Modeling the Impacts of Water Management Change on Greenhouse Gas Emission and Yields from Paddy Fields in China During 2006-2010

Han Chen[1], Chaoqing Yu[1], Changsheng Li[2], Xuecao Li[1], Jie Zhang[1], and Wei Wang[1]
[1]Center for Earth System Science, Key Lab of Earth System Numerical Simulation, Tsinghua University, Beijing, China
[2]Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, USA
Email: chenhan0111@126.com, chaoqingyu@mail.tsinghua.edu.cn,

***Abstract*—Since the early 1980s water management strategies in rice paddies in China has changed substantially, with midseason drainage gradually replacing continuous flooding. Using the process-based DNDC model and county-level database, we simulated CH_4, N_2O emission and yields from paddy fields under this change. Results indicated this change had reduced CH_4 emission by approximately 41% from 2006 to 2010 and the mitigating effect was highly uneven across the country. The highest flux reduction (>1000 kg CH_4-C ha^{-1} yr^{-1}) were Hainan, Hubei, Guangxi provinces with warm weather and multiple-cropping rice systems and the lowest flux reduction (<300 kg CH_4-C ha^{-1} yr^{-1}) appeared in Tianjin, Heilongjiang, Liaoning provinces, with cold weather and single cropping systems. Meanwhile N_2O emission was stimulated by 106% on average during this period, which offseted a large amount of the GHG radiative forcing benefit gained by CH_4 decreases. Rice yields were closely related with the intensity and the interval of drainage. This study concluded DNDC model would play an essential role to optimize county-level water management schemes across China.**

***Index Terms*—mid-season drainage, continuous flooding, rice yield, greenhouse gas emission**

I. Introduction

Global warming and the depletion of the ozone layer in the stratosphere caused by greenhouse gas (GHG) emission are two tremendous issues all the world face. Ref [1]. Agricultural activities contribute to approximately 70% of global atmospheric input of N_2O and 40% of global atmospheric input of CH_4. Ref [2]. Of particular concern is that rice is a major food crop for nearly half of the world' population. Ref. [3] Seasonally flooded rice paddies are responsible for roughly 10% of total global methane emissions to atmosphere, Ref. [4] representing a significant source of about 40Tg CH_4 yr^{-1}. Ref. [5], [6]. Numerous field studies and modeling work have shown that water management holds significant influence on GHG emission and rice yields during rice growing season.

Ref. [7] China is the primary rice production country in the world. Ref. [8] Mid-season drainage (MSD) was initiated in rice farming in northeastern China in the early 1980s owing to frequent shortages of irrigation water. With several advantages including reducing ineffective tillers, removing toxic substances and economizing water resource, Ref. [9] midseason drainage has gradually replaced continuous flooding (CF) during the 20-year period from 1980 to 2000. Ref. [10]-[13]. Studies have shown 10%-80% reduction of rice-season CH_4 emission could be achieved with the conversion to MSD. Ref. [14], [15]. Meanwhile, MSD tends to stimulate N_2O emission due to less anaerobic conditions. To quantify the impacts of water management change in paddy fields on the overall greenhouse emission, Ref. [16] the net global warming potential is introduced to account for different various effects of three gases using the CO_2-equivalent flux method. In addition, shifting water management from continuous flooding to mid-season drainage alters rice yields and water use amount, which depends primarily on the intensity of drainage and the interval between the cycles of flooding-drainage-re-flooding. Ref. [17] Water productivity is significantly higher under MSD than under CF and MSD can reduce water use up to 15% without affecting yields. However, if this proportion increases, Ref. [18], [19] contradictory results might be concluded on the responses of rice yields to drainage strategies due to less detailed water scheme records or environmental factors.

