



Nitrogen balance in paddy fields under flowing-irrigation condition

Makoto Saiki · Thi Phuong Mai Nguyen · Junko Shindo · Kei Nishida

Received: 13 February 2019 / Accepted: 31 August 2019 / Published online: 8 October 2019
© The Author(s) 2019, corrected publication 2020

Abstract Flowing irrigation which drains a large volume of water is one of agricultural techniques for ensuring rice quality. In this study, the nitrogen input and output were characterised in paddy fields under flowing irrigation based on observation in Central Japan, and the estimated nitrogen loadings were compared to the reported values in traditional paddy fields under stagnant irrigation by using budget analysis. The annual water fluxes in the studied fields were calculated to be more than ten times larger than those in traditional fields. The concentrations of most nitrogen forms in surface drainage and subsurface drainage were detected at highest level during paddling periods, while those of nitrate and nitrite in subsurface drainage increased during non-irrigation periods. The total nitrogen inputs were at upper level (236–332 kg N ha⁻¹) of or larger (490–581 kg N ha⁻¹) than

the reported values under both flowing irrigation and stagnant irrigation, and the larger contribution of irrigation pathway was observed. Surface drainage (78.3–163.5 kg N ha⁻¹) and transport to underground system (73.1–210.4 kg N ha⁻¹) were significantly higher than reported values obtained from stagnant-irrigation paddy fields. The differences between input and output were thereby estimated and the large negative balance was attributed to the soil accumulation, which was distinctly detected in the field with presumably higher adsorption capacity. Therefore, assessing the effect of water flow on soil nitrogen accumulation as well as discharge is recommended by evaluating nitrogen balance in paddy field.

Keywords Rice cultivation · Water pollution · Budget analysis · Soil accumulation

M. Saiki
Graduate School of Medicine, Engineering and
Agriculture, University of Yamanashi, 4-4-37 Takeda,
Kofu, Yamanashi 400-0016, Japan

T. P. M. Nguyen
Institute of Environmental Technology, Vietnam
Academy of Science and Technology, 18 Hoang Quoc
Viet Road, Cau Giay, Hanoi, Vietnam

J. Shindo · K. Nishida (✉)
Interdisciplinary Centre for River Basin Environment
(ICRE), University of Yamanashi, 4-4-37 Takeda, Kofu,
Yamanashi 400-0016, Japan
e-mail: nishida@yamanashi.ac.jp

Introduction

Paddy fields cause nitrogen pollution in surface and subsurface water environments (Cho et al. 2000; Guo et al. 2004; Shinozaka et al. 2016). Nitrogen flow is detected in the paddy fields as several types of inputs or outputs. Inputs include fertiliser, irrigation, precipitation and biological nitrogen fixation, whereas outputs include the assimilation of rice, surface drainage and underground flow, denitrification, volatilisation, assimilation by other plants including

algae, and accumulation in soil (Takakai et al. 2017; Liang et al. 2007; Antonopoulos 2010). Based on the relation between the amount of applied chemical fertiliser and the loading of nitrogen discharge, Liang et al. (2007) observed increased amount of surface drained nitrogen (5.05, 11.78, 19.25 and 27.86 kg N ha⁻¹) and percolated nitrogen (9.07, 18.04, 25.00 and 33.22 kg N ha⁻¹) with increase in fertiliser amount (90, 180, 270 and 360 kg N ha⁻¹) in an experiment that was conducted in China. In contrast, in Korea, Cho and Han (2002) observed little changes in surface drainage loading (111, 101 and 129 kg N ha⁻¹) and percolation loading (19, 18 and 20) with increase in applied chemical fertiliser (155, 187 and 210 kg N ha⁻¹). In Japan, Sugimoto et al. (2008) observed that 78 kg N ha⁻¹ of applied fertiliser resulted in surface drainage loading of 41.6 kg N ha⁻¹ that was higher than the value reported by Liang et al. (2007) with similar or higher level of fertilisation. According to these researches, some cases showed that the output loading increased with an increase in input from fertiliser in the same field but others showed that the output was not directly related with the amount of fertiliser when the experimental results in different fields were compared. In addition, it was reported that the nitrogen outputs from paddy fields is dependent on the volume of irrigation water rather than the amount of chemical fertiliser (The Japanese Society of Irrigation, Drainage and Rural Engineering: JSIDRE 2001). The inputs and outputs are not directly connected, and paddy fields exhibit complicated nitrogen bioreactions, including mineralisation, nitrification and denitrification (Ishii et al. 2011). These bioreactions are affected by the physicochemical factors including temperature, pH and redox conditions in the vicinity of the paddy fields (Chowdary et al. 2004). Thus, to ensure sustainable water environment, it is important to estimate and evaluate the nitrogen loading considering all the processes that occur in paddy fields.

Recently, the budget analysis has been applied to identify the mechanism of nitrogen pollution in the water environment owing to paddy fields (Cho et al. 2000; Liang et al. 2007; Zhang et al. 2013). The nitrogen budget can be used for comprehensively evaluating nitrogen loading by considering multiple inputs and outputs. In majority of the previous studies, however, irrigation, biological fixation, ammonium volatilization, denitrification, assimilation by other plants and accumulation in the soil were rarely evaluated in nitrogen

budget estimation. Roger and Ladha (1992) estimated biological N₂ fixation using blue–green algae and *Azolla* in wetland rice fields, which were 0–80 and 10–50 kg N ha⁻¹ in a rice cropping season, respectively. The contributions of volatilization and denitrification fluctuate responding to various physicochemical factors such as pH and percolation rate. Antonopoulos (2010) calculated the amount of nitrogen uptake using algae, which resulted in 9.4% of total input NH₄-N and 15.7% of total input NO₃-N. The identification of nitrogen storage in soil is necessary for managing the soil nutrient (Takakai et al. 2017).

In Japan, several agricultural techniques have been developed for improving the rice quality (Morita 2008) and for reducing the loading of nutrients from paddy fields (Haruta et al. 2015). Flowing irrigation has been applied to maintain the ponded water at a low temperature for ensuring high rice quality (Nishida et al. 2015) and to maintain a constant water depth in the paddy fields, where the soil has a high percolation rate (Takeda et al. 1991). A large volume of water is drained in flowing irrigation-type paddy. The results obtained by Yoshinaga et al. (2007) implied that runoff nitrogen was affected more by the irrigation water volume than by the area of the paddy fields. Therefore, the water environment may be notably impacted by the nitrogen discharge under flowing irrigation conditions. However, we have observed only a limited number of reports on nitrogen discharge evaluation (Takeda et al. 1991; Yamazaki et al. 2013; Hama et al. 2015) and, to our knowledge, no report on the nitrogen budget for flowing irrigation paddy fields.

