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Is rice field a nitrogen source or sink for the environment?☆

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ABSTRACT

Rice field has been traditionally considered as a nonpoint source of reactive nitrogen (N) for the environment, while it, with surrounding ditches and ponds, also contributes to receiving N inputs from atmosphere and waterbodies and intercepting N outputs from rice field. However, a comprehensive assessment of the N source or sink of rice field for the environment is lacking. Here, we conducted the 3-year systematic observations and process-based simulations of N budget at the Jingzhou site in Central China. We identified the roles of rice field and evaluated the opportunities for shifting its role from N source (i.e., outputs > inputs) to sink (i.e., outputs ≤ inputs). Rice field was found to be a N source of 24.2−28.7 kg N ha^{-1} for waterbodies (including surface and ground waters), but a N sink (2.2−8.8 kg N ha^{-1}) for the atmosphere for the wet and normal year climatic scenarios. The “4R-nutrient stewardship” (i.e., using the right type of N fertilizers, at right rate, right time, and in right place) applied in rice field was sufficient for the source-to-sink shift for the atmosphere for dry year climatic scenario, but needed to implement together with improvements of irrigation and drainage for waterbodies. Furthermore, with the combination of these improved management technologies, rice field played a role as a N sink of up to 22.8 kg N ha^{-1} for the atmosphere and up to 2.0 kg N ha^{-1} for waterbodies, along with 24% decrease in irrigation water use and 21% decrease in N application rate without affecting rice yield and soil fertility. Together these findings highlight a possibility to achieve an environmental-friendly rice field by improving agricultural management technologies.

1. Introduction

Rice field accounts for 30% of China’s sowing areas, 50% of the national water use and 14% of fertilizer use at present (FAOSTAT, 2017; Heffer et al., 2017). In the meantime, rice field poses a high risk of environmental pollution due to reactive nitrogen (N) losses through ammonia volatilization, denitrification, surface runoff, and leaching (also seepage) (Xia et al., 2016), which is considered as one of nonpoint source for both atmospheric and aquatic environments (Liu et al., 2020; Riya et al., 2015). Nonetheless, recent studies also showed that rice paddies could help receive the N inputs from atmospheric depositions, irrigation, and groundwater recharge (Natuhara, 2013). Rice field and its surrounding ditches and ponds serve as an integrative unit where the latter can store and reuse the N from runoff and leaching back to rice field (Chen et al., 2019; Takeda and Fukushima, 2006). The magnitude and destination of reactive N losses depend on climatic and edaphic conditions as well as local farmers’ management practices (Hou et al., 2018). Therefore, it is critical to comprehensively assess the role of rice field—either a N source or a N sink—for the atmosphere and waterbodies, which is a prerequisite to regulate rice field shifting

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from N source to sink. However, associate studies nowadays mainly focused on observations of nitrogen budget only in limited years and regions (Takakai et al., 2017; Saiki et al., 2020), or paid attention to specific items of N inputs and outputs (Hua et al., 2019; Zhan et al., 2020).

As a proxy indicator of N losses to the environment from agricultural soils, N surplus is defined as the difference between all N inputs and harvested N outputs (Hansen et al., 2011). Yet, N surplus is not equivalent as reactive N losses thus it is not suitable to be used for evaluating the N source or sink. For example, maize cultivated in northeast China has an N surplus of 79 kg N ha^{-1} yr^{-1}, while reactive N losses is only 18 kg N ha^{-1} yr^{-1}, primarily because the denitrification loss to N_2 was not accounted for in N losses (Zhang et al., 2019). N surplus indicator is a lump sum of N losses to the environment without separation the atmosphere from the waterbodies, which prevents us from designing and implementing targeted measures to reduce N losses. Moreover, N surplus calculates overall N losses over the whole growing season but not at a high temporal resolution (e.g., daily), which could not be used to identify any specific periods within growing season. Such limitations can be addressed by process-based modeling approaches, as they improve the biogeochemical representation of processes involved reactive N production (Leon and Kohyama, 2017; Ortiz-Reyes and Anex, 2018). However, their parameters are generally calibrated by the limited observations focusing on a part of N loss pathways, rather than the whole water and N budget components (Huang et al., 2018). Moreover, a typical systematic error is associated with process-based models partially due to the incomplete management schemes for rice field (Lerch et al., 2015). Although some efforts have been made for rice paddies such as DNDC-Rice (Katayanagi et al., 2012) and WALRUS-Paddy (Yan et al., 2016), current schemes are primarily designed for upland crops, which failed to grab rice paddies' unique irrigation, drainage, and fertilization practices, like rice field-ditch-pond system (Nazemi and Wheater, 2015; Yin et al., 2020).

Recent studies demonstrate that manipulation experiment is a useful approach to evaluate the effectiveness of various techniques that facilitate the role shift of rice field from N source to sink (Hua et al., 2019). Most of experiments explores the effectiveness of irrigation, drainage, or fertilization techniques solely (Islam et al., 2018; Ke et al., 2018; Natuhara, 2013; Zhang et al., 2017; Zhang et al., 2020), while the choice of measures depends on another ones. For example, reducing N application rates should be combined with the "4R" nutrient stewardship (i.e., right fertilizer type, right fertilizer rate, right fertilizer placement and right fertilizer time) to minimize N losses without the decrease in crop yield (Zhang et al., 2019). Another limitation associated with plot-scale manipulation experiments stems from the neglect of ditches and ponds in altering hydrological and nutrient cycling (Chen et al., 2019; Xiao et al., 2019). Undoubtedly, they can intercept both passive drainage (surface runoff) from rice paddies and active (midseason) drainage. However, no framework has been established so far with a comprehensive set of measures to identify the most reasonable combination and regulation rules for shifting rice field from a N source to a N sink.

The primary objective of this study is to test the hypothesis that rice field is N source for the atmosphere and waterbodies, but it can be shifted to a N sink through optimal combination of irrigation, drainage, and fertilization practices. First, we defined roles of rice field as a N source and a N sink and introduced a methodology to assess and regulate the roles of rice field. Second, we illustrated an experimental evidence through 3-year high-resolution and systematic observations of water and N budget in the central China, revealing the roles of rice field at different temporal resolutions. Third, we quantified the potentials of every single or combined measures for N source-to-sink shift using a well-validated process-based model (Liang et al., 2016; 2019; 2021; Shi et al., 2020). In the end, we discussed about the advantages and limitations of our quantitative methodology, as well as the implications for future policy interventions.

2. Methodology and data

2.1. Assessment of N source and sink

The concept of N source and sink originated from global change research (Watson et al., 1992). Whether a landscape is a N source or sink depends on the receptor (e.g., atmosphere, waterbodies) and the N exchange between the landscape and receptor (Fig. 1). Processes that release reactive N to the receptor are called N outputs, while the processes that receive it are called N inputs. Terrestrial ecosystems including rice paddies, waterbodies (freshwater like rivers, reservoirs, lakes, including surface and ground waters), and the atmosphere are important reservoirs for reactive N. N is constantly flowing among the three systems which act as either 'a sink' or 'a source'. A system that receives more reactive N than it gives off is defined as a N sink or else a N source.

