Impact of Nitrogen Cycling on Global Warming in Agro-Ecosystems of East Asia

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Abstract: Nitrate (NO_3-N) runoff from the pedosphere to the aquasphere causes marine eutrophication and groundwater pollution. Nitrous oxide (N_2O) emission from the pedosphere to the atmosphere causes global warming and ozone layer depletion. The current net nitrogen input (NNI), which is defined as the difference between total N input to land area (chemical fertilizer N application, import of N in food and feed, biological N_2 fixation and atmospheric N deposition) and total N output from land area (export of N in food and feed), was estimated to be 52.4 Mt N y^{-1} in East Asia, in which chemical fertilizer N application accounts for 60%. The results of simple regression analysis using reported data on stream NO_3-N runoff and NNI estimated in US and Japanese watersheds showed that NNI was significantly correlated with stream NO_3-N runoff. Using regression equation, stream NO_3-N runoff from the total land area of East Asia was estimated to be 8.61 Mt N y^{-1}, which accounted for 27% of the total applied chemical fertilizer N in East Asia.

Regression analysis using reported data on N_2O and CO_2 emission from soil and chemical fertilizer N application showed that log-transformed soil N_2O emission was significantly correlated with soil CO_2 emission and applied chemical fertilizer N. Dramatically large soil N_2O emission was found in tropical peatland cultivated with vegetables. It reached 259 kg N ha^{-1} y^{-1} at maximum, which accounted for 39% of applied chemical fertilizer N. This indicates that soil N_2O emission depends on organic matter decomposition as well as chemical fertilizer N application. Soil CO_2 emission divided by soil CN ratio can be an indicator of gross mineralized N. Much better correlation for soil N_2O emission was obtained using chemical N fertilizer application plus gross mineralized N ($P<0.001$).

Reported values of CO_2 emission from the soil of cropland, grassland and forest were significantly correlated with soil organic carbon (C) content. Soil N_2O emission in each country was estimated by substituting the mean soil organic C content of ecological zones into the regression equation. Total N_2O emission from the soil of cropland and grassland of East Asia was estimated to be 0.766 Mt N y^{-1} including indirect soil N_2O emission associated with stream NO_3-N runoff. The proportion of soil N_2O emission induced by chemical fertilizer N application and organic matter decomposition occupied 35 and 62%, respectively. These values were similar to those reported by FAO (2001).

Organic matter decomposition is an important factor inducing soil N_2O emission and its increase may intensify stream NO_3-N runoff. Chemical fertilizer N application stimulates soil organic matter decomposition, which was significant in soil with high organic matter content, such as peat soil. To improve the accuracy of estimation, high-quality geographical information including land cover area, soil organic C content, chemical fertilizer N application and manure N application as well as better parameterization for soil N_2O emission and stream NO_3-N runoff must be prepared.
Key words East Asia, nitrogen cycle, NO_3-N runoff, N_2O emission, organic matter decomposition

N application and N load

Total N input that can be absorbed by terrestrial plants doubled from 131 million t in 1890 to 283 million t in 1990 (Galloway and Cowling, 2002). Food production and human population have increased, but NO_3-N runoff from the pedosphere to the aquasphere causing coastal eutrophication and groundwater pollution, and N_2O emission from the pedosphere to the atmosphere causing global warming and ozone layer depletion, have also increased. Chemical fertilizer N application stimulates soil organic matter decomposition (Huang et al., 2004). In general, the CN ratio of soil organic matter decreases as soil organic matter decomposes and mineral N is released into the soil. The relationship between applied chemical fertilizer N and stream NO_3-N runoff in the watershed of the Yangtze River in China was investigated by Duan et al. (2000). They showed that stream NO_3 runoff increased with the increase of applied chemical fertilizer N, and the rate of stream NO_3 runoff against applied chemical fertilizer N increased after 1980 when chemical fertilizer N application exceeded 15 kg N ha^{-1} watershed y^{-1} (**Fig. 1**). This is because chemical fertilizer N application decreases the soil CN ratio, which stimulates N mineralization in soil.

