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LETTER

Trade-offs and spatial dependency of rice production and environmental consequences at community level in Southeastern China

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Abstract

Over the past three decades, farmers in China have increasingly used fertilizers to increase paddy rice production. While this approach has eased the rising demand for food, it is unclear whether it pays off in the long-run when costs associated with environmental consequences are considered. Using two case studies in Zhejiang Province, China, this paper analyzed field-based rice yields, fertilizer inputs, nitrogen leaching and greenhouse emissions and their socioeconomic values of different farm practices. The objective was to assess the trade-offs among economic gains from increased yield and environmental consequences of different paddy rice management practices. The results indicated short-term economic gains to farmers outweigh the environmental cost concerns. However, considering the lasting environmental effects, there is a significant imbalance toward a conservative farming practice. The results further indicated that synergies can be achieved if precision management practices are adopted. It was also indicated that a large spatial variation exists in yields and environmental impacts, suggesting ‘one-size fits all’ policies will likely be ineffective in reducing environmental impacts. Although only two case studies were demonstrated in this study, the approach may be generalized to other geographic regions to help guide paddy farmers in similar climatic and land use environments such as those in the subtropical regions of Southeast Asia, to achieve synergic environment practices.

1. Introduction

Rice, Oryza sativa, which was first grown in Yangtze River valley of China (Vaughan et al 2008), has been the staple food in many East and Southeast Asian countries for centuries. In Asia, rice consumption exceeds 100 kg cap⁻¹ yr⁻¹ (Zeigler and Barclay 2008). Major types of rice grown in the region include paddy rice, lowland, and upland rice, among which paddy rice is the dominant one, occupying approximately 93%. Of these paddy farms, 40% of them are irrigated or flooded (Defeng 2000, Yunus et al 2013).

Increasing paddy rice production has been the main strategy to ensure food security in China over the past few decades, in the face of reduced arable land resulting from urban development. The readily available chemical fertilizer and the incentives to increase paddy rice yields led to excessive fertilizer application in many paddy fields. This may cause an increase in greenhouse gas (GHG) emissions, particularly CH₄ (methane) and N₂O (nitrous oxide) from paddy rice fields, which further escalates climate change. In addition to GHG emissions, paddy rice farming can also result in nitrogen (N) leaching (Yang et al 2013, Tian et al 2007) to rivers and streams, lakes and oceans that can cause eutrophication and algal blooms or red tides in the coastal waters (Smith et al 2006, Howarth et al 2011, Mclellan et al 2015).
Policies on nitrogen leaching and greenhouse gas emissions from paddy farms have been reported in the past (e.g. Ju et al 2004, 2009). However, these policies should not jeopardize food security, because rice is stable food and tightly associated with socioeconomic stability in many communities in the region (Zeigler and Barclay 2008). Take Zhejiang Province as an example: rice farming contributes around 80% of grain production in this province (Zhu et al 2007). Therefore, maintaining and increasing rice yield is an important food security strategy to support the increasing population in developing countries like China and India (Cheng et al 2007).

Further, previous researchers have proposed various knowledge-based ‘optimal N fertilization’ applications (Ju et al 2009, Deng et al 2012, Qiao et al 2012, Zhang et al 2014, Zhong et al 2016). However, policies to promote ‘optimal N rate’ or set ‘N input’ limit may lead to an oversimplification of the challenges in reducing environmental consequences from paddy rice fields. Studies generally agree that current nitrogen (N) fertilization is far more than what is needed, but ‘optimal’ N application rates vary considerably from field to field, from year to year, even within a small geographic region.

Many studies on ‘optimal’ paddy rice management relied on in-situ observations from limited study sites. Scaling up site-specific findings to regional or even national level is likely problematic because spatial variations in soil and management practices will result in significant variations in rice yields, N leaching and GHG emissions (Zhao et al 2015, Liu et al 2014, Ye et al 2007, Inamura et al 2004), thus requiring spatially different ‘optimal N’ recommendations. Thus, one-size-fits-all policies may lead to over or under fertilizer applications.

Previous studies mostly focused on the impacts of either varying soil properties or farm management on rice production, but few considered both of them. A better understanding of the trade-offs between paddy rice production and environmental consequences under varying soil, management and climate conditions is needed to guide future environmental policies on fertilizer regulations.

Specifically considering spatial variability in soil, climate and farming practices, this study presented a fine-scale analysis of the trade-offs between paddy rice production, GHG emissions and N leaching using two case studies in Zhejiang Province, China. The first case study demonstrated how changes in farm practice and climate between 1991 and 2009 affected rice production and nutrient loss at the village level. The second case study explored responses of rice yield and GHG emission to alternative management scenarios under varying soil conditions. In both cases, a biogeochemical model—the DeNitrification-DeComposition (DNDC) (Li et al 1992, 1994) was used to simulate paddy rice production and environmental consequences, specifically considering farm management practices, soil and climate heterogeneity. The overall objective is to assess tradeoffs among environmental impacts and yield potentials of different management scenarios, with an emphasis on spatial heterogeneity dependency and one-size-fits-all policy implications.

### 2. Data and methods

#### 2.1. Study area

Zhejiang Province in the Yangtze River Delta is one of the most densely populated and rice-dominant agricultural regions in China (figure 1(a)). With limited arable land and increased competition for land from urban development, maintaining agricultural food production and ensuring environmental quality is an increasing challenge. Nonpoint source pollution from agricultural fields is blamed for frequent algal bloom and water pollutions in the region but solutions are lacking and policies are ineffective.

