

Estimation and comparison of nitrogen loads and attenuation in agricultural catchments of Japan and Korea

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Abstract To help in clarifying the relationship between the time lag and attenuation of nitrogen (N) loads generated in agricultural catchments, long-term trends in activities that generate N loads and in environmental N loads were estimated in catchments in Japan and Korea dominated by non-point-source emissions. Our approach used statistical data and geographical information system software to analyze pollutant loads. The method was successful in both countries because of the availability of well-developed statistics, geographical information, and weather and water quality monitoring systems, and the accumulation of research data concerning the generation of N loads and the fate of N in soils. Comparison of environmental loads with the loads observed in river water at the outlet of each catchment revealed that: (1) the effect of changes in the environmental load in a catchment appeared almost immediately in the river water quality in Korea, but did not appear clearly even 10 years later in Japan; and (2) the strength of the attenuation appeared to be much lower in Korea than in Japan. These findings suggest that regional characteristics play important roles in the sensitivity of water quality to load-generating activities.

Keywords Environmental load; GIS; non-point source; pollutant load unit; time lag

Introduction

In Japan, pollution in closed water systems has not shown a significant decrease until recently despite strict regulations established to control pollutant loads from point sources such as factories and businesses since the 1970s. In 2005, the so-called “Clean Lake Law” was revised to pay closer attention to controlling emissions from non-point sources of pollutants, including agricultural and forest lands and residential areas, so that managers could take effective countermeasures. The situation for water quality in South Korea is similar to that in Japan, and controlling non-point-source pollution has also attracted the attention of policymakers and researchers (e.g. Choi and Shin, 2002; Kim *et al.*, 2004).

Agriculture is a major contributor of nitrogen (N) loads to catchments, along with other sources such as industry, domestic wastewater, and precipitation. To protect water quality, it is important to know the contribution of these sources to the N load observed at monitoring sites so as to permit effective countermeasures against N pollution. Although it is relatively easy to estimate N loads generated by non-agricultural sources, whose loads can be monitored at the source, it is difficult to estimate agricultural N loads because the activities are spread across catchments. Therefore, the use of statistical data provides an effective and practical way to estimate N loads generated by agricultural activities on a catchment scale and can take the place of simpler methods based on the calculation of pollutant load units. Based on detailed statistical data combined with a GIS (geographical information system) software, a method for estimating N loads from

non-point sources on a catchment scale was previously developed (Takeuchi *et al.*, 2005; Itahashi *et al.*, 2006).

By applying this method, Itahashi *et al.* (2006) found that the appearance of N loads in river water was delayed with respect to the generation of the load in catchments; that is, there was an apparent “time lag”, and, as has been observed in other studies (e.g. Boyer *et al.*, 2002), N loads observed in river water were significantly attenuated compared with the potential N load after leaching through the soil surface into the groundwater. Takeuchi *et al.* (2005) found that the greater the ratio of the N load applied to the soil surface to the amount discharged into bodies of water, the later the effect of the source N load on river water quality and the greater the observed attenuation. These findings suggested that N applied to the soil takes a significant amount of time to travel through the soil–groundwater system and that a high degree of attenuation occurred before the N reached the body of water. One cause of the N attenuation was denitrification in the soil (Boyer *et al.*, 2002), thus longer travel times may increase attenuation by allowing more N to be denitrified. Although the apparent time lag may significantly affect the attenuation, few studies have reported the existence of this time lag (e.g. Tanaka *et al.*, 1998). Thus, the factors and mechanisms that control the length of the time lag are not fully understood.

Therefore, it is necessary to collect more data on the time lag through analyses in catchments with different characteristics to clarify the relationships between various parameters and the length of the time lag and the strength of the attenuation. The present study aimed to collect information on these relationships by analyzing a region in South Korea and a comparable region in Japan. During the analysis, the method had to be modified in order for results to be comparable between regions. The structures of and changes in the activities that generate N loads in both regions were then described. By comparing the results from both countries, a picture of the characteristics that determine the sensitivity of water quality to the generation of N loads was developed.

Materials and methods

An outline of the method used in this study is shown in Figure 1. As the details of the method have been reported previously (Itahashi *et al.*, 2006), only a brief description of the method and of the modifications required in this study are presented here.

