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Assessing Alternatives for Mitigating Net Greenhouse Gas Emissions and Increasing Yields from Rice Production in China Over the Next Twenty Years

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ABSTRACT

Assessments of the efficacy of mitigation of greenhouse gas (GHG) emissions from paddy rice systems have typically been analyzed based on field studies. Extrapolation of the mitigation potential of alternative management practices from field studies to a national scale may be enhanced by spatially explicit process models, like the DeNitrification and DeComposition (DNDC) model. Our objective was to analyze the impacts of mitigation alternatives, management of water, fertilizer, and rice straw, on net GHG emissions (carbon dioxide, methane, and nitrous oxide fluxes), yields, and water use. After constructing a GIS database of soil, climate, rice cropping area and systems, and management practices, we ran DNDC with 21-yr alternative management schemes for each of the approximately 2500 counties in China. Results indicate that, despite large-scale adoption of midseason drainage, there is still large potential for additional methane reductions from Chinese rice paddies of 20 to 60% over 2000–2020. However, changes in management for reducing CH_4 emissions simultaneously affect soil carbon dynamics as well as N_2O emissions and can thereby reorder the ranking of technical mitigation effectiveness. The order of net GHG emissions reduction effectiveness found here is upland rice > shallow flooding > ammonium sulfate > midseason drainage > off-season straw > slow-release fertilizer > continuous flooding. Most of the management alternatives produced yields comparable to the baseline; however, continuous flooding and upland rice significantly reduced yields. Water management strategies appear to be the most technically promising GHG mitigation alternatives, with shallow flooding providing additional benefits of both water conservation and increased yields.

Agricultural activities are responsible for approximately 50% of global atmospheric inputs of methane (CH_4) and agricultural soils are responsible for 75% of global nitrous oxide emissions (Scheehle and Kruger, 2006; USEPA, 2006), and thereby represent a significant opportunity for greenhouse gas (GHG) mitigation through reductions of CH_4 and N_2O emissions, as well as through soil carbon sequestration (Oenema et al., 2001; Cole et al., 1996). When assessing the impact of food and fiber production systems on the earth's radiation budget, the major GHGs (i.e., CO_2, CH_4, and N_2O) need to be considered (Li, 1995; Robertson et al., 2000; Smith et al., 2001; Li et al., 2004). Since each greenhouse gas has its own radiative potential (Ramaswamy et al., 2001), a net global warming potential (GWP) of a crop production system can be estimated that accounts for all three gases.

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Rice is a major crop in Asia (approximately 130 million hectares were sown in 2002; FAO, 2004), and the majority of rice production in Asia is from flooded paddy fields (<10% of sown area is upland rice; Huke and Huke, 1997). Rice paddies contribute about 11% of total global methane emissions to the atmosphere (Scheehle and Kruger, 2006; USEPA, 2006). Field studies have shown that alternative management practices such as changes in water, fertilizer, and crop residue management can have a significant influence on GHG emissions from rice paddies (Wassmann et al., 2000b; Sass et al., 1992).

China has approximately 20% of the world's rice paddies and 31% of the world's rice production (FAO, 2004). Over the past two decades, midseason drainage as an alternative water management approach has been adopted throughout China (Shen et al., 1998; Ministry of Water Resources and Utilization of China, 1996). In contrast to traditional water management, which keeps paddy soils continuously flooded during the rice-growing season, midseason drainage periodically drains rice fields or allows them to dry. Midseason drainage or drying tends to increase rice yield by increasing N mineralization in the soil and by increasing root development in the rice plants (Wassmann et al., 2000a; Lu et al., 2000). Field measurements in China indicate that midseason drainage significantly reduces CH_4 emissions, while increasing NO emissions (Zheng et al., 1997, 2000; Cai et al., 1999). Using field results such as these, Li et al. (2002) applied the process-based DeNitrification–DeComposition (DNDC) model to estimate the historical effects of midseason drainage on net GHG emissions for rice paddies in China. One-year simulations were conducted at the national scale with two water management scenarios, continuous flooding and midseason drainage. The results indicated that CH_4 emissions from China's paddy fields were reduced over the past 20 yr by about 40% (approximately 5 Tg CH_4 yr^{-1}). The decreased CH_4 emissions from Chinese paddy rice contributed in part to the decline in the rate of increase of global atmospheric CH_4 concentrations over that period (Li et al., 2002).

New questions logically follow from the Li et al. (2002) study:

(i) Can CH_4 emissions from Chinese rice paddies be reduced further?
(ii) What will be the net GHG emission effects of management alternatives given N_2O and CO_2 fluxes?
(iii) How might GHG mitigation options "rank" given crop yield and water resources effects?

Abbreviations: DNDC, DeNitrification and DeComposition; GHG, greenhouse gas; MSF, most sensitive factor; SOC, soil organic carbon.

This paper reports on a modeling study designed to address these questions.

MATERIALS AND METHODS

Rice paddy ecosystems are complex, with crop growth, soil thermo–hydro conditions, and microbial activities interacting through a number of processes. For example, any change in irrigation will simultaneously affect the temperature, moisture, pH, Eh, and substrate concentration in the soil. The altered soil environmental factors will simultaneously and collectively affect a series of biochemical or geochemical reactions that finally determine transport and transformation of the chemical elements, including C sequestration and trace gas emissions. There is usually not a linear or monotonic correlation between the cause and the result. Only models containing the fundamental processes can be capable of predicting the behaviors of the complex systems. In this study, we employed the process-based model, DNDC, to quantify the impacts of changes in farming management on CH_4, N_2O, and CO_2 fluxes, crop yield, and soil water dynamics across climatic zones, soil types, and management regimes for the rice paddies in China.

The DNDC Model

The DNDC model was originally developed for predicting carbon sequestration and trace gas emissions for nonflooded agricultural lands, simulating the fundamental processes controlling the interactions among ecological drivers, soil environmental factors, and relevant biochemical or geochemical reactions, which collectively determine the rates of trace gas production and consumption in agricultural ecosystems (Li et al., 1992, 1994, 1996). Details of management (e.g., crop rotation, tillage, fertilization, manure amendment, irrigation, weeding, and grazing) have been parameterized and linked to the various biogeochemical processes (e.g., crop growth, litter production, soil water infiltration, decomposition, nitrification, denitrification, and fermentation) embedded in DNDC. To enable DNDC to simulate C and N biogeochemical cycling in paddy rice ecosystems, we modified the model by adding a series of anaerobic processes. The paddy-rice version of DNDC (DNDC8.6) has been described and tested in recent publications (Zhang et al., 2002; Li et al., 2002, 2004; Cai et al., 2003), and is summarized briefly here.

Paddy soil is characterized by the frequent changes between saturated and unsaturated conditions driven by water management. During these changes in soil water content, the soil redox potential (i.e., Eh) is subject to substantial fluctuations between +600 and −300 mV. One of the key processes controlling CH_4 and N_2O production–consumption in paddy soils is soil Eh dynamics; CH_4 or N_2O are produced or consumed under certain Eh conditions (−300 to −150 mV for CH_4, and 200 to 500 mV for N_2O), so the two gases are produced during different stages of soil redox potential fluctuations.