For atmosphere, rice field acts as a N source when the N outputs, which are calculated as the sum of NH_3 volatilization (V_N) and N_2O emissions (E_N) minus the deposition of cropland-derived NH_3 (VD_N), exceed the N inputs calculated as the total of dry and wet depositions (DD_N and WD_N) (Fig. 1). In contrast, it acts as a N sink if the N outputs are less than N inputs, i.e.,

$$y = \begin{cases} Source_{air}, \ if \ OUT_{air} > IN_{air} \\ Sink_{air}, \ if \ OUT_{air} \leq IN_{air} \end{cases}, \tag{1}$$

where OUT_{air} refers to N outputs to the atmosphere and is defined as $V_N + E_N - VD_N$, IN_{air} refers to N inputs and is defined as $DD_N + WD_N$. It is worthy to note that only exchange of reactive N was considered in our assessment, hence neither biological nitrogen fixation consuming N_2 nor denitrification generating N_2 were excluded in the assessment.

Similarly, for the waterbodies, rice field acts as a N source when the N outputs exceeds the N inputs otherwise as a N sink. The N outputs are calculated as the sum of the N runoff (R_N), N leaching (L_N), and the deposition of cropland-derived NH_3 over the waterbodies (VDW_N), and the N inputs are calculated as the total of

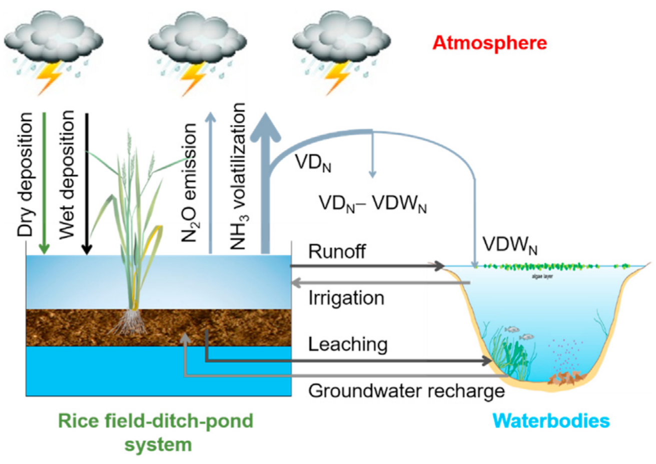

Fig. 1. N flows among three N reservoirs (rice field, waterbody, and atmosphere). VD_N and VDW_N indicate the deposition of cropland-derived NH_3 and the associated part over the waterbodies, respectively.

irrigation and groundwater recharge from waterbodies (I_N and G_N) (Fig. 1). It should be noted that particulate N was excluded as it can be absorbed or deposited during transport process:

$$y = \begin{cases} Source_{water}, \ if \ OUT_{water} > IN_{water} \\ Sink_{water}, \ if \ OUT_{water} \leq IN_{water} \end{cases}, \tag{2}$$

where OUT_{water} refers to N outputs to the waterbodies and is defined as $R_N + L_N + VDW_N$, IN_{water} refers to N inputs and is defined as $I_N + G_N$. Besides, it should be noted that if rice paddies were surrounded by ditches and ponds acting as reservoirs or irrigation source, rice field-ditch-pond system should be regarded as an integrative unit for reactive N exchanged with receptors.

For both of atmosphere and waterbodies together, rice field acts as a N source when all reactive N outputs from rice field exceed N inputs from atmosphere and waterbodies, otherwise it is a N sink (Fig. 1):

$$y = \begin{cases} Source_{both}, \ if \ OUT_{air} + OUT_{water} > IN_{air} + IN_{water} \\ Sink_{N,both}, \ if \ OUT_{air} + OUT_{water} \leq IN_{air} + IN_{water} \end{cases}, \tag{3}$$

where $Source_{N,both}$、 $Sink_{N,both}$ mean field fields are N source or sink for the both.

2.2. Regulation of N source and sink

Sustainable N and water management were two approaches to shift rice field from N source to N sink without compromising crop yield or soil fertility (Fig. 2). It should be noted that our objective was to assess the potential of N source-to-sink shift following our methodology (Fig. 2), rather than to optimize the measures considering technical or socio-economic barriers. N losses from rice field can be reduced following the implementation of “4R-nutrient stewardship” (i.e., using the right type of N fertilizers, at right rate, right time, and in right place; IFA, 2009). We optimized the combination of “4R-nutrient stewardship” by iteratively assessing how much each combination could improve the N sink of rice field. The reduction of N application was regulated from 0 to 40%. The type of fertilization includes urea, mixture of urea and manure, bulk blending fertilizer, and polymer-coated urea, where the last three fertilizers have been widely proven to be effective in reducing N losses (Ke et al., 2018; Ti et al., 2019; Zhang et al., 2017). As to the fertilizer time, different fertilizer splitting ratios (base: tillering: panicle), based on local and optimized schemes (Fu et al., 2021), have been stimulated and compared in regulation. The choice of fertilizer placement ranges from zero (i.e., broadcasting) to 30 cm (i.e., the depth of plough layer). Then regulation of fertilizer type, rate, time and placement could be combined to get the optimized 4R-nutrient stewardship attain the potential N source-to-sink shift. It should be noted that the maximum reduction in N application rate in combination depends on not only the demand for maintaining crop yields but also the constraint for achieving N surplus benchmarks (a value at economic optimum N management; Zhang et al., 2019).

Sustainable water management, including irrigation and drainage, is a secondary measure to regulate N runoff and N leaching from rice field (Li et al., 2020), while it also improves water use efficiency (Fig. 2). We provided a framework to determine what and when water management practices are applied, where irrigation water is pumped from, and what is the destination of runoff from rice field and discharge from ditch and ponds (Fig. 2). To be noted, the rate of irrigation depends on the maximum water level and irrigation water availability (Yin et al., 2020). Irrigation is used if the rice field reaches the minimum water level but will be skipped if precipitation is large enough on the same or next day. Ditch and pond, which store the antecedent rainfall water or the runoff from rice field, are firstly used for irrigation, while the waterbodies nearby rice field are the backup if insufficient. Drainage is separated into passive path, which is naturally induced by extreme rainfall, and active path that is inevitable during mid-season drainage and milky maturity stage (Fu et al., 2021). The rate of passive drainage depends on precipitation and maximum rainfall storage capacity, while the rate of active drainage is mainly based on ponded water depth, precipitation and storage capacity surplus from the ditch and pond. The time of passive drainage is determined by the rainfall event, and the time of active drainage depends on rice phenology, rainfall event, occupancy of storage capacity of ditch and pond, and N concentration of ponded water. Although rainfall-induced runoff