This study intended to characterise the nitrogen input and output in paddy fields under flowing irrigation in Japan. The nitrogen loadings to water environments were estimated based on field observation and then the nitrogen balances were evaluated using budget analysis, and the water-derived nitrogen flow of the flowing irrigation-type paddy fields was compared with the traditional paddy fields under stagnant irrigation-type.

Methodology

Study area

The study area located at 35.6°N 138.5°E in Kai City, Yamanashi Prefecture, Japan, includes two paddy

fields, E1 (0.11 ha: 37 × 30 m; soil depth: 55 cm) and W2 (0.11 ha: 33 × 33 m; soil depth: 10 cm), managed by a farmer (Table 1). This research experiment was conducted from 2013 to 2015, and the fields were detailed in a previous report (Nguyen et al. 2015). The farmer applied organic fertiliser in early spring only in the first year of our experiment, and chemical fertiliser was used for a basal fertiliser before the first irrigation every year. The water management type of both the fields was flowing irrigation. The irrigation water was supplied to each paddy field continuously through the inlet gate systems from the end of May to the end of September (irrigation period). However, in July, the farmer stopped irrigation for approximately 1 week to dry the soil of the paddy fields. After the final drainage, no irrigation water flew until next spring (non-irrigation period). Further, the ponded water was directly drained from the paddy fields to a ditch through outlets (surface drainage) or was percolated into the soil. The percolated water was partly discharged via pipes installed below the paddy soil (subsurface drainage). E1 had four such outlets for subsurface

drainage at depths of 51, 70, 75 and 78 cm from the soil surface in the rice paddy, and the outlet was at a 77 cm depth in W2.

Field survey and analysis

The E1 and W2 paddy fields were surveyed at weekly intervals from 21 May, 2013, to 20 December, 2015, and at hourly intervals during paddling, mid-summer drainage, final drainage and heavy rain events. During the survey, the acidity and electric conductivity (EC) of irrigation, surface drainage and subsurface drainage water, the water level of ponded water and discharge of surface drainage and subsurface drainage water were measured on site. The surface drainage, subsurface drainage, irrigation and soil water were collected during irrigation period, and the surface drainage and subsurface drainage water samples were collected at non-irrigation period too. Surface soil, fertiliser, rice, duckweed and algae as solid samples were also collected. Soil samples were obtained after basal fertilisation (nine from E1 and five from W2 in 2013;

Table 1 Agricultural practices of the experimental fields and information of the fertiliser and the rice yield

Period	Year	Date	Activity	Note about the fertiliser and the rice yield (nitrogen content)
Non-irrigation	2013	Feb. – Mar.	First fertilisation	Organic fertiliser; 0.90%N; 2000 kg ha ⁻¹ for both fields
		4 May	Basal fertilisation	Chemical fertiliser; N:P:K = 8:8:8; 600 kg ha ⁻¹ for both fields
Irrigation	2013	21 May	Pre-flooding, paddling	
		25 May	Transplanting	
		18 – 25 Jul.	Mid-summer drainage	
		19 Sep.	Final drainage	
Non-irrigation	2014	12 Oct.	Harvesting	Rice grain: 5406 kg ha ⁻¹ in E1 (0.88%N); 5785 kg ha ⁻¹ in W2 (0.90%N)
		4 May	Basal fertilisation	Chemical fertiliser; N:P:K = 8:8:8; 900 kg ha ⁻¹ for both fields
Irrigation	2014	20 May	Pre-flooding, paddling	
		24 May	Transplanting	
		20 – 27 Jul.	Mid-summer drainage	
		19 Sep.	Final drainage	
Non-irrigation	2015	11 Oct.	Harvesting	Rice grain: 5406 kg ha ⁻¹ in E1 (0.88%N); 6427 kg ha ⁻¹ in W2 (0.96%N)
		4 May	Basal fertilisation	Chemical fertiliser; N:P:K = 10:12:12; 727 kg ha ⁻¹ for E1, 545 kg ha ⁻¹ for W2
Irrigation	2015	27 May	Pre-flooding, paddling	
		31 May	Transplanting	
		17 – 21 Jul.	Mid-summer drainage	
		23 Sep.	Final drainage	
Non-irrigation	2015	13 Oct.	Harvesting	Rice grain: 5036 kg ha ⁻¹ in E1 (0.88%N); 5727 kg ha ⁻¹ in W2 (0.84%N)

seven from E1 and three from W2 in 2014; four from E1 and four from W2 in 2015) and after harvesting (two samples from E1 and four from W2 in 2014; four from E1 and four from W2 in 2015). Fertiliser samples (one sample of organic fertiliser in 2013 and one sample of chemical fertiliser in each of the 3 years) and rice samples (four samples from E1 and four from W2 in 2013; six from E1 and four from W2 in 2014; three from E1 and four from W2 in 2015) were obtained from the farmer. Three samples of duckweed and algae were skimmed from an area measuring 10×12 cm on the pond water surface in September 2018 and were further stored in plastic bags. Rainwater samples were collected 11 times in 2013 and 2015 at the University of Yamanashi (5 km north of the study area). After sampling, the concentrations of dissolved total nitrogen (DTN), ammonium nitrogen ($\text{NH}_4\text{-N}$), nitrite nitrogen ($\text{NO}_2\text{-N}$) and nitrate nitrogen ($\text{NO}_3\text{-N}$) in the water samples were measured, and the dissolved organic nitrogen (DON) concentration was calculated by subtracting the $\text{NH}_4\text{-N}$, $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$ from DTN. The nitrogen content in the surface soil and rice samples and $\delta^{15}\text{N}$ in the soil samples were also measured. All the chemical analyses were conducted according to a previous report (Nguyen et al. 2015). The samples of duckweed and algae were dried over night then weighed.

The daily weather data (precipitation, temperature, wind speed and humidity) recorded at Kofu meteorological station, which is located approximately 6 km southwest of our study area, were obtained from the Japan Meteorological Agency (JMA 2016).

Estimation of the water balance

Water balance was estimated on a daily basis by

$$\Delta WD = I + P - D - B - G - E, \quad (1)$$

where ΔWD denotes the daily change in the water depth of the ponded water, and I , P , D , B , G and E denote the daily flux (mm day^{-1}) of irrigation, precipitation, surface drainage, subsurface drainage, percolation to groundwater and evapotranspiration, respectively. ΔWD , D and B were obtained by the field survey, and the values for the unobserved periods were filled by the average values of observations before and after. E was calculated from the local temperature, wind speed and humidity data using the ET_0 calculator version 3.1 (Food and Agriculture Organization of the

United Nation: FAO 2015). The permeability coefficient of Darcy's Law during the irrigation periods was estimated by using hourly observation ΔWD , D and E , that were recorded on the day without irrigation flow and precipitation. Such observation was conducted four times for E1 and five times for W2, and the calculated permeability coefficients were averaged and used for estimating total permeated water flux. G during irrigation periods was then calculated by subtracting B from total permeated water. G during the non-irrigation periods was calculated by subtracting the total B and total E from P in case of a rainfall event that started from December 11, 2015. Finally, I was calculated based on Eq. (1) from other fluxes measured or estimated above.

