Monitoring and modeling of nitrogen leaching caused by nitrogen fertilizer application to green tea fields in Japan

Yuhei Hirono[1], Shigekazu Nakamura[2], Tomohito Sano[3], Kunihiko Nonaka[3]

[1] National Agriculture and Food Research Organization, 2769, Kanaya-Shishidoi, Shimada, Shizuoka, 428-8501, Japan, E-mail: hirono@affrc.go.jp
[2] Shizuoka Prefectural Research Institute of Agriculture and Forestry, Mobata, Shimizu, Shizuoka, 424-0101, Japan
[3] National Agriculture and Food Research Organization, 2769, Kanaya-Shishidoi, Shimada, Shizuoka, 428-8501, Japan

Abstract
Large amounts of nitrogen fertilizer are required in the cultivation of tea (*Camellia sinensis* (L.)), relative to other crops, resulting in nitrate contamination of surrounding water systems and high rates of nitrous oxide emissions. In response to these problems, the amount of nitrogen fertilizer applied to tea fields in Japan has been decreased by the improvement of fertilizer application methods in recent years. In this study, we aimed to assess the changes in water quality due to the reduction of nitrogen input and determine the environmental response to improved fertilizer application methods in tea fields. First, we analyzed 21-year water quality monitoring data in an intensive tea-growing area in Japan. We found nitrate concentrations significantly decreased at most studied sites in water systems in the tea-growing area, indicating that water quality was improved by reducing nitrogen fertilizer application in tea fields. Second, we modeled nitrogen leaching from tea field soil based on the data obtained by lysimeter experiments. This showed that the calculated amounts of water and nitrogen leachate agreed well with the observed results.

Introduction
Large amounts of nitrogen (N) are required as fertilizer for the cultivation of tea (*Camellia sinensis* (L.)), compared with other crops. Previously, the amount of fertilizer applied to green tea fields often exceeded 1000 kg N ha^{-1} y^{-1} (Tokuda and Hayatsu 2001). The main reason for the high rate of fertilizer application is that it can increase the quality of Japanese green tea. However, heavy application of N fertilizer does not always increase the yield and quality of tea products, instead it alters the N cycle and it leads to environmental problems including increased nitrate-nitrogen (NO_3^--N) concentration in the surrounding water systems and high rate of emissions of nitrous oxide (N_2O), one of the major greenhouse gasses and ozone-depleting substances. To address these problems, efforts have been made in the recent years by farmers and related authorities in Japan to reduce the amounts of N fertilizer applied to tea fields. In addition to the reduction of the amount of fertilizer use, improvement of soil and fertilizer managements have also been implemented. Correspondingly, we need to determine the changes in water quality that have emerged since the reduction in N fertilizer application to green tea fields, and to quantitatively assess the effect of improved fertilizer management on the environmental N loading from N fertilizer application to tea fields. The objectives of this study were to reveal how changes in fertilizer application rates impact local water quality and to predict the water quality for future reduced fertilizer application rates.

Methods
Trends in NO_3^--N concentrations in surrounding water systems
The study area was the Makinohara Plateau and its surrounding areas in Shizuoka Prefecture, Japan (Fig. 1). The Makinohara Plateau is a diluvial plateau with an altitude of about 200 m. Most of the surface is covered with Yellow Soil (corresponding to Acrisols, Alisols or Cambisols in World Reference Base for Soil Resources (WRB) (Classification Committee of Cultivated Soils 1996)) and Andosols. Annual rainfall was approximately 2213 mm (Fig. 4), and annual mean temperature was 15.1°C during the study period (1996–2015). Most of the land use in the area is agricultural land and forest. Tea is the principal crop in the study area. Water sampling was conducted once a month (1996–2011) or once every 2 months (2011–2016) at 16 sites as follows: three drainage sites around tea fields, one irrigation ditch site, four spring water sites, one ground water site and seven stream sites (Fig. 1). Water samples were manually collected into polyethylene bottles at each site. The samples were brought back to the laboratory and stored in a refrigerator until required for analysis. Concentrations of NO_3^--N of each samples were measured. We have already reported the results of the trend analysis during the period from 1996–2005 (Hirono et al. 2009). In this study, we report the subsequent time-series changes in water quality along with agricultural N fertilizer application rates during the period from 1996 to 2016.