Two case study areas—Anji County (30.6391°N, 119.4842°E) and Dasong River watershed (30.6391°N, 119.4842°E) in the province (figures 1(b) and (c)) were selected, based on two previous studies (Xu 2011, Wang et al 2017). Anji and Dasong cover 1886 km² and 108.76 km², respectively. Anji County is within the Tiaoxi River watershed that drains into Taihu Lake, one of the most algal bloom prone inland lakes in China. It was estimated that about 30%–40% of riverine N sources were discharged from paddy fields (Tian et al 2012, Ye et al 2017). Similarly, the Dasong River watershed (108.76 km²) was blamed for frequent eutrophication of the Xiangshan Bay of China’s east coast. Land use in this region is diverse, but rice farming may have contributed more than 25% of N discharged to rivers in the area (Nobre et al 2010).

#### 2.2. Data collection

##### 2.2.1. Anji county data

Climate data were downloaded from the China Climate Data Portal (http://data.cma.cn) and soil data were provided by Zhejiang University at 1: 2 500 000 scale. Between 1991 and 2009, mean daily temperature ranged from 14 °C to 18 °C and mean annual precipitation ranged from 1027 mm yr⁻¹ to 1650 mm yr⁻¹ (figure 2). Locations and area of paddy rice fields were derived from three Landsat 5 TM images covering this county, acquired in 1991, 1994 and 2001 respectively. Reported total area of farmland in Anji County (Li and Yang 2007) was used for validation purpose (table 1). The 2001 Landsat 5 image was selected to determine

| Year | Farmland | Paddy field (based on images) | Percentage (paddy field/farmland) |
|------|----------|------------------------------|-----------------------------------|
| 1991 | 220 km²  | 199 km²                      | 90.4                              |
| 1994 | 208 km²  | 194 km²                      | 91.3                              |
| 2001 | 210 km²  | 193 km²                      | 91.9                              |
Figure 1. Location of (a) Zhejiang Province, (b) surveyed villages in Anji County overlaid with paddy rice fields derived from Landsat 5 images, and (c) field sites in Dasong River watershed.

Figure 2. Mean daily temperature (°C) and mean annual precipitation (m yr⁻¹) for Anji County from 1991 to 2009.

the location of paddy rice fields in this county because there was little change in cropland area between 1991 and 2001. The land use at the village level was intersected with the soil map to obtain areal-weighted soil properties for each village.

Farm management information was collected through surveys and interviews with local farmers. For each village, a group discussion was held that involved 1–2 local government officials, 1–2 fertilizer retailers and 4–6 farmer representatives. Fertilizer use information was collected for 1991, 1995, 2000, 2005 and 2009 (table 2), including manure and N input, historical rice yields, planting and harvest dates, inundation dates (start and end dates), weeding and residue management. The fraction of crop residues returned to field increased from 10%–100% around 2005 for nearly all villages but three (70% for Chengbei 1 and 2, and 10% for Laoshikan village). The soil was loam with moderate acidity (table 2). Flooding depth is about 8–10 cm in all villages.

Typical crop rotation in Anji County is single rice followed by wheat or rapeseed. Rice fields were flooded continuously with one or multiple midseason drainage (table 2). Among the 18 villages surveyed, about half of them use direct-seeded and the rest used transplant rice seedlings.

2.2.2. Dasong river watershed data
The soil information was collected from a total of 12 randomly selected paddy rice plots (figure 1(c)), each being about 0.3 hectare. Field soil samples were collected before growing season and analyzed in labs to
Table 2. Soil and farm management information of the surveyed villages in Anji County.

| No | Village   | Plant–harvest (M/D) | Flooding (M/D) | SOC (g kg\(^{-1}\)) | pH  | Bulk density (g cm\(^{-3}\)) | Clay fraction (%) | Soil texture |
|----|-----------|---------------------|----------------|----------------------|-----|----------------------------|------------------|-------------|
| #1 | Shuanghe  | 5/10–10/20          | 6/1–8/7        | 13.31                | 6   | 1.46                       | 17.46            | loam        |
|    |           |                     | 8/23–9/15      |                      |     |                            |                  |             |
| #2 | Guwan     | 6/15–9/20           | 6/25–7/28      | 18.14                | 6   | 1.36                       | 19.94            | loam        |
|    |           |                     | 8/14–9/10      |                      |     |                            |                  |             |
| #3 | Wunikeng  | 5/20–10/7           | 5/31–6/20      | 12.21                | 5.2 | 1.42                       | 31.94            | clay loam   |
|    |           |                     | 7/5–8/15       |                      |     |                            |                  |             |
| #4 | Chengbei 1| 6/20–10/10          | 5/20–8/10      | 17.85                | 5.8 | 1.37                       | 26.12            | loam        |
|    |           |                     | 8/17–8/30      |                      |     |                            |                  |             |
| #5 | Chengbei 2| 6/5–10/20           | 6/23–8/9       | 17.1                 | 6   | 1.37                       | 20.3             | silt loam   |
|    |           |                     | 8/18–9/5       |                      |     |                            |                  |             |
| #6 | Sunjia    | 6/1–10/10           | 5/20–7/24      | 13.49                | 5.5 | 1.44                       | 19               | loam        |
|    |           |                     | 8/6–9/20       |                      |     |                            |                  |             |
| #7 | Zhangzhi  | 5/15–10/7           | 5/5–9/20       | 13.31                | 6   | 1.46                       | 17.46            | loam        |
|    |           |                     | with three drains\(^b\) |            |     |                            |                  |             |
| #8 | Baofu     | 5/20–10/10          | 5/5–9/5        | 15.21                | 5.2 | 1.42                       | 31.94            | clay loam   |
|    |           |                     | with three drains\(^b\) |            |     |                            |                  |             |
| #9 | Lijiajang | 5/15–10/10          | 5/5–9/4        | 7.3                  | 6   | 1.55                       | 14.22            | silt loam   |
|    |           |                     | with seven drains\(^a\) |            |     |                            |                  |             |
| #10| Meixi     | 6/10–9/30           | 6/25–8/20      | 13.31                | 6   | 1.46                       | 17.46            | loam        |
|    |           |                     | 8/30–9/10      |                      |     |                            |                  |             |
| #11| Laoshikan | 6/10–10/30          | 5/20–10/15     | 17.62                | 6   | 1.42                       | 16.83            | loam        |
|    |           |                     | with three drains\(^b\) |            |     |                            |                  |             |
| #12| Xiaoyun   | 6/20–9/20           | 6/15–8/20      | 16.8                 | 6   | 1.39                       | 20.62            | loam        |
|    |           |                     | with five drains\(^a\) |            |     |                            |                  |             |
| #13| Liang     | 5/10–10/5           | 5/20–9/15      | 13.31                | 6   | 1.46                       | 17.46            | loam        |
|    |           |                     | with three drains\(^b\) |            |     |                            |                  |             |
| #14| Heiping   | 5/15–10/20          | 5/30–8/9       | 7.15                 | 5.2 | 1.52                       | 24.63            | loam        |
|    |           |                     | 8/21–9/15      |                      |     |                            |                  |             |
| #15| Sizhuang  | 5/10–9/30           | 5/25–7/25      | 19.83                | 5.4 | 1.41                       | 20.86            | loam        |
|    |           |                     | 8/10–9/20      |                      |     |                            |                  |             |
| #16| Zhuangshan| 5/5–10/20           | 5/25–7/24      | 16.69                | 6   | 1.39                       | 22.52            | loam        |
|    |           |                     | 8/6–10/5       |                      |     |                            |                  |             |
| #17| Xiaochengba| 5/1–10/10          | 5/15–6/24      | 17.62                | 6   | 1.42                       | 16.83            | loam        |
|    |           |                     | 7/1–9/20       |                      |     |                            |                  |             |
| #18| Heluxi    | 5/10–10/5           | 5/25–7/24      | 13.31                | 6   | 1.46                       | 17.46            | loam        |
|    |           |                     | 8/6–9/25       |                      |     |                            |                  |             |