Regulated with the Nernst and Michaelis–Menten equations, DNDC tracks the swelling and shrinking of a series of the “anaerobic balloons” driven by depletions of O_2, NO_3^-, Mn^{4+}, Fe^{3+}, and SO_4^{2-} consecutively, and hence estimates soil Eh dynamics as well as rates of reductive–oxidative reactions, which produce and consume CH_4 or N_2O in the soil. Among the electron acceptors, Fe^{3+} is usually abundant in soils and hence could significantly affect the Eh dynamics and hence CH_4 production. Increase in contents of O_2, NO_3^-, Mn^{4+}, Fe^{3+}, and SO_4^{2-} will slow down the processes of decrease in the soil Eh driven by the soil microbes. Artificially adding the oxidants into a soil with anaerobic conditions well built up will cause sudden elevation of the soil Eh and hence depress CH_4 production. A detailed discussion about the correlation between CH_4 production and Fe^{3+} content has been reported in a separate paper (Fumoto et al., unpublished data). By tracking Eh dynamics, the model links the soil water regime to trace gas emissions for rice paddy ecosystems. A virtual “anaerobic balloon” was developed in DNDC to divide each of the simulated soil layers into relatively aerobic and anaerobic zones, in which the production and consumption rates of CH_4 or N_2O are simultaneously quantified with the Nernst and Michaelis–Menten equations. Rice growth is precisely modeled in the modified DNDC to track the dynamics of biomass, which dominates CH_4 transport from the soil to the atmosphere. The DNDC model predicts daily CH_4 and N_2O fluxes from rice fields through the growing and fallow seasons, as they remain flooded or shift between flooded and drained conditions.

This new DNDC model has been tested against several methane flux data sets from wetland rice sites in the United States, Italy, China, Thailand, and Japan (Li et al., 2002; Cai et al., 2003). Both CH_4 and N_2O fluxes were measured at five of the tested rice paddy sites where midseason drainage was applied (Zheng et al., 1997; Cai et al., 1999). The DNDC model was tested against the observations from the five sites in China with satisfying results (Cai et al., 2003). A validation case is shown in Fig. 1, which demonstrates a fair agreement between observed and modeled CH_4 and N_2O fluxes regarding their patterns and magnitudes for a paddy rice field applied with midseason drainage in China. The DNDC model captured the episodes of CH_4 emission depressions and N_2O emission increases during the soil drying periods by tracking the soil Eh dynamics, CH_4 oxidation, labile organic matter decomposition, and stimulated nitrification and denitrification fueled by the increased ammonium and nitrate production due to the conversions of soil anaerobic to aerobic conditions driven by the midseason drainage. [Field data were adopted from Zheng et al. (1997).] The results from the tests indicate that DNDC is capable of estimating the seasonal patterns and magnitudes of CH_4 and N_2O fluxes from the sites, although discrepancies exist.

County-Scale GIS Database

To capture heterogeneous GHG emissions and rice productivity in China, we assembled rice cropping system, soil, climate, water management, residue management, fertilizer, and optimum yield data profiles for each of the approximately 2500 Chinese counties. The model domain contained 30 million ha of rice paddies in China (Fig. 2) (Frolking et al., 2002). The following 11 different rice crop rotations are in our database: single-rice, double-rice, rice–winter wheat, rice–rapeseed, rice–vegetables, rice–oats, rice–soybeans, rice–rice–vegetables, rice–rice–legume–hay, rice–rice–winter wheat, and rice–rice–rapeseed. The area occupied by each rotation in each county was quantified by combining the county-scale statistical database of crop-sown areas with a Landsat TM–derived land-cover map for all of mainland China (Frolking et al., 2002). The majority of rice production occurs in southern China, and particularly along the Yangtze River. Daily weather data (maximum and minimum air temperatures, precipitation) for 1990 from 610 weather stations across China were acquired from the National Center for Atmospheric Research (http://dss.ucar.edu/index.html, verified 9 Feb. 2006). Station data were assigned to each county on a nearest neighbor basis. Maximum and minimum values of soil texture, pH, bulk density, and organic carbon content were derived for each county by digitizing national soil maps (Institute of Soil Science, 1986) and other information (National Soil Survey Office of China, 1997). Soil Mn, Fe, and sulfate content were set to average values for

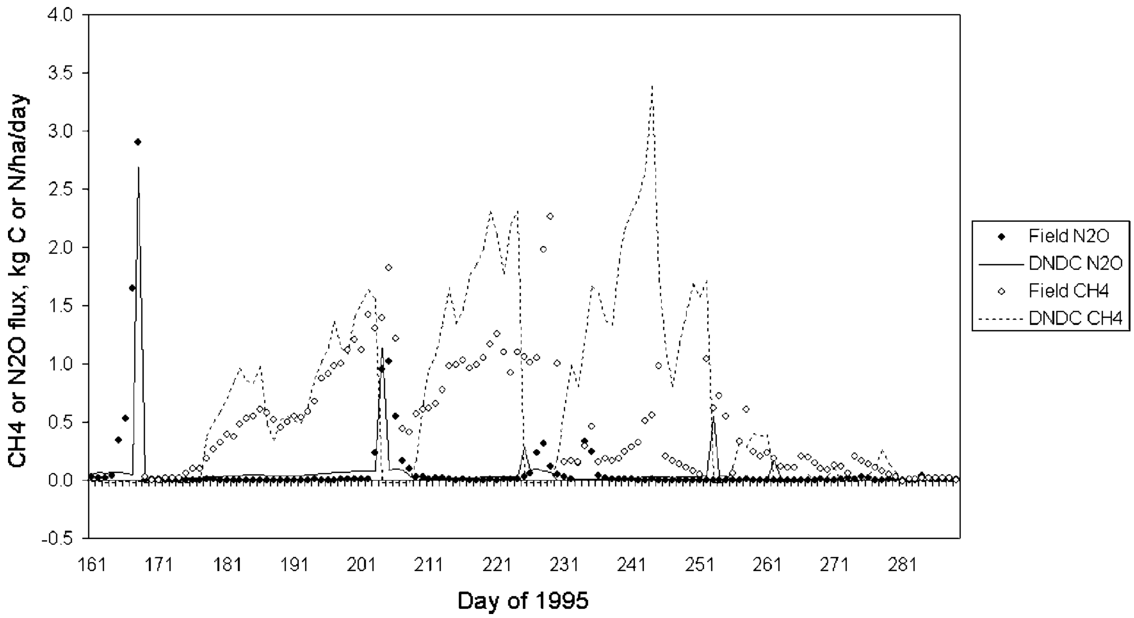

Fig. 1. Comparison between observed and DeNitrification and DeComposition (DNDC)–modeled CH_4 and N_2O fluxes from a paddy rice field applied with midseason drainage in Wu County, Jiangsu Province, China, in 1995.

Chinese paddy soils: Mn = 30 mg kg^{-1} soil, Fe = 80 mg kg^{-1} soil, and sulfate = 220 mg kg^{-1} soil (Li, 1992). General data on water management, fertilizer use, tillage, planting and harvest dates, and crop residue management were taken from Central Radio and Television School of Agriculture (1995), Huang et al. (1997), Cui et al. (1994), Liu and Mu (1993), and Anonymous (1992).