Study sites

Study sites were selected in the Goesan region of central South Korea (Republic of Korea) and in the Lake Kasumigaura watershed of central Japan (Figure 2). The Korean study area is hilly and is covered by forested land (64% of the total area) and agricultural land (upland crops, orchards, rice paddies, and livestock areas; 27%). These values are

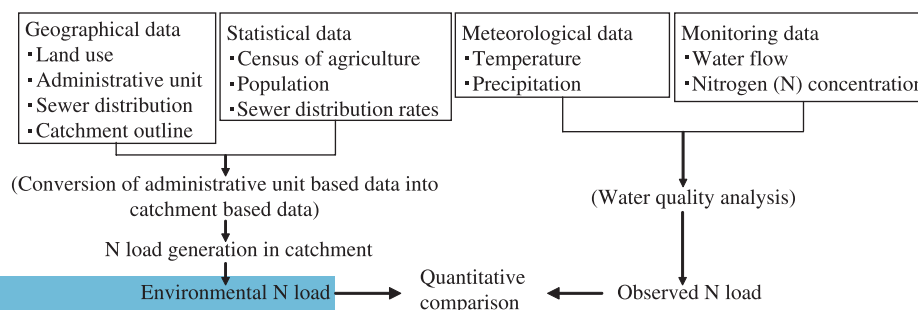


Figure 1 The outline of the method of analysis used in the present study

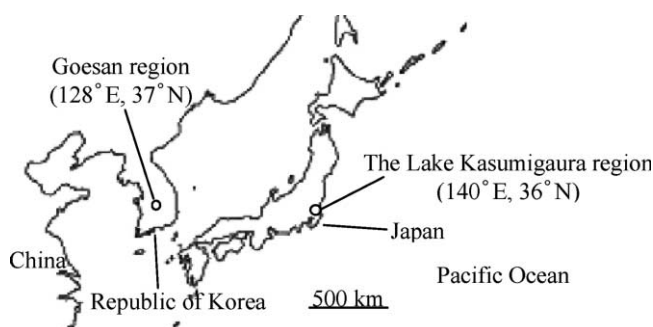


Figure 2 Location of the study sites

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close to the national averages for South Korea as a whole: 64% forest (FAO Statistics Division, 2005) and 20% agricultural (OECD, 2006). The Japanese study area is flatter and is covered by agricultural fields (49%) and forested land (25%), which means that the area has more agricultural land use and less forest than the national averages for Japan: 14% (OECD, 2006) and 69% (FAO Statistics Division, 2005), respectively. There were no significant point sources of pollution such as industrial complexes in either area, suggesting that both regions were dominated by non-point sources, especially agriculture.

Annual average temperature and precipitation are similar in both regions: 11.2°C and 1276 mm (average between 1991 and 2000; Y. Ishigooka *et al.* (National Institute for Agro-Environmental Sciences, Japan), personal communication) for the Goesan region and 14.3°C and 1161 mm (average between 1979 and 2003; Japan Meteorological Agency, 2006) for the Kasumigaura region. However, some differences between two regions can be listed as follows: the geological feature (granite for Goesan *versus* volcanic ash for Kasumigaura), the effective soil depth (shallow *versus* deep, respectively) and the agricultural practices including cropping types and seasons.

In the Goesan region, two catchments were selected (Goesan-S, 48.1 km²; Goesan-L, 120.1 km²) based on the availability of water quality monitoring sites at the outlet of each catchment. Out of 20 catchments within the Kasumigaura region, two catchments were selected for this study: Kasumi-S and Kasumi-L (44.9 and 110.1 km², respectively). In these four names, -S stands for the smaller of the two catchments, and -L stands for the larger of the two catchments.

Preparation of digital maps

Grid-based GIS software (self-made, Itahashi *et al.*, 2006) was used to perform our analyses. The grid size was set to 13 m along both map axes in order to represent the mosaic pattern of land use in both countries. Paper maps including land use, administrative unit, and so on, were scanned and imported into the GIS (Figure 1). The GIS data were used to convert data based on administrative units into catchment-based data.

Estimation of the environmental N load

Instead of estimating the potential N outflow in the previous study (Takeuchi *et al.*, 2005; Itahashi *et al.*, 2006), the environmental N load in this study was estimated, which is defined as the proportion of the generated N load that was potentially discharged into the environment, namely the soil surface and bodies of water. For the purpose, artificial removals of portions of the N load generated by domestic life and the loss through volatilization during composting of animal waste were subtracted from the generated N load.