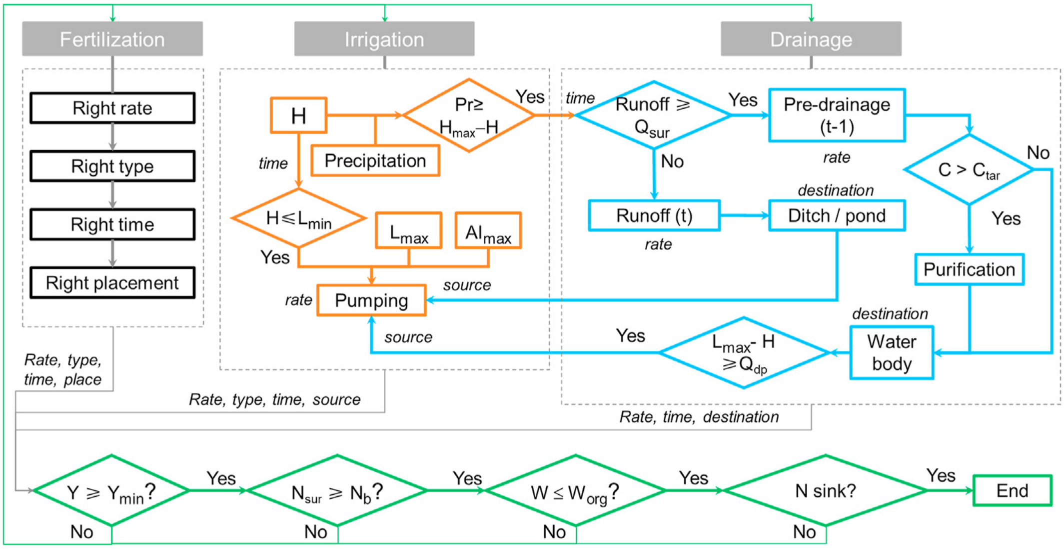

Fig. 2. Framework for shifting rice field from N source to sink. Note that H is ponded water level; Pr is precipitation; L_{max} is maximum water level; L_{min} is minimum water level; AI_{max} is irrigation water availability; H_{max} is maximum rainfall storage capacity; Q_{sur} is the surplus water capacity of pond and dich; Pre-drainage (t-1) and Runoff (t) are drainage from rice field prior to precipitation and after precipitation; C is N concentration in pond and dich; C_{tar} is the target standard of N concentration; Q_{dp} is water storage in pond and dich; Y_{min} is the minimum crop yield; N_b is N surplus benchmark, W_{org} is baseline irrigation water use.

is inevitable, ponded water with lower N concentration could be actively pre-drained to ditch and pond to avoid large N runoff loss to adjacent waterbodies during rainfall events. The drainage destination is the ditch and pond if their storage capacity surplus exceeds the runoff from rice field, otherwise the waterbodies. What's worth mentioning is that water in ditch and pond would be attenuated through biological and physical degradation. Before active drainage from ditch and pond to waterbodies, the water will be further purified in constructed wetlands to meet the target standard of N concentration (1.5 mg/L).

2.3. *Case study*

Field observations were conducted in 2017–2019 at the Jingzhou Agrometeorological Experimental Station (30°21′N, 112°09′E) in suburb of Jingzhou city, Hubei province, China (Fig. 3), with humid monsoon climate and a mean air temperature of 27 °C during rice season in 2017–2019 and corresponding precipitation of 634 mm in 2017, 427 mm in 2018, and 207 mm in 2019, respectively (Wu et al., 2020). Rice has been rotated with rapeseed for the last 10 years. Soil is classified as Hydragric Anthrosol, with clay content of 19.8% and bulk density of 1.1 g cm^{-3} in topsoil (0–20 cm). Other soil properties such as pH, soil organic carbon, and total N content are 8.1, 7.9 g C kg^{-1}, 1.2 g N kg^{-1}, respectively.

The experiment was conducted at three different plots as replicates, each of which has an area of 150 m^2 (i.e., 25 m × 6 m). The plots, surrounded by wide croplands and an industrial factory, were completely isolated by levees and covered with plastic. Seedlings of rice were manually transplanted in June with a density of 9 plants m^{-2}, and harvested in September. Based on local farmer's practices, water management in plots was flooding-midseason drainage-frequent water logging with intermittent irrigation, pumped from minor tributary of Yangtze River. Pre-flooding was initiated before transplantation, followed by frequent water logging except for midseason drainage. No irrigation was applied afterwards during the period of physiological maturity. Total applied irrigation was at 905 mm in 2017, 1007 mm in 2018, and 915 mm in 2019. Total applied fertilizers were 171.1 kg N ha^{-1}, 26.7 kg P ha^{-1} and 40.4 kg K ha^{-1} for each of rice growing season. A mixture of urea and ammonium sulfate was incorporated as basal fertilizer (BF), followed by two times of topdressings. Phosphorous and potassium fertilizers were also applied but together at rates of 23.1 kg P ha^{-1} and 34.9 kg K ha^{-1} in BF, respectively, with additional applications in TF2 (3.6 kg P ha^{-1} and 5.5 kg K ha^{-1}, respectively). More details in agricultural management in 2017–2019 can be found in Table S1.

2.4. *Data of N inputs and outputs*

We measured all N inputs and outputs at Jingzhou site over rice season (including 20-day fallow period before rapeseed season) in 2017–2019, except N_2O emissions and NH_3 re-deposition. Wet deposition and irrigation were automatically recorded for each event (APS-3A, Xianglan, China for precipitation, CaipoCPS, Beijing, China for irrigation) and water samples were collected. Dry N depositions were calculated by multiplying the sampled gaseous (NO_2, NH_3 and HNO_3) and particulate N concentrations and associated deposition velocities. Ogawa passive samplers (Ogawa & Co., FL, USA) were used to collect NH_3 and NO_2 samples. Another passive sampler (USDA Forest Service, CA, USA) was used to collect HNO_2/HNO_3 samples. High volume aerosol samplers (Laoshan Elec. Inc., Qingdao, China) were used to collect total suspended particulates (TSP) at a flow rate of 1.05 m^3 min^{-1}. Passive samplers were continuously exposed to gaseous N for two weeks. Active samplers were operated 24 h for particulate N every week on Monday, which was manually altered during rainfall events. Deposition velocities for gaseous and particulate N were calculated using a meteorological model (Zhan et al., 2017), where meteorological parameters were measured at 2-m height at 30-min interval (CNR4 Net Radiometer, CSAT3, HFP01, Campbell, USA).

NH_3 volatilization flux was measured by the dynamic chamber twice a day at a flow rate of 15 headspace volumes min^{-1} during whole rice season in 2017. Based on these high-frequency flux observations, an improved Jayaweera-Mikkelsen model was well calibrated to simulate daily NH_3 fluxes under ambient condition in 2017–2019 (Zhan et al., 2019). The net N leaching flux (i.e., N leach minus groundwater recharge) was calculated as the product of subsurface water flux and N concentration. Subsurface water flux was quantified at a daily interval based on water balance approach (Fu et al., 2019), i.e., the difference between the sum of precipitation and irrigation and the sum of evapotranspiration, surface runoff, and the changes of soil water storage and ponded water depth between two consecutive sampling times. N concentration was

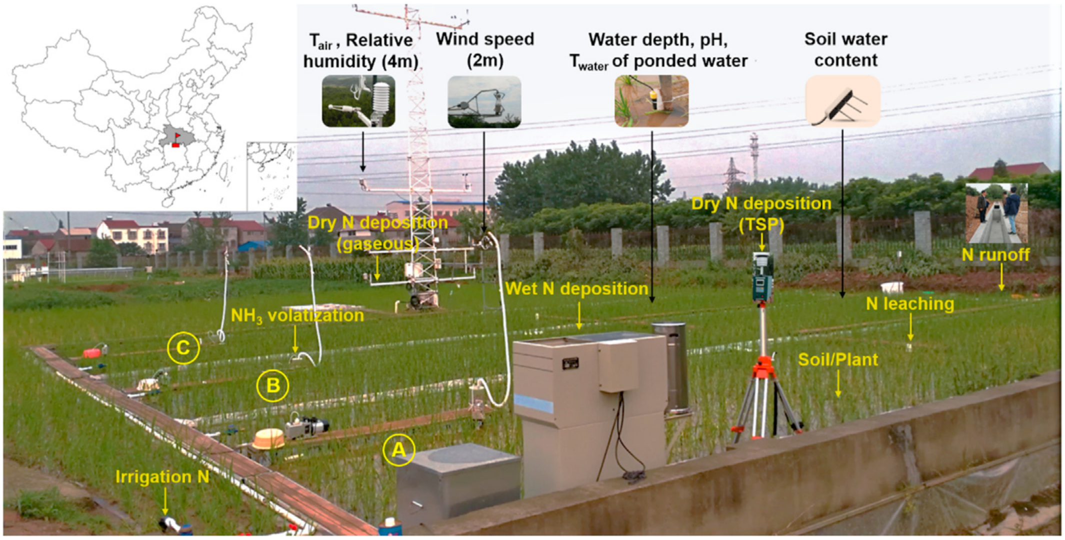

Fig. 3. Study site and field observation. Water and N budget components were measured synchronously for the three replicates (A, B, C). Climatic factors were also observed for model simulation.