However, field observations of GHG emission and yields can be challenging to conduct in various paddy fields across a large region, thus to what degree GHG effects could be reduced under this water scheme change remains unclear. Meanwhile, despite with benefits of GHG emission mitigation, the impacts of intermittent drainage water strategies on rice yields are still controversial, which is essential to food security in China. Consequently, a quantitative relationship or model describing underling mechanisms of interactions among water regimes, GHG emissions and rice yields are needed. Here, we introduced a biogeochemical model Decomposition and Denitrification (DNDC) with a county-level GIS database of climate, soil, vegetation and management to achieve the following goals: 1) identify the impacts of various water regimes on national GHG emission; 2) evaluate impacts of various water regimes on national rice production in China.

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II. Method

A. DNDC Model

DNDC (Denitrification-Decomposition) was originally developed for predicting agriculture carbon sequestration and trace gas emissions. Ref. [20] It is a process-based model, which integrates biochemistry and geochemistry reactions together to trace the carbon (C) and nitrogen (N) transport and transformation in the plant-soil system. The DNDC model consists of six sub-models, namely soil climate, plant growth, decomposition, nitrification, denitrification and fermentation, respectively (Fig. 1). Ref. [21] DNDC predicts SOC dynamics mainly by quantifying the SOC input from crop littler incorporation and manure amendment as well as the SOC output through decomposition. DNDC simulates crop growth based on photosynthesis, respiration, water and N demand, C allocation, crop yield and litter production. Besides, DNDC has been embedded with various agriculture management practices, which is of significant importance for identification of optimal management practices.

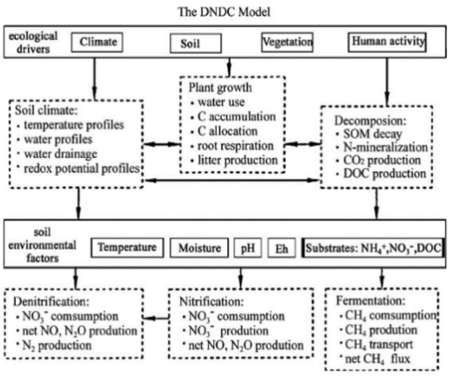

Figure 1. The structure of DNDC model

B. Sensitivity Test

It is essential to conduct sensitivity testing before model validation and calibration to identify the most sensitive parameters in terms of the greenhouse gas emissions and rice yields thus speed up model calibration and validation. The global warming potential (GWP) indicator is adopted to assess the greenhouse effects of various GHGs on various spatial and temporal scales. Based on this method, the greenhouse effects of CH_4 and N_2O can be converted to a uniform indicator of CO_2. For different time scales, the conversion coefficients are listed in Table I.

TABLE I. Ref.[16] The Conversion Coefficients of Different GHGs Based on CO_2

Temporal Scale	CH_4	N_2O
Year	kg CO_2-eq kg^{-1}	
20	62	275
100	23	296
500	7	156

The GWP for a specific temporal scale can be calculated as Equation (1), where t represents different temporal scale (i.e., 20, 100 and 500 years), $GWP_t^{CH_4}, GWP_t^{N_2O}$ denotes the conversion coefficients in Table I, and $\Delta CO_2, \Delta CH_4, \Delta N_2O$ represents the flux change from continuous flooding to midseason drainage.

$$\left(CO_{2-eq}\right)_t = \Delta CO_2 \cdot \frac{44}{12} + \Delta CH_4 \cdot \frac{16}{12} \cdot GWP_t^{CH_4} + \Delta N_2O \cdot \frac{44}{28} \cdot GWP_t^{N_2O} \quad (1)$$

From Fig. 2 we can see that soil texture is the most sensitive parameter among all the environmental factors. In addition, GHG emission is sensitive to SOC and temperature as well. The changes in rainfall and soil pH have little effect on greenhouse gas emissions.