Estimation of the nitrogen budget

The nitrogen budget (N_{budget}) was estimated by

$$N_{budget} = N_{fer} + N_{irri} + N_{pre} + N_{fix} - (N_{rice} + N_{drain} + N_{sub} + N_{per} + N_{vol} + N_{den} + N_{other}), \quad (2)$$

where N_{fer} , N_{irri} , N_{pre} and N_{fix} denote the amounts of nitrogen inputs from fertiliser, irrigation, precipitation and biological fixation, respectively; N_{rice} , N_{drain} , N_{sub} , N_{per} , N_{vol} , N_{den} and N_{other} denote the amounts of nitrogen outputs by rice uptake, surface drainage, subsurface drainage, percolation, ammonia volatilisation, denitrification and uptake by other plants, respectively. N_{irri} , N_{pre} , N_{drain} , N_{sub} and N_{per} were calculated by multiplying the daily water flux with the concentration of each form of nitrogen. The concentrations in unobserved days were interpolated by the average of the observed values before and after. The nitrogen concentration in subsurface drainage was used for calculating N_{sub} with all nitrogen forms and N_{per} with only nitrite and nitrate. The multiplication of the nitrogen content with the amount of applied fertiliser, yield of rice plant and amount of duckweed and algae generated N_{fer} , N_{rice} and N_{other} , respectively. The nitrogen content of fertiliser and rice grain, the amount of applied fertiliser and the rice grain yield were shown in Table 1. The ratio of straw to grain in our study were assumed as 0.96 that was the average of values in references (Ha et al. 2001; Zhang et al. 2012). The amounts (dry weight) of duckweed and algae were measured as 33 g m^{-2} and 0.26 g m^{-2} ,

respectively. The values of 3.1% (Li et al. 2009) and 3.3% (Meltem et al. 2008) were applied for the nitrogen content in duckweed and algae, respectively. N_{fix} was assumed to be 50 kg N ha⁻¹ in a crop season according to the maximum value for *Azolla* in the paddy fields as reported by Roger and Ladha (1992). Hayashi et al. (2006) suggested that N_{vol} depends on the amount of chemical fertiliser and pH value of ponded water, then they proposed volatilization ratio to the applied chemical fertiliser ($1.4 \pm 0.8\%$) estimated based on the experiments in lysimeter plots for paddy fields in central Japan. In this study, the pH value of ponded water was similar to that obtained by Hayashi et al. (2006), and the same ratio was used for the calculation of N_{vol} for each year. N_{den} was calculated by multiplying the NO₃-N concentrations in ponded water by its depths and denitrification rate constant (0.13 day⁻¹) that was estimated on the basis of a one-order reaction by Liang et al. (2007) for research in Jiaxing, China.

Results

Water balance

The estimated water balances are presented in Fig. 1. For inflows to E1 and W2, irrigation was observed to constitute a 30–45 times and 13–16 times larger proportion than precipitation, respectively. For outflows, percolation, surface drainage and subsurface drainage were the main components of E1. On the other hand, in outflows for W2, both of percolation and surface drainage constituted more than 40% of the total outflow and subsurface drainage constituted less than 10% of the total outflow, except for 2015. In W2 in 2015, surface drainage was considerably low

