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Evaluating impact of land use and N budgets on stream water quality in Hokkaido, Japan

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Abstract

This study was conducted to evaluate the impact of land use system and N loadings to the environment estimated from N budgets on quality of stream water in Hokkaido, Japan. A case study was carried out in three towns of southern Hokkaido, which are Shiraoi, Yakumo, and Shizunai, characterized by intensive poultry farming (IPF), dairy cattle farming (DCF), and race horse farming (RHF), respectively. The estimation of N budgets using an N flow model indicated that the highest disposal N (880 Mg N yr^{-1}) was generated in the IPF town and it resulted in 250 kg ha^{-1} yr^{-1} surplus N in croplands. The disposal N was much lower in the DCF and the RHF town (102 and 71 Mg N yr^{-1}, respectively) than that of the IPF town. Cropland surplus N in DCF town was 31 kg N ha^{-1} yr^{-1}, whereas RHF town had negative N balance. The linear regression analysis indicated that NO_3-N concentration in stream water was significantly correlated with the proportion of upland field in drainage basins. The regression slopes varied among the towns, and it was the highest for IPF (0.040), intermediate for DCF (0.023) and the lowest for RHF town (0.006). The multiple regression analysis showed that regression slopes were significantly correlated (R^2 = 0.77 at 5% level) with livestock disposal N and cropland surplus N. Therefore, we assumed that these regression lines were the baselines for non-point source pollution, and the regression slopes were determined to act as impact factors of stream

water quality. However, two sampling sites in the IPF area were scattered above the baseline. This fact strongly suggests that the area was affected by point source pollution.

Introduction

There is growing concern on environmental degradation due to N pollution. Losses of N from agricultural fields have been widely reported as the major cause for such pollution. Many developed countries are experiencing environmental pollution due to intensive crop and livestock production (Bouwman and Booij, 1998). Intensive livestock production is becoming increasingly concentrated in small areas. Disposal of excreta from cattle feedlots without pollution of soil and water resources is very challenging (Chang and Entz, 1996). A practice of large-scale livestock husbandry, depending on imported feed and disposal of livestock excreta, could be a major cause of N cycle alteration resulting in N pollution of the environment. Recently, there has been a growing trend of this practice in Japan. Nutrient cycling through food and feed systems in Japan was limited in environmental loading in 1960s, but the system was later enormously loaded with N because of importing a huge amount of feed on a large scale (Hakamata, 1992). Hokkaido is one of the livestock husbandry areas in Japan, and is widely known as a primary dairy farming area (Hojito, 1998). Nagumo and Hatano (2000a) estimated the livestock excrement generated in Hokkaido as 133 Gg N annually, which occupied about 90% of the total excrement N generated by humans and livestock each year.

A correlation between land use and water quality has been frequently reported (Smart et al., 1985; Jordan et al., 1997; Lichtenberg and Shapiro, 1997; Hirose and Kuramoto, 1981; Tabuchi et al.., 1995). In a case study conducted in Hokkaido, Tabuchi et al. (1995) found that the proportion of agricultural land, consisting of upland field including grassland, were positively correlated with NO_3-N concentration, measured during the summer period, in stream water. They also reported that the regression co-efficient varied among the regions according to land use systems. Furthermore, Shimura and Tabuchi (1997) found that the stocking density of cattle and measured NO_3-N concentration had a high correlation. They indicated that the higher concentration was due to an increase in stocking density of cattle. In order to evaluate the impact of agricultural practice on water pollution at farm or regional scale, there has been a substantial effort in developing methodologies (Barry et al., 1993; Matsumoto, 1997; Zebarth et al., 1999). Nagumo and Hatano (2000b) evaluated the impact of N cycling associated with production and consumption of food on N pollution of stream water at town scale in Hokkaido. They concluded that the N flow model, composed of N budgets in human, livestock, and cropland sub-systems, was a useful method for estimating N cycling in relation to pollution of stream water. Southern Hokkaido, near or around the Funka Bay area is reported to have potential N loadings due to livestock excrement followed by livestock farming regions such as Tokachi, which has resulted in an eutrophication problem in the estuaries (Nagumo and Hatano, 2001). The objective of this study is to evaluate the impact of land use and N loadings, estimated from budgeting methods, on quality of stream water. A case study was conducted in three towns of southern Hokkaido. The results obtained were compared with the findings of previous studies and were evaluated at the regional scale in Hokkaido.

