183.
- Monfreda, C., N. Ramankutty, and J. A. Foley (2008), Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000, *Global Biogeochem. Cycles*, *22*, GB1022, doi:10.1029/2007GB002947.
- Nugroho, S. G., J. Lumbanraja, H. Suprpto, Sunyoto, W. S. Ardjasa, H. Haraguchi, and M. Kimura (1994), Effect of intermittent irrigation on methane emission from an Indonesian paddy field, *Soil Sci. Plant Nutr.*, *40*(4), 609–615.
- Pan, S. F., et al. (2014a), Complex spatiotemporal responses of global terrestrial primary production to climate change and increasing atmospheric CO₂ in the 21st century, *Plos One*, *9*(11), doi:10.1371/journal.pone.0112810.
- Pan, S., H. Tian, S. R. Dangal, Z. Ouyang, B. Tao, W. Ren, C. Lu, and S. Running (2014b), Modeling and monitoring terrestrial primary production in a changing global environment: Toward a multiscale synthesis of observation and simulation, *Adv. Meteorol.*, *2014*.
- Pan, S., S. R. Dangal, B. Tao, J. Yang, and H. Tian (2015), Recent patterns of terrestrial net primary production in Africa influenced by multiple environmental changes, *Ecosyst. Health Sustainability*, *1*(5), 1–15.
- Pathak, H., S. Prasad, A. Bhatia, S. Singh, S. Kumar, J. Singh, and M. C. Jain (2003), Methane emission from rice-wheat cropping system in the Indo-Gangetic plain in relation to irrigation, farmyard manure and dicyandiamide application, *Agric. Ecosyst. Environ.*, *97*(1–3), 309–316.
- Pison, I., B. Ringeval, P. Bousquet, C. Prigent, and F. Papa (2013), Stable atmospheric methane in the 2000s: Key-role of emissions from natural wetlands, *Atmos. Chem. Phys.*, *13*(23), 11,609–11,623.
- Portmann, F. T., S. Siebert, and P. Doll (2010), MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling, *Global Biogeochem. Cycles*, *24*, GB1011, doi:10.1029/2008GB003435.
- Pregitzer, K. S., A. J. Burton, J. S. King, and D. R. Zak (2008), Soil respiration, root biomass, and root turnover following long-term exposure of northern forests to elevated atmospheric CO₂ and tropospheric O₃, *New Phytol.*, *180*(1), 153–161.
- Prigent, C., F. Papa, F. Aires, W. Rossow, and E. Matthews (2007), Global inundation dynamics inferred from multiple satellite observations, 1993–2000, *J. Geophys. Res.*, *112*, D12107, doi:10.1029/2006JD007847.
- Prigent, C., F. Papa, F. Aires, C. Jimenez, W. B. Rossow, and E. Matthews (2012), Changes in land surface water dynamics since the 1990s and relation to population pressure, *Geophys. Res. Lett.*, *39*, L08403, doi:10.1029/2012GL051276.
- Redfern, S. K., N. Azzu, and J. S. Binamira (2012), Rice in Southeast Asia: Facing risks and vulnerabilities to respond to climate change, *Building resilience for adaptation to climate change in the agriculture sector*, *23*, 295.
- Ren, W., H. Q. Tian, M. L. Liu, C. Zhang, G. S. Chen, S. F. Pan, B. Felzer, and X. F. Xu (2007), Effects of tropospheric ozone pollution on net primary productivity and carbon storage in terrestrial ecosystems of China, *J. Geophys. Res.*, *112*, D22S09, doi:10.1029/2007JD008521.
- Ren, W., H. Q. Tian, X. F. Xu, M. L. Liu, C. Q. Lu, G. S. Chen, J. Melillo, J. Reilly, and J. Y. Liu (2011), Spatial and temporal patterns of CO₂ and CH₄ fluxes in China's croplands in response to multifactor environmental changes, *Tellus B*, *63*(2), 222–240.
- Ren, W., H. Q. Tian, B. Tao, Y. Huang, and S. F. Pan (2012), China's crop productivity and soil carbon storage as influenced by multifactor global change, *Global Change Biol.*, *18*(9), 2945–2957.