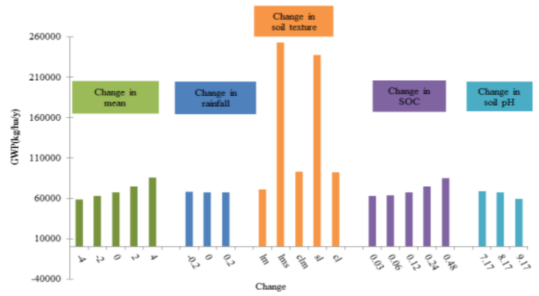

Figure 2. Sensitivity of GWP to environment factors including temperature, precipitation, soil texture, SOC content and soil pH. The alternative climate/soil conditions, with asterisks, are baseline conditions. The soil texture 'lm', 'lms', 'clm', 'sl', 'cl' respectively stand for 'loam', 'loamy sand','clay loam', 'sand loam', 'clay'.

For rice yields, we can find from Fig. 3 that changes in natural conditions such as rainfall, temperature, soil texture, and SOC have no significant impacts on rice yields. It seems that rice yields are more related to crop parameters, such as the max grain yield or water demand and so forth. Therefore, the four crop parameters need to be calibrated as it is challenging to achieve those over a large region.

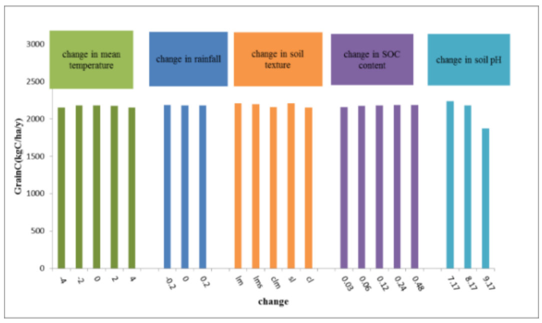

Figure 3. Sensitivity of Grain-C to environment factors including temperature, precipitation, soil texture, SOC content and soil pH. The alternative climate/soil conditions, with asterisks, are baseline conditions. The soil texture 'lm', 'lms', 'clm', 'sl', 'cl' respectively stand for 'loam', 'loamy sand', 'clay loam', 'sand loam', 'clay'.

Therefore, soil texture and SOC are the most sensitive variables that could most effectively mitigate the greenhouse gas emissions in a typical paddy rice ecosystem, while for the grain yield, crop parameters may be more sensitive.

C. Regional Database Construction.

There are more than 1600 counties with rice rotated crop systems in China and the driven data to run DNDC

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includes climate, soil, crop and management. Meteorological data were acquired from the National Center for Atmospheric Research (http://dss.ucar.edu/index.html), which was procedured previously to match the requirement of DNDC. Management information including planting and harvest date, fertilization and manure were obtained through Statistical yearbooks. For crop parameters which are challenging to achieve aross large regions, an indirectly method was introduced: for crop maximum biomass and accumulated temperature given a specific region, a representative crop species, which adapted to the ambient surroundings, was assigned. Thus the crop growth information could be estimated through this representative species. For instance, the accumulated temperature can be achieved through the accumulation of average local temperature and crop growth days. Besides, due to the variations of regional meteorological condition, the crop growth period is acquired from Farming Database of China (http://zzys.agri.gov.cn/nongshi.aspx).

D. *Model Calibration*

In our study, the DNDC model has been tested against the observations of provicial yields and site-level GHG emission from three field sites in China: Wangcheng county, Beibei county and Sanjiang plain (Fig. 4 and Fig. 5). It can be seen from Fig. 4 that the results of simulated yield of each province during 2006-2010 fit the observations well and the R-square reached 0.73. From Fig. 4 we can see that although discrepancies exist, DNDC can capture the patterns and magnitudes of CH_4 and N_2O emission. Results indicate that DNDC is capable of evaluating impacts of water schemes on GHG emissions and rice yields.