Reference Case and Mitigation Scenarios

We quantified the potential impacts of alternative management (mitigation) practices relative to a reference case (i.e., baseline scenario) over the period from 2000 through 2020. In addition to a baseline, we designed seven alternative management scenarios: continuous flooding, midseason drainage, shallow flooding, upland rice, off-season straw amendment, ammonium sulfate, and fertilizer with a slow release rate. Each alternative management scenario was assumed to be applied to 100% of the rice paddies in China. To avoid the influence on management from inter-annual climate impacts, we used 1990 weather throughout our 21-yr simulation. We examined data, compiled by C. Bruce Baker at the National Climate Data Center, on annual temperature anomalies for China from 1901–

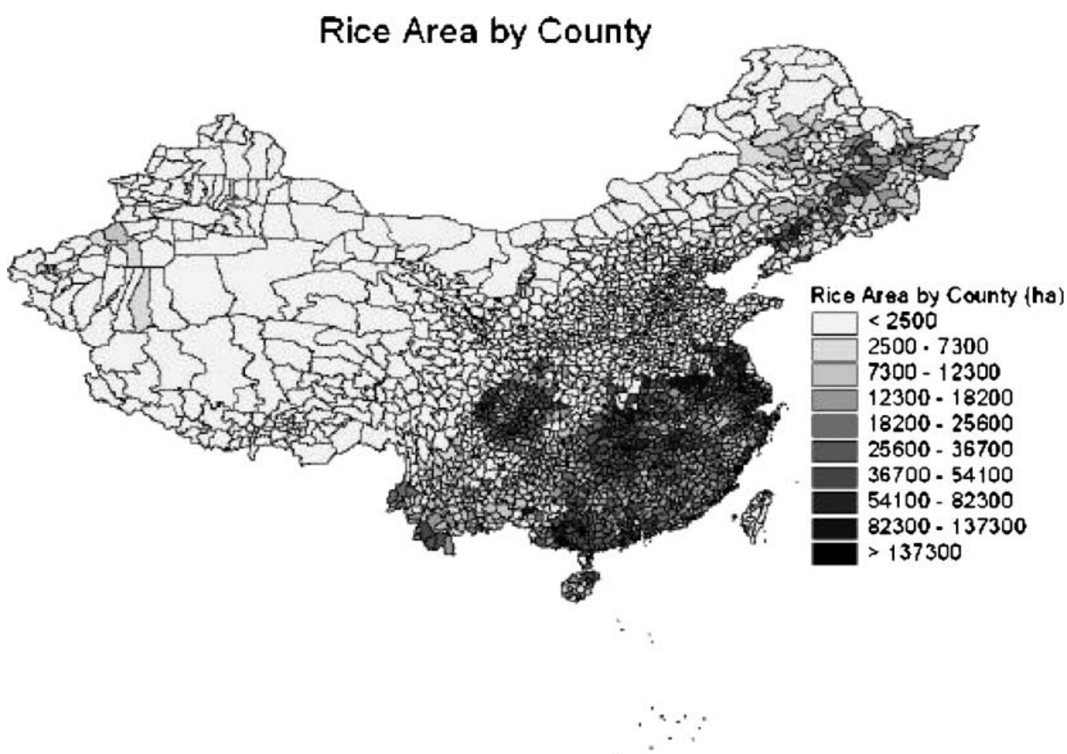

Fig. 2. County-scale distribution of rice paddies in China.

1998 to assess if 1990 was a typical year in terms of annual temperature across China. Based on these data, 1990 annual temperature anomaly was 0.5°C, which was slightly higher than the mean during this period, but well within the range of interannual variation. Therefore, we used the 1990 climate for all of our scenario runs. For each management scenario, we assumed that each alternative was implemented in 2000 and continuously used through 2020 with no phase in or partial adoption period. We did not include multiple mitigation alternatives within a single model run. For each management scenario, we ran the DNDC model for 21 yr (2000 through 2020) for each of the approximately 2500 counties in China to simulate changes in soil carbon, emissions of methane (CH_4) and nitrous oxide (N_2O), rice yields, and water consumption.

For our baseline scenario, we assumed that rice crop yield increased by 1% annually from 2000–2020; 80% of rice paddies in China were managed with midseason drainage, and 20% with continuous flooding; the rate of aboveground crop residue (leaves + stems) incorporation increased by 5% every year from 15% in 2000 to 50% in 2008 and remained at 50% thereafter; rice fertilizer application rate was 140 kg N ha^{-1} per season; soil was tilled conventionally; no manure was applied; and 1000 kg rice straw C was amended at the beginning of the rice growing season each year.

The continuous flooding scenario represents the conventional water management prevailing before 1980. In comparison with the midseason drainage scenario, under which fields are dried multiple times within a growing season, our continuous flooding scenario assumes that 100% of fields are continuously flooded with a surface water layer about 5 to 10 cm during the whole growing season.

The midseason drainage scenario assumes a shift from 80 to 100% adoption of midseason drainage across China. In this scenario, the rice fields are dried three times with even intervals within a growing season and the surface water layer is 5 to 10 cm for the remaining time (i.e., flooded time).

The shallow flooding scenario simulates a new water management practice, which is currently being recommended to the rice farmers in China. Shallow flooding assumes the rice paddies are marginally covered by the flooding water, with the water table fluctuating 5 to 10 cm above and below the soil surface. This alternative management practice can increase yield and save water (Li, 1992; Chen, 2004).

Shifting straw amendment from in-season to off-season can reduce availability of dissolved organic carbon (DOC) released from the fresh straw to methanogens. The off-season straw scenario assumes that the rice straw amendment is applied two months before, rather than at the beginning of the rice growing season.

For the ammonium sulfate scenario, the baseline fertilizer types, assumed to be equal parts of urea and ammonium bicarbonate, were replaced with ammonium sulfate. When sulfate is added into the paddy soil, the oxidant can be used as an electron acceptor by the soil microbes under deeply anaerobic conditions, resulting in elevated soil Eh, which creates unfavorable conditions for CH_4 production (Wassmann et al., 1993).

In the slow release rate fertilizer scenario, nitrogen is slowly released from the coated or tablet fertilizer at a constant rate over a 30-d period following fertilizer application. The slow-release fertilizer is applied in the same amount and at the same time as in the reference case. This technique usually increases fertilizer use efficiency and hence alters the relevant soil C and N dynamics.

The upland rice scenario represents another potential future management alternative for rice production in China. Planting rice as an upland crop has been studied in many laboratories although it may take years to spread as a major management practice in the rice producing regions. For this scenario we assume the fields do not receive any flooding water.

We used an approach we refer to as the most sensitive factor (MSF) approach to estimate uncertainty in emission estimates based on a range of soil parameters within each county. Based on sensitivity tests to prioritize the environmental factors including soil properties, temperature, and precipitation (Li et al., 2004), the most sensitive factors for CH_4 and N_2O emissions from rice paddies are soil texture and soil organic carbon (SOC) content, respectively. Therefore, by varying these "most sensitive factors," namely soil texture and SOC, over the ranges reported in the county-scale database, we produced a range of CH_4 and N_2O emissions for each cropping system in each county. The MSF method has been validated against a traditional uncertainty analysis approach, such as Monte Carlo analyses (Li et al., 2004). All simulations were conducted for each county by choosing soil parameter values spanning observed ranges and running DNDC for each of the 11 rice cropping systems. We therefore obtained temporally differentiated crop yields, GHG fluxes, and water consumption at county scale. National and major rice basin yields, GHG fluxes, and water consumption were derived from weighted averages of the county-level results.

Since each of the management alternatives simultaneously affected CO_2, CH_4, and N_2O fluxes, a net effect of each scenario on global warming needs to be assessed. For this study, the net impact was defined to be the sum of the warming forces of all GHGs based on 100-yr global warming potentials (GWP), according to the Intergovernmental Panel on Climate Change (1996). The warming forces of CH_4 and N_2O are 21 and 310 times higher, respectively, than that of CO_2 per unit of weight. Although the GWPs were updated by the IPCC in the Third Assessment Report (Intergovernmental Panel on Climate Change, 2001), estimates of emissions in this paper use the GWPs from the Second Assessment Report (Intergovernmental Panel on Climate Change, 1996), to be consistent with international reporting standards under the United Nations Framework Convention on Climate Change (UNFCCC). The GWP value for each scenario is calculated as follows:

$$\mathrm{GWP}_i = \mathrm{CO}_{2i} + \mathrm{N_2O}_i \times 310 + \mathrm{CH}_{4i} \times 21;$$

with

$$\mathrm{CO_{2i}} = \mathrm{C}_i \times (44/12)$$

$$\mathrm{N_2O_i} = \mathrm{N}_i \times (44/28)$$

$$\mathrm{CH_{4i}} = \mathrm{C}_i \times (16/12)$$

where GWP_i (kg CO_2 equivalent ha^{-1} yr^{-1}) is the GWP induced by scenario i; CO_{2i}, N_2O_i, and CH_{4i} are CO_2 flux (kg CO_2 ha^{-1} yr^{-1}), N_2O flux (kg N_2O ha^{-1} yr^{-1}), and CH_4 flux (kg CH_4 ha^{-1} yr^{-1}), and C_i and N_i are fluxes in carbon and nitrogen units, respectively (kg C ha^{-1} yr^{-1} and kg N ha^{-1} yr^{-1}), induced by scenario i.

