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

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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 CH₄, N₂O emission and yields from paddy fields under this change. Results indicated this change had reduced CH₄ emission by approximately 41% from 2006 to 2010 and the mitigating effect was highly uneven across the country. The highest flux reduction (>1000 kg CH₄-C ha⁻¹ yr⁻¹) were Hainan, Hebei, Guangxi provinces with warm weather and multiple-cropping rice systems and the lowest flux reduction (<300 kg CH₄-C ha⁻¹ yr⁻¹) appeared in Tianjin, Heilongjiang, Liaoning provinces, with cold weather and single cropping systems. Meanwhile N₂O emission was stimulated by 106% on average during this period, which offseted a large amount of the GHG radiative forcing benefit gained by CH₄ 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 N₂O and 40% of global atmospheric input of CH₄. Ref. [2]. Of particular concern is that rice is a major food crop for nearly half of the world’s 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 CH₄ 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 CH₄ emission could be achieved with the conversion to MSD. Ref. [14], [15]. Meanwhile, MSD tends to stimulate N₂O 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 CO₂-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 underlying 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.
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 litter 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.

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_{2}O can be converted to a uniform indicator of CO_{2}. For different time scales, the conversion coefficients are listed in Table I.

![Figure 1. The structure of DNDC model](image)

![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'.](image)

![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'.](image)

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_{2}O} denotes the conversion coefficients in Table I, and \Delta CO_{2}, \Delta CH_{4}, \Delta N_{2}O represents the flux change from continuous flooding to midseason drainage.

\[
\text{GWP}_{t} = \text{GWP}_{t,CH_{4}} \times \Delta CH_{4} + \text{GWP}_{t,N_{2}O} \times \Delta N_{2}O
\]

(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.

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.

C. Regional Database Construction.

There are more than 1600 counties with rice rotated crop systems in China and the driven data to run DNDC...
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 previously matched to 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 across 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 provincial 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 CH₄ and N₂O emission. Results indicate that DNDC is capable of evaluating impacts of water schemes on GHG emissions and rice yields.

![Figure 4](image-url)

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

![Figure 5](image-url)

**Figure 5.** Comparison between observed and DNDC-modeled results in paddy fields across China. (A) Wangcheng county in Hunan province: N₂O emission; (B) Beibei county in Chongqing city: CH₄ emission; (C) Sanjiang plain in Heilongjiang province: CH₄ emission.

<table>
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<th>2009</th>
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</tbody>
</table>

**Figure 6.** CH₄ and N₂O emission and yield change due to water management change from 2006-2010
III. RESULTS AND DISCUSSION

A. CH₄ Emission Reduction

Shifting water management from continuous flooding to midseason drainage decreased CH₄ emission. Results indicate that the change in water management reduced CH₄ 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 CH₄ 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 CH₄-C ha⁻¹ yr⁻¹) were obtained in Hainan, Hebei, Guangxi, Fujian and Jiangxi provinces, with warm weather and multiple-cropping rice systems. The lowest flux reduction (<300 kg CH₄-C ha⁻¹ yr⁻¹) happened in Tianjin, Heilongjiang, Jilin and Liaoning 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 CH₄ production in the cool paddies. Ref. [26] DNDC modeled CH₄ 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 CH₄ production due to more aerobic conditions. Therefore, CH₄ mitigation increased from 2008 to 2010 both in South and North China.

B. N₂O Emission Increase

The simulated results of DNDC illustrated a nationwide N₂O 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 N₂O emission. Fig. 7 explained the impacts of SOC on the N₂O emission change in 2010: The province-level distribution of N₂O 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 N₂O emission.

The increased emission of N₂O offset a large fraction of the greenhouse gas radiative forcing benefits gained by the decrease in CH₄ emissions. Ref.[8] Maximum CH₄ reductions and minimum N₂O 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 CH₄ reduction and low N₂O increase than SOC content. Both site-level and region-level modeled results illustrated CH₄ and N₂O emission were more subject to clay fraction than SOC content.

<table>
<thead>
<tr>
<th>Year</th>
<th>20-YEAR CO₂ EQUIVALENT</th>
<th>100-YEAR CO₂ EQUIVALENT</th>
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</thead>
<tbody>
<tr>
<td>2010</td>
<td></td>
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</table>

Figure 7. CH₄ and N₂O emission change distribution compared with SOC and clay fraction distribution in 2010

Figure 8. GWP of 20-year, 100-year and 500-year in 2010.
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, 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 CO₂-equivalent emissions differed with the chosen time horizon. Theoretically, N₂O had a much longer atmospheric adjustment time than CH₄ and CO₂. The maximum GWP of N₂O might occur between 100 and 500 and the maximum GWP of CH₄ might occur between 20 and 100. Therefore, the total net provincial CO₂-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 CH₄ emission and increase provincial N₂O 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

<table>
<thead>
<tr>
<th>Yield (kg/ha)</th>
<th>CF</th>
<th>MSD</th>
<th>MSD-CF</th>
<th>Yield (kg/ha)</th>
<th>CF</th>
<th>MSD</th>
<th>MSD-CF</th>
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<td>7040.0</td>
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<td>Henan</td>
<td>7902.5</td>
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<td>7410.0</td>
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<td>Hubei</td>
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<td>8167.5</td>
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<td>Hunan</td>
<td>8152.5</td>
<td>6127.5</td>
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<td>3765.0</td>
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CF, continuous flooding; MSD, mid-season drainage.

APPENDIX A: THE GREENHOUSE GAS EMISSION CHANGE IN 2010

<table>
<thead>
<tr>
<th>Year</th>
<th>CF</th>
<th>MSD</th>
<th>N₂O</th>
<th>CH₄</th>
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<th>CH₄</th>
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<td>4</td>
<td>6221</td>
<td>357</td>
<td>6</td>
<td>602</td>
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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  -4881  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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REFERENCES


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