Four sources of N loads in this study were considered: natural inputs, domestic life, crop production and animal husbandry. Pollutant load units were used for estimating N

loads generated by domestic life and animal husbandry (e.g. Ukita and Nakanishi, 1989). N loads were calculated on an annual basis at 5- or 10-year intervals using agricultural census data collected between 1950 and 2000 in Japan (Statistics Department of Ministry of Agriculture, Forestry, and Fisheries of Japan, 1950–2000) and between 1960 and 2000 in Korea (Ministry of Agriculture of Korea, 1960–2000).

Natural inputs. The N load from natural inputs involves N present in precipitation and N fixation by forested land. The N load in precipitation equaled the product of the annual amount of precipitation in each region (e.g. Japan Meteorological Agency, 2006) and the N concentration in rainwater (Tamaoki *et al.*, 1991; Park and Lee, 2002). The amount of N fixed in forested land equaled the product of the N fixation rate (ca. $10 \text{ kg N ha}^{-1} \text{ y}^{-1}$; Yoshida, 1981) and the area of forested land in each catchment.

Domestic life. Human wastes and gray water were considered in this load. Loads from both sources equaled the product of the population in the area and the pollutant load units. The environmental load was then calculated as the product of the N load and an N removal ratio that was defined based on the method of wastewater treatment (e.g. Ukita and Nakanishi, 1989). The proportions of the population that used each type of wastewater treatment were estimated using published data (e.g. National Land Agency, 1983–1991; Japan Sewerage Works Association, 1994; Choi, 2003).

Crop production. The environmental load caused by crop production was estimated using the soil–surface N balance. Standard fertilizer application rates published by local governments of both countries and N fixation rates (Yoshida, 1981) were used to determine the N input for each crop type, and the standardized N uptake (e.g. Ogawa 2000), or N contents of harvested crop in food composition data and the agricultural statistics published by the local government were used to estimate the output of N (i.e. the proportion of applied and fixed N that was not taken up by crops).

Animal husbandry. Animal wastes were considered and the N load was estimated as the product of the number of animals of each type in the study area and the appropriate pollutant load unit for each animal type (cattle, swine, and poultry were the major livestock animals in both areas). As most of the animal wastes were composted and applied to the farm land as soil amendments (Statistics Department of Ministry of Agriculture, Forestry, and Fisheries of Japan, 2000; Hong and Kwun, 2001), the N load was treated as equal to the application of this compost to the soil surface, but after subtracting the portion of N lost through ammonia volatilization and denitrification during composting and just after application of the compost to the soil (e.g. Saito *et al.*, 1989).

N load observed in river water

The annual N load in the river water was estimated as the product of the annual average N concentration in the water at the outlet of each catchment (Japan National Institute for Environmental Studies, 2006; Korean National Institute of Environmental Research, 2006) and the annual discharge of water, which was estimated based on the water balance data for the catchment. The water balance was calculated by subtracting the amount of potential evapotranspiration from the amount of annual precipitation using national weather monitoring data (e.g. Japan Meteorological Agency, 2006). The load was estimated between 1972 and 2003 in Japan and between 1992 and 2000 in South Korea.

Results and discussion

Long-term structural changes in activities that generate N loads

The detailed statistical and geographical data collected by both countries clearly revealed structural changes in the activities that generated N loads in the study areas between 1950 and 2000 in Japan and between 1960 and 2000 in South Korea. Figure 3 shows the long-term trends in the cultivated area for the five main crop groups and in the number of animals and humans in the Kasumi-L and Goesan-L catchments, which were similar in size. The trends for the smaller Kasumi-S and Goesan-S catchments were similar, and are not presented here.

In the Kasumi-L catchment (Figure 3a), the cultivated area for paddy rice was stable at about 1400 ha from 1950 until 1975, then slowly decreased until 2000, when it occupied more land area than all other crop groups including field crops (wheat, barley, peas and beans, potatoes, corn, and forage crops), vegetables (e.g. eggplant, sweet peppers, watermelon), industrial crops (e.g. tea, tobacco), and fruit trees (e.g. chestnut, pear, grape, tangerine) in 2000. The cultivated area of all crops showed a similar decrease, though the decrease began slightly earlier or later for different crop groups and was greatest for field crops. Field crop cultivation was most popular before 1970, and rapidly decreased thereafter. Cultivation of vegetables and fruit trees became popular after 1970, but more recently, the cultivated area of both crops gradually decreased. These trends were similar to those in the other catchments within the Kasumigaura region (data not shown). In the Goesan-L catchment (Figure 3b), similar trends were observed, with the exception that fruit trees were much less popular than in Japan and showed no increase in popularity during the study period.