- Sass, R., F. Fisher, Y. Wang, F. Turner, and M. Jund (1992), Methane emission from rice fields: The effect of floodwater management, *Global Biogeochem. Cycles*, *6*, 249–249, doi:10.1029/92GB01674.
- Satpathy, S. N., S. Mishra, T. K. Adhya, B. Ramakrishnan, V. R. Rao, and N. Sethunathan (1998), Cultivar variation in methane efflux from tropical rice, *Plant Soil*, *202*(2), 223–229.
- Setyanto, P., A. Makarim, A. Fagi, R. Wassmann, and L. Buendia (2000), Crop management affecting methane emissions from irrigated and rainfed rice in Central Java (Indonesia), in *Methane Emissions from Major Rice Ecosystems in Asia*, edited by R. Wassmann, R. S. Lantin, and Heinz-Ulrich Neue, pp. 85–93, Kluwer Acad., Dordrecht, Netherlands.
- Singh, J. S., S. Singh, A. S. Raghubanshi, S. Singh, and A. K. Kashyap (1996), Methane flux from rice/wheat agroecosystem as affected by crop phenology, fertilization and water level, *Plant Soil*, *183*(2), 323–327.
- SNCCCC (2012), Second National Communication on Climate Change of The People's Republic of China.
- Song, C. C., L. L. Wang, H. Q. Tian, D. Y. Liu, C. Q. Lu, X. F. Xu, L. H. Zhang, G. S. Yang, and Z. M. Wan (2013), Effect of continued nitrogen enrichment on greenhouse gas emissions from a wetland ecosystem in the Sanjiang Plain, Northeast China: A 5 year nitrogen addition experiment, *J. Geophys. Res. Biogeosci.*, *118*, 741–751, doi:10.1002/jgrg.20063.
- Spahni, R., et al. (2011), Constraining global methane emissions and uptake by ecosystems, *Biogeosciences*, *8*(6), 1643–1665.

- Subadiyasa, N., N. Arya, and M. Kimura (1997), Methane emissions from paddy fields in Bali Island, Indonesia, *Soil Sci. Plant Nutr.*, *43*(2), 387–394.
- Tao, B., H. Q. Tian, G. S. Chen, W. Ren, C. Q. Lu, K. D. Alley, X. F. Xu, M. L. Liu, S. F. Pan, and H. Virji (2013), Terrestrial carbon balance in tropical Asia: Contribution from cropland expansion and land management, *Global Planet. Change*, *100*, 85–98.
- Tao, Z. (1998), Methane emission from rice fields in difference regions of China and mitigation options, *Agro-environ. Prot.*, *17*, 1–7.
- Tian, H. Q., X. F. Xu, M. L. Liu, W. Ren, C. Zhang, G. S. Chen, and C. Q. Lu (2010), Spatial and temporal patterns of CH₄ and N₂O fluxes in terrestrial ecosystems of North America during 1979–2008: Application of a global biogeochemistry model, *Biogeosciences*, *7*(9), 2673–2694.
- Tian, H. Q., X. F. Xu, C. Q. Lu, M. L. Liu, W. Ren, G. S. Chen, J. Melillo, and J. Y. Liu (2011), Net exchanges of CO₂, CH₄, and N₂O between China's terrestrial ecosystems and the atmosphere and their contributions to global climate warming, *J. Geophys. Res.*, *116*, G02011, doi:10.1029/2010JG001393.
- Tian, H. Q., et al. (2012), Food benefit and climate warming potential of nitrogen fertilizer uses in China, *Environ. Res. Lett.*, *7*(4).
- Tian, H. Q., K. Banger, T. Bo, and V. K. Dadhwal (2014), History of land use in India during 1880–2010: Large-scale land transformations reconstructed from satellite data and historical archives, *Global Planet. Change*, *121*, 78–88.
- Tian, H. Q., Q. C. Yang, R. G. Najjar, W. Ren, M. A. M. Friedrichs, C. S. Hopkinson, and S. F. Pan (2015a), Anthropogenic and climatic influences on carbon fluxes from eastern North America to the Atlantic Ocean: A process-based modeling study, *J. Geophys. Res. Biogeosci.*, *120*, 757–772, doi:10.1002/2014JG002760.
- Tian, H. Q., et al. (2015b), Global methane and nitrous oxide emissions from terrestrial ecosystems due to multiple environmental changes, *Ecosyst. Health Sustainability*, *1*(1, 4).