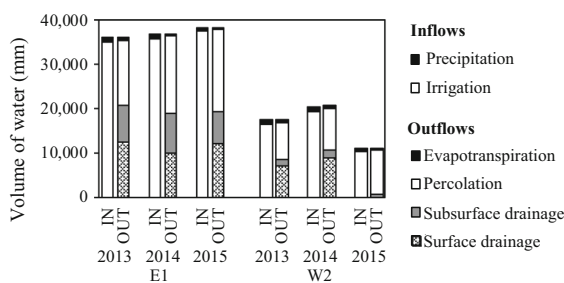


Fig. 1 The annual water balance for each rice paddy

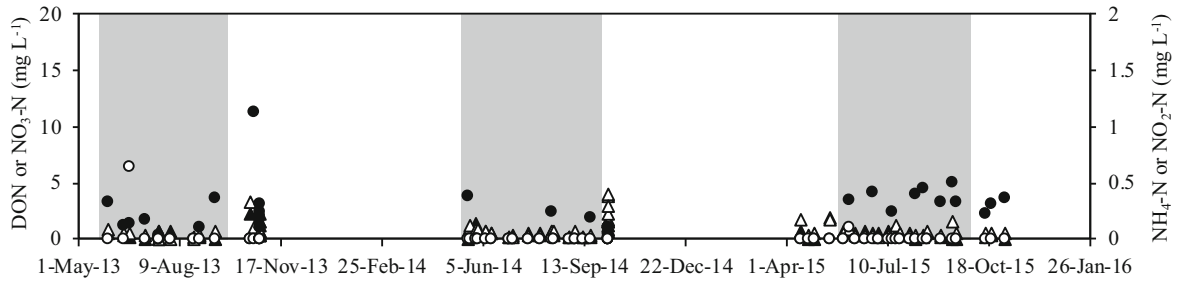
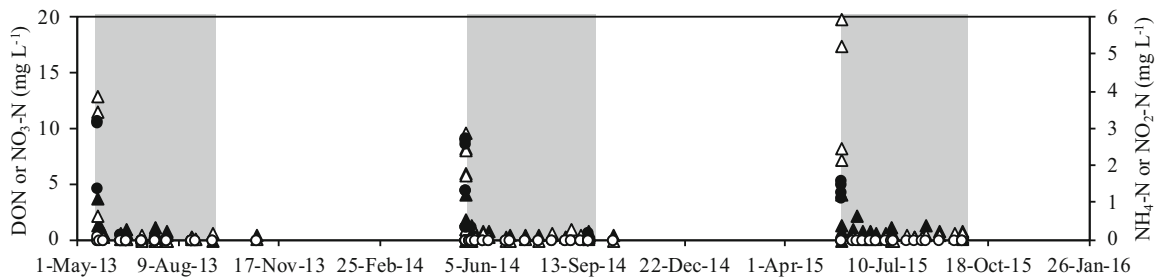
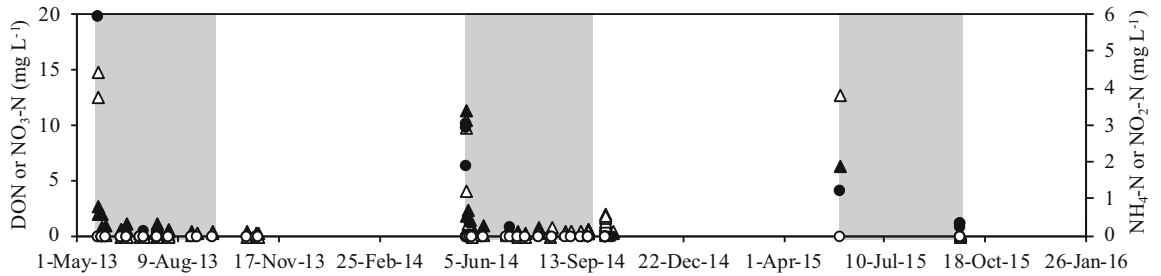
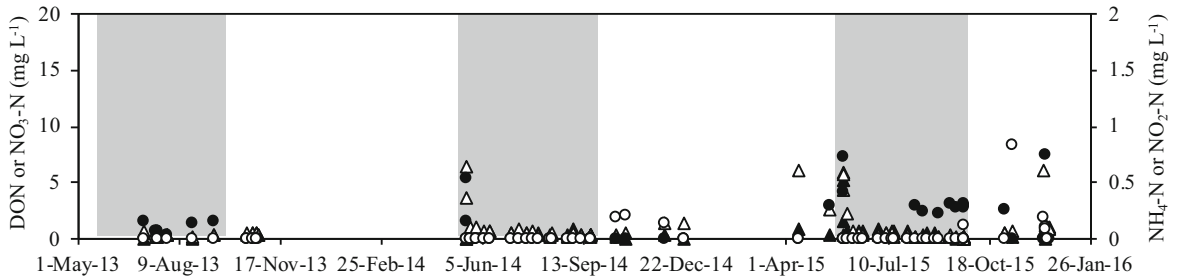
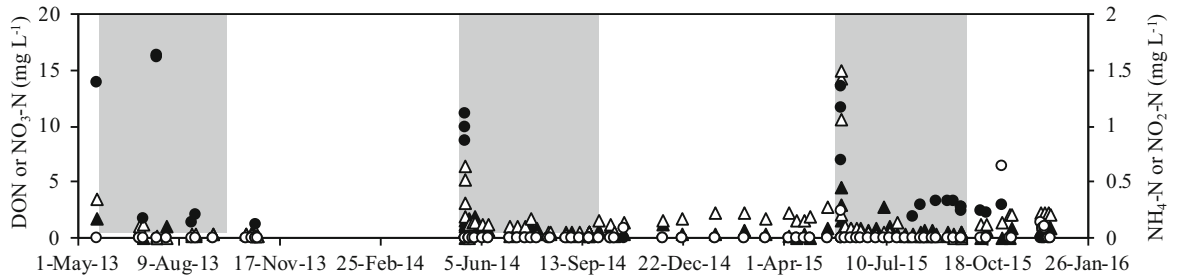
because the farmer more tightly closed the drainage gate than that in other years. Evapotranspiration was considerably small (< 3.6% of total outflow) in both the fields. The annual water flux for E1 was about twice as much (36,010–38,035 mm) as for W2 (11,265–20,522 mm), which exhibited high values for subsurface drainages and for percolation. In our study fields, the permeability coefficients were estimated as 196 ± 46 mm day⁻¹ in E1 and 80 ± 63 mm day⁻¹ in W2. A considerable water flux was thus estimated in total. Surface drainage constituted the second largest outflow, averaging 31.2% of the total outflow for E1 and 42.2% of that for W2.

Nitrogen concentrations in water samples

The nitrogen concentrations in rainwater were at lower level (DON: 0.0 mg L⁻¹; NH₄-N: 0.29 mg L⁻¹; NO₂-N: 0.0028 mg L⁻¹; NO₃-N: 0.12 mg L⁻¹) within the range previously reported in Japan: 0.21–4.0 mg L⁻¹ for NO₃-N and 0.26–2.5 mg L⁻¹ for NH₄-N (Kyaw et al. 2005; Yoshinaga et al. 2004; Takeda et al. 1991). The temporal variations of the nitrogen concentration of each form in irrigation and in surface and the subsurface drainage obtained by analysing the water samples are depicted in Fig. 2. The maximum nitrogen concentrations in irrigation water were 1.44, 1.56 and 0.51 mg L⁻¹ for DON, NO₃-N and NH₄-N, respectively. In this study, NO₂-N concentration was detected only two times in irrigation periods. All the forms of nitrogen except NO₂-N in both surface and subsurface drainages were high at the paddling time and after paddling, they decreased rapidly. However, ~ 0.3 mg L⁻¹ of NH₄-N was detected in subsurface drainage even after the paddling period, and NO₂-N and NO₃-N in subsurface drainage increased during the non-irrigation periods, whereas undetected or at low level during irrigation periods.

Nitrogen balance

The calculated input and output values based on nitrogen balance are depicted in Fig. 3. In case of nitrogen inputs, irrigation was constantly the largest, and the precipitation was significantly small (< 1.5% of total input) in both E1 and W2. The total input of E1 was twice as large as that of W2 because of large irrigation water flux. The outputs for E1 were distributed among rice, surface drainage, subsurface

(a) Irrigation water**(b) Surface drainage in E1****(c) Surface drainage in W2****(d) Subsurface drainage in E1****(e) Subsurface drainage in W2**

◀ **Fig. 2** Change in nitrogen concentration for each form of nitrogen. Close triangle: DON; close circle: NH₄-N; open triangle: NO₃-N; open circle: NO₂-N; grey zone, irrigation period

drainage and percolation; the contribution of subsurface drainage for W2 was only 6.7–7.1% of the total output, and rice, drainage and percolation were observed to dominate total output of W2. The surface drainage, subsurface drainage and percolation for E1 were within 91.5–163.5 kg N ha⁻¹, 72.4–98.3 kg N ha⁻¹ and 74.9–112.1 kg N ha⁻¹, and those for W2 except for 2015 were within 78.3–113.0 kg N ha⁻¹, 17.5–25.1 kg N ha⁻¹ and 55.6–94.0 kg N ha⁻¹, respectively. The percolations of E1 and W2 were similar while the nitrogen that was transported to the underground system (by subsurface drainage and percolation) in E1 (147.3–210.4 kg N ha⁻¹) having higher water permeability was twice that observed in W2 (73.1–119.1 kg N ha⁻¹). Nitrogen assimilated by rice in E1 (66.5–75.4 kg N ha⁻¹) was ~ 30% smaller than that in W2 (86.3–98.4 kg N ha⁻¹) for all the years. The emissions to the atmosphere from both fields by volatilisation and denitrification were low. In W2 in 2015, surface drainage was considerably low due to the tight control of surface drainage water output as described before; however, the other outputs remained similar with those in 2013 and 2014. Eventually, the total output of E1 was 1.3, 1.1 and 2.3 times larger than that of W2 in 2013, 2014 and 2015, respectively.