\(^{a}\) each mid-season drainage lasts about 3–5 days.  
\(^{b}\) each mid-season drainage lasts about 7–14 days.

Table 3. Soil properties of sampled paddy rice fields in Dasong river watershed.

| No | Site Village | Soil pH | SOC (g kg\(^{-1}\)) | Bulk density (g cm\(^{-3}\)) | Clay fraction (%) | Soil texture |
|----|--------------|---------|---------------------|----------------------------|------------------|-------------|
| #1 | Dai          | 4.65    | 21.82               | 1.13                       | 0.16             | loam        |
| #2 | Huashan      | 4.79    | 28.88               | 1.16                       | 0.17             | silty loam  |
| #3 | Fangqiao     | 6.61    | 11.00               | 1.49                       | 0.27             | silty clay loam |
| #4 | Guanshan     | 5.94    | 26.86               | 1.18                       | 0.29             | silty clay loam |
| #5 | Guanjiang    | 5.02    | 27.20               | 1.08                       | 0.24             | silty loam  |
| #6 | Henshan      | 6.5     | 29.54               | 1.18                       | 0.29             | silty clay loam |
| #7 | Xitou        | 5.19    | 24.14               | 0.98                       | 0.15             | sandy loam  |
| #8 | Tangjia 1    | 6.21    | 21.29               | 1.19                       | 0.33             | silty clay loam |
| #9 | Tangjia 2    | 7.28    | 15.89               | 1.38                       | 0.26             | silty loam  |
| #10| Xichen       | 7.22    | 18.70               | 1.09                       | 0.26             | silty loam  |
| #11| Xianyi       | 7.03    | 17.02               | 1.14                       | 0.35             | silty clay loam |
| #12| Zhouxi       | 4.9     | 21.14               | 1.05                       | 0.26             | silty loam  |

obtain soil properties (table 3). The soil texture information was determined using the classical sieve and pipette method (SPM). Soil organic content (SOC) was determined from the Walkley-Black method. The soil pH properties were measured potentiometrically and the bulk density was measured by cutting ring method. Soil textures were mostly silty clay loam or silt loam soil. As indicated by the pH values, most soils are acid in the study sites. A substantial variation in SOC (11–29.54 g kg\(^{-1}\)) among sampled fields, along with other soil properties, suggests different cropping histories and land management practices.

The climate data, including daily precipitation and temperature data for the watershed were downloaded from China Climate Data Portal (www.chinaccdp.org/). Farm management information (table 4) was obtained through interviews with local farmers who either owned or leased those paddy fields. Single rice and one-time midseason drainage were prevalent throughout the Dasong River watershed (table 4). Unlike those in Anji County, farmers in Dasong river watershed did not grow a second crop after the first harvest, and all paddy fields in this area were seedling-transplanted paddies.
### Table 4. Farm management information of sampled rice fields in Dasong River watershed.