- Tian, H. Q., W. Ren, B. Tao, G. Sun, A. Chappelka, X. K. Wang, S. F. Pan, J. Yang, J. Y. Liu, and S. B. Felzer (2016a), Climate extremes and ozone pollution: A growing threat to China's food security, *Ecosyst. Health Sustainability*, *2*(1).
- Tian, H. Q., et al. (2016b), The terrestrial biosphere as a net source of greenhouse gases to the atmosphere, *Nature*, *531*(7593), 225–228.
- Tokida, T., M. Adachi, W. G. Cheng, Y. Nakajima, T. Fumoto, M. Matsushima, H. Nakamura, M. Okada, R. Sameshima, and T. Hasegawa (2011), Methane and soil CO₂ production from current-season photosynthates in a rice paddy exposed to elevated CO₂ concentration and soil temperature, *Global Change Biol.*, *17*(11), 3327–3337.
- US-EPA (2012), Global anthropogenic non-CO₂ greenhouse gas emissions: 1990–2030.
- Van Bodegom, P. M., P. H. Verburg, D. van der Gon, and A. C. Hugo (2002), Upscaling methane emissions from rice paddies: Problems and possibilities, *Global Biogeochem. Cycles*, *16*(1), 1014, doi:10.1029/2000GB001381.
- van Groenigen, K. J., C. W. Osenberg, and B. A. Hungate (2011), Increased soil emissions of potent greenhouse gases under increased atmospheric CO₂, *Nature*, *475*(7355), 214–U121.
- Wang, P., L. Wei, X. Du, W. Zhang, Y. Huang, W. Sun, and W. Liu (2008), Simulating changes of methane emission from rice paddies of China, 1990–2000, *Geo-Info. Sci.*, *10*(5), 573–577.
- Wang, Z. Y., Y. C. Xu, Z. Li, Y. X. Guo, R. Wassmann, H. U. Neue, R. S. Lantin, L. V. Buendia, Y. P. Ding, and Z. Z. Wang (2000a), A four-year record of methane emissions from irrigated rice fields in the Beijing region of China, *Nutr. Cycling Agroecosyst.*, *58*(1–3), 55–63.
- Wang, Z., D. Zeng, and W. Patrick Jr. (1997), Characteristics of methane oxidation in a flooded rice soil profile, *Nutr. Cycling Agroecosyst.*, *49*(1–3), 97–103.
- Wang, Z., Y. Xu, Z. Li, Y. Guo, R. Wassmann, H. Neue, R. Lantin, L. Buendia, Y. Ding, and Z. Wang (2000b), A four-year record of methane emissions from irrigated rice fields in the Beijing region of China, in *Methane Emissions From Major Rice Ecosystems in Asia*, edited, pp. 55–63, Springer.
- Wania, R., et al. (2013), Present state of global wetland extent and wetland methane modelling: Methodology of a model inter-comparison project (WETCHIMP), *Geosci. Model Dev.*, *6*(3), 617–641.
- Wassmann, R., M. Wang, X. Shangguan, X. Xie, R. Shen, Y. Wang, H. Papen, H. Rennenberg, and W. Seiler (1993), First records of a field experiment on fertilizer effects on methane emission from rice fields in Hunan-Province (PR China), *Geophys. Res. Lett.*, *20*(19), 2071–2074, doi:10.1029/93GL01915.
- Wassmann, R., X. J. Shangguan, D. X. Cheng, M. X. Wang, H. Papen, H. Rennenberg, and W. Seiler (1996), Spatial and seasonal distribution of organic amendments affecting methane emission from Chinese rice fields, *Biol. Fertil. Soils*, *22*(3), 191–195.
- Wassmann, R., L. Buendia, R. Lantin, C. Bueno, L. Lubigan, A. Umali, N. Nocon, A. Javellana, and H. Neue (2000), Mechanisms of crop management impact on methane emissions from rice fields in Los Baños, Philippines, *Nutr. Cycling Agroecosyst.*, *58*(1–3), 107–119.
- Wei, Y., et al. (2014), The North American Carbon Program Multi-scale Synthesis and Terrestrial Model Intercomparison Project - Part 2: Environmental driver data, *Geosci. Model Dev.*, *7*(6), 2875–2893.