Materials and methods

Study sites

Three towns in southern Hokkaido, Shiraoi, Yakumo, and Shizunai, were selected (Figure 1) for representing various land use types and livestock farming practices. Main characteristics of the study sites are summarized in Table 1. Shiraoi is characterized by intensive poultry farming (IPF) along with beef cattle and pig, where livestock density is 23 animal unit (a.u.) ha^{-1} of agricultural land. Beef cattle density is 5 a.u. ha^{-1} and poultry is about 17 a.u. ha^{-1} in Shiraoi. Yakumo is characterized by dairy cattle farming (DCF) with intermediate livestock density of 2.1 a.u. ha^{-1}. Racehorse farming (RHF) with the lowest livestock density of 0.8 a.u. ha^{-1} is characteristic of Shizunai. Forests, urban areas, and agricultural land are the common features of these three towns. The arable lands including grassland and excluding paddy fields were defined as upland fields in this study. The major cereal and vegetable crops grown in uplands are wheat, maize, sugar beet and potato. Soil type in three towns is mainly Andosols, characterized by volcanic deposits derived from Mt. Tarumae, Eniwa, Usu and Komagatake. The annual average temperatures degree are 6.5 °C, 7.9 °C, and 7.7 °C; and annual average rainfall are 1669 mm, 1232 mm, and 1077 mm at

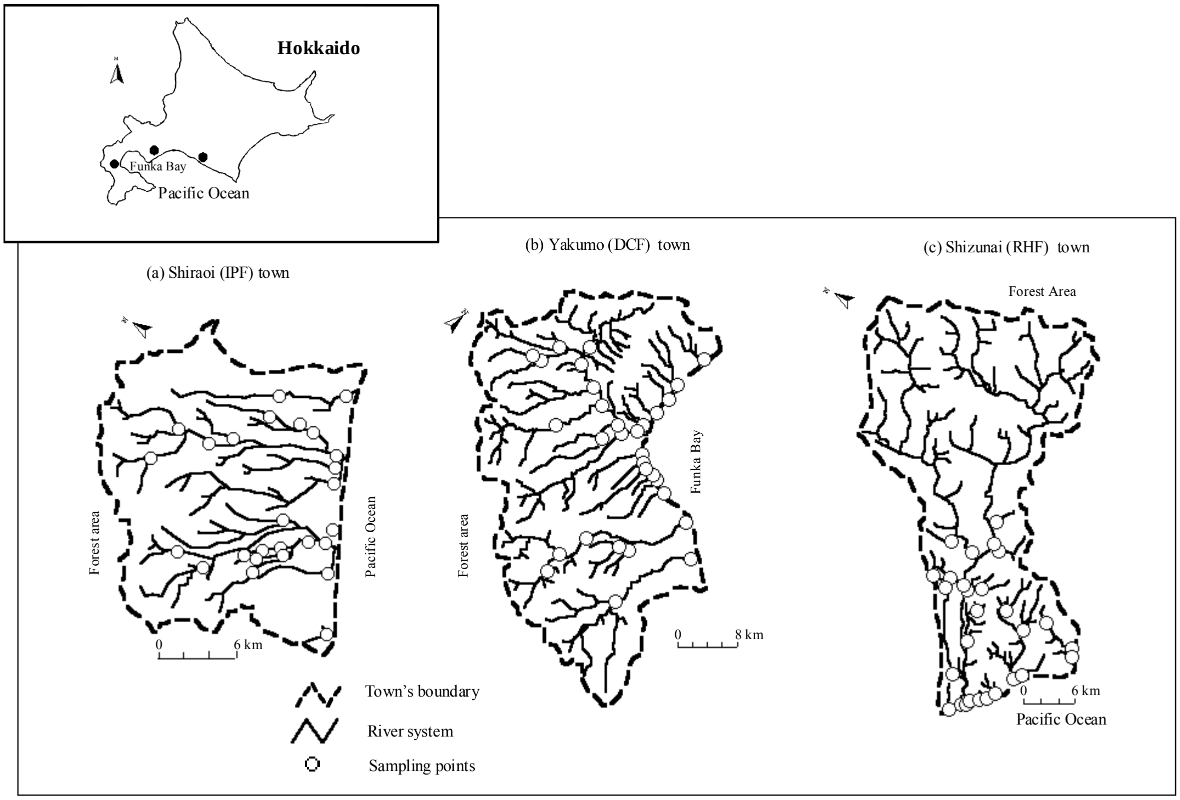

Figure 1. Location of study sites showing river system and distribution of sampling sites.

Table 1. Area, population and livestock of the study sites

		Town		
		Shiraoi (IPF)	Yakumo (DCF)	Shizunai (RHF)
Total area (ha)		42562	61791	73079
Agricultural land (ha)		694	5450	4198
Population		22812	18097	23240
Livestock head	Dairy cattle	0	11300	782
	Beef cattle	3262	179	60
	Pig	7000	0	0
	Poultry	1170000	0	0
	Horse	337	6	3272
Livestock density (a.u. ha^{-1})[a]		23	2.1	0.8

[a] 1 a.u. equals either one dairy or beef cattle, 8 pigs, 1.3 horse or 100 poultry and livestock density is calculated as per unit of agricultural land

Shiraoi (Shiraoi, 1996), Yakumo (Yakumo, 1998), and Shizunai (Shizunai, 1997), respectively.