analyzed for the leaching water samples collected at the depth of 90 cm twice a day over the whole rice season, following the sampling methods of Liang et al. (2017). Water samples were collected and manually analyzed for N runoff for each event (Wu et al., 2020). In addition, N_2O emission flux and NH_3 re-deposition were determined based on the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019). The deposition of cropland-derived NH_3 over the waterbodies was simply calculated as a part of VD_N based on the proportion of the area of the waterbodies within a region with a radius of 10 km.

2.5. Process-based model

An integrated soil-crop process-based model (WHCNS) was used to predict how water and N management practices regulate N sinks and sources of rice field (Liang et al., 2021). The model has been successfully applied to simulate hydrological and N processes and crop growth for both upland crop and paddy rice systems across China (Liang et al., 2019; Shi et al., 2020). The model integrated meteorological module, combined transport module of soil water, heat and nitrogen, crop growth module, organic matter module, root water and nitrogen absorption module, inorganic nitrogen module and field management module. The Penman-Monteith equation (Allen et al., 1998) recommended by FAO was used to calculated Potential evapotranspiration (ET). Simulation of water infiltration and redistribution processes was based on the modified Green-Ampt model (Hachum and Alfaro, 1980) and Richards equation. Crop parameters in the model (specific leaf weight, crop coefficient, distribution coefficient, etc.) are derived from Driessen and Konijn (1992) and corrected according to observed values. The solute transport and organic matter turnover theories are directly derived from DAISY model (Hansen et al., 2012). These modules are organically combined , and the accuracy the simulation of key processes including soil water movement, soil organic matter turnover, organic nitrogen mineralization, ammonia-hydrolyzing, nitrogen volatilization, nitrification and denitrification, crop transpiration and crop nitrogen absorption was improved. The detailed methodology of WHCNS model can be found in Liang et al. (2021).

Additional management module is specifically embedded in the WHCNS to determine the rate, type, time, and placement of fertilization as well as the rate, time, and source or receptor of irrigation and drainage. Irrigation and drainage are automatically simulated following the framework in Fig. 2, where associated parameters (e.g., maximum and minimum irrigation water levels, maximum rainfall storage capacity, water storage in pond and dich) are determined by the choice of water management. The purification capacity before drainage to waterbodies is calculated by adjusting the attenuation coefficients, a combination of biological and physical degradation (Table S3). The rate, time, and placement of fertilization are set by adjusting the boundary conditions for the model. The type of fertilizers is set by adjusting the first-order kinetic parameter of hydrolysis rate and ammonia volatilization (Table S3).

The WHCNS model was first calibrated to minimize the error between the simulated and observed values during two rice seasons in 2017–2018, including water and N budget components as well as rice growth processes (Table 1). It was then validated by the observation data in 2019. The values of key measures were listed in Tables S2–S4. After the validation, the model was utilized in: (1) assessing N sources and sinks of rice field under different climatic scenarios to validate the robustness of 3-year observations, where precipitation at 25th, 50th, and 75th percentiles, on behalf of wet year, normal year and dry year, over 1957–2016 were 579, 504, and 371 mm during rice season, respectively, (2) measuring the sensitivity of N source and sink under different water or N management practices, and (3) evaluating the potential of the N source-to-sink shift with sustainable water and N management. All those model-based scenarios were simulated for N receptors as atmosphere, waterbodies, and the both (i.e., atmosphere and waterbodies combined).

3. Results

3.1. Assessment of N source and sink

Our study shows that rice field was a N source regardless of which receptor was chosen, except for the atmosphere in 2017 (Fig. 4a). N outputs to the atmosphere ranged from 24.8 to 29.3 kg N ha^{-1}, most (>95%) of which were contributed by the NH_3 volatilization, while N inputs from dry and wet depositions were 16.8–39.9 kg N ha^{-1}, comparably with other observations in this region (Xu et al., 2015; Yu et al., 2019). N outputs to the waterbodies, dominated by N leaching were 17.8–45.3 kg N ha^{-1} in 2017–2019, were almost two times larger than N inputs from the waterbodies. Similar results were found for the receptor with atmosphere and waterbodies combined, i.e., N outputs from rice field surpassed N inputs by 19–62%. It's worthy to note that N runoff loss of observation were similar to average values in Central China from Hou et al. (2016, 2018), while N leaching covered results in this region from Gao et al. (2016).

N sources and sinks of rice field fluctuated mostly at the daily interval (Fig. 5). For the atmosphere, rice field typically acted as N source during the short-term periods after basal and topdressing fertilizer applications resulting in large NH_3 volatilization, but afterwards it acted as a N sink particularly during rainfall events. For the waterbodies, there were large fluctuations in N inputs and outputs as well as the differences between them (i.e., N outputs minus N inputs). Rice field was N source in >60% of the whole rice season, especially during high rainfall events (>40 mm) that induced massive runoff and leaching, or in fertilization periods with high N concentration in ponded water. Rice field was N sources only in limited events like rainfall and fertilizer applications for the atmosphere and water bodies combined. Those results imply that rice field may act as a “purifier” for cleaning air and water pollution during the rest of rice seasons.

To validate the robustness of our results, we further quantified the N source and sink of rice field under three climatic scenarios (Fig. 4c). To do so, we used the WHCNS model that was well validated for N uptake, N losses, and N storage change (Figs. S1–S3, Table 1) and could reproduce the results as to the roles of rice field for atmosphere, waterbodies, and both (Fig. 4b). These analyses confirmed that rice field remained as a N source except for the atmosphere when climatic scenarios were at wet year and normal year.

3.2. Sensitivity of N source and sink

The well-validated WHCNS model was also applied to quantify the sensitivity of the N source and sink of rice field in response to water and fertilization management practices under three climatic scenarios. As shown in Fig. 6, We separately discussed sensitivity of different management practices respectively, by altering one specific water and fertilization management measure while keeping others constant as farmers' practice. For continuous variables like fertilizer rate and placement, we set conditions equidistantly, while enumerated potential measures for categorical variables like fertilizer type, timing and water management. Reduction in N application rate substantially decreased the N outputs from rice field (Fig. 6a), which reduced the N sources linearly from 171.1 kg N

Table 1
Observed and simulated water and N budgets and crop growth at Jingzhou station from 2017 to 2019.