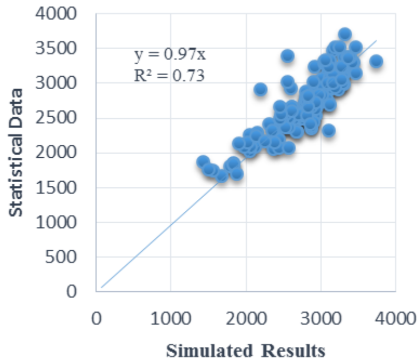


Figure 4. Comparison of provincial modeled and observed rice yields from 2006 to 2010

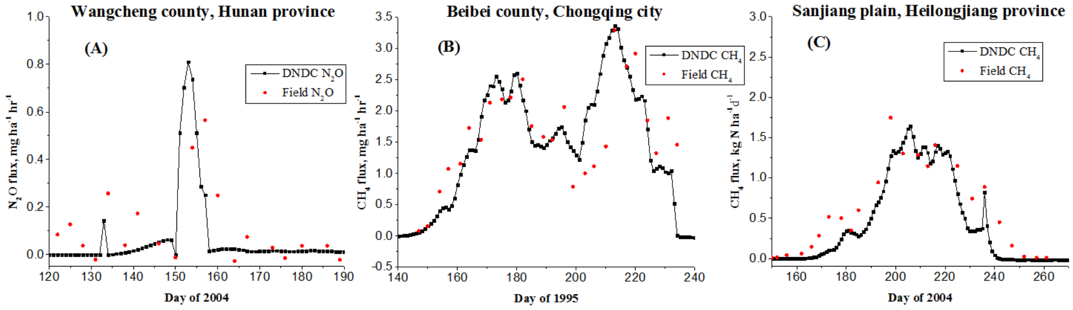


Figure 5. Comparison between observed and DNDC-modeled results in paddy fields across China. (A) Wangcheng county in Hunan province: N_2O emission; (B) Beibei county in Chongqing city: CH_4 emission; (C) Sanjiang plain in Heilongjiang province: CH_4 emission.