Estimation of N budget

The N flow model, developed by Matsumoto (1997) and simplified by Nagumo and Hatano (2000b), was used to estimate the N budget associated with production and consumption of food and feed. The flow model consists mainly of three sub-systems, which are humans, livestock, and croplands (Figure 2). Input N and output N for each sub-system were estimated. The excreted N from humans and livestock, which is not used or recycled but disposed, was defined as disposal N. The livestock manure, which exceeds the volumetric capacity of farmyard barn, is openly piled up near or around the farm or disposed of permanently in Hokkaido and such manure is included in disposal N. Surplus N in cropland was estimated by subtracting outputs from inputs of cropland sub-system. The sum of disposal N and surplus N in cropland of this flow model was termed as N load to the environment. The method for estimating N budgets was referred to that of Nagumo and Hatano (2000b), along with related information and data on primary units referred to, which are presented in Table 2. A brief description of input and output sources of three sub-systems in N flow model and the estimation methods, which were modified or added, are described here. The human sub-system includes N flows from the imported and self-supplied food towards human excretion. Input variables of livestock sub-system were assumed as feed and litter bedding and the outputs were excretion, export of livestock and its products, and ammonia volatilization during collection and storage of manures. Input of N through grazing was not included in this study due to lack of reference. The export of livestock and its products in the study sites was referred to SID, MAFF (1996). Inputs of cropland sub-system were assumed as compost and chemical fertilizers, crop residues, rainfall, irrigation, and biological N fixation. Whereas the outputs were crop uptake, denitrification and ammonia volatilization from applied manure in cropland. According to Barry et al. (1993), the amount of manure-N volatilized during collection combined with storage and after field application were assumed to be 28% (of total manure-N) and 10% (of manure-N applied), respectively. Denitrification loss was estimated to be 18% of the amount of N in chemical fertilizers applied (Koshino, 1976). The data and information on annual cultivated lands, planted area of individual crop, and crop yields were referred to the MAFF (1995).

Water sampling and land use analysis

Water samples were collected from a total of 85 sampling sites (Figure 1) during the plant-growing season in summer (August 24-September 4) in 1999. The summer period was chosen for sampling specially for comparing the result with that of the previous study conducted by Tabuchi et al. (1995) at Hokkaido. The sites for water sampling were selected along the main stream and at the outlets of tributaries ensuring that drainage basins of all major upland fields would be covered. In the laboratory, samples were filtered with pre-rinsed 0.2 μm filter paper and NO_3-N concentration was determined using the Ion

Table 2. Information and sources referred to for N budget estimation

	Unit	Total	Imported	Self-supplied		Reference
Human food	kg N			Crop	Livestock	
consumption	person^{-1} yr^{-1}	2.87	1.8	1.05	0.02	SID, MAFF (1992); RCSTA (1982)
Feed	kg N					
consumption	head^{-1} yr^{-1}			Crop prod.	Crop residues	
Dairy cattle		175.4	42.2	133.1	0.1	SID, MAFF (1995); AFFRCS, MAFF (1995)
Beef cattle		75.7	70.5	3.4	1.8	
Pig		8.4	8.4	0	0	
Horse		38.3	0	38.3	0	
Chicken		1	1	0	0	
Bedding litter consumption						
Dairy cattle	kg N	0.3	0.2	0.1		SID, MAFF (1995); Kyuma (1984)
Beef cattle	head^{-1} yr^{-1}	4.5	2.5	2		AFFRCS, MAFF (1995)
Pig		0.1	0.1	0		
Horse		0.3	0	0.3		
Livestock export						Kametaka et al. (1994)
Dairy cattle	kg N	21.7				SID, MAFF (1996); RCSTA (1982)
Beef cattle	head^{-1} yr^{-1}	1				
Pig		5.3				
Horse		3.5				
Chicken		0.4				
Livestock excrement						Nyukantori (1976)
Dairy cattle	kg N	88				
Beef cattle	head^{-1} yr^{-1}	88				
Pig		12				
Horse		68.3				
Chicken		0.9				
N fixation	kg N	Paddy	Upland	Upland	Grassland	
	ha^{-1} yr^{-1}	field	non-legume	legume		Yoshida (1981)
		30	5	140	15	

Chromatography. Drainage basin of each sampling point was identified in the topographic maps of 1:25000 scales by hand-delineated boundaries. Major land uses such as uplands, forests and urban settlements were then read by dividing the respective drainage basins into square messes (4x4 mm^2 in size). The proportion of upland field and other land uses were calculated as the percentage of total drainage area of sampling points. The drainage basin for each sampling point was calculated in such a way that the sampling points at lower reach streams include the drainage basins of all upper streams and tributaries that mix into it.