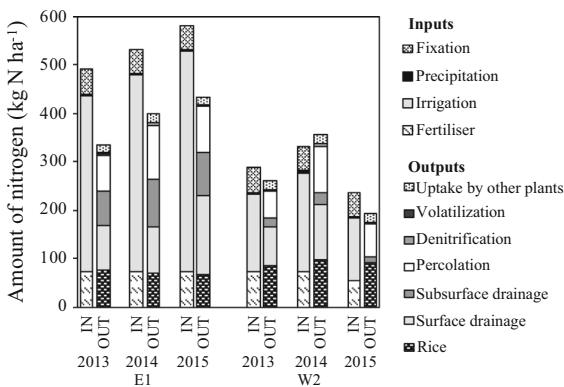


Fig. 3 The annual nitrogen budget for each paddy field

Discussion

Evaluation of water flux

Previous researchers reported ten times smaller water flux than that exhibited by this study under both stagnant irrigation and flowing irrigation (Table 2). The surface drainage fluxes for E1 and W2 were 31.2% and 42.2% of the total outflux, respectively, and were within the ranges of the previously reported values for both the two irrigation types: 29.8–45.2% of the total outflux for flowing-irrigation type and 7.9–73.4% of the total outflux for stagnant-irrigation type. The average percolation rate was 2 mm day⁻¹ as calculated by Zhao et al. (2009) and 3.25 mm day⁻¹ as observed by Cho and Han (2002) in stagnant-irrigation type. In flowing-irrigation type, Takeda et al. (1991) reported the water requirement (based on evapotranspiration and percolation) to be 15–23 mm day⁻¹, and Hama et al. (2015) estimated the percolation rate to be 30 mm day⁻¹. In our study, higher percolation rates were exhibited when compared to these previous studies (139 mm day⁻¹ in E1 and 76 mm day⁻¹ in W2 in average during the irrigation periods). The average percolation fluxes were 45.3% and 45.8% of total outflux for E1 and W2, respectively, and were also within the ranges of previous values: 42.3–66.2% of total out flux for flowing irrigation and 4.8–67.3% of total out flux for stagnant irrigation. In the flowing irrigation, the ranges for surface drainage and percolation were smaller than those in stagnant irrigation, implying the stable water discharge of not only surface drainage but also percolation under flowing condition.

Characterisation of nitrogen concentration

Hama et al. (2015) observed NO₃-N (0.53–0.73 mg L⁻¹) and Total Dissolved Nitrogen (0.7–1.7 mg L⁻¹) in irrigation water and NH₄-N and NO₂-N were below the detection limit, and the maximum DON concentration was estimated as 1 mg L⁻¹. On the other hand, NO₃-N and NH₄-N of irrigation water were detected: average of 0.66 and 0.16 mg L⁻¹ in the paddy field located near industrial park (Takeda et al. 1991). Both of the paddy fields of this study were irrigated by waters containing nitrogen concentrations within the range of those of other studies in Japan. Previous reports also showed similar

Table 2 Water balances of paddy fields from literatures

Irrigation type	Inflow (mm)			Outflow (mm)				Balance (%)	Calculation days (days)	Literature
	I	P	Total	D	G	E	Total			
Stagnant	967	1510	2477	1324	618	491	2433	1.8	365	Cho et al. (2000)
	816	1231	2048	1027	561	452	2040	0.4	294	Cho and Han (2002)**
	2176	1595	3771	2768	183	821	3771	0.0	365	Sugimoto et al. (2008)**
	1781	522	2303		1699*	528	2227	3.3	76	Feng et al. (2004)
	906	589	1495	255	808	463	1495	0.0	124	Hama et al. (2011)**
	1156	660	1816	144	1222	451	1816	0.0	118	Hitomi et al. (2007)
	–	750	750	502	201	–	703	6.2	138	Zhao et al. (2012)**
Flowing	4007	509	4516	1357	3018	185	4560	–1.0	103	Hama et al. (2015)
	3735	926	4661	2105	1970	584	4659	0.0	138	Takeda et al. (1991)**

*Sum of drainage and infiltration; **Average of the reported values

variations in which the nitrogen concentrations were high at the paddling time then decreased in surface drainage (Sugimoto et al. 2008; Takeda et al. 1991) and percolation (Sugimoto et al. 2008) regardless of irrigation water management type. On the other hand, during non-irrigation period, Takeda et al. (1991) reported the increase of total nitrogen and $\text{NO}_3\text{-N}$ concentrations in both subsurface drainage and percolation caused by enhancement of oxidation under dry soil condition.

Comparison of nitrogen balance between different irrigation types

The study results for nitrogen loading and nitrogen balance within the paddy fields are summarised in Table 3. According to previous reports, the total input for flowing-irrigation type was 222 kg N ha^{-1} and was $85\text{--}270 \text{ kg N ha}^{-1}$ in case of stagnant-irrigation type; the nitrogen inputs for both the irrigation types were similar. In this study, the total inputs were $490\text{--}581 \text{ kg N ha}^{-1}$ in E1 and $236\text{--}332 \text{ kg N ha}^{-1}$ in W2 (Fig. 3). Comparing our results with the previous researches, although the water volume differed by ten times, the total input amount of nitrogen in E1 was twice as large as the reported values, and that in W2 was at upper level of reported results. The inputs through irrigation were the only factor being much larger than previous reports in both the fields. With respect to outputs, the nitrogen runoff through surface drainage was significantly higher than reported results under stagnant irrigation. Cho and Han (2002)

estimated an exceptionally large amount of nitrogen in surface drainage ($118.7 \text{ kg N ha}^{-1}$) under stagnant irrigation in Korea, in which the total nitrogen remained at higher concentration level in ponded water and eventually in surface drainage water after fertilisation than that obtained in our study under flowing irrigation. The subsurface drainage was reported as $39.4\text{--}47.7 \text{ kg N ha}^{-1}$ under stagnant irrigation only by Takakai et al. (2017). In this study under flowing irrigation, the nitrogen loss by subsurface drainage ranged from $21.3 \text{ kg N ha}^{-1}$ in W2 to $86.9 \text{ kg N ha}^{-1}$ in E1. These results imply that the irrigation type, i.e. flowing and stagnant irrigation, does not simply affect the nitrogen loading, controlled by both nitrogen concentration and water flux, through surface drainage and subsurface drainage. The output of percolation was similar to that observed in a previous report under flowing irrigation (Takeda et al. 1991), and higher than those under stagnant irrigation. As the result, the total output amounts of nitrogen in the present study were estimated to be at maximum level compared to the reported values, owing to contribution of large water flux under flowing irrigation.