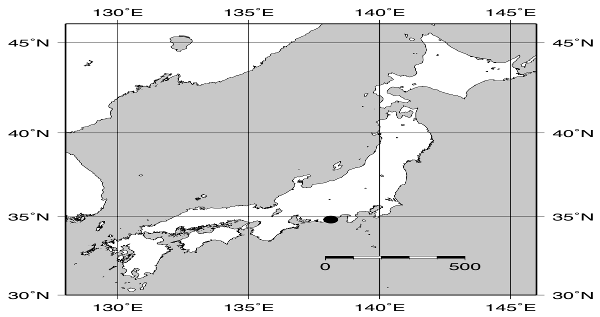

Figure 1. Study area and locations of the water sampling sites. D, drainage; G, groundwater; I, irrigation ditch; Sp, springwater; St, stream.

Modeling of N leaching from tea fields

Modeling of water and N transport in tea fields was conducted using a computer simulation model, Version 4.16 of Hydrus-1D (Šimůnek et al. 2013). For water transport, potential evapotranspiration rates were calculated beforehand using the Penman–Monteith equation. Weather data used in this calculation were obtained from AMeDAS of the Japan Meteorological Agency (Kikugawa–Makinohara, Shizuoka) and the weather-monitoring station of the National Agriculture and Food Research Organization (NARO). Soil hydraulic properties were represented by the implemented model of van Genuchten (1980). The following parameters were used for this model: saturated water content (θ_s), residual water content (θ_r), empirical factors (α, n) and saturated hydraulic conductivity (K_s). These were predicted using the neural network prediction model implemented in Hydrus-1D through the input of measured values of clay, silt and sand contents of soil used for lysimeter experiments. For solute transport, the nitrification and denitrification process was considered to be a first-order reaction. We also considered active solute uptake by roots; the results of Maehara and Hakamata (1976) were used to determine the seasonal changes of N uptake by roots. The upper boundary was represented by atmospheric variable boundary conditions with specified irrigation rates, fertigation (application of liquid fertilizer using irrigation systems) rates, precipitation rates, evaporation rates, and ammonium-N (NH_4^+-N) and NO_3^--N concentrations in the liquid fertilizer. The lower boundary was represented by a seepage boundary condition and a zero concentration gradient.

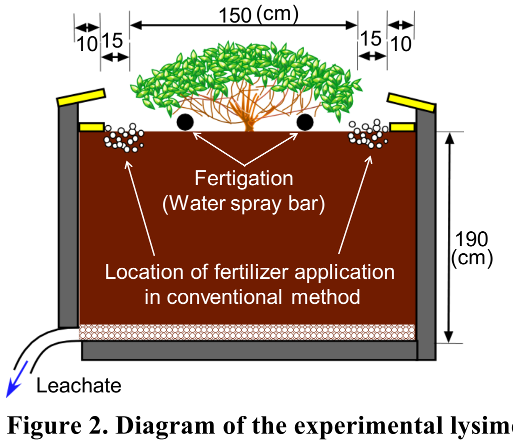

Figure 2. Diagram of the experimental lysimeter and location of fertilizer application.

Datasets obtained from lysimeter experiments conducted at the Tea Research Center of the Shizuoka Prefectural Research Institute of Agriculture and Forestry from April 2003 to March 2007 were used for modeling. Each lysimeter (2.0 m in width, 1.5 m in length and 1.9 m in depth) was filled with yellow soil (clay loam) and included five tea plants (Fig. 2). Five methods of fertilizer application were compared. One was the conventional method of manually applying fertilizer beside tea plants (CV). In the CV lysimeter, nitrogen was applied as rapeseed meals, fish lees, urea, ammonium sulfate and ammonium nitrate. Another was applying no fertilizer (N0). The others were fertigation methods of automatically applying liquid fertilizer under the canopy of tea plants using a water spray bar (F500, F200, and F50) (Table 1). These fertigation methods were different in the N concentration of the liquid fertilizer (500, 200, and 50 mg-N L^{-1}). The dataset of CV lysimeter was used for calibration and the datasets of the other lysimeters were used for validation of the model. Nitrogen was applied as ammonium nitrate, and the fertigation conditions are given in Table 1. For each lysimeter, the amount of leachate from the bottom was measured and subsamples were collected from storage tanks and the concentrations of NH_4^+-N and NO_3^--N were determined using ion chromatography analysis.