Results

N budget at town scale

N budgets were estimated at town scale and the N flow values in three sub-systems of the flow model are presented in Figure 2. In IPF town, the main flow of N was import of feed to and the excretion from livestock (Figure 2a), which resulted in a disposal N as high as 880 Mg N yr^{-1}. About 76% of the total livestock excretion of 1068 Mg N yr^{-1} was disposed without recycling on croplands. The disposed livestock excretion was 12 times greater than

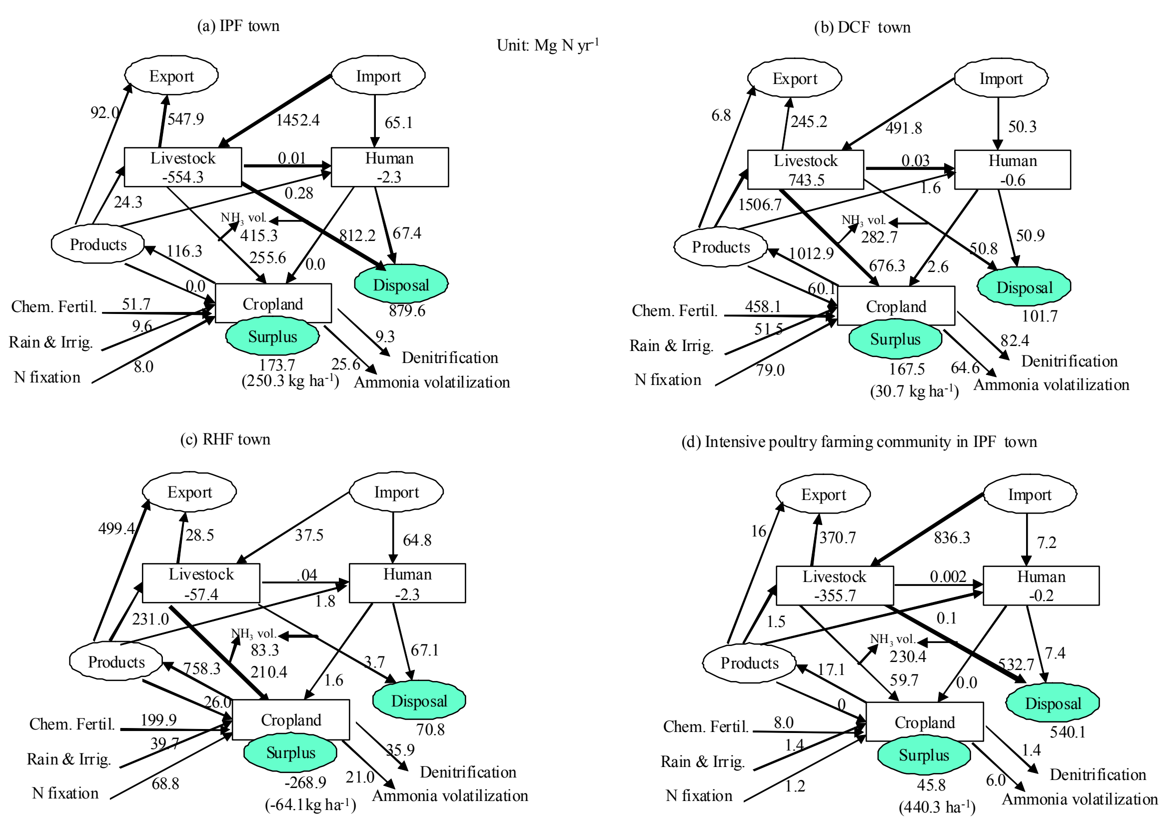

Figure 2. N budgets estimated from N flow Model at town scale (a-c) and at community scale (d).

the total excrement produced by human population in the town. Surplus N in cropland was about 174 Mg N yr^{-1}, which is equivalent to 250 kg N ha^{-1} yr^{-1} (per unit of cropland) in the IPF town. On the other hand, total disposal N in DCF and RHF towns were much lower as 102 and 71 Mg N yr^{-1}, respectively (Figure 2 b and c). A major part of livestock excrement (98% in RHF town and 93% in DCF town) was utilized in croplands in these two towns. Consequently, a large part of total disposal N was occupied by human excrement (95% in RHF town and 50% in DCF town). In the IPF and RHF town, the livestock sub-system was un-balanced (Figure 2 a, c and d). The reason for this is that grazing (important component of feeding for horse and beef cattle) was not included due to the lack of references for Hokkaido and that there were some discrepancies in primary units so that output N per unit of animal was larger than input in case of poultry and pig. The overall cropland surplus N in DCF town was about 168 Mg N yr^{-1}, and is equivalent to 31 kg N ha^{-1} yr^{-1}. However, the RHF town resulted in negative N surplus in cropland.