However, trends in animal husbandry differed between the two regions. Swine and poultry populations reached a peak in 1985 in the Kasumi-L catchment (Figure 3c), and decreased thereafter, but increased after 1990 in the Goesan-L catchment (Figure 3d). Trends in human population also differed between regions; populations increased gradually in the Kasumi-L catchment (Figure 3c) and decreased continuously in the Goesan-L catchment (Figure 3d).

Long-term trends in the environmental N load

Based on the structural changes in activities that generate N loads, the long-term trends in the environmental N load in all four catchments were estimated (Figure 4). In this

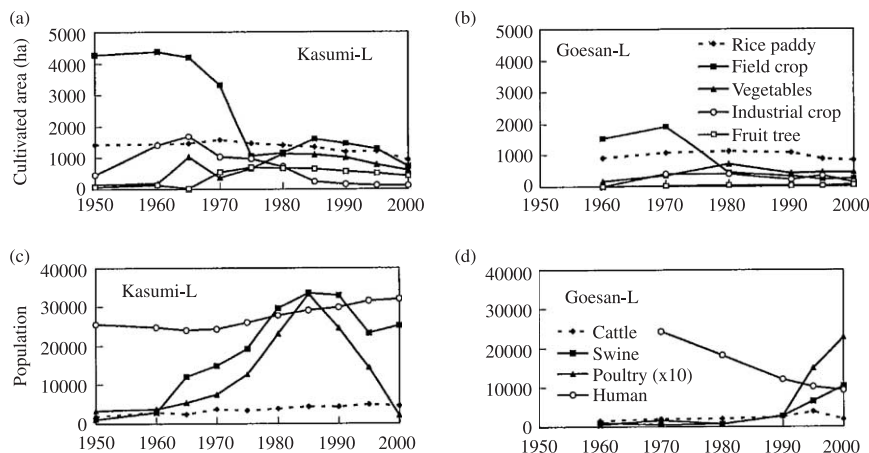


Figure 3 Long-term trends in the structure of the agricultural activities that generated N loads in the Kasumi-L (a, c) and Goesan-L catchments (b, d). (a and b) show cultivated area for each crop group (c and d) show populations of human and major livestock animals

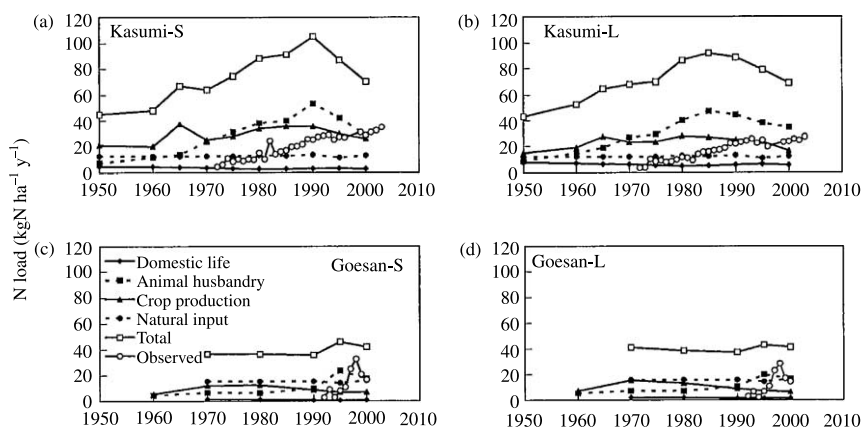


Figure 4 Long-term trends in the estimated environmental N load and in the observed load measured in river water at the outlet of each catchment of Kasumi-S (a), Kasumi-L (b), Goesan-S (c) and Goesan-L (d)

figure, environmental N loads in each of the four categories are presented per unit area (ha) so that the results from the four catchments can be directly compared.

Long-term trends in the total environmental N load in the Japanese catchments fluctuated between 1950 and 2000, but showed an overall increase until about 1990, followed by a sharp decline (Figure 4a, b). These fluctuations mainly resulted from changes in the N load from animal husbandry. The load from this activity was relatively small at the beginning of the period, but gradually increased until 1990 in the Kasumi-S and until 1985 in the Kasumi-L. Thereafter, it decreased sharply in both catchments. These trends seemed to reflect the drastic decrease in poultry populations and the smaller decrease in swine populations in the Kasumigaura region (Figure 3c).

The N load from crop production continuously accounted for a large proportion of the total load, and remained relatively stable throughout the study period (Figure 4a, b) despite the drastic changes in the crop groups cultivated in the region (Figure 3a). This apparent stability seems to have resulted from the shift from field crops (low N load as a result of low input and low output of N) to vegetables (a higher N load as a result of high input and high output of N).