RESULTS

Impacts of Management Alternatives on Greenhouse Gas Emissions

Any change in management practices (e.g., water management, tillage, fertilization, and manure amendment) will simultaneously alter the soil environmental conditions (e.g., temperature, moisture, pH, Eh, and substrate concentration gradients), and hence affect the soil

C and N driving processes such as decomposition, nitrification, denitrification, and fermentation. The changes in the soil biogeochemical processes will finally affect the availability of soil N and water to the crops and hence alter the crop yields. Since crop residue is the major source of soil organic carbon (SOC), the change in crop yield and also litter will redefine the soil organic matter balance and hence affect the CH_4, soil CO_2, and N_2O emissions.

Methane

From 2000–2020, CH_4 emissions slightly increased with most of the tested scenarios due to the soil C accumulation (Fig. 3). Under the baseline conditions, the national CH_4 emissions were 7.5 to 8.0 Tg C per year for 2000–2020. Change in water management from continuous flooding to midseason drainage or shallow flooding introduced more atmospheric oxygen, the most effective oxidant, into the paddy soil profile, and hence depressed CH_4 production. Figure 3 and the other figures in this paper portray the midpoint of the range in DNDC simulations where the range was derived using the aforementioned MSF uncertainty analysis. The nationally averaged CH_4 emission flux was about 760 kg C ha^{-1} per year if 100% of the rice paddies in China were managed with the continuous flooding. The CH_4 emissions were reduced to 330 and 150 kg C ha^{-1} by replacing the continuous flooding with midseason drainage and shallow flooding, respectively. A shift to upland rice scenario totally eliminated CH_4 emissions and could potentially turn Chinese rice production into a weak sink of atmospheric CH_4 (-1 kg C ha^{-1}). The change in fertilizer type or timing of straw amendment only slightly decreased CH_4 emissions at the national scale although the modeled results indicated the effects were more significant for some specific counties.

Carbon Dioxide

Under the baseline conditions, the national CO_2 emissions from rice agriculture were -15.4 to -9.4 Tg C per year from 2000–2020, thus the rice paddies in China as a whole were a net sink of atmospheric CO_2. Under the baseline scenario, the nationally averaged soil C sequestration rate increased from 480 to 700 kg C ha^{-1} per year during the period of 2000–2008, within which the rate of crop residue incorporation increased from 15 to 50% (Fig. 4). After 2008, the increasing rate of SOC decreased as a constant fraction (i.e., 50%) of crop residue was incorporated with elevated decomposition rates, and hence the rate of SOC increase gradually approached equilibrium at about 500 kg C ha^{-1}. In comparison with the baseline (i.e., 80% midseason drainage), shallow flooding and upland rice scenarios decreased soil C sequestration; and applying ammonium sulfate slightly increased C sequestration.

Nitrous Oxide

Under the baseline conditions, the national N_2O emissions from rice agriculture were 0.41 to 0.23 Tg N per year from 2000–2020. The continuous flooding scenario produced the least N_2O emissions (4.3 kg N ha^{-1}). Shifting to

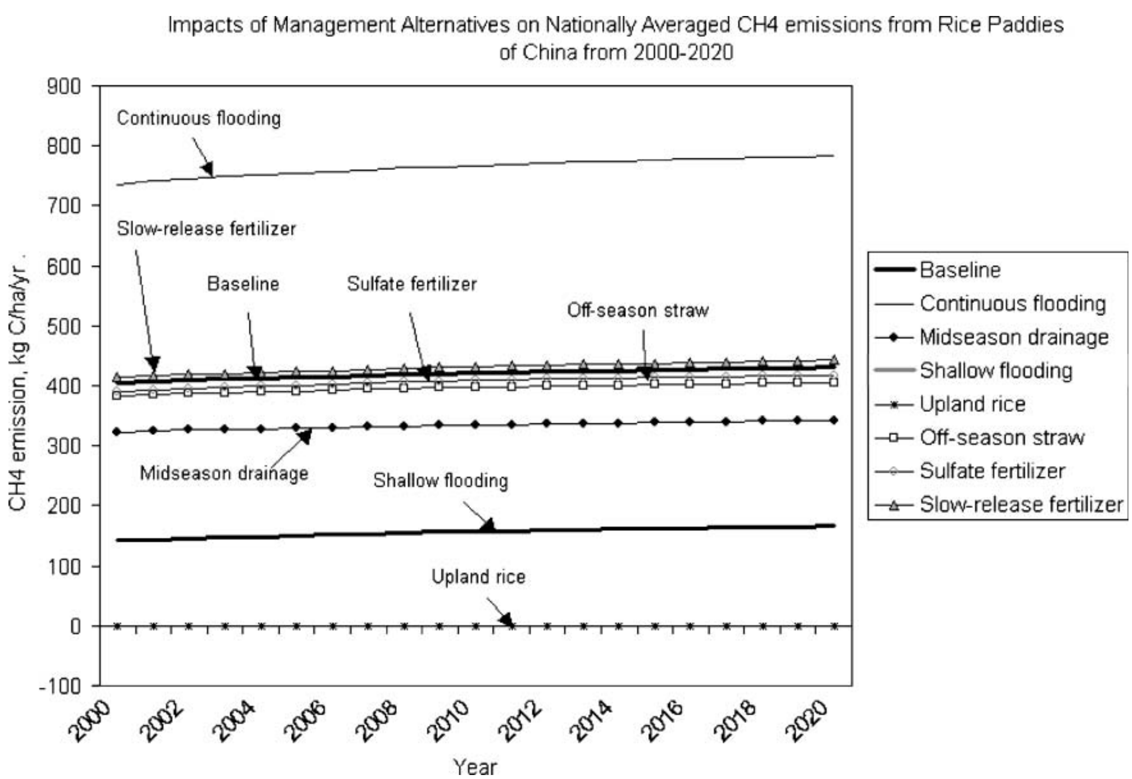

Fig. 3. Modeled nationally averaged methane emissions from rice paddies in China from 2000–2020 by management scenario.