| Number | Sites          | Plant-Harvest (M/D)      | Flooding     | Flooding depth | Fertilization (kg N ha\(^{-1}\)) | Straw residue |
|--------|----------------|--------------------------|--------------|---------------|----------------------------------|---------------|
| #1     | Dai village    | 6/30–12/23              | 6/30—7/7     | 10 cm         | Compound: 67.5                  | 10%           |
| #2     | Huashan village| 5/30–11/02              | 5/30—6/30    | 3 cm          | Compound: 67.5                  | 10%           |
| #3     | Fangqiao village| 6/10–11/10              | 5/20—6/20    | 8 cm          | Compound: 67.5                  | 10%           |
| #4     | Guanshan village| 5/25–11/15              | 5/25—6/25    | 4 cm          | Compound: 108                   | 20%           |
| #5     | Guanjiang village| 6/20–11/28              | 6/20—7/30    | 5 cm          | Compound: 40.5                  | 40%           |
| #6     | Henshan village| 5/12–10/25              | 6/30—7/7     | 15 cm         | Compound: 81                    | 20%           |
| #7     | Xitou village  | 6/20–10/15              | 6/5—7/20     | 8 cm          | Compound: 67.5                  | 30%           |
| #8     | Tangjia village1| 5/25–10/15              | 5/20—6/20    | 3 cm          | Compound: 81                    | 10%           |
| #9     | Tangjia village2| 5/25–10/15              | 5/20—6/20    | 3 cm          | Compound: 81                    | 10%           |
| #10    | Xichen village | 6/20–11/05              | 6/30—7/7     | 10 cm         | Compound: 67.5                  | 10%           |
| #11    | Xianyi village | 5/20–11/05              | 5/20—6/20    | 2 cm          | Compound: 34                    | 10%           |
| #12    | Zhouxi village | 6/25–11/20              | 6/25—7/25    | 4 cm          | Compound: 54                    | 30%           |

#### 2.3. Paddy rice modeling

The process-based DeNitrification-DeComposition (DNDC) model (Li et al. 1992, 1994) was initially developed to simulate the dynamic interactions among different C and N pools in the soil and plant (Li et al. 2001, Zhang et al. 2002) and subsequently has been calibrated and validated over the past twenty years including those by the model developer (e.g. Li et al. 2001, Zhang et al. 2010, Deng et al. 2011). The model has four primary components: climate, soil, vegetation, and management practices to govern the biogeochemical processes that determine crop yield, GHG emissions, and nitrogen leaching. With different management options, soil condition and plant information as inputs, the DNDC model was used to simulate environmental consequences and rice yield potentials.

#### 2.4. Experimental design and model simulations

The DNDC model was first calibrated by comparing simulated yields to reported yields from the case study areas and comparing simulated fluxes against published values (figure 3). Once calibrated, the model was used to simulate paddy rice yield, GHG emissions and N leaching for the subsequent trade-offs analyses among different management options. The model was run based on single rice rotation without considering wheat or rapeseed as the second cropping. Information on direct-seeded versus seeding-transplanting methods were not explicitly simulated.

**2.4.1. Village level simulation**

The calibrated DNDC model was run to simulate nitrogen loss ratio (NLR) pattern at the village level for Anji County, where NLR was defined as the ratio of nitrogen leached, including N runoff, to total N input:

\[
\text{NLR} = \frac{\text{N leached}}{\text{Total N fertilizer input}}
\]

Two simulations were made to discern the effects of climate variation and farm management practices:

1. **Historical climate scenario:** simulation with historical (1991 to 2009) climate data and surveyed farm management information for five times from 1991 to 2009. Given that continuous management data was not available, the simulation period was divided into five groups, each representing the closest date when management data were surveyed (see table 5).
2. **2005 climate scenario:** simulation with the historical management data, but climate data was fixed to 2005 condition.

**2.4.2. Field level simulation**

The DNDC model was run with current climate and different managements using field level soil information and climate data of 2014 for Dasong River watershed to assess the sensitivity of rice yield and GHG to three alternative management scenarios:

1. Varying N fertilizer input from 0–150 kg N ha\(^{-1}\).
2. Varying flooding duration from 50 to 120 d.
3. Varying rice straw return from 10%–60%.

#### 2.5. Model validation

The differences between simulated and observed yields were less than 5% at the county level for Anji and...
Table 5. Experimental design for paddy rice farming simulations in Anji County.

| Group ID | Year of survey data | Group of simulation years | Climate for historical and scenarios | Climate for 2005 scenario |
|----------|---------------------|---------------------------|--------------------------------------|--------------------------|
| 1        | 1991                | 1991 to 1993              | 1991 to 1993                         |                          |
| 2        | 1995                | 1994 to 1997              | 1994 to 1997                         |                          |
| 3        | 2000                | 1998 to 2002              | 1998 to 2002                         | 2005                     |
| 4        | 2005                | 2003 to 2007              | 2003 to 2007                         |                          |
| 5        | 2009                | 2008 to 2009              | 2008 to 2009                         |                          |

Figure 3. Model validation of (a) rice yields, (b) CH$_4$ emission, (c) N$_2$O emission and (d) N loss (runoff plus leaching) against observed or reported values in Zhejiang Province and Taihu Lake region. Data on annual rice yields (means with standard errors) were based on the village level and the field level values from Anji county and Dasong river watershed, respectively. For nutrient fluxes, only annual mean values were presented. Observed data on CH$_4$ (Wang et al. 1990, 2001, 1994, Huang et al. 2004, Zheng et al. 2011, Zhong et al. 2016, Sun et al. 2016, Yao et al. 2012), N$_2$O (Zou et al. 2009, Li et al. 2013, Zhong et al. 2016, Zhang et al. 2009, Sun et al. 2007, Yao et al. 2012, Hou et al. 2016) and N loss via leaching and runoff (Wang et al. 1996, Fang et al. 2005, Li et al. 2007, Jiao et al. 2007, Tian et al. 2007, Zhao et al. 2012, 2015, Yang et al. 2013, Xue et al. 2014) from paddy fields in Zhejiang province and Taihu Lake region were compiled from the literature.

3. Results and discussion

The results suggest that variations in climate and farm management practices in Anji County had significant impacts on rice yield and environmental consequences, with substantial spatial variations among paddy fields. For Dasong River watershed, it was found that the relationship between rice yields and GHG emissions was...
very sensitive to soil conditions and farm management options, and there seemed to have been plenty of room for N use efficiency improvements.