In other studies listed in Table 3, nitrogen balances are evaluated with multiple inputs and outputs of waterflow, rice uptake and air emissions. The rice uptake was not considered as a major contributor to total nitrogen outputs by Takeda et al. (1991), Cho and Han (2002), Sugimoto et al. (2008) and Zhao et al. (2012). These studies did not account for the nitrogen assimilated by rice because they focused only on the

Table 3 Comparative summary of estimated nitrogen balances for paddy fields

Input (kg N ha ⁻¹)		Output (kg N ha ⁻¹)										IN-OUT (kg N ha ⁻¹)	Balance (%)	Irrigation type	References		
N _{fer}	N _{iri}	N _{pre}	N _{fix}	Total	N _{rice}	N _{drain}	N _{sub}	N _{per}	N _{vol}	N _{den}	N _{other}					N _{acc}	Total
72.7	408.0	4.1	50.0 ^a	534.8	70.6	116.4	86.9	93.3	3.6 ^a	1.0 ^a	17.5	-	389.3	145.5	27.2	Flowing	This study_E1 ^f
72.0	183.1	4.5	50.0 ^a	309.6	92.4	95.6	21.3	74.8	4.7 ^a	1.0 ^a	17.5	-	307.3	2.3	0.7	Flowing	This study_W2 ^f
120.0	-	-	-	120.0	44.0	-	-	35.7 ^d	13.3	-	-	-	27.0	120.0	0.0	Stagnant	Chowdhary et al. (2004) ^f
120.0	-	-	-	120.0	49.1	-	-	47.2 ^e	-	-	-	-	22.7	119.0	1.0	Stagnant	Chowdhary et al. (2004) ^f
69.0	11.3	4.5	-	84.8	73.3	5.1	-	9.1	-	-	-	-	87.5	-2.7	-3.2	Stagnant	Hama et al. (2011) ^f
79.5	-	8.8 ^a	43.0 ^a	131.3	96.5	-	-	-	1.1 ^a	21.6 ^{ab}	-	-	119.2	12.1	9.2	Stagnant	Katayanagi et al. (2013)
100.0	-	-	-	100.0	99.1	0.0	-	1.3	6.6	0.2	-	-	126.5	-7.3	-7.3	Stagnant	Zhao et al. (2009)
300.0	-	-	-	300.0	180.1	0.0	-	1.9	35.6	0.5	-	-	283.2	31.9	12.8	Stagnant	Zhao et al. (2009)
90.0	-	-	-	90.0	35.7	5.1	-	9.1 ^c	26.5	3.9	-	-	90.0	0.0	0.0	Stagnant	Liang et al. (2007)
180.0	-	-	-	180.0	80.7	11.8	-	18.0 ^c	47.8	7.3	-	-	180.0	0.0	0.0	Stagnant	Liang et al. (2007)
270.0	-	-	-	270.0	108.6	19.3	-	25.0 ^c	72.7	10.1	-	-	270.0	0.0	0.0	Stagnant	Liang et al. (2007)
360.0	-	-	-	360.0	137.7	27.9	-	33.2 ^c	103.6	14.9	-	-	360.0	0.0	0.0	Stagnant	Liang et al. (2007)
160.0	96.0	13.5	0.0	269.5	239.0	0.0	-	6.3	14.0	80.5	-	-	339.8	-70.3	-26.1	Stagnant	Kyaw et al. (2005) ^f
70.0	2.9	16.3	20.0	109.3	65.1	6.4	39.4	-	1.0 ^a	22.0 ^{ab}	-	-	44.0	65.6	59.8	Stagnant	Takakai et al. (2017)
70.0	3.0	16.3	20.0	109.3	70.3	6.5	45.7	-	1.0 ^a	22.6 ^{ab}	-	-	26.1	83.3	76.2	Stagnant	Takakai et al. (2017)
70.0	3.0	16.3	20.0	109.3	75.1	7.9	47.7	-	1.0 ^a	22.2 ^{ab}	-	-	50.5	58.8	53.8	Stagnant	Takakai et al. (2017)
119.1	90.4	12.2	-	221.7	-	43.8	-	95.0	-	-	-	-	138.8	-	-	Flowing	Takeda et al. (1991)
77.7	7.9	12.6	-	98.1	-	41.7	-	2.1	-	-	-	-	43.7	-	-	Stagnant	Sugimoto et al. (2008) ^f
184.0	25.3	34.7	-	244.0	-	118.7	-	19.0	-	-	-	-	137.7	-	-	Stagnant	Cho and Han (2002) ^f
300.0	-	-	-	300.0	-	14.6	-	4.7	-	-	-	-	19.2	-	-	Stagnant	Zhao et al. (2012) ^f

N_{acc}: nitrogen accumulation in the soil

^aEstimated or published value

^bN_{den} including N₂O emission

^cN_{per} including lateral seepage

^dSum of N_{per} and N_{den}

^eSum of N_{per}, N_{vol} and N_{den}

^fAverage of the reported values and average of the values from this study in 2013–2015 for E1 and in 2013–2014 for W2

estimation of nitrogen loading by water flows. Additionally, the uptake by other plants was not considered in all of the previous reports which studied nitrogen balance in paddy field. In Kyaw et al. (2005), there was a large negative balance between the total input and the total output because of the high nitrogen removal capacity owing to the high nitrogen uptake by the whole rice plant body, high denitrification activity and low water flow to avoid surface water drainage. In our study, to the contrary, the large positive balance was found in E1. We assumed these differences to be attributed to the accumulation in the soil, because we considered the conceivable other major factors for outputs. The amount of accumulated nitrogen was estimated to be 27.2% of the total input for E1 and 0.7% of that for W2 by performing nitrogen budget analyses. Takakai et al. (2017) studied the nitrogen loss in a field with upland-paddy rotation and different histories of manure application by measuring the change in the soil nitrogen content and found soil nitrogen was significantly decreasing. To the contrary, Zhao et al. (2009) observed the positive amount of residual nitrogen (19.2% and 21.7% of chemical fertiliser) determined using the ^{15}N tracing method with rice–wheat rotation in China. In addition, Chowdary et al. (2004) and Liang et al. (2007) also reported the nitrogen left in the soil as 8–20% of the total input with a balanced nitrogen amount. Compared with these positive accumulations, our nitrogen balance attributed to soil accumulation in E1 was relatively larger. For identifying the soil characteristics, we measured the nitrogen contents and stable isotope ratios (Fig. 4). The isotope ratios of the surface soil nitrogen were slightly different ($p < 0.05$). The nitrogen content in the surface soil, however, was demonstrated to be significantly different ($p < 0.01$) between E1 and W2: higher in E1 than in W2 implying the higher potential of soil adsorption in E1, and it showed the increasing tendency during the period of our experiment in the both field. In addition, the depth of the ploughed soil in E1 (55 cm) was greater than that in W2 (10 cm), and it may also cause the significant nitrogen accumulation in E1. Previous studies have reported that the accumulation rate observed in a field would increase with increasing application of chemical fertilisers (Liang et al. 2007; Zhao et al. 2009). However, E1 exhibited a higher accumulation than other studies in Table 3, in some of which the amount of applied fertiliser is much higher