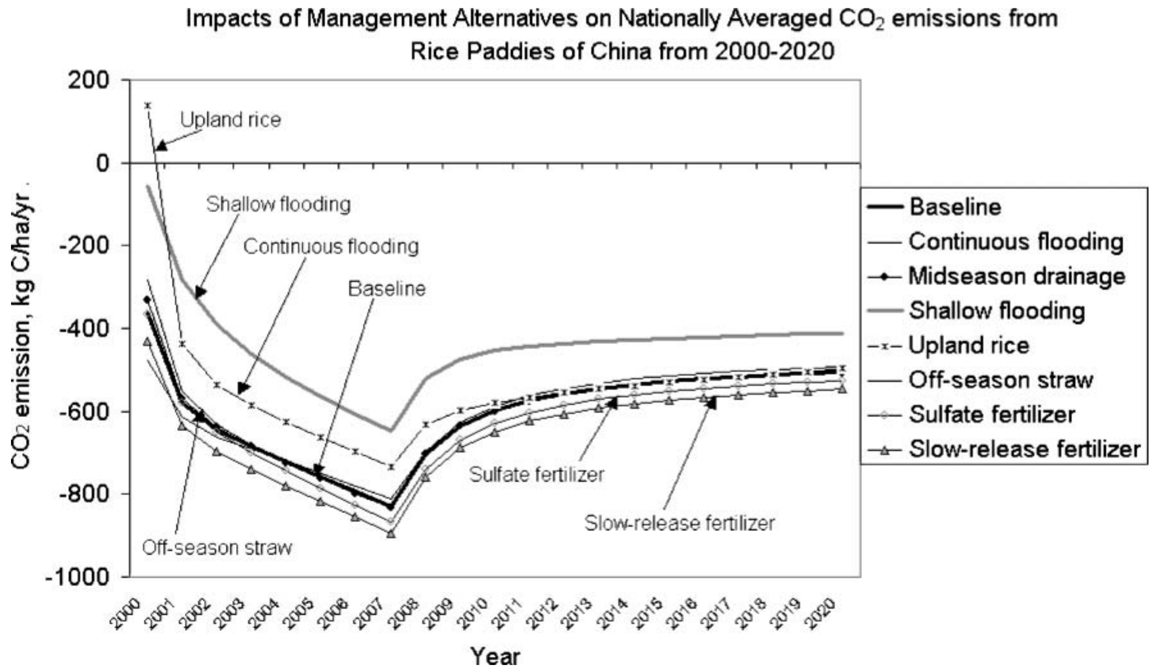

Fig. 4. Modeled nationally averaged carbon dioxide emissions from rice paddies in China from 2000–2020 by management scenario.

midseason drainage significantly increased the nationally averaged N_2O flux to 17.4 kg N ha^{-1} mainly due to the dramatic exchange between the soil aerobic and anaerobic conditions (Fig. 5). Shallow flooding also increased N_2O flux, but to a rate (9.8 kg N ha^{-1}) lower than midseason drainage. Change in fertilizer type to ammonium sulfate substantially decreased N_2O emissions. Shifting timing of straw incorporation from in-season to off-season had little effect on N_2O due to the weak impact of timing of straw amendment on the soil N dynamics. During the 21-yr simulation, N_2O emissions gradually decreased due to evolution of SOC partitioning for most scenarios except upland rice and sulfate fertilizer under which N_2O emissions slightly increased.

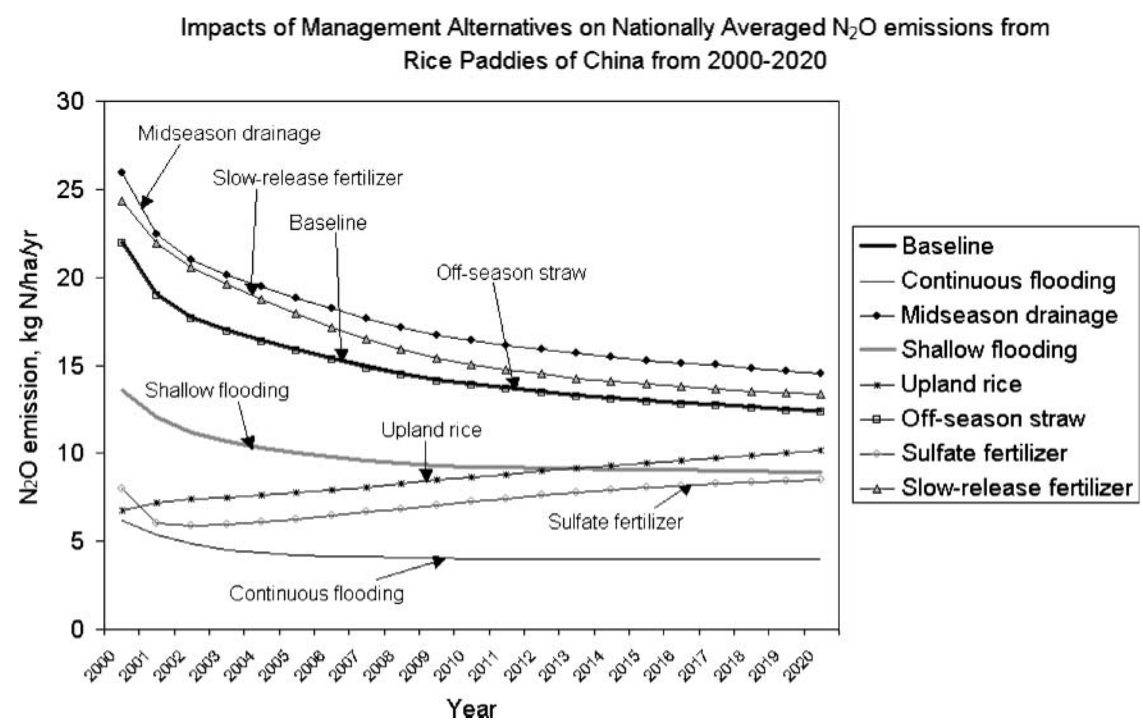

Fig. 5. Modeled nationally averaged nitrous oxide emissions from rice paddies in China from 2000–2020 by management scenario.

Global Warming Potential (GWP, or Carbon Dioxide Equivalency)

The dynamic GWP values for all the tested scenarios are shown in Fig. 6. The results indicate that the most promising management alternatives for mitigating net greenhouse gases, on a GHG basis only, are upland rice, shallow water flooding, and ammonium sulfate fertilizer substitution. A number of results stand out in comparing the net GHG results to the single flux results. First, upland rice and shallow water flooding were the dominant CH_4 reduction strategies; however, ammonium sulfate had little effect on methane but successfully reduced N_2O emissions. Slow release fertilizer, on the other hand, increased soil carbon content but performed poorly with respect to the other two gases. Similarly, continuous flooding was very successful at lowering N_2O emissions, but produced a net increase in GHG emissions due to significantly higher CH_4 emissions. Overall, CH_4 dominated the rice paddy GWPs for most of the tested scenarios—60 to 90% of total GWPs except for the upland rice scenario. Nitrous oxide was the second most influential gas in the GWPs. Based on a study by Li et al. (2004), the N_2O fluxes induced by midseason drainage could offset about 40% of the benefit gained by CH_4 reduction through adopting the alternative water management practice. It is worth noting that across the 21-yr period, net emissions are fairly stable for each scenario; most of the nonlinearity and non-monotonicity can be attributed to the particular residue management practice modeled. In addition, the ordinal emissions reduction ranking of the scenarios is unchanged across the period (i.e., the GWP curves do not intersect), thereby allowing us to identify clear dominance with strategies. In comparison with the baseline, the order of technical mitigation effectiveness for the management alternatives is upland rice > shallow flooding > ammonium sulfate > midseason drainage > off-season straw.

Impacts of Management Alternatives on Crop Yield and Water Consumption

Any changes in management will alter a series of soil environmental factors (e.g., temperature, moisture, pH, Eh, and substrate concentration gradients), which will in turn affect the soil water, C and N dynamics, and hence the crop growth and yield. With the embedded biogeochemical processes in DNDC, the model predicted rice yield and water demand for each of 11 rice cropping systems at county scale for China from 2000–2020 under the tested alternative management conditions.