N balance associated with agriculture and food consumption

According to FAO statistics (2005), the present consumption of chemical nitrogen (N) fertilizer in East Asian countries (EA; ASEAN + Japan, China, and Korea) is estimated to be 31.5 Mt N y^{-1}, which accounts for 37% of the world consumption (FAO, 2005). The area of these countries is 1.46×10^9 ha, which is 11% of the world land area. Therefore, there is concern about the severe impact of N load on the environment in those countries. N input to a watershed includes chemical fertilizer N application, N_2 fixation, atmospheric N deposition and import of N in food and feed. On the other hand, N output from the watershed includes export of N in food and feed, N runoff, NH_3 volatilization and denitrification. The difference between N input and output accumulates in the watershed. Net N input is defined by the difference between total N input to the watershed and export of N in food and feed.

The N flows can be determined from the following data sets: activity data including human and livestock population, export of agricultural products, area of land use, chemical fertilizer N application, and manure N application in agricultural land; and inventory data including N content in food, feed and chemical fertilizer; N demand and N disposal rate for humans and livestock; emission factors of N_2, N_2O and NH_3; and N_2 fixation rate, atmospheric N deposition rate, and N inflow by irrigation.

In this study, the ecological zone area of each country as reported by IIASA (2001) was used for land use area, and other activity data refers to the values in FAO statistics (2005). However, Brunei and Singapore were not included in the estimation due to their very small agricultural area. All land use areas in Laos were estimated from FAO statistics due to a lack of data in the IIASA report. Inventory data refers to the data set reported in Mishima et al. (2004) and Shindo et al. (2003). However, atmospheric N deposition was assumed to be equal to NH_3 volatilization.

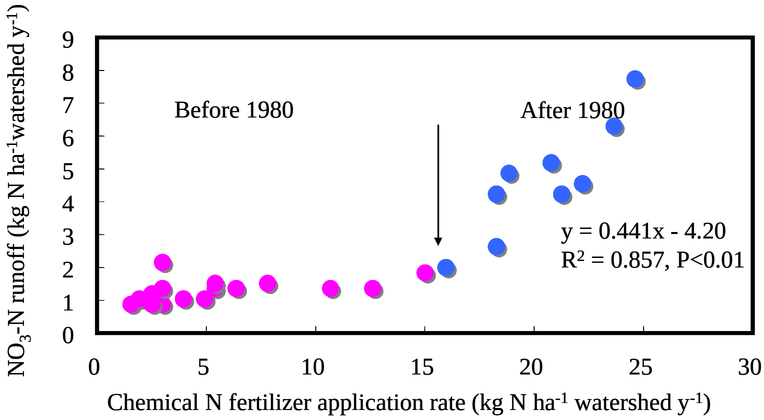

Fig. 1 Variation of stream NO_3-N runoff through the Yangtze River watershed associated with the change in chemical fertilizer N application (Duan et al., 2000)

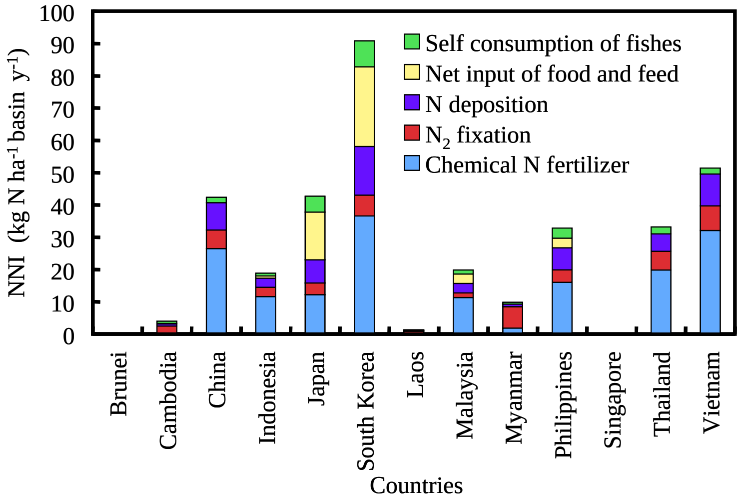

Fig. 2 Composition of net N input (NNI)

Estimated NNI and its composition are shown in **Fig. 2**. Countries having a chemical fertilizer N application rate exceeding 15 kg N ha^{-1} watershed y^{-1} are China, South Korea, Philippines, Thailand and Vietnam. Japan and Indonesia showed chemical fertilizer N application exceeding 12 kg N ha^{-1} watershed y^{-1}. Taking into consideration the results on the relationship between stream NO_3-N runoff and chemical fertilizer N application in the Yangtze River watershed shown in Fig. 1 (Duan et al., 2000), most countries in East Asia may have soil conditions stimulating stream NO_3-N runoff.