Results

Trends in water quality in surrounding water systems

As reported in Hirono *et al.* (2009), the reduction of N use in green tea fields in Japan successively improved water quality in surrounding water systems in tea-growing areas in the first decade of the study (1996–2005) at most of the study sites (Fig. 3). In particular, there were significant downward trends in NO_3^--N concentrations in drainage around the tea field (Figs. 3a, b) and shallow spring water (Fig. 3c), which were thought to be strongly influenced by leachate from tea fields. However, the trends in water quality at such sites, including drainages and spring water, varied in the subsequent decade. Most sites did not show great decreasing trends in NO_3^--N concentrations and had small annual variations; however, there were seasonal fluctuations according to the periodical fertilizer application and meteorological conditions (Figs. 3a,b). Moreover, most of the stream sites showed significant decreasing trends in the second decade of the study, even at the site at which increasing trends had been seen in the first decade (Fig. 3f). These results showed that the current concentration changes at drainage and spring water sites reach a steady state because the fertilizer application rates leveled off in this area. In contrast, the NO_3^--N concentrations at stream sites are still within a transition period from the concentrations under heavy N application to those under reduced N application to tea fields. Thus, the concentrations in these streams should continue to decrease into the future.

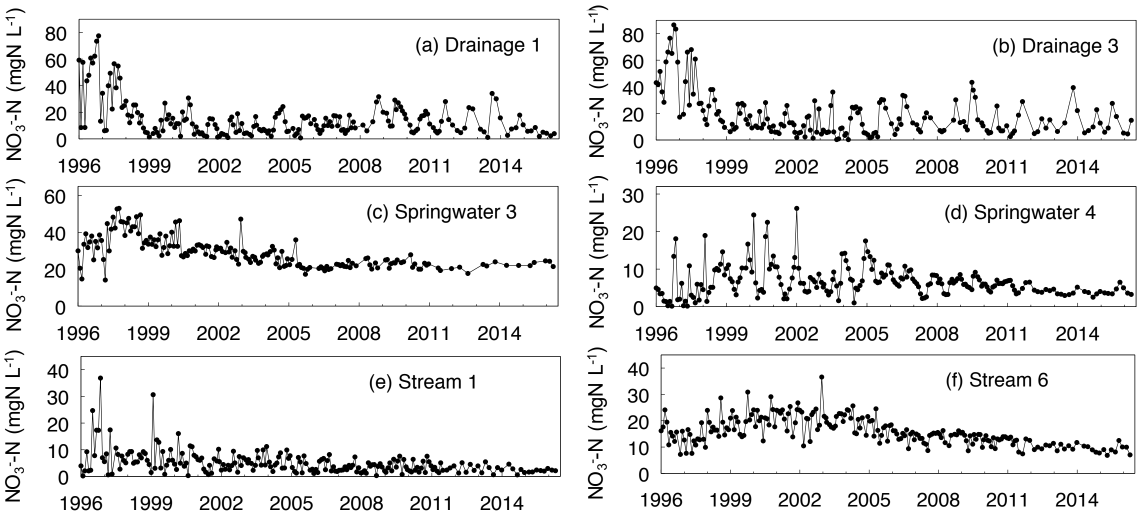

Figure 3. Time-series changes in NO_3^--N concentrations at drainage sites (a,b), springwater sites (c, d), and stream sites (e, f). Note that each graph has different scale of y-axis.

Modeling of N transport in tea fields under fertigation management

The largest amount of annual water leachate was observed in 2004 in response to the highest annual precipitation among the 4 years (Figure 4). The annual precipitation in 2005 was lower than usual and the amount of annual water leachate in that year was only about half of that in 2004. A comparison between the observed and calculated amounts of water leachate showed that there was good agreement for all lysimeters (Table 1), indicating that the Hydrus-1D model can derive a close estimation for the water transport in tea fields. A comparison of the observed and calculated average amounts of N leachate also showed good agreement (Table 1) although we sometimes observed large differences between the observed and the calculated values of the cumulative amount of N leachate, especially in 2004 and 2006 (Fig. 4). Although the reason was unclear, one possible reason was ununiformity of soil. Preferential flow through macropores can sometimes cause faster transport of solutes, but was not considered in this model. The amount of N calculated as gas production, which was assumed to be N_2O emission, corresponded to 2–3% of the N fertilizer application rates. The values agreed well with the values of N_2O emission factors from tea field soils reported by Akiyama *et al*. (2006); thus this model can provide a good estimation of the N_2O emission rates from tea field soil as well as amounts of N leachate.

Table 1. Irrigation rate, N application rate, and comparison of the observed and calculated cumulative amounts of water and N leachate from the bottom of each lysimeter (4-year average).