- Weller, S., B. Janz, L. Jörg, D. Kraus, H. S. Racela, R. Wassmann, K. Butterbach-Bahl, and R. Kiese (2016), Greenhouse gas emissions and global warming potential of traditional and diversified tropical rice rotation systems, *Global Change Biol.*, *22*(1), 432–448.
- Wieder, W. R., J. Boehnert, G. B. Bonan, and M. Langseth (2014), RegridDED harmonized world soil database v1.2. Data set. Available on-line [http://daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA.
- Wood, C., Y. Qiao, P. Li, P. Ding, B. Z. Lu, and Y. M. Xi (2010), Implications of rice agriculture for wild birds in China, *Waterbirds*, *33*, 30–43.
- Xiao, X. M., S. Boles, J. Y. Liu, D. F. Zhuang, S. Frolking, C. S. Li, W. Salas, and B. Moore (2005), Mapping paddy rice agriculture in southern China using multi-temporal MODIS images, *Remote Sens. Environ.*, *95*(4), 480–492.
- Xu, X. F., H. Q. Tian, C. Zhang, M. L. Liu, W. Ren, G. S. Chen, C. Q. Lu, and L. Bruhwiler (2010), Attribution of spatial and temporal variations in terrestrial methane flux over North America, *Biogeosciences*, *7*(11), 3637–3655.
- Xu, Y. C., Q. R. Shen, M. L. Li, K. Dittert, and B. Sattelmacher (2004), Effect of soil water status and mulching on N₂O and CH₄ emission from lowland rice field in China, *Biol. Fertil. Soils*, *39*(3), 215–217.
- Yagi, K., and K. Minami (1990), Effect of organic matter application on methane emission from some Japanese paddy fields, *Soil Sci. Plant Nutr.*, *36*(4), 599–610.
- Yagi, K., H. Tsuruta, K. I. Kanda, and K. Minami (1996), Effect of water management on methane emission from a Japanese rice paddy field: Automated methane monitoring, *Global Biogeochem. Cycles*, *10*(2), 255–267, doi:10.1029/96GB00517.
- Yan, H. M., M. K. Cao, J. Y. Liu, D. F. Zhuang, J. K. Guo, and M. L. Liu (2005), Characterizing spatial patterns of multiple cropping system in China from multi-temporal remote sensing images, *Trans. CSAE*, *21*(4), 85–90.
- Yan, X. Y., H. Akiyama, K. Yagi, and H. Akimoto (2009), Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines, *Global Biogeochem. Cycles*, *23*, GB2002, doi:10.1029/2008GB003299.
- Yang, Q. C., et al. (2014), Spatiotemporal patterns of evapotranspiration along the North American east coast as influenced by multiple environmental changes, *Ecology*, *8*(4), 714–725.

- Zak, D. R., K. S. Pregitzer, J. S. King, and W. E. Holmes (2000), Elevated atmospheric CO₂, fine roots and the response of soil microorganisms: A review and hypothesis, *New Phytol.*, *147*(1), 201–222.
- Zhang, B., and G. Q. Chen (2014), China's CH₄ and CO₂ emissions: Bottom-up estimation and comparative analysis, *Ecol. Indic.*, *47*, 112–122.
- Zhang, W., Y. Q. Yu, Y. Huang, T. T. Li, and P. Wang (2011a), Modeling methane emissions from irrigated rice cultivation in China from 1960 to 2050, *Global Change Biol.*, *17*(12), 3511–3523.
- Zhang, W., Q. Zhang, Y. Huang, T. T. Li, J. Y. Bian, and P. F. Han (2014), Uncertainties in estimating regional methane emissions from rice paddies due to data scarcity in the modeling approach, *Geosci. Model Dev.*, *7*(3), 1211–1224.
- Zhang, Y., Y. Y. Wang, S. L. Su, and C. S. Li (2011b), Quantifying methane emissions from rice paddies in Northeast China by integrating remote sensing mapping with a biogeochemical model, *Biogeosciences*, *8*(5), 1225–1235.
- Zheng, F. X., et al. (2011), Effects of elevated ozone concentration on methane emission from a rice paddy in Yangtze River Delta, China, *Global Change Biol.*, *17*(2), 898–910.