Crop Yields

Under baseline conditions, potential crop yield was assumed to increase at a rate of 1% per year but with fertilizer application rate constant. The modeled crop yields (vs. optimum yields) increased from 6074 to 6393 kg dry matter ha^{-1} in the period of 2000–2020 with an average annual increase of 0.5% (Fig. 7). Modeled results indicated that the constant fertilizer rate limited the crop yield growth to a suboptimal level. However, the relative impacts of management alternatives on yields can still be recognized. In comparison with the baseline yields, the scenarios of slow-release fertilizer, 100% midseason drainage, shallow flooding, off-season straw amendment, and ammonium sulfate increased crop yields. Only applications of upland rice and continuous

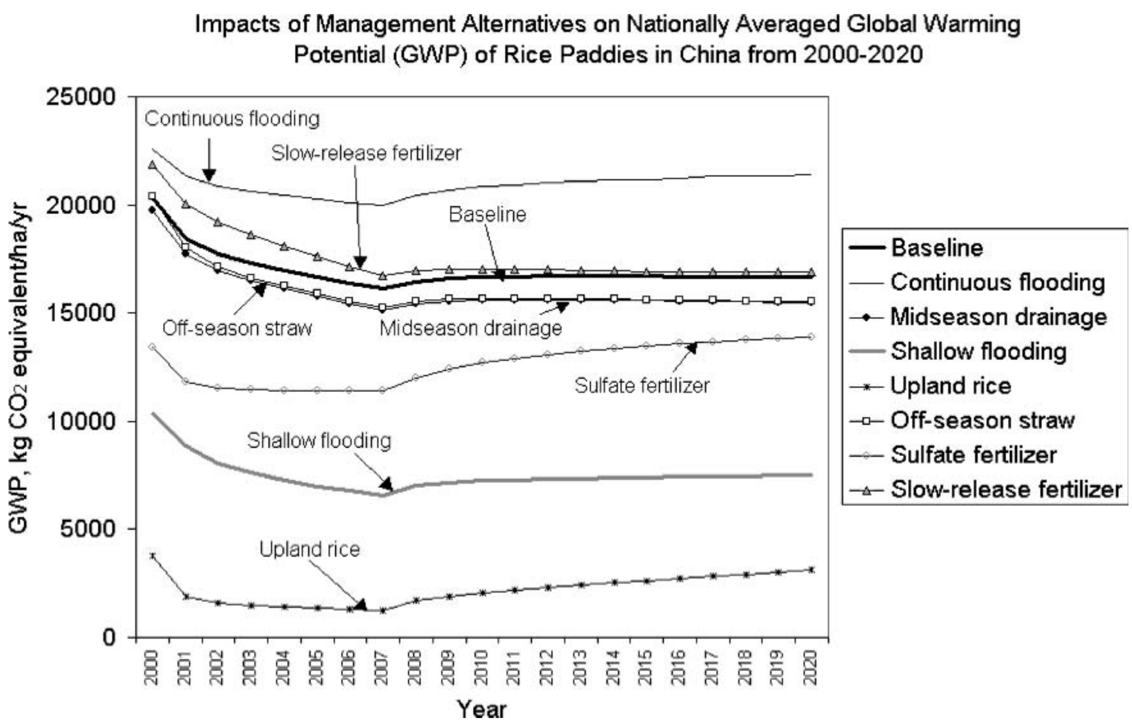

Fig. 6. Net effect of the management alternatives on nationally averaged global warming potential (GWP) of rice paddies in China from 2000–2020.

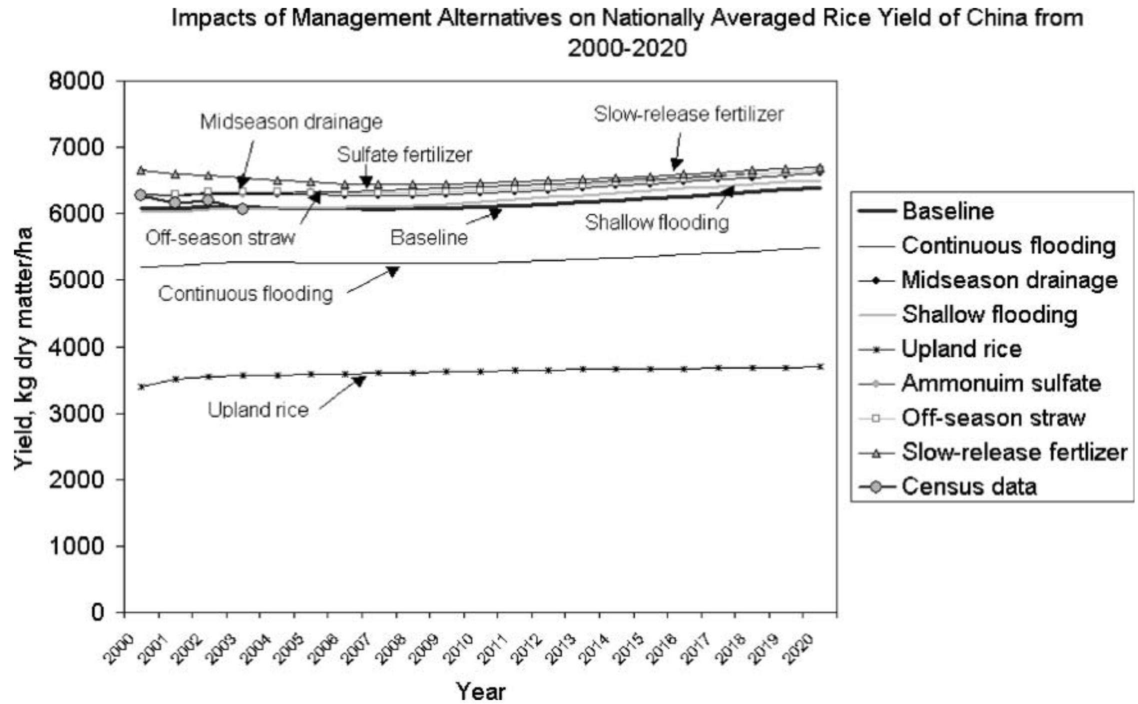

Fig. 7. Impacts of management alternatives on average rice yield in China from 2000–2020.

flooding decreased yields. Based on literature, the average upland rice yield is about one third of that of wetland rice (Fageria et al., 1991). The officially reported national average rice yields are 6237, 6163, 6188, and 6060 kg dry matter ha^{-1} for 2000, 2001, 2002, and 2003, respectively (Ministry of Agriculture of People's Republic of China, 2003). The census data are in the range of DNDC-predicted yields with baseline and midseason drainage scenarios for the same period although the trends differ (Fig. 7). In contrast to our assumption of 1% increase in yield for 2000–2003, actual yields decreased due to the transition of market demand for rice with higher quality instead of high yield in China from 2000–2003 (Jianjun Qiu, personal communication).