Type	Component	2017		2018		2019		RMSE
		Observed	Simulated	Observed	Simulated	Observed	Simulated	
Inputs	Irrigation	905.5	–	1007.2	–	914.8	–	–
	Precipitation	633.9	–	427.2	–	206.9	–	–
	Irrigation N	19.1	–	17.1	–	14.6	–	–
	Atmospheric depositions	39.9	–	22.7	–	16.8	–	–
	Fertilizer N	171.1	–	171.1	–	171.1	–	–
	Seed	21.6	–	4.3	–	2.1	–	–
Outputs	ET	691.3	678.9	422.1	466.3	–	373.2	1.05
	Runoff	197.8	185.1	113.8	122.1	0.0	0.0	3.36
	Leaching	644.6	682.73	888.9	893.3	742.8	760.5	15.30
	Plant N uptake	165.2	175.7	141.7	151.7	134.9	143.6	6.88
	N leaching	30.9	31.2	33.8	34.0	13.9	13.7	0.49
	N runoff	11.0	10.0	3.1	2.9	0	0	0.13
	NH_3 volatilization	34.0	33.6	–	33.7	–	40.9	0.50
Crops	Aboveground biomass	17.1	16.4	17.1	16.1	15.4	15.6	1.24
	Stalk biomass	7.2	7.1	7.2	6.7	6.2	6.0	0.59
	Grain biomass	9.9	9.3	9.9	9.4	9.3	9.6	1.11

Note: Units for water and N budget components are mm and kg N ha^{-1}, respectively. Unit for biomass is Mg ha^{-1}. RMSE refers to Root Mean Square Error and is calculated for the 3 years at the daily scale.

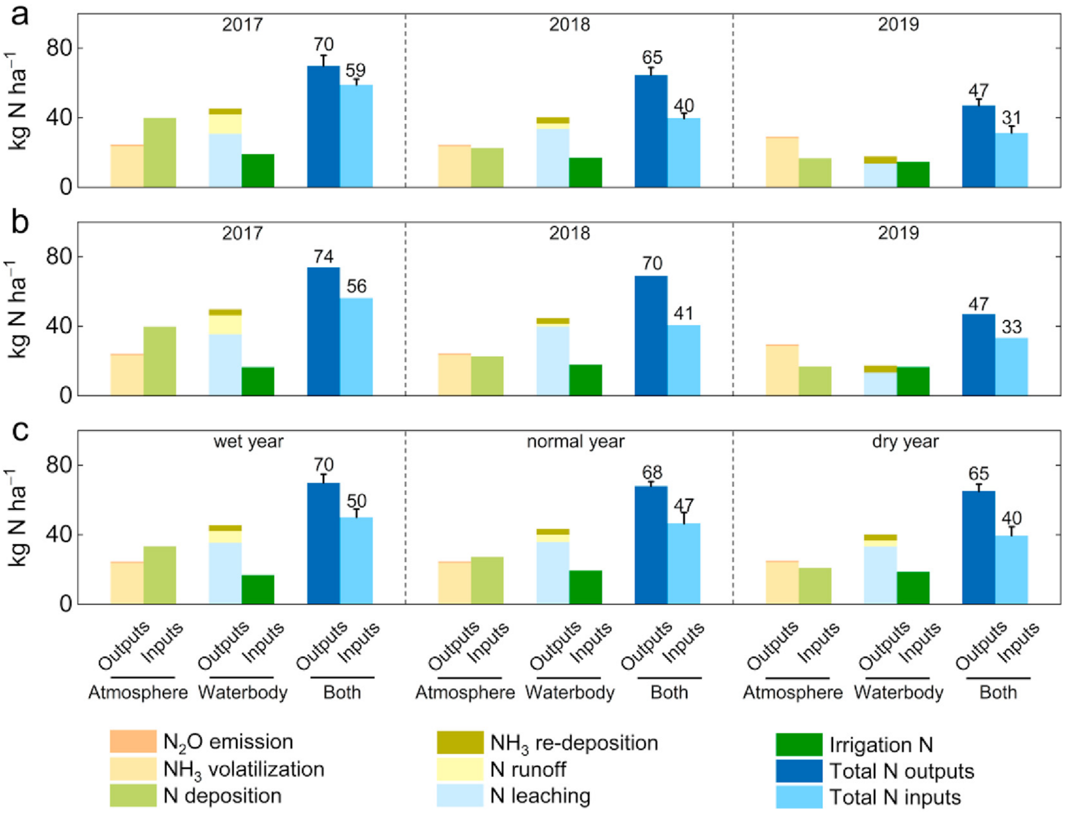

Fig. 4. N inputs and outputs of rice field for the atmosphere, waterbodies, and the combined. a. 3-year field observations. b. modeling results in 2017–2019. c. modeling results for wet, normal and dry climatic scenarios.

ha^{-1} at current rate to 102.6 kg N ha^{-1} at 60% of current rate. Moreover, N sink was enhanced from 2.5 to 11.3 kg N ha^{-1} for the atmosphere, and rice field was shifted from a N source at 19.9 kg N ha^{-1} to a N sink at 2.2 kg N ha^{-1} for the both in wet year. However, rice yield was decreased by up to 22% accordingly when solely reducing the N application rate. Fertilizer substitution could decrease N outputs from rice field to the atmosphere and waterbodies (Fig. 6b). For instance, for the both, the N sources of rice field were declined by a half when mixed urea and manure (4:1) were used and by >80% when bulk blending fertilizers were applied. The rice field was further shifted to a N sink of 4.0–8.9 kg N ha^{-1} using polymer-coated fertilizers. In contrast, change in fertilizer placement, particularly below 10 cm in soils, showed no difference on the N source-to-sink role shift in rice field because of its contrasting effects between the atmosphere and waterbodies (Fig. 6c). The incorporation and deep placement of fertilizers decreased NH_4^+ concentrations in ponded water thereby inhibiting NH_3 volatilization (Zhan et al., 2021), but also significantly stimulated N leaching. In addition, change in fertilizer timing slightly influenced the N source and sink roles of rice field (Fig. 6d). In general, lowering