The N load from domestic life seemed stable at low levels throughout the study period (Figure 4a, b) even though the total population increased continuously (Figure 3c). This apparent stability can be attributed to a simultaneous increase in the efficiency of wastewater treatment in the region. Early in the study period, gray water was mostly discharged into local bodies of water without treatment, and was thus the main source of environmental load from domestic life, but once improved sewer systems and septic tanks were installed in the region, the per-capita load gradually decreased.

In contrast, the total environmental load in the Goesan region was much lower than in the Kasumigaura region and was stable from 1970 to 1990 in the Goesan-S catchment (Figure 4c) and from 1970 to 2000 in the Goesan-L catchment (Figure 4d). This pattern resulted primarily from stabilities in the sum of the loads from crop production and animal husbandry. In both catchment (Figure 4c, d), the decreased loads from crop production seemed to be outweighed by the increased loads from animal husbandry, resulting in apparent peaks in the total load in 1995.

Comparison of the environmental load with the observed load in river water

Figure 4 also shows trends in the N load observed in river water at the outlet of each catchment. The trend in this observed load in the Kasumigaura region was a continuous

increase throughout the study period, even after an apparent peak in the environmental load in 1985 or 1990, and the observed load was consistently lower than the total environmental load (Figure 4a, b). This relationship was also seen in other catchments in the region (data not shown).

These findings were consistent with those of Itahashi *et al.* (2006), in which the potential N outflow was analyzed. Given that most of the environmental load in the Kasumigaura region represented inputs at the soil surface rather than direct discharges into bodies of water, the results suggest that the environmental N load at the soil surface took a considerable length of time to travel through the soil–groundwater system until it reached open water, and that significant attenuation in N levels occurred during this travel. The length of this travel time appears to be at least 10 and 15 years in the Kasumi-S and Kasumi-L catchments, respectively, based on the difference between the peak in the environmental load and the expected peak in water quality data, which has not appeared before 2003. The magnitude of the attenuation before the N load reaches open water can be defined as the apparent reaching ratio (i.e. the proportion of an N load that reaches a body of water), which equals the ratio of the expected maximum observed load in the river to the maximum environmental load. These values equaled 0.33 and 0.30 for the Kasumi-S and Kasumi-L catchments, respectively, and were similar to the value of 0.25 reported by Boyer *et al.* (2002) for 16 catchments with large variations in land use and population density in northeastern USA.

In contrast, obvious peaks in the observed loads in the Goesan region were seen in 1998, and these peaks appeared almost immediately after the peak environmental N loads, which occurred in 1995 (Figure 4c, d). This suggests that the apparent travel time for N in this region was around 3 years, which was much shorter than in the Kasumigaura region. At the same time, the apparent strengths of attenuation in the Goesan region were much lower than in the Kasumigaura region: the apparent reaching ratios were 0.71 and 0.66 in the Goesan-S and Goesan-L catchments, respectively.

These observations suggest that in the Kasumigaura region, the effects of changes in activities that generate N loads in the catchment tended to appear after a considerable delay in the river water, and that as a result, the river water is relatively less affected by these N loads; in contrast, the changes appear promptly in the Goesan region, which appears to be affected more strongly by changes in N load. These results suggest the importance of considering the travel time of N through the soil–groundwater system when calculating the apparent reaching ratio, because failing to consider this parameter in calculations would lead to incorrect results in some cases, such as in the Kasumigaura region. In other areas, travel time is less important, as was the case in the Goesan region.

The difference in the sensitivity of bodies of water in the two regions can be attributed to differences in regional characteristics rather than differences in catchment size; Figures 4a and 4c represent small catchments and Figures 4b and 4d represent large catchments, but the patterns are similar for both catchment sizes. Differences in the regional characteristics include topography (flat land *versus* hills), geology (volcanic ash *versus* granite), soil characteristics (deep *versus* shallow), and agricultural practices, among other factors. Further studies in other regions with different characteristics would help to elucidate the factors that control the strength of attenuation and the time lag.

Conclusions

By comparing the environmental N loads with the loads observed in river water at the outlet of similar catchments in South Korea and Japan, it was discovered that the effect of changes in the environmental N load in a catchment appeared almost immediately in the river water in South Korea, but did not appear clearly even after 10 years in Japan,

and that the strength of attenuation appeared much lower in South Korea than in Japan. These findings suggest that regional characteristics play important roles in the sensitivity of bodies of water to activities that generate N loads.

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