3.1. Fertilization and nutrient loss

**Fertilizer and yields trade-offs:** The total N input for surveyed villages in Anji County remained around 250 kg N ha\(^{-1}\), but reduced to less 200 kg N ha\(^{-1}\) after 2000. However, chemical N fertilizer input (urea plus compound fertilizer) increased quickly since 1995 (figure 4(a)). While manure was the main source for N input in 1990s, chemical N fertilizer has replaced manure as the main fertilizer input since the early 2000s (figure 4(a)) as the number of villages using manure as fertilizers reduced from thirteen (13) in 1990 to four (4) in 2009. This is because chemical fertilizer, when compared to manure, is readily available for applications and far more convenient to handle, thus less labor intensive. Labor saving has been overlooked in the past as a driver for increased chemical fertilizer uses; however, as China’s economy continues to grow, migration of rural young population to urban cities, leaving seniors behind in the farm fields (Chang et al. 2011). The choice between manure and chemical fertilizer is thus an easy one, when labor is considered.

From the economic perspective, fertilizer prices have been kept quite low for the past two decades (1990s-2010s) due to regulation and state subsidies to the fertilizer production industry (Li et al. 2014). Subsidized fertilizer price, in turn, incentivized the widespread of excessive N fertilizer uses across China (Li et al. 2013). Replacing manure with chemical N fertilizer increased rice yields (figure 4(b)), but also reduced the amount of organic matter returned to soils (figure 4(c)), which led to a decrease in soil organic carbon (SOC) after 2000 (figure 4(d)).

**Environmental trade-offs:** Temporal changes in temperature and precipitation (figure 2) seem to have stronger impacts on methane emission and nitrogen loss from paddy rice fields. The average CH\(_4\) emissions increased significantly from 1991 (∼200 Kg C ha\(^{-1}\) to 2009 (∼300 Kg C ha\(^{-1}\)) (figure 5(a)). One might speculate that increased N fertilizer applications promoted CH\(_4\) emission. However, previous studies found N application may promote or inhibit CH\(_4\) emission, depending on local soil texture and/or climate conditions (Cheng-Fang et al. 2012, Xie et al. 2010). In fact, simulation under the 2005 climate scenario (figure 5(b)) suggests that CH\(_4\) emission would only increase marginally (11%) if climate variation were not considered. In Anji county, the elevated temperature during the 1991–2009 period (figure 2(a)) may explain the increase in CH\(_4\) emission because higher soil temperature could potentially enhance methanogenic activity and therefore higher bio-methane production (Allen et al. 2003, Sun et al. 2016, Tian et al. 2015).

Recently, a field experiment in the region also confirms the relationship (Sun et al. 2016). Comparison of simulated N loss pattern under historical and 2005 climate scenario indicates that...
changes in N leaching and N\textsubscript{2}O emission over past two decades were more strongly influenced by precipitation variation than the N rates. For instance, the amount of average N leached from paddy fields decreased from 52.5 to 35.2 kg N/ha\,yr\textsuperscript{-1}, or a 33% reduction, between 1991 and 2009 (figure 6(a)). However, when precipitation pattern holds constant at 2005 level, N leaching increased by 37.8% (figure 6(b)). This was likely caused by increased N fertilizer applications and reduced manure input because N fertilizers are much easier to be leached (Fan et al 2017). Similarly, N\textsubscript{2}O emission fluctuates between 1991 and 2009 without a clear increasing or decreasing trend (figure 6(c)). However, a clear decreasing trend in N\textsubscript{2}O emission can be observed when 2005 precipitation is used throughout the simulation period (figure 6(d)). The reduction in N\textsubscript{2}O emission under 2005 climate condition is primarily caused by the elimination of manure fertilizer: several field studies found that application of manure could result in higher N\textsubscript{2}O emission compared to chemical fertilizer (Akiyama and Tsuruta 2003, Zou et al 2006, Jin et al 2010). The contrasting results under historical and 2005 climate data scenarios clearly demonstrated the importance of taking climate variation into GHG mitigation plans.

Fertilizer use efficiency: Between 1991 and 2009, the fertilizer use efficiency indicator, NLR values, have decreased for most villages, but substantial spatial variation existed within the county. Village level NLR between 1991 and 2009 ranged from 0.01 to 0.48 (mean = 0.19, SD = 0.15) and 0.03 to 0.37 (mean = 0.15, SD = 0.11) respectively. Improvement in NLR is most evident between 1991 and 2000, with mean NLR values decreased from 0.19 to 0.12, which
is consistent with the decreasing trend in N leaching. After that, NLR rose again by 0.01 to 0.2 (mean = 0.06) for many villages, although still lower than those in the 1990s. The rebound of NLR signaled that further increasing N rates without better nutrient management would lead to lower N use efficiency. In fact, there is about a 20% gap between crop N demand and crop N uptake in 2009 (results not presented), even though N fertilizer input has increased more than 50% since 2005. This suggests there is plenty of room to improve fertilizer use efficiency and farm management practices.

3.2. Management impacts on N and GHG emissions

Simulated results suggest that current rice management practices are far from being optimal and there is plenty of room to reduce GHG emissions without jeopardizing rice yields. However, the most effective management options for N2O emissions are quite different, depending on field soil conditions. There is a large spatial variation in CH4 and N2O fluxes (figure 7) among paddy fields, suggesting that both management practices and soil conditions are affecting CH4 and N2O emissions.

The N2O emissions were particularly sensitive to the soil pH and SOC conditions. Soils with a higher SOC content tend to release more N2O (figure 7) because soil organic matter provides source materials to soil microbial activities. Soils with a pH value between 6–8 tend to release more N2O because denitrification bacteria are more active within this range (Saleh-Lakha et al 2009). Low pH (4.65) at site #1 and low SOC (11.0 g kg−1) at site #3 explain why N2O emissions are lowest among all sites (figure 7), even though N application rates in these two fields are relatively high.