Treatment	Irrigation rate (mm/y)	N application rate (kg-N/ha/y)	N concentrations in liquid fertilizer (mg-N/L)	Water leachate (mm/y)		N leachate (kg-N/ha/y)	
				Observed	Calculated	Observed	Calculated
CV	0	486	-	1331	1473	54.1	65.8
F500	54	270	500	1421	1531	48.8	51.2
F200	135	270	200	1549	1616	40.0	42.6
F50	540	270	50	2020	2065	45.7	56.1
N0	270	0	0	1810	1758	20.4	11.9

CV, conventional method; F500, F200, and F50, fertigation methods; N0, no fertilizer application.

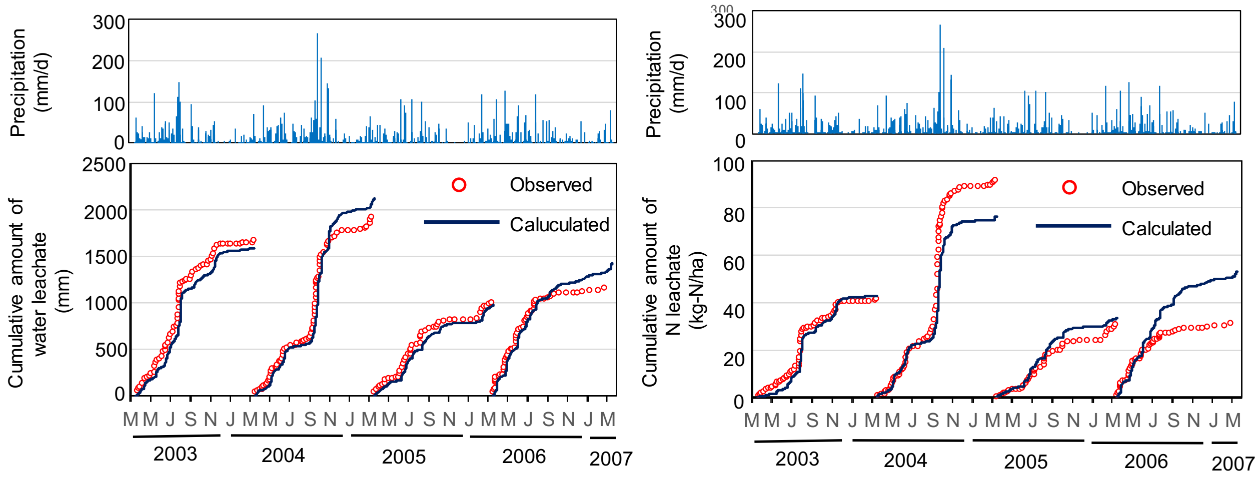

Figure 4. Comparison between the observed and calculated cumulative amounts of water and N leachate from the bottom of a lysimeter (F500. This graph shows one of five treatments presented in Table 1.).

Conclusion

The main findings of this study were as follows. (i) The NO_3^--N concentrations in surrounding water systems in an intensive tea-growing area in Japan were reduced by the recent reduction of N fertilizer use in tea fields. (ii) The Hydrus-1D simulation model that calculates N leaching is a useful tool to recommend optimal fertilizer management practices in green tea fields in Japan.

Acknowledgment

This work was partially supported by JSPS KAKENHI Grant Number 26850155.

References

Akiyama H, Yan XY and Yagi K (2006). Estimations of emission factors for fertilizer-induced direct N_2O emissions from agricultural soils in Japan: Summary of available data. Soil Sci. Plant Nutr. 52, 774–787.

Classification Committee of Cultivated Soils (1996). Classification of Cultivated Soils in Japan. Press, National Institute of Agro-Environmental Science, Tsukuba, Japan, p.61.

Hirono Y, Watanabe I and Nonaka K (2009). Trends in water quality around an intensive tea-growing area in Shizuoka, Japan. Soil Sci. Plant Nutr. 55, 783–792.

Maehara and Hakamata (1976). The seasonal absorption of mineral nutrients in relation to the growth of three-year-old tea plant. Study of Tea. 50, 49–62 (in Japanese with English summary).

Šimůnek J, Šejna M, Saito H, Sakai M and van Genuchten MT (2013). The HYDRUS-1D Software Package for Simulating the One-Dimensional Movement of Water, Heat and Multiple Solutes in Variably-Saturated Media, Version 4.16. Department of Environmental Sciences, University of California Riverside, Riverside, California, USA.

Tokuda S and Hayatsu M (2001). Nitrous oxide emission potential of 21 acidic tea field soils in Japan. Soil Sci. Plant Nutr. 47, 637–642.

van Genuchten MT (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892-898.