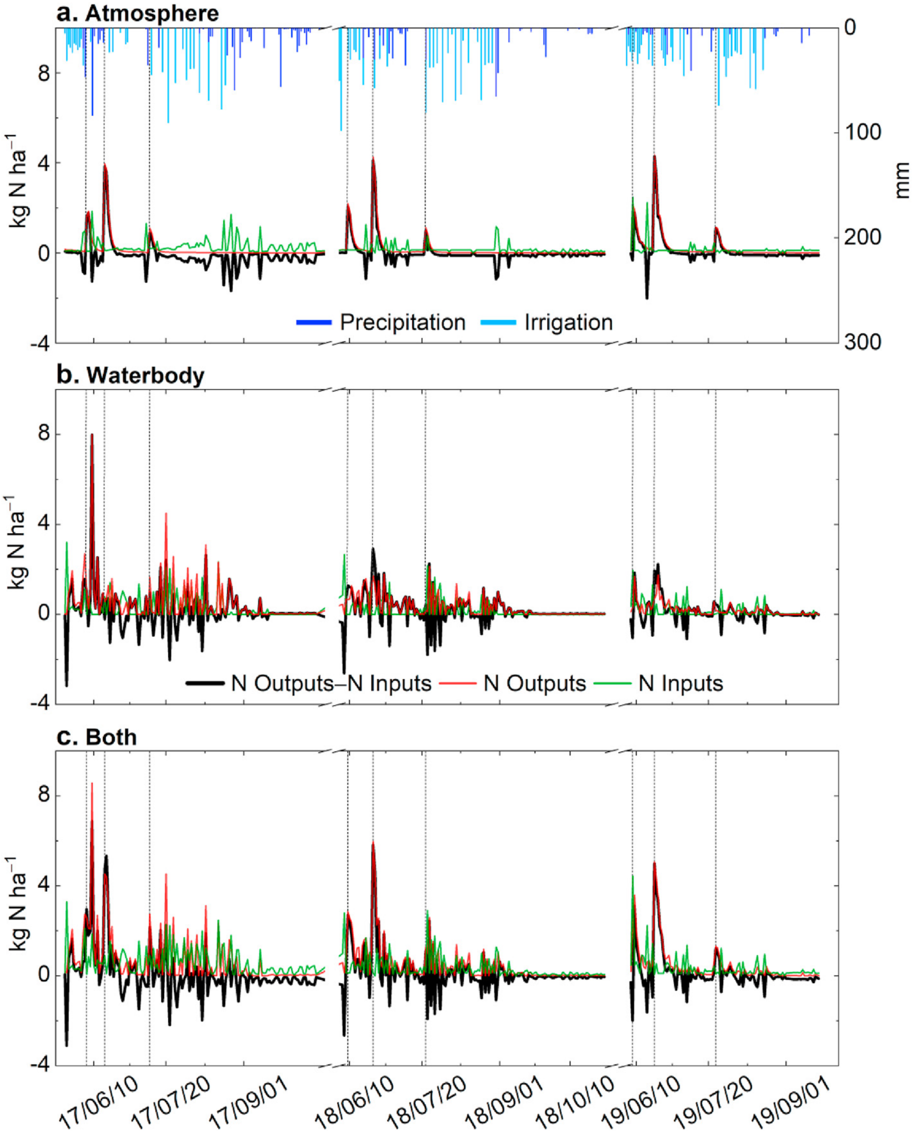

Fig. 5. N inputs and outputs of rice field at daily interval. a. the atmosphere, b. waterbodies, c. the both. The definition of inputs and outputs was found in Equations (1)–(3). Rice field is a source when outputs−inputs is larger than zero, otherwise a sink. Note that the dashed lines indicate the time of fertilization.

basal fertilizer proportion, which improves rice yield as previously reported (Fu et al., 2021), and increased the N source from 16.6 kg N ha^{-1} (basal: 80%, tillering: 5%, panicle: 15%) to 22.4 kg N ha^{-1} (basal: 40%, tillering: 45%, panicle: 15%) for the both. Overall, these findings underscore the need for changing fertilizer types and reducing N application rate at the Jingzhou site.

Fig. 6e indicates that the change in water management had large effects on N source and sink of rice field for the waterbodies as well as the waterbodies and atmosphere combined. Shallow-wet irrigation adopts lower maximum and minimum water level to reduce unnecessary water use, and enhance water stress as well, while improved drainage refers to a series passive and active drainage regulation measures combined with appropriate ditch and pond systems. The specific information could be found in Section 2.2 and Fig. 2. The use of shallow-wet irrigation saved irrigation inputs by 18–20% compared to farmers' practice, since lower maximum water level is required for irrigation. Meanwhile, this measure reduced N leaching by 31–34% through lowering infiltration rate, which exceeded the reduction in N inputs via irrigation thereby declining N sources by 17–35%. A single use of improved drainage saved irrigation water by 6–10% as water reused from the ditches and ponds back to rice field. More importantly, this measure stored both active and passive discharges from rice field thus reduced N runoff directly into the waterbodies by 82–100%, leading to 7–27% reduction in N sources.

3.3. Potential of N source-to-sink shift

Fig. 7 shows the potential of N source-to-sink shift through sustainable N and water management for wet, normal and dry climatic scenarios, with the details of N budget, N surplus and rice yield in Table S5. Fig. 8 shows the best measures of fertilization, irrigation and drainage for dry year climatic scenario, with the details for the rest two scenarios in Table S6. When the "4R-nutrient stewardship" was adopted only with the best measures, N sink of rice field was enhanced for the atmosphere under the wet and normal year climatic scenarios (from 8.8 to 23.2 kg N ha^{-1} and from 2.2 to 18.0 kg N ha^{-1}, respectively, Fig. 7), and rice field was shifted from a N source (3.9 kg N ha^{-1}) to a N sink (10.2 kg N ha^{-1}) under the dry year climatic scenario. Although those measures could

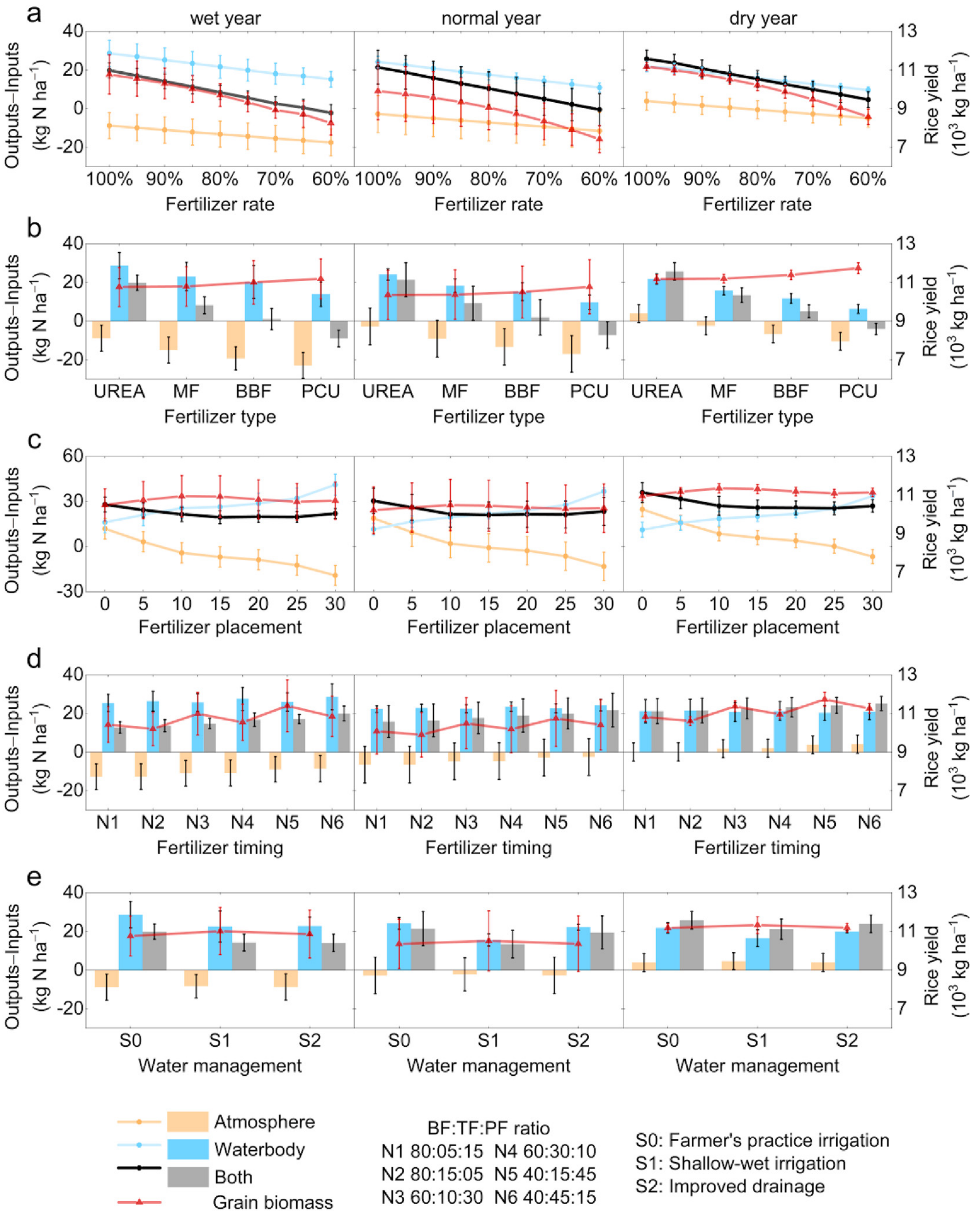

Fig. 6. Sensitivity of N source and sink to measures for wet, normal and dry climatic scenarios. a. fertilizer rate, b. fertilizer type, c. fertilizer placement, d. fertilizer timing, e. water management.