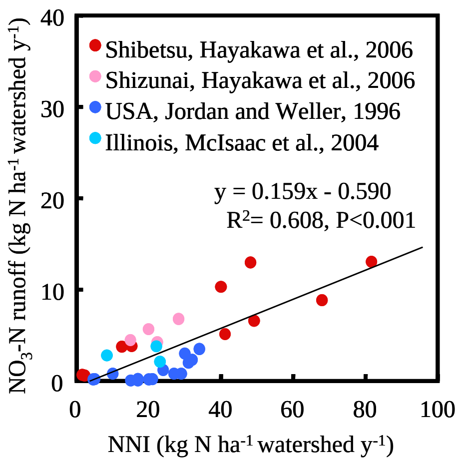

Fig. 3 Relationship between net N input (NNI) and stream NO_3-N runoff in watershed

NNI and NO_3-N runoff

Figure 3 shows the plots of NNI and stream NO_3-N runoff measured for 12 watersheds in Hokkaido, Japan (Hayakawa, 2006) and 18 watersheds in the US (Jordan and Weller, 1996; McIsaac et al., 2004). The results of simple regression analysis showed a significant relationship (P<0.001). Using the regression model, stream NO_3-N runoff in the Yangtze River watershed was estimated to be 6.54 kg N ha^{-1} watershed y^{-1}. The NNI in the Yangtze River watershed was estimated to be 40.4 kg N ha^{-1} watershed y^{-1} using data from the China Statistical Yearbook (2004) for 2 cities and 14 provinces including the Yangtze River watershed after modifying the total NNI of the cities and provinces by 0.38 of the ratio of the area of the Yangtze River watershed (181 M ha) to the total area of the cities and provinces (481 M ha). On the other hand, stream NO_3-N runoff was estimated to be 6.86 kg N ha^{-1} watershed y^{-1} by substituting 25.1 kg N ha^{-1} watershed y^{-1} of applied chemical fertilizer N (China Statistical Yearbook, 2004) into the regression equation shown in **Fig. 1**. Both estimates of NO_3-N runoff in the Yangtze River watershed corresponded well with each other. Therefore, the relationship shown in **Fig. 3** may be suitable for estimating stream NO_3-N runoff in East Asia with high chemical fertilizer N application. The NNI in East Asia was estimated to be 52.4 Mt N y^{-1}. Thus, total stream NO_3-N runoff was estimated to be 8.61 Mt N y^{-1}, which corresponded to 27% of the total chemical fertilizer N application in East Asia.

N_2O emission

According to an FAO report (2001), N_2O emission from the soil of cropland and grassland in East Asia is estimated to be 0.674 Mt N y^{-1}, corresponding to 19% of the total N_2O emission from the soil of the global cropland and grassland area. Soil N_2O emission depends strongly on not only N application but also soil organic matter decomposition (Huang et al., 2004; Mu et al., 2005). The results of simple regression analysis using reported data on soil N_2O emission and soil CO_2 emission or chemical fertilizer N application showed that log-transformed soil N_2O emission was significantly correlated with soil CO_2 emission (P<0.001) and applied chemical fertilizer N (P<0.001). This indicates that soil N_2O emission depends on organic matter decomposition as well as chemical fertilizer N application. Soil CO_2 emission divided by the soil CN ratio can be an indicator of gross mineralized N (Mu et al., 2005). A significant relationship between soil N_2O emission and chemical fertilizer N application plus gross mineralized N was obtained (**Fig. 4**).