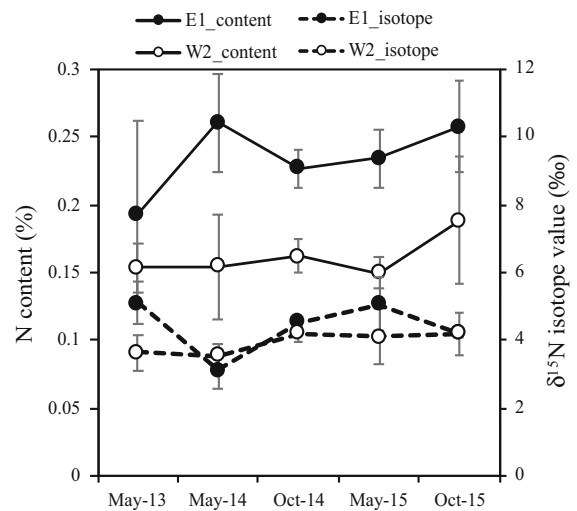


Fig. 4 Changes in nitrogen content and in the $\delta^{15}\text{N}$ isotope value of soil for each paddy field

than that in E1. With respect to total input, E1 was largest because of high nitrogen input by flowing irrigation. The nitrogen accumulation in soil may be enhanced not only by the amount of applied fertiliser but also by the water flow characteristics.

Conclusions

In this study, the nitrogen balances for two paddy fields were estimated under flowing-irrigation condition using four factors as inputs and seven factors as outputs. The observed fields exhibited high percolation rates because of the installation of subsurface drainage. The calculated annual water flows were observed to be more than 10 times larger than that observed in previous reports. Regarding the changes in nitrogen concentration in water over time, it rapidly decreased after paddling in both surface and subsurface drainage waters. The $\text{NO}_3\text{-N}$ and DON concentrations constituted 43% and 47% of the dissolved nitrogen in irrigation water, respectively. Furthermore, the $\text{NH}_4\text{-N}$ concentration was also detected even though majority of the previous studies did not detect it in irrigation water. The sizes of the nitrogen balances were near the higher levels or much higher than the levels that were reported in previous studies. Notably, there was a large difference in nitrogen input via irrigation water between our study and previous

studies. The nitrogen balances in our study fields showed large difference between the total input and the total output: the positive balance was considered to be caused by not taking nitrogen accumulation in soil into account. According to previous researchers, the nitrogen remaining in the soil was related to the amount of applied fertiliser. However, the fertiliser rates in our study fields were not higher level compared with the experimental fields in other studies. Therefore, in addition to effect of fertilizer application, the effect of nitrogen input via water flow on soil accumulation as well as nitrogen discharge to water environment is to be assessed by evaluating the nitrogen balances for better control of environmental quality.

Acknowledgements We are grateful to Mr. Okamoto Takehiro for his help in the field as well as in the laboratory. We are also grateful to Dr. Ishidaira Hiroshi and Dr. Nakamura Takashi for assessing the research methodology. We would like to thank Mr. Ootogro Kohsi for kindly providing access to his paddy fields. This study was financially supported by Grant-in-Aid for Scientific Research (No. 15K06270) from Japan Society for the Promotion of Science (JSPS) and by Support for Reginal Research from University of Yamanashi.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Antonopoulos VZ (2010) Modelling of water and nitrogen balances in the ponded water and soil profile of rice fields in Northern Greece. *Agric Water Manag* 98:321–330. <https://doi.org/10.1016/j.agwat.2010.08.026>
- Cho JY, Han KW (2002) Nutrient losses from paddy field plot in central Korea. *Water Air Soil Pollut* 134:215–228. <https://doi.org/10.1023/A:1014119807982>
- Cho JY, Han KW, Choi JK (2000) Balance of nitrogen and phosphorus in a paddy field of Central Korea. *Soil Sci Plant Nutr* 46(2):343–354. <https://doi.org/10.1080/00380768.2000.10408789>
- Chowdary VM, Rao NH, Sarma PBS (2004) A coupled soil water and nitrogen balance model for flooded rice fields in India. *Agric Ecosyst Environ* 103:425–441. <https://doi.org/10.1016/j.agee.2003.12.001>
- FAO (2015) ET0 Calculator. FAO Databases & Software. <http://www.fao.org/land-water/databases-and-software/eto-calculator/en/>. Accessed 16 October 2015
- Feng YW, Yoshinaga I, Shiratani E, Hitomi T, Hsesebe H (2004) Characteristics and behaviour of nutrients in a paddy field area equipped with a recycling irrigation system. *Agric Water Manag* 68:47–60. <https://doi.org/10.1016/j.agwat.2004.02.012>
- Guo HY, Zhu JG, Wang XR, Wu ZH, Zhang Z (2004) Case study on nitrogen and phosphorus emissions from paddy field in Taihu region. *Environ Geochem Health* 26:209–219. <https://doi.org/10.1023/B:EGAH.0000039583.71423.b4>
- Ha SR, Dung PA, Lee BH (2001) Impacts of agrochemical fertilizer on the aquatic environment of paddy fields in Vietnam. *Water Sci Technol* 43(5):193–202
- Hama T, Nakamura H, Kawashima S, Kaneki R, Mitsuno T (2011) Effects of cyclic irrigation on water and nitrogen mass balances in a paddy field. *Ecol Eng* 37:1563–1566. <https://doi.org/10.1016/j.ecoleng.2011.03.032>
- Hama T, Jikumuru C, Kobayashi T, Kawagoshi Y, Shima T, Fujimi T (2015) Potential of groundwater recharge and nitrogen removal by a paddy field in the middle area Shirakawa River Watershed in Kumamoto. *IDRE J* 299:II_89–II_93. https://doi.org/10.11408/jsidre.83.ii_89 (in Japanese)
- Haruta S, Sudo M, Eguchi S, Okubo T, Kuroda H, Takeda I, Fujiwara T, Yamamoto T, Hitomi T, Shiratani E, Yokota K, Inoue T (2015) Effluent N, P and COD loads from paddy fields in Japan: a critical review. *J Jpn Soc Water Environ* 38(4):81–91. <https://doi.org/10.2965/jswse.38.81> (in Japanese)
- Hayashi K, Seiichi Nishimura S, Yagi K (2006) Ammonia volatilization from the surface of a Japanese paddy field during rice cultivation. *Soil Sci Plant Nutr* 52:545–555. <https://doi.org/10.1111/j.1747-0765.2006.00053.x>
- Hitomi T, Yoshinaga I, Miura A, Hamada K, Shiratani E, Takaki K (2007) Research for effluent of DOM and hydrophobic acids from a paddy field. *Trans JSIDRE* 250:73–81. <https://doi.org/10.11408/jsidre2007.2007.419> (in Japanese)
- Ishii S, Ikeda S, Minamisawa K, Senoo K (2011) Nitrogen cycling in rice paddy environments: past achievements and future challenges. *Microbes Environ* 26(4):282–292. <https://doi.org/10.1264/jsme2.ME11293>
- JMA (2016) The recorded weather data and download. JMA. <https://www.data.jma.go.jp/gmd/risk/obsdl/index.php>. Accessed 23 Jan 2016
- JSIDRE (2001) Science for natural clean water in agricultural area. JSIDRE, Japan (in Japanese)
- Katayanagi N, Ono K, Fumoto T, Mano M, Miyata A, Hayashi K (2013) Validation of the DNDC-Rice model to discover problems in evaluating the nitrogen balance at a paddy-field scale for single-cropping of rice. *Nutr Cycl Agroecosyst* 95(2):255–268. <https://doi.org/10.1007/s10705-013-9561-1>
- Kyaw KM, Toyota K, Okazaki M, Motobayashi T, Tanaka H (2005) Nitrogen balance in a paddy field planted with