Land use analysis and NO_3-N concentration

The major land use pattern in the drainage basin of each sampling point is given in Figure 3. Generally, forests in three towns dominated upper catchments of stream sampling sites. Cropland and urban settlements shared land use at lower altitudes and plain areas. In the IPF town, proportion of upland area ranged from 0 to 35% of the total land. The range of upland proportion was 0-97% and 0-60% in DCF and RHF towns, respectively. NO_3-N concentration in stream water varied according to the land use pattern (Figure 4). The distribution of measured NO_3-N concentration showed that upper drainage basins, dominated by forests had a lower level of NO_3-N concentration, which is below 0.5 mg L^{-1}. The range of NO_3-N concentrations in some agricultural dominated catchments was 1-4 mg L^{-1} as shown in Figure 4. NO_3-N concentration in the IPF town reached up to 10.9 mg L^{-1}, and exceeded the drinking water standard of 10 mg L^{-1} as set by USEPA (Spalding and Exner, 1993). The stream outlets to the Pacific Ocean or the Funka Bay (Figure 4) had higher nitrate concentration compared to upper catchments, but the concentration was below 1 mg L^{-1}. It was probably due to dilution by upper-forested stream water, vegetation

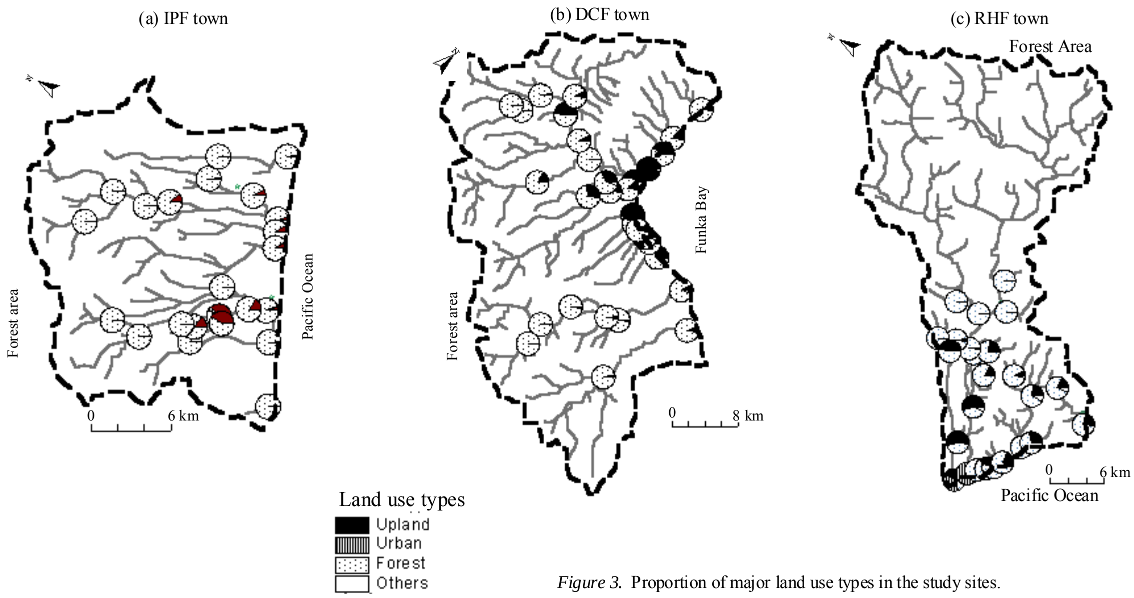

Figure 3. Proportion of major land use types in the study sites.