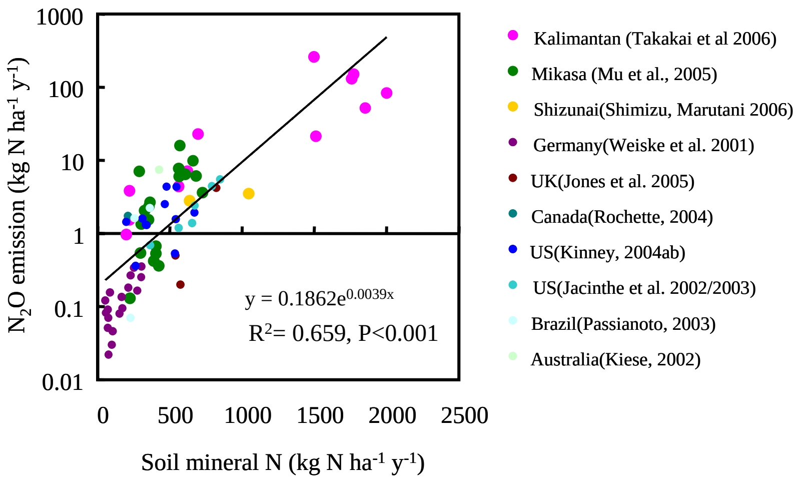

Fig. 4 Soil mineral N and N_2O emission
Soil mineral N = fertilizer N + CO_2 emission / (soil CN ratio)

Akiyama and Tsuruta (2003) and Huang et al. (2004) showed that N_2O emission and CO_2 emission increased with a decrease in the CN ratio of applied organic matter. However, Huang et al. (2004) showed that both soil N_2O emission and soil CO_2 emission were significantly correlated with dissolved organic C concentration in soil solution. Furthermore, both soil N_2O emission and soil CO_2 emission were stimulated by the application of chemical fertilizer N with organic matter application. This shows that N_2O might be produced through the denitrification process in the soil and that it was stimulated by chemical fertilizer N application. Lipschultz et al. (1981) reported that the N_2O/NO ratio is 0.2 - 1.0 in the nitrification process and 100 in the denitrification process. Kusa et al. (2002) showed that the N_2O/NO ratio increased with an increase of precipitation, and that the increase of

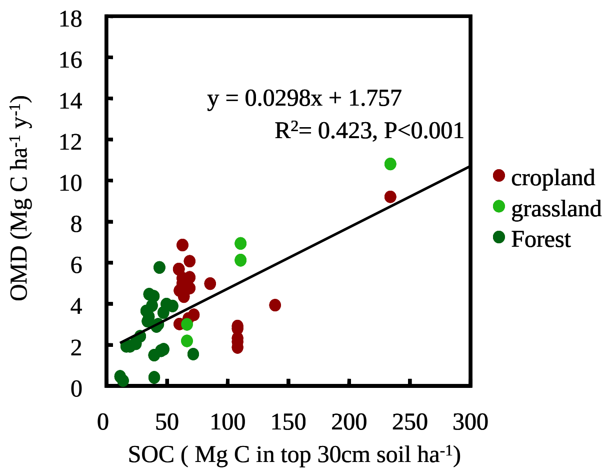

Fig. 5 Soil carbon content (SOC) and organic matter decomposition (OMD)

the N_2O/NO ratio increased soil N_2O emission.

There was a significant relationship between soil CO_2 emission and soil organic C content in the top 30 cm of soil using reported data on cropland, grassland and forest in various climate zones (**Fig. 5**). Soil CO_2 emission in each ecological zone in East Asian countries was estimated by substituting the mean value of soil organic C in each ecological zone reported by IPCC (2001) into the regression equation in **Fig. 5**. However, IPCC (2001) reported the value of soil organic C content in the top 1 m of soil. Therefore, the value was modified by assuming that 70% of the soil organic C in the top 1 m of soil was included in the top 30 cm of soil. Manure C applied to cropland and grassland was estimated by dividing the applied manure N obtained from FAO statistics (2005) and the mean CN ratio of the applied manure. The CO_2 emission associated with manure decomposition was obtained by using a manure C decomposition rate of 18% (AFFRCS, 1985) and adding it to the CO_2 emission associated with soil organic matter decomposition in grassland and cropland. Soil N_2O emission from cropland and grassland in each country was estimated from the regression equation in **Fig. 4** using the total CO_2 emission from cropland and grassland and the applied chemical fertilizer N and the land use area in each country. However, the soil CN ratio in each ecological zone was assumed to be 12. This estimate was compared to the value of FAO (2001) and the value calculated by the IPCC-recommended equation (N_2O emission = 0.0125[nitrogen input] + 1) (IPCC, 1997). The N_2O emission associated with stream NO_3-N runoff was obtained by using an N_2O-N/NO_3-N ratio of 0024 (Sawamoto et al., 2005).