Simulations with varying N input confirmed that N was overused in these fields. Annual N fertilizer input (urea plus compound fertilizer) for the 12 fields in Dasong river watershed averaged at 212 ± 121.5 kg N/ha. This input level generally exceeds crop N demand in this watershed. There seems to be a tipping point in nitrogen fertilizer applications at 37.5 kg N ha−1, at which rate both yields can be maintained while N2O emission was kept minimal (figure 8).

Field flooding is another important factor in GHG emissions. Simulated results showed that CH4 emission is positively correlated to flooding period (figure 9) and flood depth (results not presented) because the anaerobic environment under flooding condition is more suitable for the methanogenic activity. Given that extended flooding duration does not help with increasing rice yields, it is reasonable to keep flooding days to about 70–80 d and low drainage rice strains so that the CH4 emission from paddy fields can be substantially reduced (figure 9). In addition, results suggest that flooding depth would greatly affect CH4 emissions. Among the 12 paddy fields, half of them presented a CH4 rate lower than 15 kg ha yr−1. This is largely because flooding depths in these fields (2–4 cm) are much lower than in other fields (8–15 cm) (table 4). Previous studies also found water-saving irrigations could reduce CH4 emission by more than 80%, when compared with traditional irrigation practices (Xu et al 2015, Hou et al 2016). Still, field based measurements is needed for future validation to understand the unusual low CH4 rate (7 kg C ha yr−1).

3.3. Opportunities and challenges for policy interventions

Survey results indicate that farmers in Anji County tend to increase paddy rice yield (thus thus income) by growing a second crop after rice harvest, while those in Dasong River watershed simply applied more fertilizers to maintain yields. If the increasing trend of N fertilizer input continues, most farmers in the region would apply more fertilizers than needed, more than 200 kg N ha yr−1. There have been some studies to suggest policy interventions, including eliminating fertilizer subsidies (Kahrl et al 2010) and imposing a fertilizer tax (Liu and Luan 2012). However, these suggestions are unlikely to be politically acceptable because increasing farmer’s income (yields) is also a priority for the central government. ‘Optimal N rate’ is another
popular policy suggestion, but the two case studies clearly demonstrated that substantial spatial-temporal variation exist at both the village and field levels, suggesting ‘one-size fits all’ policies will not achieve desired GHG emission reduction goal without sacrificing farmer’s benefits.

At the field level, more ‘smart’ or adaptive fertilizer management strategies, such as the ‘4R’ technique (Bruulsema et al 2009), which refers to applying right formulation at the right time and right rates in the right locations, are needed to synergize rice production and environment conservation. However, application of ‘4R’ technique for small farms can be more challenging than adopting ‘optimal N rate’, as it requires more efforts for training and capacity building. Currently, farmers typically over-apply fertilizers as an ‘insurance’ or receive blanket fertilizer recommendations from local extension services, but studies in Zhejiang Province suggested that farmers are quite interested in techniques like ‘4R’ because they enable increase in yields at lower fertilizer inputs (Wang et al 2003, Fang et al 2005). While profits are likely the main motivation for farmers to adopt new technologies, saving the environment has started to motivate farmers to take actions to reduce N inputs. Widespread of these technologies, however, would be constrained by accessibility of technical support. One possible solution is to provide real-time simulation results to farmers via smartphones or computers to allow direct access to the information needed for optimal N input. This is possible by coupling detailed database (e.g. local soil) with online information delivery, but more government support would be needed to build the capacity.

4. Conclusions

Excessive N use existed in these two study areas and thus has significant impacts on GHG emissions and N leaching. Adjusting farm management practices (such as reduced N input and flooding duration) could reduce GHG emissions and N leaching while maintaining rice yield.

There is a significant spatial and temporal variability in soil and climate that significantly impact rice yields and GHG emissions. Therefore, a single uniform fertilizer policy across the region will likely be ineffective to overcome the spatial heterogeneity issue to achieve optimal N application rate.
The use of agroecosystem models such as DNDC allows an effective analysis of paddy rice yields, nitrogen leaching, greenhouse gas emissions and various management options that can all be optimized to achieve a win-win scenario. Future research, however, is needed to expand such research to larger geographic areas to encompass much diverse soil types, rice cultivars, climate and management, with geospatial tools and methods.