largely reduce the N outputs to waterbodies by 44–54% due to the huge descent of N leaching (Table S5), rice field was still a N source (8.21 kg N ha^{-1}) under the wet year climatic scenario. The combination of shallow-wet irrigation and improved drainage, mainly targeting at N runoff and leaching (Table S5), reduced N sources of rice field by 26–39% for the waterbodies, and 50%, 41%, and 19% for the both under all the three scenarios, respectively. However, it has no significant effect for the atmosphere.

Finally, when the measures from sustainable N and water management were combined together, rice field acted as N sink of22.8 and 17.1 kg N ha^{-1} under the wet and normal year climatic scenarios, respectively, and was shifted from a N source of3.9 kg N ha^{-1} to a N sink of 9.5 kg N ha^{-1} under the dry year climatic scenario (Fig. 7). The N sources for the waterbodies was significantly reduced from 28.7 to 2.0 kg N ha^{-1} under the wet year climatic scenario, and further changed to a N sink of 2.0 kg N ha^{-1} under the rest two scenarios. For the both, rice field was shifted from a N source of 19.9–25.8 kg N ha^{-1} to a N sink of 11,7–20.8 kg N ha^{-1}, along with 24% decrease in irrigation water use and 21% decrease in N application rate without affecting rice yield and soil fertility (Table S5).

4. Discussion

Here we developed a new methodology that provides a quantitative way to identify the N source or sink roles of rice field at

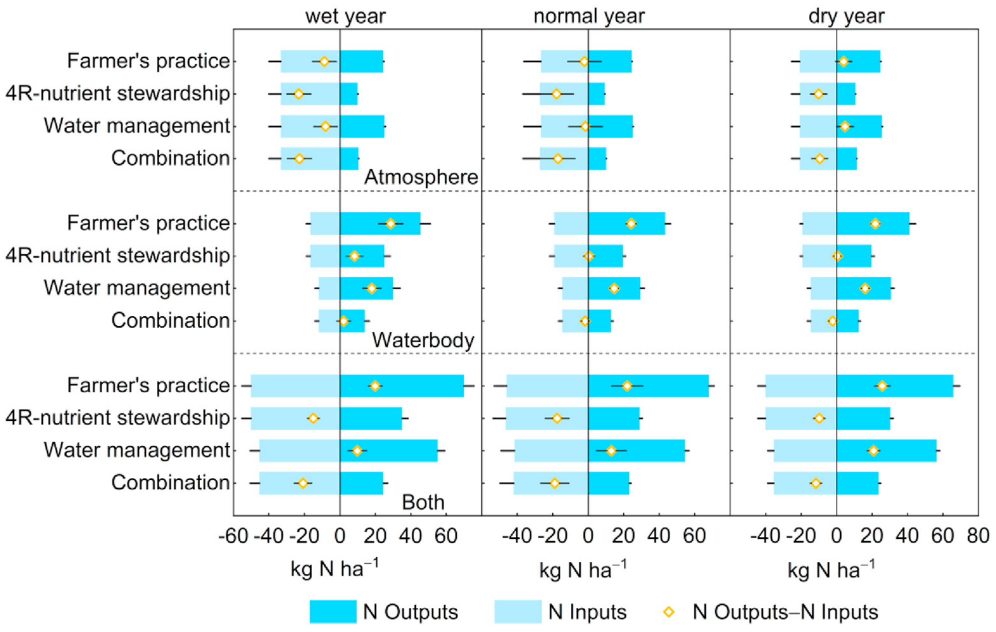

Fig. 7. Potential of N source-to-sink shift through sustainable N and water management for wet, normal and dry climatic scenarios. The 4R-nutrient stewardship is a combination of the right type of N fertilizers, at the right rate, right time, and in the right place. Water management is a combination of shallow-wet irrigation and improved drainage.

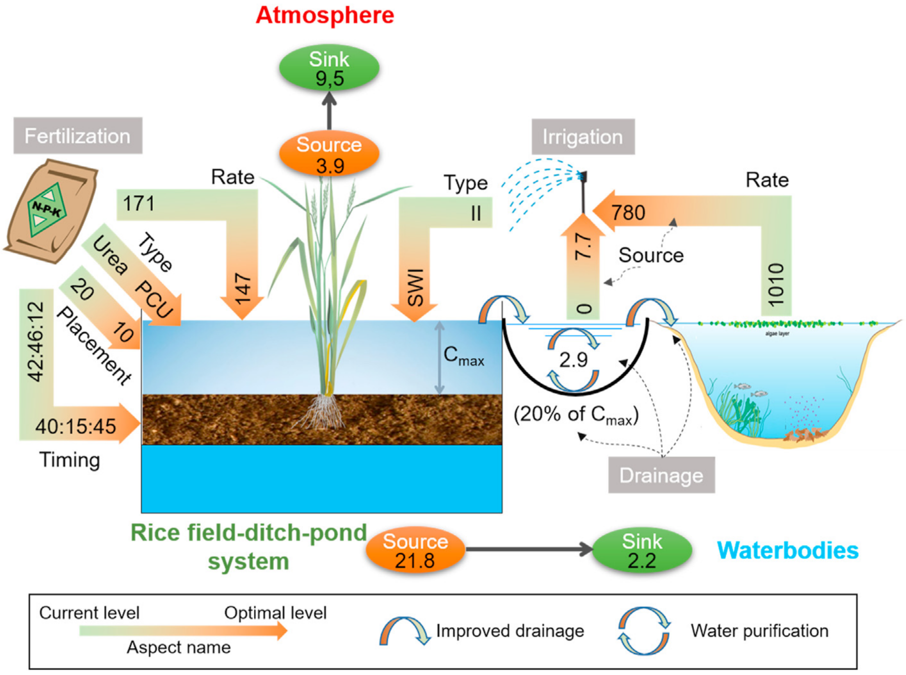

Fig. 8. Best measure of fertilization, irrigation and drainage for dry year climatic scenario. Note that II and SWI are the abbreviations of Intermittent Irrigation and Shallow-wet irrigation, respectively; C_{max} is maximum capacity of rice fields. The units for N application rate and N source or sink are kg N ha^{-1}, respectively. The units for the depth of placement and irrigation application rate are cm and mm, respectively. The details of regulation could be found in 2.2.

different temporal resolutions and help regulate its role through improved management technologies. The methodology was derived from years of experience in the fields of flux observation, biogeochemical modeling, and innovative management technologies for soil-crop systems, and is adaptable and adjustable to other crop types (e.g., wheat, maize), targeted elements (e.g., phosphorous), temporal resolutions (e.g., daily, monthly, annual), spatial scales (e.g., plot, landscape). Our methodology expands previous research in three aspects: (i) On top of the definitions of N surplus, the roles of rice field over the atmosphere and waterbodies are redefined and quantified on when and to what extent rice field acts as N source or sink. (ii) We introduced a model-based framework to identify the combination of water and N managements for N source-to-sink shift along with the improvement of water and N use efficiencies without compromising the rice yield. (iii) Our methodology provides a reference for measuring the sensitivity of a

N source or sink to water and N management, which could be useful when farmers or decision makers choose the combination of key measures prior to the consideration of socio-economic costs. This is especially useful given the current and future growth of cropland N losses due to the increasing food demands. Thus, instead of asking “whether is rice field a non-point pollution source or not?”, we prefer to ask a more policy relevant question: “how to shift rice field from N source to sink most effectively?”.