Table 1 Estimation of N_2O emission from cropland and grassland in East Asia (Mt N y^{-1})

	Total emission	Emission source		
		Chemical N fertilizer	Organic matter decomposition	NO_3-N runoff*
This study**	0.765	0.270	0.474	0.021
IPCC default**	0.901	0.394	0.507	
FAO (2001)****	0.674	0.252	0.422	

*0.24% of NO_3-N runoff
**70% of soil organic carbon present in top 30 cm of soil
***0.0125×N input + 1
****0.8% of N fertilizer

As shown in **Table 1**, total N_2O emission in East Asia was 0.765 Mt N y^{-1}. The proportion of N_2O emission induced by chemical fertilizer N application, organic matter decomposition and stream NO_3-N runoff is 35, 62 and 3%, respectively. Total N_2O emission was 1.1 times higher than the value from the FAO study (FAO, 2001), but 0.86 times lower than the value calculated by the IPCC-recommended equation (IPCC, 1997). Both N_2O emissions induced by chemical fertilizer N application and organic matter decomposition were higher in this study than in the FAO study, but lower in this study than the value calculated by the IPCC-recommended equation. The ratio of N_2O emission induced by chemical fertilizer N application to that by organic matter decomposition was 0.57 in this study, 0.60 in the FAO study and 0.77 using the IPCC-recommended equation. The IPCC equation may overestimate especially the N_2O emission induced by chemical fertilizer N application. In the FAO study, estimation is conducted for every 0.5° grid cell on the earth's surface. N_2O emission in each grid cell is estimated based on the combination of climate zone, soil type, crop type, fertilizer type and agricultural management. This is probably the most reliable way of estimating N_2O emission; however, many data sets not only for N_2O emission but also other inventory and activity data are needed. Estimation of N_2O emission presented here is still rough as it did not divide land use into crop type, but it may be a strategic method for small- to large-scale evaluation because it is possible to intensively collect only a few key explanatory variables for the controlling independent variable.

The N_2O emission associated with soil organic matter decomposition is characteristically shown in the agricultural fields in tropical peatland (Takakai et al., 2006). Within the plots in **Fig. 4**, N_2O emission from peat soil cultivated with vegetables in Indonesia reached 239 kg N ha^{-1} y^{-1} at maximum, which corresponds to 38% of applied chemical fertilizer N. Acid-tolerant *Janthinobacterium* sp. strain A1-13 is isolated from the peat soil as the most prominent N_2O-producing bacterium through the denitrification process (Hashidoko et al., 2006). Essentially, this bacterium is common in tropical forests but does not possess any activities for NO_3 reduction. Forest exploitation and N fertilizer application likely produce bacterium with

NO_3 reduction activity. The bacterium produces N_2O and decomposes organic matter at pH 3.8 and the activity increases with increasing temperature up to 40°C, indicating that *Janthinobacterium* sp. strain A1-13 has adapted to agricultural fields of acidic tropical peat soil.

Conclusion

East Asia is the most prominent region in the world applying chemical fertilizer N. This may have increased soil organic matter decomposition and accelerated stream NO_3-N runoff and soil N_2O emission, enhancing marine eutrophication and global warming. Global warming stimulates soil organic matter decomposition throughout the world. In this study, stream NO_3-N runoff was regressed by the regional N budget and soil N_2O emission was regressed by soil CO_2 emission and applied chemical fertilizer N. Using the regression equations, large-scale evaluation was conducted. However, this is still a rough way of estimating stream NO_3-N runoff and soil N_2O emission due to the lack of precise inventory and activity data. But this may be a strategic method if we could obtain highly significant regression equations, because it is possible to intensively collect only a few key explanatory variables to explain the independent variable. Estimated stream NO_3-N runoff and soil N_2O emission using the regression models corresponded well to previously reported values. The N_2O emission induced by organic matter decomposition is larger than that induced by chemical fertilizer N application. Stream NO_3-N runoff corresponded to 27% of chemical fertilizer N application and the proportion of stream NO_3-N runoff to applied chemical fertilizer N increased with the increase of chemical fertilizer N application. Therefore, the most important mitigation option for reducing the environmental N load may be to amend the quality of soil organic matter as well as to reduce the application of chemical fertilizer N.

To improve the accuracy of estimation, the quality of data on geographical information including land cover area, soil organic C content, chemical fertilizer N application and manure N application must be increased and better regression models for estimating soil N_2O emission and stream NO_3-N runoff must be prepared by intensive monitoring.

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