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References

Akiyama H and Tsuruta H 2003 Nitrous oxide, nitric oxide, and nitrogen dioxide fluxes from soils after manure and urea application J. Environ. Qual. 32 423–31
Allen L H, Albrecht S L, Colón-Guasp W, Covell S A, Baker J T, Pan D and Boote K J 2003 Methane emissions of rice increased by elevated carbon dioxide and temperature J. Environ. Qual. 32 1978–91
Bruulsema T, Lemunyon J and Herz B 2009 Know your fertilizer application nitrogen dioxide fluxes from soils after manure and urea J. Environ. Qual. 38 73–7
Chang H, Dong X-Y and MaPhail F 2011 Labor migration time use patterns of the left behind children elderly in rural China World Dev. 39 2199–210
Cheng-Fang L, Dan-Na Z, Zhi-Kui K, Zhi-Sheng Z, Jin-Ping W, Ming-Li C and Cong-Gui C 2012 Effects of tillage and nitrogen fertilizers on CH4 and CO2 emissions and soil organic carbon in paddy fields of central China PLoS One 7 e34642
Cheng S-H, Zhang J-Y, Fan Y-Y, DU J-H and Cao L-Y 2007 inorganic fertilizer on nitrogen leaching in clayey fluvo-aquic soils a lysimeter study Sci. Total Environ. 592 206–14
Dou Z X 2013 Analysis of China's rice yield-scaled global warming potential in rice Field Crop. Res. 150 230–9
Fang B, Wang G-H, Van D B M and Roetter R 2005 Identification of technology options for reducing nitrogen pollution in cropping systems of Pujiang J. Zhejiang Univ. Sci. B 6 224–29
Huang Y, Zhang W, Zheng X, Li J and Yu Y 2004 Modeling methane emission from rice paddies with various agricultural practices J. Geophys. Res. D Atmos. 109 D08113
Hatano R 2010 Effect of chemical fertilizer and manure application on N2O emission from reed canary grassland in Hokkaido, Japan Soil Sci. Plant Nutr. 56 53–63
Ju X-T et al 2009 Reducing environmental risk by improving N management in intensive Chinese agricultural systems Proc. Natl Acad. Sci. 106 3041–6
Ju X, Liu X, Zhang F and Roelcke M 2004 Nitrogen fertilization, soil nitrate accumulation, and policy recommendations in several agricultural regions of China Ambio 33 300–5
Kahel F, Li Y, Su Y, Temmikte G, Wilkes A and Xu J 2010 Greenhouse gas emissions from nitrogen fertilizer use in China Environ. Sci. Policy 13 688–94
Li C, Froliking S and Harris R 1994 Modeling carbon biogeochemistry in agricultural soils Glob. Biogeochem. Cycles 8 237–54
Liu S, Froliking S and Froliking T A 1992 A model of nitrous-oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity J. Geophys. Res. 97 9759–76
Li C, Zhang Y, Cao M, Crill P, Dai Z, Froliking S, Moore B, Salas W, Song W and Wang X 2001 Comparing a process-based agro-ecosystem model to the IPCC methodology for developing a national inventory of N2O emissions from arable lands in China Nutr. Cycling Agroecosyst. 60 159–75
Li S, Zhang Y, Nadjiony D D P and Wesley D J 2014 Fertilizer industry subsidies in China: who are the beneficiaries? China Agric. Econ. Rev. 6 433–51
Li X-Y, Zhang W-F, Xu M-L, Huang G Q, Onenema O, Zhang F S and Dou Z X 2013 An analysis of China’s fertilizer policies: Impacts on the industry, food Security, and the environment J. Environ. Qual. 42 972–81
Li Z-F and Yang G-S 2007 Correlation analysis of cultivated land change and economic development in Huzhou City [J] Chinese J. Eco-Agric. 3 37
Liang X Q, Chen Y X, Li H, Tian G M, Ni W Z, He M M and Zhang Z I 2007 Modeling transport and fate of nitrogen from urea applied to a near-trench paddy field Environ. Pollut. 150 313–20
Liu K and Liu S 2012 Analysis on the applicability of fertilizer tax in China Adv. Mater. Res. 433–440 1346–9
Liu Z, Zhou W, Shen J, He P, Lei Q and Liang G 2014 A simple assessment on spatial variability of rice yield and selected soil chemical properties of paddy fields in South China Geoderma 235–236 39–47
McCallan E, Robertson D, Schilling K, Tomer M, Kostel J, Smith D and King K 2015 Reducing nitrogen export from the corn belt to the gulf of Mexico: agricultural strategies for remediating hypoxia J. Am. Water Resour. Assoc. 51 263–89

Hou H, Yang S, Wang F, Li D and Xu J 2016 Controlled irrigation mitigates the annual integrative global warming potential of methane and nitrous oxide from the rice-winter wheat rotation systems in southeast China Ecol. Eng. 86 239–46
Howarth R et al 2011 Coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems D coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems Ecol. Environ. 9 18–26