Using the new methodology, we studied the rice field’s N source or sink role at Jingzhou site in central China and found out that it acted as a N source for the waterbodies and the waterbodies and atmosphere combined. This is consistent between 3-year observations and scenario simulations. However, this conclusion may not be applicable to all cropping areas in China or to the rice fields under future climate change. Our scenario simulations and sensitivity analyses indicate that the role of rice field was largely determined by fertilization (i.e., rate, type, timing, placement), irrigation (i.e., rate, type, timing, and source), drainage (i.e., rate, timing, and destination), local climate and edaphic conditions. In contrast to the Jingzhou site, rice paddies across east China suffered from higher atmosphere N depositions due to intensive emissions of N but lower NH_3 volatilizations due to widespread acidic soils (Yu et al., 2019), suggesting a larger N sink for the atmosphere. Rice paddies in northwest China (e.g., Yinchuan Plain) may act as a N source to the atmosphere largely due to lower N depositions (Wen et al., 2020).

How to determine the N source or sink role of rice field for the waterbodies is more complicated compared to the atmosphere since there are multiple components affecting N inputs and outputs. Rice paddies in northeast China (e.g., the Liaohe River Delta) may act as a N source for the waterbodies, because of high saturated hydraulic conductivity (Dai et al., 2019) but low re-deposition of NH_3 volatilization and irrigation water requirement under cold weather (Yin et al., 2020; Yu et al., 2019). In contrast, early rice paddies in south China (e.g., the Pearl River Delta) may act as a N sink due to a low saturated hydraulic conductivity and a large irrigation water requirement in the subtropical climate. Terraced rice fields, located particularly in the Yunnan-Guizhou Plateau, southwest China, lead to N flows from upstream paddy plot to the downstream (Onishi et al., 2012). Hence, it is necessary to apply our assessment methodology for the whole terraced fields as an independent system to avoid the hydrological connectivity between the plots.

It should also be noted that the assessment methodology needs to cover both growing and fallow periods. During fallow period, rice fields are highly probable to be N sink for atmosphere and N source for waterbodies attributed to absence of fertilization and irrigation. Fallow season is only 20 days before rapeseed season at Jingzhou site, but may act as a significant role in northeast China, South Korea, and Japan where fallow seasons are usually around 200 days. Besides, involving rapeseed season into assessment would enhance both N sink for atmosphere and N source for waterbody, because of a lower NH_3 volatilization and a less irrigation demand for rapeseed growth (see Fig. S4 for results observed only in the first year). The sustainable N and water management we proposed would reinforce N sink for atmosphere and shift N source to sink for the both, but it might be a challenge to reduce N source for waterbody for the whole rice-rapeseed rotation, implying a significance for improving mitigation measures. Additionally, because of the negligible size of ditches and ponds at Jingzhou site, we did not take them into account in assessment of N source and sink in case study, which would lead to slight overestimation of N source or underestimation of N sink theoretically. However, rice field-ditch-pond system needs to be regarded as an integrated unit when this methodology was applied in other areas if the storage capacity of ditch-pond is large or can be expanded in the future.

The case study at Jingzhou site indicated that “4R-nutrient stewardship” was sufficient to shift rice field from a N source to a N sink. Combined with improved irrigation and drainage, “4R-nutrient stewardship” enhanced the N sink role for waterbodies even under the wet year climatic scenario. However, to encourage the smallholder farmers, who are typically with limited resources and knowledge, to adopt evidence-based management technologies is challenging mostly because of the lack of policy interventions (Cui et al., 2018). On one hand, operation costs and labor resources would be significantly increased when replacing urea with enhanced-efficiency fertilizers, changing fertilizer broadcasting to incorporation or deep placement, and shifting manual operations to automatic irrigation and drainage. On the other hand, to implement these key measures, a series of equipment are required for sustainable water management. More importantly, changing farmers’ habits requires more than scientifically sound and advanced technologies (Spielman et al., 2010). Vigorous campaign collaborations and engagement mechanisms are required, such as (1) identifying the key measures to maximize the N sink locally, (2) providing basic knowledge related to sustainable water and N management to progressive farmers, (3) developing innovative technology and management systems to be economically viable and readily adopted by farmers, (4) enabling these farmers to operate equipment, (5) increasing famer’s problem-solving skills, and (5) fostering input subsidy policies to encourage farmers applying these technology and management systems(Cui et al., 2018).

It should be noted that the applicable key measures differ by regions, depending on local environmental conditions as well as socio-economic level and farmers’ perception. For example, the decision of deep placement of fertilizer is a trade-off between environmental effects to atmosphere and waterbodies. The right fertilizer type varies across regions as well, and the applications of ditch and pond are flexible. For example, in northeast China, active drainage should be recycled back to rice field to prevent N runoff due to the use of pre-flooding, while deep placement of fertilizers should be avoided to reduce N leaching. In south China, N runoff loss was much higher, probably four times, than that in north China (Hou et al., 2016, 2018), hence ditch and pond systems surrounding rice field are necessary since they act as a “buffer” for the passive drainage induced by extreme precipitation. If applicable, reduction in fertilizer application rate and deep placement of fertilizers should be applied to decline NH_3 volatilization. In both east and west China, enhanced-efficiency fertilizers should be applied particularly in alkaline soils. Shallow-wet irrigation, instead of intermittent irrigation, could be an efficient approach to reduce leaching loss. Nonetheless, the double cropping rice might not be applicable attributed to high precipitation during early rice, especially from April to June. Subsurface tile drainage systems there could be equipped beneath the root zone particularly in the rice cropping areas with high saturated hydraulic conductivity.

Overall, a comprehensive methodology for assessing and regulating N source or sink of rice field for the environment could be applied in the other Asian countries where account for ~90% of global rice sown areas (FAOSTAT, 2017). Hence, to better assess and regulate the N source or sink of rice field, multiple improvements will be necessary upon our current methodology, such as: (i) establishing a nationally coordinated high-resolution field observation network that focuses on water and N budget of rice paddies as well as the records of fertilization, irrigation, and drainage practices; (ii) conducting well designed experiments for the whole rice field-ditch-pond system to quantify the sensitivity of N outputs and inputs to diverse management practices, and to identify the measures reducing in N outputs while avoiding pollution swapping; (iii) improving the process-based modeling system to accommodate the regional differences in N source or sink of rice fields, and to quantify the underlying mechanisms behind the empirical parameterization between diverse management practices and N outputs; and (iv) compiling a high-resolution dataset to understand current fertilizer application, irrigation, and drainage practice by farmers over rice growing seasons, which is beneficial for the nationwide assessments and the design of regulation plans.

Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2021.117122.

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