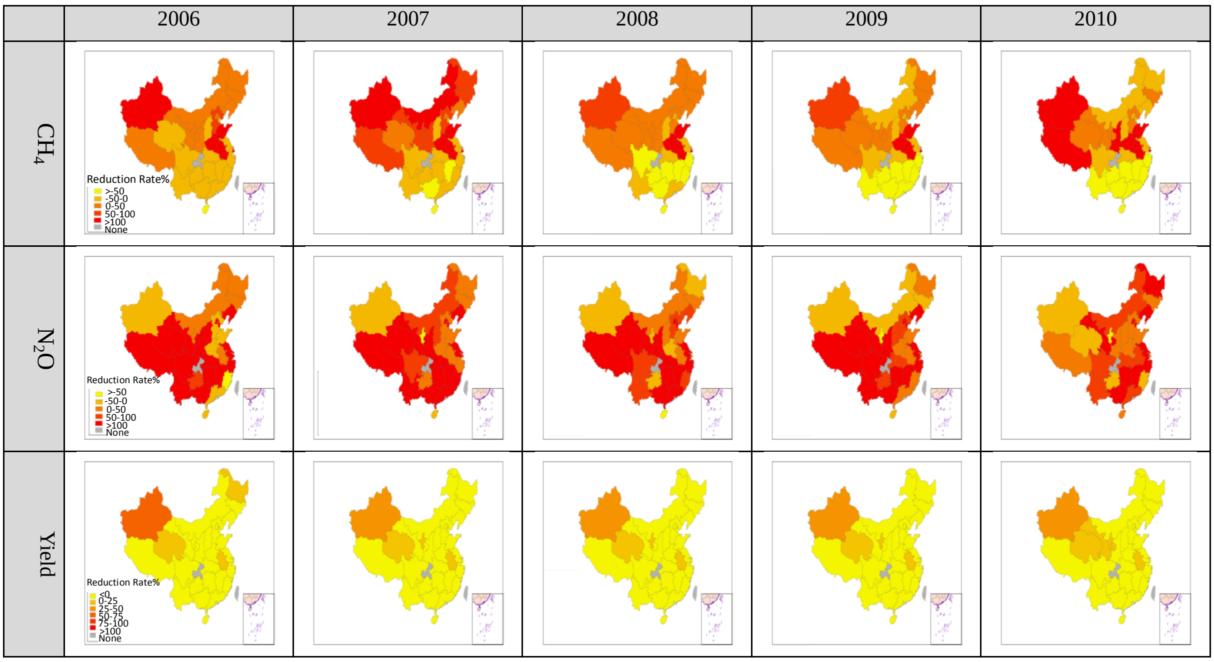


Figure 6. CH_4 and N_2O emission and yield change due to water management change from 2006-2010

III. Results and Discussion

A. CH_4 Emission Reduction

Shifting water management from continuous flooding to midseason drainage decreased CH_4 emission. Results indicate that the change in water management reduced CH_4 emission by roughly 29%, 38%, 45%, 47% and 46% from 2006 to 2010 respectively in China. The results were corroborated with relevant field experiments which demonstrated a 10%-80% reduction of crop-season CH_4 emission due to conversion to mid-season draining [18], [22]-[24]. Besides, the impacts of water management conversion appeared significant spatial heterogeneity among different regions. The highest flux reduction (>1000 kg CH_4 -C ha-1 yr-1) were obtained in Hainan, Hubei, Guangxi, Fujian and Jiangxi provinces, with warm weather and multiple-cropping rice systems. The lowest flux reduction (<300 kg CH_4 -C ha-1 yr-1) happened in Tianjin, Heilongjiang, Liaoning, Gansu provinces, with cold weather and single cropping systems (Appendix A).

Methane emission reduction potential was also closely related to soil characteristics. Ref. [25] The high SOC contents, long crop season and high rice biomass enhanced CH_4 production in the cool paddies. Ref. [26] DNDC modeled CH_4 emissions from paddy soils tended to increase with high SOC content and pH as well as low soil clay fraction. The results agreed to this tendency and the reduction of methane emission was higher in Heilongjiang, Jilin and Liaoning provinces with higher SOC than the other Northern China provinces (Appendix A).

Fig. 6 indicates inter-annual synoptic perturbations contributed to the inter-annual variations with the same soil, management and crop parameters in DNDC model. The highest flux reduction occurred in 2009 and 2010, when drought happened frequently in North and Southwest China, respectively. Given relatively less precipitation, paddy fields became less flooded, which would suppress CH_4 production due to more aerobic conditions. Therefore, CH_4 mitigation increased from 2008 to 2010 both in South and North China.

B. N_2O Emission Increase

The simulated results of DNDC illustrated a nationwide N_2O emission increase: 79%, 132%, 100%, 89% and 132% for from 2006 to 2010 respectively. Ref. [27] Theoretically, more aerobic environments and more SOC, higher clay fraction could stimulate N_2O emission. Fig. 7 explained the impacts of SOC on the N_2O emission change in 2010: The province-level distribution of N_2O emission changes substantially kept in pace with SOC distribution in China. Discrepancy happened in Fujian and Guizhou provinces, Ref. [28] which might derive from the impacts of clay fraction that were more dominant than SOC to N_2O emission.

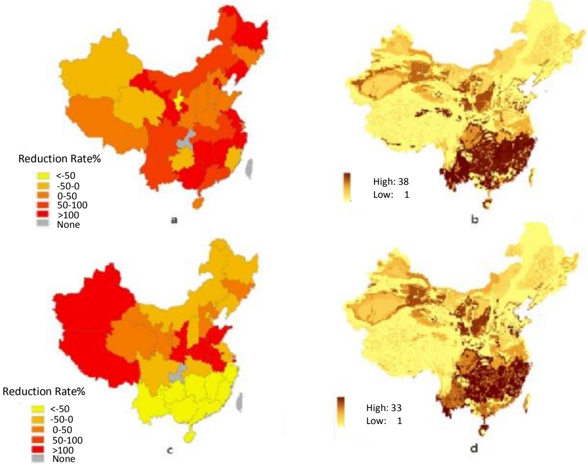


Figure 7. CH_4 and N_2O emission change distribution compared with SOC and clay fraction distribution in 2010