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Nobre A M et al 2010 Assessment of coastal management options by means of multilayered ecosystem models Estuar. Coast. Shelf Sci. 87 43–62
Qiao J, Yang L, Yan T, Xue F and Zhao D 2012 Nitrogen fertilizer reduction in rice production for two consecutive years in the Taihu Lake area Agric. Ecosyst. Environ. 146 103–12
Saleh-Lakha S, Shannon K E, Henderson S L, Goyer C, Trevors J T, Zehnder J B J and Burton D L 2009 Effect of pH and temperature on denitrification gene expression and activity in Pseudomonas mandelii Appl. Environ. Microbiol. 75 3903–11
Smith V H, Joeye S B and Howarth R W 2006 Eutrophication of freshwater and marine ecosystems Limnol. Oceanogr. 51 351–5
Sun H, Zhou S, Fu Z, Chen G, Zou G and Song X 2016 A two-year field measurement of methane and nitrous oxide fluxes from rice paddies under contrasting climate conditions Sci. Rep. 6 28253
Tian P, Zhao G, Li J, Gao J and Zhang Z 2012 Integration of monthly water balance modeling and nutrient load estimation in an agricultural catchment Int. J. Environ. Sci. Technol. 9 163–72
Tian Y-H, Yin B, Yang L-Z, Yin S-X and Zhu Z-L 2007 Nitrogen runoff and leaching losses during rice-wheat rotations in Taihu Lake Region, China PEDOSPHERE 17 445–56
Tian Z, Niu Y, Sun L, Li C, Liu C and Fan D 2015 China’s rice field greenhouse gas emission under climate change based on DNDC model simulation Ying Yong Sheng Tai Xue Bao 26 793–9
Vaughan D A, Lu B R and Tomooka N 2008 The evolving story of rice evolution Plant Sci. 174 394–408
Wang Minxing, Dai A, Shen R and Haibao W 1990 CH4 emission from a Chinese rice paddy field Acta Meteorol. Sin. 4 265–75
Wang G, Zhang Q and Huang C 2003 SSNM-A new approach to increasing fertilizer N use efficiency and reducing N loss from rice fields J. Zhejiang Univ. Agric. Life Sci. 29 67–70
Wang J, Wang S, Chen Y, Zheng J, Li C and Ji X 1996 Study on the nitrogen leaching in rice fields Acta Pedol. Sin. 33 28–36
Wang L, Wan H, Shao X and Qi J 2017 Analyses and management practices of paddy field CH4 and N2O emissions in the Dasongjiang watershed, Zhejiang province, China Bull. Sci. Technol. 5 217–23
Wang M, Li X, Chen H, Shao Z and Liu Q 1994 An observational study of methane emission of rice paddies in Zhejiang Lin'an Q. J. Appl. Meteorol. 5 402–8
Wang X, OuYang Z and Mao H 2001 Application of DNDC model in estimation of CH4 and N2O emissions in agricultural ecosystems in Yangtze River Delta Chinese J. Environ. Sci. 22 15–9
Xie B et al 2010 Effects of nitrogen fertilizer on CH4 emission from rice fields: multi-site field observations Plant Soil 326 393–401
Xu H 2011 A Fine—Scale Analysis of Nitrogen Use Efficiency of Paddy Rice Systems: A Case Study in Anji County in Zhejiang, China (East Lansing, MI: Michigan State University)
Xu Y, Ge J, Tian S, Li S, Ngay-Robertson A L, Zhan M and Cao C 2015 Effects of water-saving irrigation practices and drought resistant rice variety on greenhouse gas emissions from a no-till paddy in the central lowlands of China Sci. Total Environ. 505 1043–52
Xue L, Yu Y and Yang L 2014 Maintaining yields and reducing nitrogen loss in rice–wheat rotation system in Taihu Lake region with proper fertilizer management Environ. Res. Lett. 9 115010
Yang S, Peng S, Xu J, Hou H and Gao X 2013 Nitrogen loss from paddy field with different water and nitrogen managements in Taihu Lake Region of China Commun. Soil Sci. Plant Anal. 44 2393–407
Yao Z, Zheng X, Dong H, Wang R, Mei B and Zhu J 2012 A 3 year record of N2O and CH4 emissions from a sandy loam paddy during rice seasons as affected by different nitrogen application rates Agric. Ecosyst. Environ. 152 1–9
Ye H, Yuan X, Han L, Marip J B and Qin J 2017 Risk assessment of nitrogen and phosphorus loss in a hilly–plain watershed based on the different hydrological period: a case study in Xiaoai watershed Sustain. 9 1493
Ye Q, Zhang H, Wei H, Zhang Y, Wang B, Xia K, Huo Z, Dai Q and Xu K 2007 Effects of nitrogen fertilizer on nitrogen use efficiency and yield of rice under different soil conditions Front. Agric. China 3 30–6
Yunus M, Singh N and De Kok I J 2013 Environmental Stress: Indication, Mitigation and Eco-conservation (Dordrecht: Springer)
Zeigler R S and Barclay A 2008 The relevance of rice Rice 13 1–10
Zhang F, Qi J, Li F M, Li C S and Li C B 2010 Quantifying nitrous oxide emissions from Chinese grasslands with a process-based model Biogeosciences 7 2039–50
Zhang L, Yu D, Shi X, Weindorf D C, Zhao L, Ding W, Wang H, Pan J and Li C 2009 Simulation of global warming potential (GWP) from rice fields in the Tai-Lake region, China by coupling 1.50 000 soil database with DNDC model Atmos. Environ. 43 2737–46
Zhang X, Yin S, Li Y, Zhaung H, Li C and Liu C. 2014 Comparison of greenhouse gas emissions from rice paddy fields under different nitrogen fertilization loads in Chongming Island, eastern China Sci. Total Environ. 472 381–8
Zhang Y, Li C, Zhou X and Moore B I I I 2002 A simulation model linking crop growth and soil biogeochemistry for sustainable agriculture Ecol. Modell. 151 75–108
Zhao X, Zhou Y, Min J, Wang S, Shi W and Xing G 2012 Nitrogen runoff dominates water nitrogen pollution from rice-wheat rotation in the Taihu Lake region of China Agric. Ecosyst. Environ. 156 1–11
Zhao Z, Yue Y, Sha Z, Li C, Deng J, Zhang H, Gao M and Cao L 2013 Assessing impacts of alternative fertilizer management practices on both nitrogen loading and greenhouse gas emissions in rice cultivation Atmos. Environ. 119 393–401
Zheng F et al 2011 Effects of elevated ozone concentration on methane emission from a rice paddy in Yangtze River Delta, China Glob. Change Biol. 17 896–910
Zhong Y, Wang X, Yang J, Zhao X and Ye X 2016 Exploring a suitable nitrogen fertilizer rate to reduce greenhouse gas emissions and ensure rice yields in paddy fields Sci. Total Environ. 565 420–6
Zhu D, Chen H, Zhang X, Lin X and Zhang Y 2007 Evolution of rice cropping system and planting zonation in Zhejiang province Acta Agric. Zhejiangensis 19 423
Zou J, Huang Y, Qin Y, Liu S, Shen Q, Pan G, Lu Y and Liu Q 2009 Changes in fertilizer-induced direct N2O emissions from paddy fields during rice-growing season in China between 1980s and 1990s Glob. Change Biol. 15 229–42
Zou J, Huang Y, Zheng X and Wang Y 2007 Quantifying direct N2O emissions in paddy fields during rice growing season in mainland China: dependence on water regime Atmos. Environ. 41 8030–42
Zou J, Huang Y, Zong L, Zheng X and Wang Y 2006 Effect of organic material incorporation in rice season on N2O emissions from following winter wheat growing season Huaxing Jing Ke Xue 27 1264–8

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