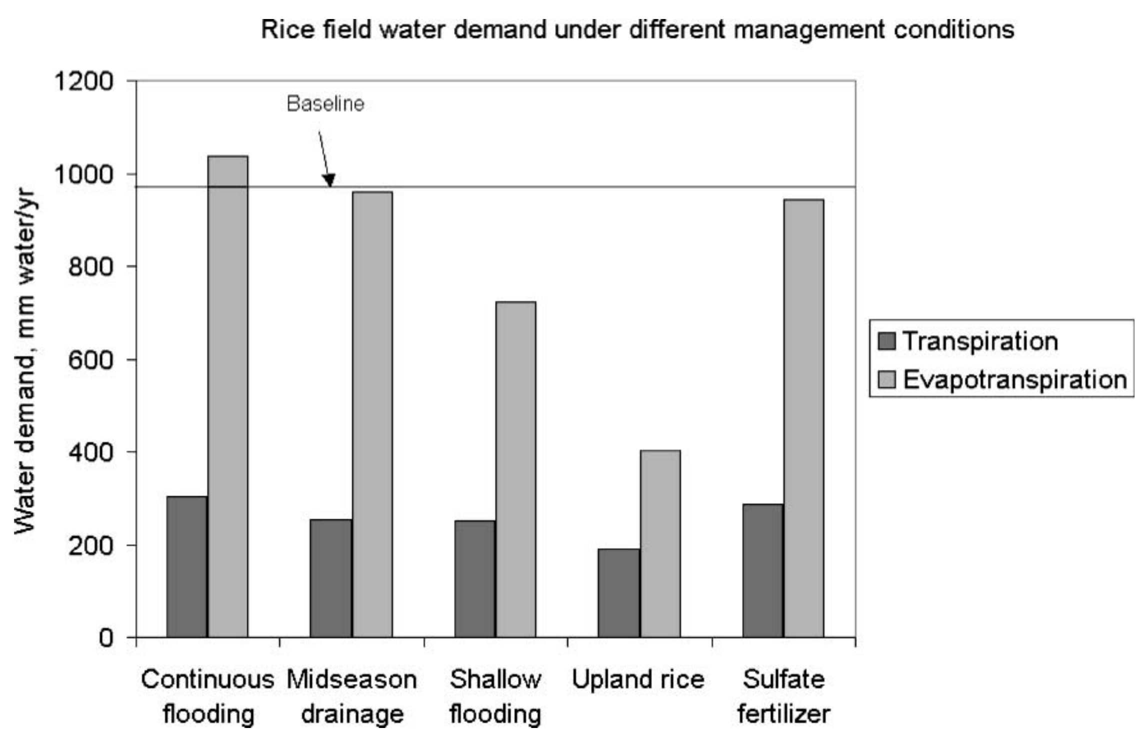

Fig. 8. Impacts of management alternatives on average water demand for rice production.

Water Consumption

Shifting from continuous flooding to midseason drainage, shallow flooding and upland rice significantly decreased water consumption (evapotranspiration) from 1040 to 960, 720, and 400 mm yr^{-1}, respectively (Fig. 8). Converting the conventional continuous flooding to the water-saving practices mainly reduced the soil and surface water evaporation while the crop physiological demand for water (i.e., transpiration) remained relatively unchanged. Other alternatives related to fertilization or straw amendment only slightly affected water consumption. The above-described predictions provided essential information for assessing impacts of management alternatives on agroecosystems regarding GHG emissions, crop yield, and water conservation.

DISCUSSION

Synthesizing Effects

Among the terrestrial ecosystems, agricultural systems are significant GHG sources. Agroecosystems are highly managed and hence represent an important opportunity for mitigating GHG emissions. The study reported in this paper was an effort to assess the effectiveness at the national scale of the ongoing or potentially applicable farming management alternatives. From the 21-yr simulations with the DNDC model for entire rice paddies in China, we quantified the impacts of seven alternative scenarios on CH_4, CO_2, and N_2O emissions at county scale for 11 rice cropping systems in our database for approximately 2500 counties. In addition to net GHG effects, DNDC estimated the crop yield and water use implications of the mitigation scenarios to show how management options might be prioritized. The impacts of the management options on GHG emissions, crop yield, and water consumption at the national level for China are summarized in Table 1 and highlighted here:

- There is still a large potential for additional methane emission reductions of 20 to 60% from Chinese rice paddies through alternative management practices in 2000–2020 even though CH_4 emissions have been reduced by about 50% through converting water management from continuous flooding to midseason drainage in 1980–2000.
- Any changes in the tested farming management for reducing CH_4 emissions simultaneously affect soil carbon dynamics as well as N_2O emissions. Alternative management options must be assessed based on their net effects on all of the three major greenhouse gases.
- Methane flux will dominate the emissions outcome for all but the management shifts in fertilizer use, and CO_2 flux is inconsequential in net emissions.
- Neither continuous flooding nor slow-release fertilizer are appealing net GHG mitigation alternatives.
- The emissions and yield benefits of 100% adoption (versus our baseline assumption of 80%) of midseason drainage are modest.

Table 1. Impacts of changes in management from the baseline on greenhouse gas (GHG) emissions, crop yield, and water consumption for China (the values are national averages for 2000–2020).

Management option	CH_4	N_2O	CO_2	GWP†	Yield	Water	Yield/GWP	GWP/yield	Water/yield
	— kg CO_2 eq ha^{-1} —		kg CO_2 ha^{-1}	kg CO_2 eq ha^{-1}	kg C ha^{-1}	mm yr^{-1}	kg C (kg CO_2 eq)$^{-1}$	kg CO_2 eq (kg C)$^{-1}$	mm (kg C)$^{-1}$
Continuous flooding	9 645	−5133	5	4 517	−341	66	−0.05	3.22	0.09
Midseason drainage	−2 411	1283	−1	−1 129	85	−9	0.02	−0.67	−0.02
Shallow flooding	−7 402	−2440	591	−9 251	22	−248	0.18	−3.78	−0.10
Upland rice	−11 794	−3018	239	−14 573	−1019	−566	0.51	−5.28	−0.11
Off-season straw	−663	−40	21	−682	98	0	0.01	−0.53	−0.02
Ammonium sulfate	−367	−3668	−85	−4 120	106	0	0.06	−1.88	−0.02
Slow-release fertilizer	287	727	−191	823	152	0	0.00	−0.08	−0.02

† Global warming potential.

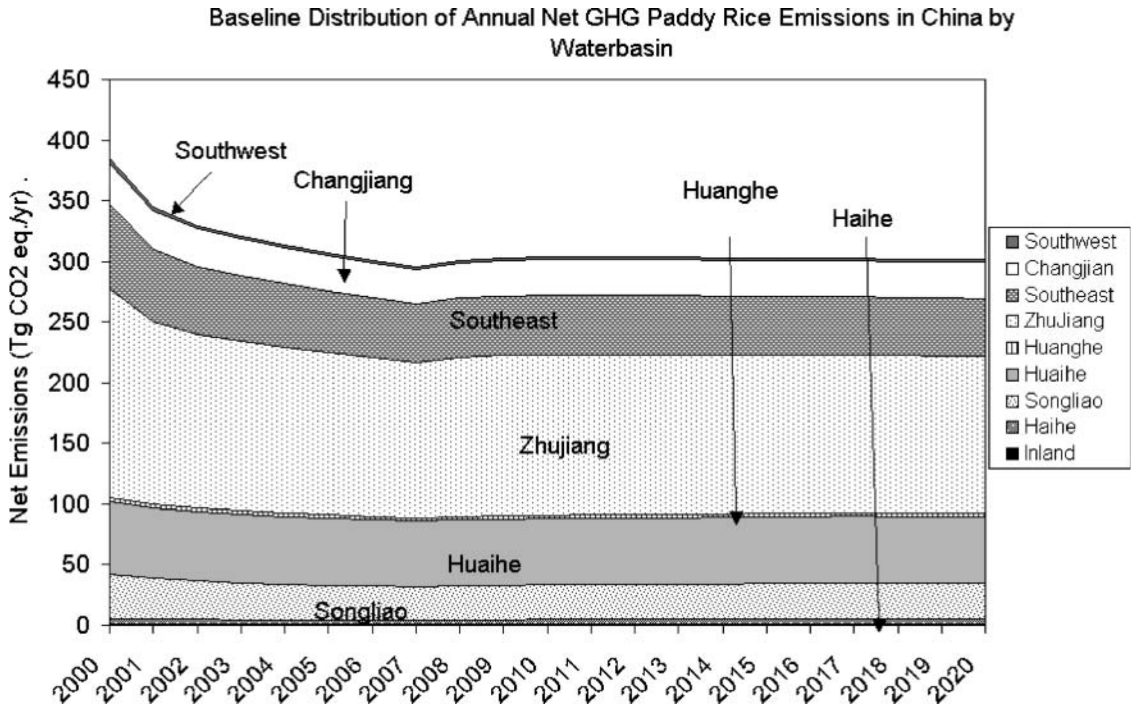

Fig. 9. Baseline national global warming potential (GWP) by water basin from 2000–2020.