The increased emission of N_2O offset a large fraction of the greenhouse gas radiative forcing benefits gained by the decrease in CH_4 emissions. Ref.[8] Maximum CH_4 reductions and minimum N_2O increases were obtained when the mid-season draining was applied to rice paddies with warm weather, high soil clay content, and low soil organic matter content. The modeled results illustrated that Hubei, Guangdong, Hainan, Jiangxi and Inner Mongolia provinces were this kind of regions. When high SOC and high clay fraction synchronized in southern China, clay fraction would be a more dominant driven factor leading to high CH_4 reduction and low N_2O increase than SOC content. Both site-level and region-level modeled results illustrated CH_4 and N_2O emission were more subject to clay fraction than SOC content

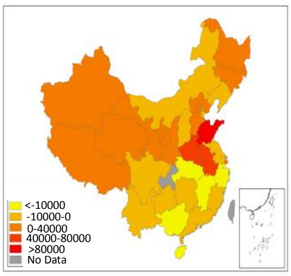
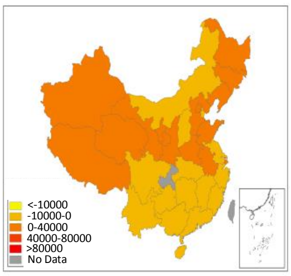
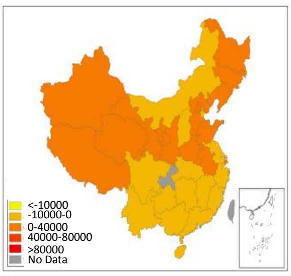
2010	20-YEAR CO_2 EQUIVALENT	100-YEAR CO_2 EQUIVALENT	500-YEAR CO_2 EQUIVALENT
OVERALL GHG EMISSION			

Figure 8. GWP of 20-year, 100-year and 500-year in 2010.

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C. Global Warming Potential (GWP) Change

Fig. 8 shows that the responses of overall GHG emission to changing water management were not spatially uniform and differs with time horizon chosen. On a national scale, most northern provinces presented a GHG emission increase (Heilongjiang, Gansu, Henan, Jilin and Qinghai provinces) and most southern provinces (Jiangsu, Zhejiang, Hubei, Hunan, Guangdong, Sichuan and Yunnan provinces) appeared a GHG emission reduction when shifting water management from continuous flooding to midseason drainage (Appendix A). The Northern-Southern discrepancy was closely related to soil characteristics, climatic conditions and planting pattern.

The provincial CO_2-equivalent emissions differed with the chosen time horizon. Theoretically, N_2O had a much longer atmospheric adjustment time than CH_4 and CO_2. The maximum GWP of N_2O might occur between 100 and 500 and the maximum GWP of CH_4 might occur between 20 and 100. Therefore, the total net provincial CO_2-equivalent emissions were determined by provincial greenhouse gases emission and time scale.

D. Yield Change

The simulated yields of DNDC present a nationwide reduction: 14%, 10%, 11%, 11% and 10% from 2006 to 2010 respectively and the results of 2010 are shown in Table II. Ref. [8] This was inconsistent with the conclusion that mid-season drainage reduced water use while increased crop yield. The possible reason for this discrepancy might be the variety of strength and intensity of mid-season drainage that would definitely influence rice yields and water consumption. It would be of significance to establish a thorough drainage strategy which comprehensively considered the relationship between yields, greenhouse gas emission and water resources given a specific environment condition.