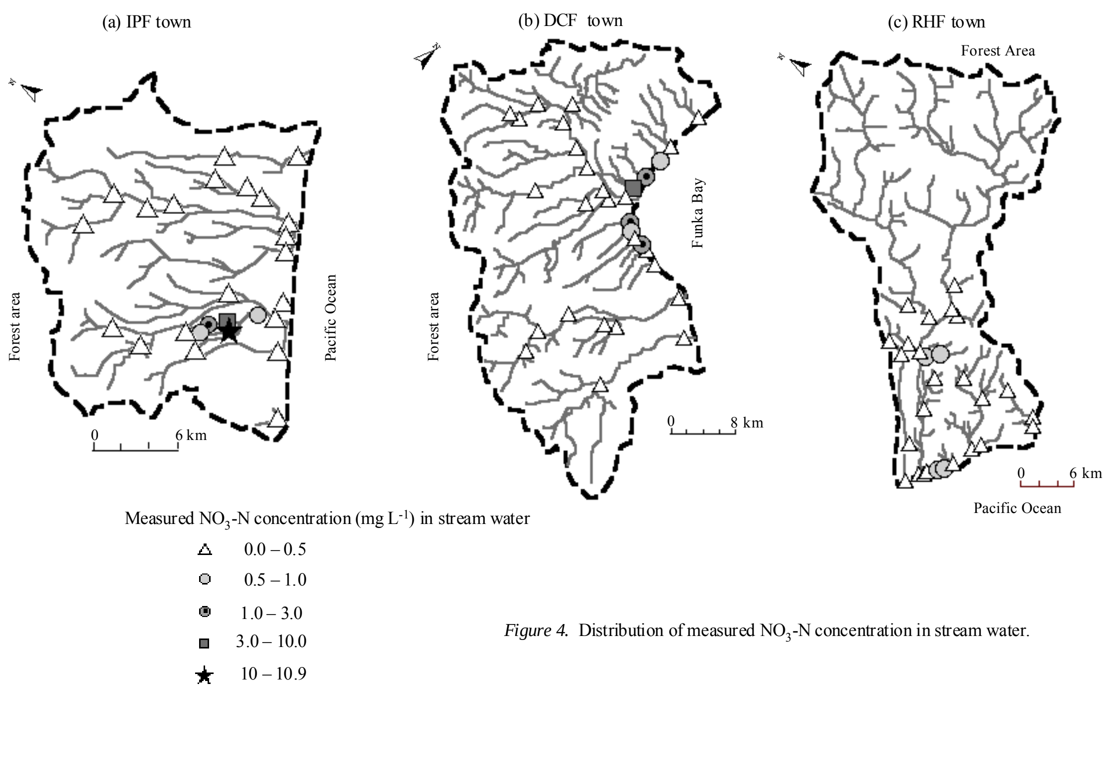

Figure 4. Distribution of measured NO_3-N concentration in stream water.

uptake, and denitrification in the riparian zone (Lowrance et al., 1984; Jordan et al., 1993; Jacobs and Gilliam, 1985).

Relationship between upland percentage and NO_3-N concentration

A regression analysis showed that NO_3-N concentration in stream water was significantly correlated with the proportion of upland field in drainage basins in DCF town (r=0.83) and IPF town (r=0.78) at <1% significant level, and in RHF town (r=0.42) at <5% significant level (Figure 5). Two sampling points in IPF town, having remarkably higher NO_3-N concentration, were excluded in this analysis. The regression slope was largest (0.04) for