- The change in output per unit of CO_2 equivalent emissions (yield GWP^{-1}) is a measure of productivity per unit of emissions, where larger positive values are preferable, and a statistic for considering the effects on emissions and yields simultaneously. Despite the large decline in yields associated with conversion to upland rice, the output per unit of equivalent emissions is higher than that for shallow flooding and ammonium sulfate where yields increased and emissions declined substantially. It should be noted that this statistic is a physical measure of the economic return on emissions. A true monetary measure of the return would require the output price of rice and a carbon equivalent price.
- As an alternative, the change in emissions per unit output (GWP $yield^{-1}$) is a measure of changes in emissions intensity. These ratios reveal that emissions intensity increases with continuous flooding and shows the greatest improvement (decrease) with upland rice, shallow water flooding, and ammonium sulfate fertilizer, respectively.
- Clearly, water use declines for all of the water conserving management alternatives. However, the improvement in water use efficiency (yield $water^{-1}$) is similar for shallow water flooding and upland rice despite the more substantial decrease in the rate of water use for upland rice; and, there was only modest improvement in water use efficiency.

Considering the multiple physical changes in emissions, yields, and water use reinforces the technical mitigation effectiveness order suggested by the net GHG effects: upland rice > shallow flooding > ammonium sulfate > midseason drainage > off-season straw. Technical effectiveness identifies the potential of mitigation alternatives and can suggest particularly promising options.

The alternative mitigation practices simulated in this study have been actually applied in China either for many

Table 2. Distribution of net greenhouse gas (GHG) 2000–2020 emissions effects across major river basins in China from conversion to shallow water flooding.

Basin name	Average annual proportion of baseline emissions reduced	Average annual reduction	Proportion of national paddy rice acreage	Proportion of average annual national reduction	Average annual reduction per hectare
		1000 kg CO_2 eq			kg CO_2 eq ha^{-1}
Inland	0.52	−415 395	0.00	0.00	−9213
Haihe	0.58	−2 346 338	0.01	0.01	−11 248
Songliao	0.46	−13 522 372	0.10	0.08	−7 116
Huaihe	0.55	−30 545 538	0.13	0.18	−12 729
Huanghe	0.58	−1 674 906	0.01	0.01	−8 349
ZhuJiang	0.58	−78 540 207	0.17	0.46	−25 232
Southeast	0.53	−26 681 240	0.08	0.16	−17 640
Changjian	0.56	−16 825 005	0.48	0.10	−1 899
Southwest	0.44	−996 033	0.02	0.01	−3 257

Table 3. China annual average net global warming potential (GWP) ranges for each management alternative.

	Net GWP							
	Baseline	Continuous flooding	Midseason drainage	Shallow flooding	Upland rice	Off-season straw	Ammonium sulfate	Slow-release fertilizer
	Tg CO_2eq							
Midpoint	315	389	296	140	41	298	235	326
Upper estimate	484	641	445	232	71	468	379	454
Lower estimate	146	136	148	47	11	128	90	199

years (e.g., for midseason drainage and off-season straw amendment) or just started (e.g., for shallow flooding and upland rice). In this study, we predicted their impacts on crop yields, water use, and GHG emissions with the modeling approach. We hope the results from this study would assist the mitigation efforts in the country. While this study solely addresses the technical effectiveness, decisions regarding adoption of various mitigation options require consideration of additional factors, including economics and social factors.

Sub-National Heterogeneity

Since the simulations were conducted at county scale, the modeled results can be resampled to calculate GHG emissions at regional, watershed, or national scales. Under the baseline conditions, the national CH_4, CO_2, and N_2O emissions from rice agriculture in China were 7.5 to 8.0 Tg C, −15.4 to −9.4 Tg C, and 0.41 to 0.23 Tg N from 2000–2020, respectively. The national rice GWP under the baseline conditions was 353 to 302 Tg CO_2 equivalent yr^{-1}. The spatially integrated GWPs of rice agriculture for major water basins in China are shown in Fig. 9. The ZhuJiang, Huaihe, and Southeast basins combined are responsible for 78% of cumulative net GHG emissions over the 21-yr period. ZhuJiang alone is responsible for 43%.

Figure 9 illustrates the importance of geographic heterogeneity in paddy rice GHG emissions and the effectiveness of mitigation options. While rice acreage is an important factor with ZhuJiang accounting for 17% of Chinese planted paddy rice acreage, Changjian is home to 48% of planted paddy rice acreage but only generates 10% of cumulative net GHG emissions due to lower net emissions per hectare. Despite their large emissions contribution, the ZhuJiang, Huaihe, and Southeast basins combined only account for 38% of the Chinese planted paddy rice acreage.

Given the heterogeneity in biophysical conditions and net emissions, there are substantial differences in the emissions response to a change in management. Table 2 shows the distribution of emissions responses to a change in management from the baseline to shallow water flooding. First, it is interesting to note that the average annual reduction in emissions was around 50% for all water basins, which, given baseline emissions levels, generated large differences in each basin's contribution to the national reduction. While basin level reduction shares of the total are somewhat consistent with basin acreage shares, some basins assumed a much larger responsibility for emissions reductions than their acreage share would suggest. For example, the ZhuJiang basin was responsible for 46% of the reduction (from only 17% of the acreage), while the Changjian basin was responsible for 10% of the reductions (from 48% of the acreage). Another way to compare net emissions mitigation potential is by looking at emissions reduction per hectare. The ZhuJiang basin was most productive at mitigating emissions at 25 232 kg CO_2 equivalent emissions reduced per hectare. However, small acreage basins also appear to be quite capable. The Southeast and Haihe basins exhibit the potential to reduce net emissions by 17640 and 11248 kg CO_2 equivalent ha^{-1}, respectively, while the large paddy rice area of Changjian was only able to mitigate 1899 kg CO_2 equivalent ha^{-1}.

Emissions Uncertainty

We used the most sensitive factor (MSF) approach to estimate the range in GHG emissions for each county (Li et al., 2004). By varying these "most sensitive factors," namely soil texture and SOC, over the ranges reported in the county-scale database, we produced a range of CH_4 or N_2O emissions for each cropping system in each county. Table 3 presents the range and midpoint of our national annual average GWP estimates for each scenario. As noted above, midpoint values were used for all of the analysis discussed previously. The most important observation is that the ranges in annual average CO_2 equivalent emissions are significant for each management option. Therefore, uncertainty in soil properties introduces large uncertainty into net GHG estimates (upper versus lower estimates), as well as estimated changes in emissions from changes in rice management. This result suggests the need for a better characterization of the influential biophysical conditions associated with paddy rice GHG emissions, in particular, the distribution of those conditions.

CONCLUSIONS

While this study was conducted with a focus on China, these results also provide insight into potential for GHG emissions reductions for other parts of the world with rice or upland agriculture. Both water resources and environmental impacts are becoming urgent issues in most agricultural regions including rice-producing countries. In the United States and Europe, no-till or other management alternatives are being tested for their effectiveness on mitigating GHG emissions. The concepts and methods adopted in this study can be readily applied for the agroecosystems where upland crops dominate. The conclusions from this specific study could vary for other cropping systems, but the methodologies will remain applicable.

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