IV. Conclusions

Shifting water management from continuous flooding to midseason drainage would reduce provincial CH_4 emission and increase provincial N_2O emission. The overall GHG emission was suppressed under this change. The spatially uneven responses to water management change were in close relation with weather, soil, and planting pattern. Meanwhile, the strength and intensity of mid-season drainage would alter rice yields. It was concluded that a optimized county-level water scheme was need to take greenhouse gas emission and water resources into consideration on the premise of yield stability in paddy fields and DNDC would play an essential role to address these issues.

TABLE II. The Rice Yield Change due to Water Scheme Conversion in 2010

Yield (kg/ha)	CF	MSD	MSD-CF	Yield (kg/ha)	CF	MSD	MSD-CF
Beijing	7862.5	7040.0	-822.5	Henan	7902.5	7877.5	-27.5
Tianjin	7825.0	7410.0	-415.0	Hubei	8202.5	8167.5	-37.5
Hebei	7947.5	7297.5	-650.0	Hunan	8152.5	6127.5	-2025.0
Shanxi	4670.0	3765.0	-905.0	Guangdong	6382.5	5625.0	-757.5
Inner_Mongolia	7935.0	7747.5	-187.5	Guangxi	5975.0	4762.5	-1212.5
Liaoning	7887.5	7795.0	-92.5	Sichuan	7570.0	7260.0	-310.0
Jilin	8477.5	8465.0	-12.5	Guizhou	6790.0	6175.0	-612.5
Heilongjiang	7137.5	7080.0	-57.5	Yunnan	7797.5	7127.5	-670.0
Shanghai	9065.0	7640.0	-1425.0	Tibet	615.0	182.5	-432.5
Jiangsu	8682.5	8182.5	-500.0	Shaanxi	6397.5	6120.0	-277.5
Zhejiang	8420.0	7065.0	-1355.0	Gansu	7000.0	7072.5	70.0
Anhui	6120.0	6182.5	62.5	Qinghai	472.5	482.5	10.0
Fujian	6495.0	6315.0	-180.0	Ningxia	8015.0	8407.5	392.5
Jiangxi	7275.0	5345.0	-1930.0	Xinjiang	6510.0	8665.0	2155.0
Shandong	9327.5	9320.0	-7.5	Hainan	5507.5	4675.0	-830.0

CF, continuous flooding; MD, mid-season drainage.

Appendix A: The Greenhouse Gas Emission Change in 2010

Year	CF			MSD			MSD-CF			Rice Area
2010	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	△CO_2	△CH_4	△N_2O	Kha
	(kgC/ha)	(kgC/ha)	(kgN/ha)	(kgC/ha)	(kgC/ha)	(kgN/ha)	(kgC/ha)	(kgC/ha)	(kgN/ha)	
Beijing	3911	581	0	3747	570	4	-164	-11	4	0
Tianjin	2677	1557	0	2921	1250	3	244	-307	3	16
Hebei	3321	914	4	3708	953	6	387	39	2	80
Shanxi	3671	2253	5	3764	1445	7	93	-808	2	1
Inner_Mongolia	1516	3166	4	3025	1991	5	1509	-1175	2	92
Liaoning	3921	596	2	4333	530	5	412	-65	3	678
Jilin	5619	342	4	6221	357	6	602	15	2	674