- whole crop rice (*Oryza sativa* cv. Kusahonami) during two rice-growing season. *Biol Fertil Soils* 42:72–82. <https://doi.org/10.1007/s00374-005-0856-5>
- Li H, Liang X, Lian Y, Chen LXY (2009) Reduction of ammonia volatilization from urea by a floating duckweed in flooded rice field. *Nutr Manag Soil Plant Anal* 73(6):1890–1895. <https://doi.org/10.2136/sssaj2008.0230>
- Liang XQ, Chen YX, Li H, Tian GM, Zhang ZJ, Ni WZ, He MM (2007) Nitrogen interception in floodwater of rice in Taihu region of China. *J Environ Sci* 19:1474–1481. [https://doi.org/10.1016/S1001-0742\(07\)60240-X](https://doi.org/10.1016/S1001-0742(07)60240-X)
- Meltem UD, Chakkrid S, Krishna RP (2008) Bioavailability of dissolved organic nitrogen in treated effluents. *Water Environ Res* 80(5):397–406. <https://doi.org/10.2175/106143007X221454>
- Morita S (2008) Prospect for developing measures to prevent high-temperature damage to rice grain ripening. *Jpn J Crop Sci* 77(1):1–12. <https://doi.org/10.1626/jcs.77.1> (in Japanese)
- Nguyen TPM, Nakamura T, Shindo J, Nishida K (2015) Application of stable isotopes to identify nitrogen sources in the outflow waters from paddy. *J Water Environ Technol* 13(5):371–381. <https://doi.org/10.2965/jwet.2015.371>
- Nishida K, Uo T, Yoshida S, Tsukaguchi T (2015) Effect of water depth, amount of irrigation water, and irrigation timing on water temperature in paddy field during continuous irrigation with cool running-water. *JSIDRE J* 300:I_185–I_194 (in Japanese)
- Roger PA, Ladha JK (1992) Biological N₂ Fixation in wetland rice fields: estimation and contribution to nitrogen balance. *Plant Soil* 141:41–55
- Shinozuka K, Chiwa M, Nakamura K, Nagao S, Kume A (2016) Stream water nitrogen eutrophication during non-irrigated periods in a paddy-dominated agricultural basin in a snowfall area in Japan. *Water Air Soil Pollut* 227:2219. <https://doi.org/10.1007/s11270-016-2906-z>
- Sugimoto Y, Komai Y, Kunimatsu T (2008) Evaluation of loading rate of nitrogen from rice-paddy by small watershed method. *J Water Technol* 6(2):113–126
- Takakai F, Kikuch T, Sato T, Takeda M, Sato K, Nakagawa S, Kon K, Sato T, Kaneta Y (2017) Changes in the nitrogen budget and soil nitrogen in a field with paddy-upland rotation with different histories of manure application. *Agriculture* 7(39). <https://doi.org/10.3390/agriculture7050039>
- Takeda I, Kunimatsu T, Kobayashi S, Maruyama T (1991) Pollutants balance of a paddy field area and its loadings in the water system—studies on pollution loading from a paddy field area (II). *Trans JSIDRE* 153:63–72. https://doi.org/10.11408/jsidre1965.1991.153_63 (in Japanese)
- Yamazaki T, Ishikawa S, Nagasaka S, Sasada K, Kohno E (2013) Research study on the water quality purification function of paddy fields regarding differences in irrigation method and farmland utilization. *J Jp Soc Civil Eng* 69(4):183–195 (in Japanese)
- Yoshinaga I, Feng Y, Singh RK, Shiratani E (2004) Dissolved nitrogen model for paddy field ponded water during irrigation period. *Paddy Water Environ*, 2:145–152. <https://doi.org/10.1007/s10333-004-0053-4>
- Yoshinaga I, Miura A, Hitomi T, Hamada K, Shiratani E (2007) Runoff nitrogen from a large sized paddy field during a crop period. *Agric Water Manag* 87:217–222. <https://doi.org/10.1016/j.agwat.2006.06.020>
- Zhang Q, Yang A, Zhang H, Yi J (2012) Recovery efficiency and loss of 15 N-labelled urea in a rice-soil system in the upper reaches of the Yellow River basin. *Agric Ecosyst Environ* 158:118–126. <https://doi.org/10.1016/j.agee.2012.06.003>
- Zhang JH, Liu JL, Zhang JB, Cheng YN, Wang WP (2013) Nitrate-nitrogen dynamics and nitrogen budgets in rice-wheat rotation in Taihu Lake region, China. *Pedosphere* 23(1):59–69. [https://doi.org/10.1016/S1002-0160\(12\)60080-0](https://doi.org/10.1016/S1002-0160(12)60080-0)
- Zhao X, Xie YX, Xioung ZQ, Yan XY, Xing GX, Zhu ZL (2009) Nitrogen fate and environmental consequence in paddy soil under rice-wheat rotation in the Taihu lake region, China. *Plant Soil* 319:225–234. <https://doi.org/10.1007/s11104-008-9865-0>
- Zhao X, Zhou Y, Min J, Wang S, Shi W, 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. <https://doi.org/10.1016/j.agee.2012.04.024>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.