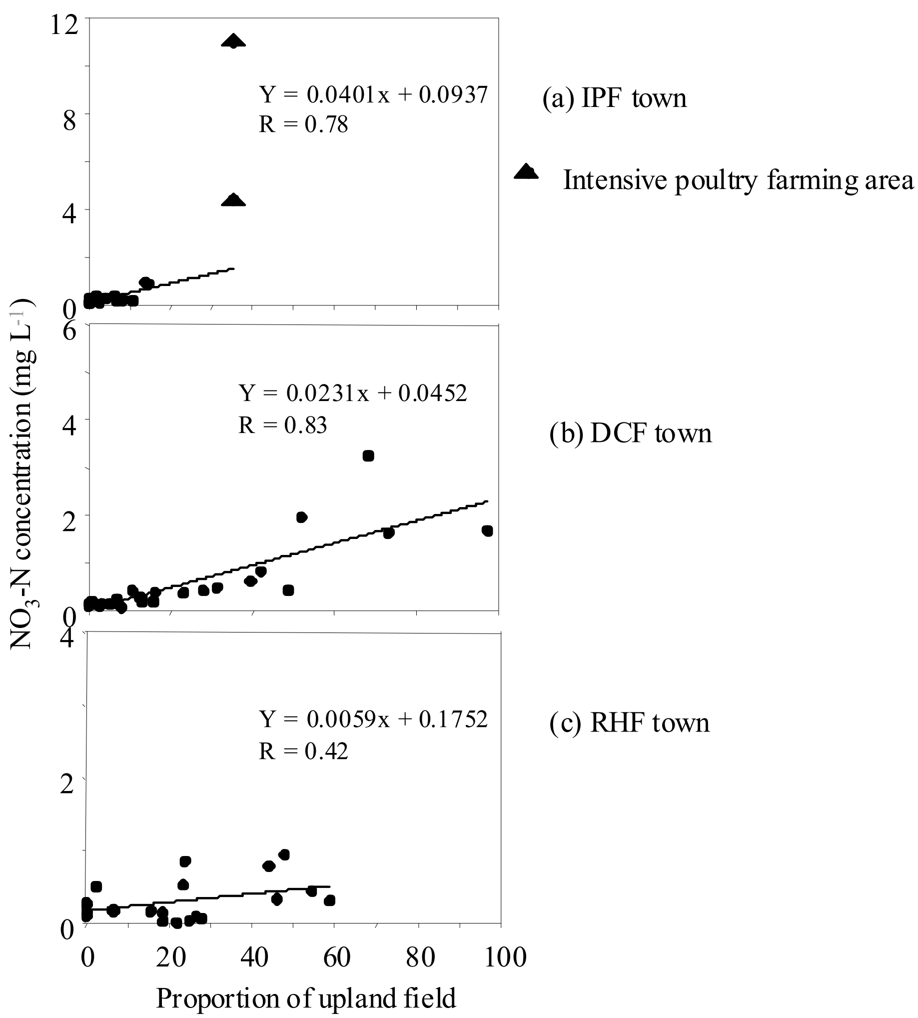

Figure 5. Relationship between proportion of upland field and NO_3-N concentration in stream water.

IPF town, intermediate for DCF town (0.023) and smallest for RHF town (0.006). The slopes indicated an impact intensity of upland field on stream water. Therefore, we defined the slope as impact factors of water quality. The impact factor was resulted from non-point source pollution, and therefore the regression lines were assumed as the baselines. Two sampling points scattered far from the base line due to high NO_3-N concentration in the IPF town were probably affected by point source pollution. The N budget at community scale estimated for the community of IPF town, which includes these two sampling points is presented in Figure 2d. The disposal N was 540 Mg N yr^{-1} in this community, which occupied about 61% of the total disposal N in the IPF town. Only about 10% of the livestock excrement was utilized in croplands, and the greater remaining part was disposed of. The disposed livestock excrement occupied about 99% of the total disposal N generated in this community. Surplus N per unit area of cropland was also extremely high as 440 kg N ha^{-1} yr^{-1}. The result indicated that the excessive high flow of disposal N could have resulted in point source pollution in this intensive poultry farming community.

Discussion

N loading to the environment due to disposal and surplus N, estimated by N budgets, differed according to the type and intensity of livestock. The load was the highest in intensive poultry accompanied by beef cattle farming compared to that of dairy cattle and horse farming towns. Zebarth et al. (1999) also studied the effect of livestock production on N load to the environment at a district scale in British Columbia, Canada. They reported a distinct variation in cropland surplus N with respect to the intensity and type of livestock, ranging from -24 (at no livestock area) to 238 kg N ha^{-1} in intensive poultry and swine production. A similar results were obtained in this study, which showed a negative N balance (-64 kg N ha^{-1}) in HRF town, 31 kg N ha^{-1} cropland surplus N in DCF town, and 250 kg N ha^{-1} in the IPF town (Figure 2a-c). The N surplus value <50 kg N ha^{-1} is expected under optimal N management in agriculture lands (Zebarth et al., 1999); hence, the surplus N in the intensive livestock farming area exceeded 5 times of the optimum value.

N loads due to livestock excretion could have resulted from its inadequate management. In Hokkaido, most livestock farms are reported to have manure barns. About

90% of them, however, are reported to be without cover. The excreta over the volumetric capacity of farmyard barns was openly piled up near the surrounding area or disposed of permanently. In both cases, manure exposes to rain and snowfall. This has probably induced in leaking out via surface run-off and leaching into sub-surface or ground water. In this study, two sampling points with high NO_3-N concentration in the IPF town could be the result of point source pollution, induced by inadequate manure handling practices. On the other hand, in DCF town, disposed excretion was less than 7% (Figure 2b), as most of it was utilized in croplands. A negative N surplus in the RHF town could probably be due to the fact that the quantity of livestock manure applied in croplands was low, as horses are raised mainly on pasture lands, which could lead to a higher crop uptake than the fertilizers and manures applied.

In this study, NO_3-N concentration in stream water was significantly correlated with the proportion of upland fields. A similar result was obtained in Kushiro, Nemuro and Obihiro districts in Hokkaido (Tabuchi et al., 1995). Grassland areas dominated Land use in Kushiro. Nemuro had primarily grassland areas with high cattle density, and Obihiro had upland fields accompanied by grasslands. Tabuchi et al. (1995) estimated the regression slopes (impact factors) to be 0.01 for Kushiro, 0.02 for Nemuro and 0.03 for Obihiro, as shown in Table 3. Results of the N budgets for these regions, which were estimated by Nagumo and Hatano (2000a) are also summarized in Table 3. A multiple regression analysis showed that impact factor had the best correlation (R^2 = 0.77 at 5% level of significance) with a combination of livestock disposal N and cropland surplus N (Table 4). This correlation clearly indicates that a rise in livestock disposal N and cropland surplus N increase the NO_3-N concentration of stream water.