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Heilongjiang	3709	216	1	4697	210	3	988	-5	2	2769
Shanghai	5165	240	8	1466	3714	9	-3699	3473	1	108
Jiangsu	3267	2335	2	3615	1649	10	349	-686	8	2234
Zhejiang	-1319	10416	7	4259	4604	15	5578	-5812	8	923
Anhui	4734	147	5	-610	5920	8	-5344	5773	3	2245
Fujian	2229	4091	11	4335	1461	9	2106	-2630	-2	855
Jiangxi	-2607	11383	2	3357	4070	9	5964	-7312	7	3318
Shandong	6426	260	9	-2809	10431	13	-9235	10171	4	128
Henan	5482	995	13	-1156	8180	17	-6638	7186	4	628
Hubei	-3071	13125	6	2196	6636	11	5266	-6489	5	2038
Hunan	3824	5629	2	5264	2106	13	1441	-3523	11	4031
Guangdong	-1174	8278	5	3013	3797	9	4187	-4481	4	1953
Guangxi	-1306	9656	1	3510	2129	12	4817	-7527	11	2094
Sichuan	2759	3316	7	4286	1792	12	1527	-1524	4	2005
Guizhou	2921	4355	12	4930	1983	9	2008	-2372	-3	696
Yunnan	3851	1428	5	4106	690	7	255	-738	2	1021
Tibet	3348	17	1	3672	35	1	324	19	0	1
Shaanxi	4219	1809	15	4002	1360	13	-217	-449	-2	122
Gansu	2117	1566	0	2343	1722	3	226	156	3	6
Qinghai	-516	53	0	275	59	0	791	6	0	
Ningxia	4624	862	11	4622	1105	5	-2	243	-7	83
Xinjiang	4338	1214	26	2960	2795	18	-1378	1580	-7	67
Hainan	-5364	12879	16	2621	3517	23	7985	-9361	7	324
China(Gg/yr)	47038	160260	123	102394	85482	286	55356	-74779	163	

CF, continuous flooding; MD, mid-season drainage.

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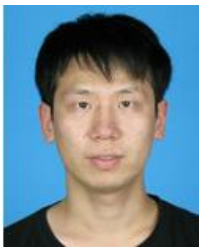

Han. Chen, born on 01/11/1990, received his bachelor degree majoring on the science and technology of remote sensing in Wuhan university, Wuhan city, China in 2012. Now he is working on his Ph.D program majoring on ecology in Tsinghua University.

His main interetes include biogeochemistry of carbon, nitrogen in terrestrial ecosystems like soil-plant and soil- atmosphere (GHG) interactions and impacts of environmental change (climate, land-use); the application and development of a biogeochemical model DNDC (i.e., De Nitrification-De Composition) and enhancement of plant growth sub-model for large-scale yield simulation.

Mr. Chen has won National Scholarship of Tsinghua University in 2013 and published several papers on high-quality journals including International Journal of Remote Sensing and Environmental Modelling & Software**.**

Chaoqing. Yu was born on 07/02/1972, received his bachelor degree majoring on physical geography in Southwest China Normal Univer sity, Chongqing city, China in 1994; his master degree majoring on GIS in Chinese Academy of Sciences, Beijing, China in 1997; his master degree majoring on computer science in Kent State University, Kent city, USA, in 2001; his doctor degree majoring on GIS Pennsylvania State University, USA, in 2005; Now his is an associate professor at Tsinghua University.

His main interetes include Climate change and disaster risk; Spacal information science and remote sensing; The interactions between society and envrionement and their computer representation; The theroy, teconology and system of Geo Agent.

Prof. Yu has published more than 20 first-class papers on agricultural droughts, water management and crop growth modeling in high-quality journals including Nature magazines.

Changsheng. Li, born on 02/01/1942, received his bachelor degree majoring on geochemistry in University of Science and Technology of China, Beijing city, China in 1964; his master degree majoring on ecology in Chinese Academy of Sciences, Beijing, China in 1981; his doctor degree majoring on biogeochemistry in Univ Wisconsin - Madison, USA, in 2005; Now his is a tenured professor at Institute for the St udy of Earth, Oceans, and Space, University of New Hampshire, USA.

He is the founder of DNDC (i.e., DeNitrification-De Composition) that simulates carbon and nitrogen biogeochemistry in agro-ecosystems. This model has been funded by NSF, EPA,NASA and NSDA and widely used for predicting crop yields, carbon dynamics in agricultural soil, fertilizer pollution and greenhouse gas emission.

Prof. Li is the editor and reviwer of a series of journals including biogeochemical cycle, biogeochemistry and global change biology etc.