Using the regression coefficient of best fitted multiple regression equation; impact factors for all districts in Hokkaido region were predicted. The distribution of predicted impact factor is presented in Figure 6. The predicted impact factors reflected the pattern of livestock disposal and surplus N in croplands. The livestock husbandry area showed high impact factor, which could be due to disposal and heavy application of animal excreta in the area. However, impact factor is the indicator for raising NO_3-N concentration in stream

Table 3. Nitrogen loadings and Impact Factors from present and previous studies

Location	Total area (km^2)	Estimated disposal N: Human	Estimated disposal N: Livestock	Surplus N	Impact Factor
		($Kg\ N\ km^{-2}\ y^{-1}$)			
IPF[a]	426	0.16	1.91	0.41	0.040
Obihiro[b]	2847	0.08	0.36	1.47	0.030
DCF[a]	618	0.08	0.07	0.23	0.023
Nemuro[b]	2005	0.05	0.36	-1.8	0.020
Kushiro[b]	2147	0.33	0.18	-0.93	0.010
RHF[a]	731	0.09	0.01	-0.34	0.006

[a]present study

[b]Disposal N and Surplus N data - referrred to Nagumo & Hatano (1999) and Impact Factor data- referred to Tabuchi et., al (1995)

Table 4. Regression analysis for N loading variables and impact factors

Equation		Regression coefficient	P	*a*	r and R^2 value
Simple regression					r
$y = b$ X human disposal N + a		-0.028	0.66	0.025	0.23
$y = b$ X livestock disposal N + a		0.014	0.06	0.015	0.80
$y = b$ X surplus N + a		0.006	0.26	0.022	0.55
Multiple regression					R^2
$y = b1$ X human disposal N + $b2$ X livestock disposal N + a	*b1*	-0.038	0.37	0.019	0.73
	b2	0.015	0.07		
$y = b1$ X human disposal N + $b2$ X surplus N + a	*b1*	-0.017	0.79	0.025	0.33
	b2	0.006	0.35		
$y = b1$ X livestock disposal N + $b2$ X surplus N + a	*b1*	0.012	0.09	0.016	0.77
	b2	0.004	0.27		
$y = b1$ X human disposal N + $b2$ X livestock disposal N + $b3$ X surplus N + a	*b1*	-0.03	0.49	0.020	0.83
	b2	0.013	0.13		
	b3	0.004	0.39		

y = impact factor; a = constant value; $b, b1, b2, b3$ = regression coefficients water due to non-point source pollution. Problems of N loading from point source pollution still remain.

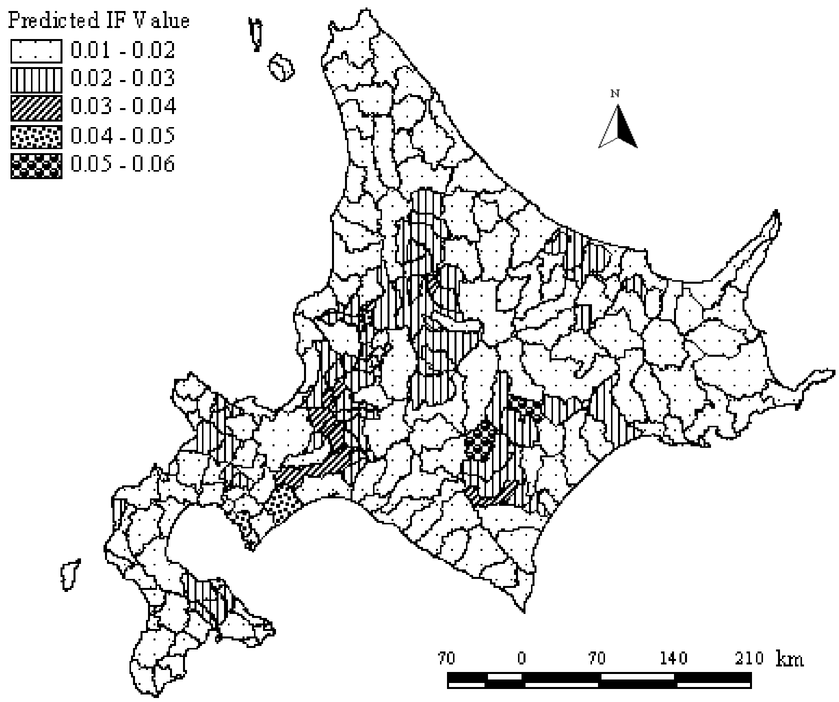

Figure 6. Distribution of predicted impact factor of stream water quality in Hokkaido region.

Conclusions

Disposal N generated from livestock excrement and surplus N in cropland influence the quality of stream water. Thus, in case of non-point source pollution areas, the method of N budget estimation could be a useful tool in predicting impact on water quality. This method, however, could not quantitatively estimate the impact factor for areas affected by point source pollution.

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