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ORIGINAL ARTICLE

Assessing the impact of phosphorus cycling on river water P concentration in Hokkaido

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Abstract

We estimated phosphorus (P) budgets for all 212 cities, towns, and villages of Hokkaido, Japan. We also carried out water sampling from all major rivers flowing in the respective areas during the snowmelt season and measured total P (TP) concentration. Surplus P in the agricultural land was estimated by subtracting the amount of crop uptake from the input sources, such as the amount of chemical and compost fertilizers, crop residues, rainfall and irrigation. The livestock excreta P not utilized on farmland was assumed to be disposed P. Total P concentrations in most of the river water ranged from undetectable to 1 mg L^{-1}, rarely reaching up to 2.32 mg L^{-1}, and the areas surrounding the Funka Bay had comparatively higher concentrations. More than two-thirds of the areas had the surplus P in farmland ranging from negative values to 30 kg ha^{-1} of farmland, and areas with mixed farmland and livestock husbandry had higher surplus values ranging from 31 to 72 kg ha^{-1}, indicating that the source of the residual P was applied chemical and manure fertilizers. Total P concentration in river water was not correlated with the proportion of upland field and urban area or with the farmland surplus P resulting from the P cycling and the municipal waste P that mixes into the river water. However, TP concentration was positively correlated with the proportion of Andisol area occupied by farmlands ($r = 0.25$, $P < 0.01$). The TP concentration was also correlated with the topographic factors in areas ($r = 0.49$, $P < 0.01$) that possess more than 50% of Andisols in farmlands. Multiple regression analysis showed that TP concentration was best explained by a combination of disposed excreta, the Andisol area occupied by farmland, the application rate of chemical fertilizers and topographic factors ($r^2 = 0.21$, $P < 0.001$). Thus, P losses from farmlands to river water during the snowmelt season could mainly be attributed to fertilizer management and soil type along with the topographic condition of the area.

Key words: phosphorus concentration, phosphorus budget, river water quality, surplus phosphorus, topography.

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INTRODUCTION

Agricultural land use has been associated with increased nutrient loading (Pionke and Urban 1985; Turner and Rabalais 1991), and runoff and leaching of non-point source nutrients from farmlands may lead to degradation of water quality in estuaries (Toth and Fox 1998). Nitrogen (N) and P are the major nutrients being lost from farmlands due to agricultural activities. These nutrients can cause eutrofication problem in estuaries. Phosphorus in runoff from agricultural land is an important component of non-point source pollution and can accelerate eutrophication of lakes and streams (Ekholm *et al.* 2005). Eutrophication or nutrient enrichment of surface waters is an important environmental problem in many areas because it produces excessive algal growth that can cause the death of fish by creating anoxia conditions when the algae die and bacteria decompose the algae using the dissolved oxygen (Ramos 1996). There has been a gradual increase in the concentration of nutrients in river water worldwide (Cloern 2001). Total P should not exceed 0.05 mg L^{-1} in rivers entering lakes and reservoirs to control eutrophication (Daniel *et al.* 1998).

Excess fertilization and manure application create N and P surpluses on agricultural lands (Carpenter *et al.* 1998). In agriculture, nutrient losses to surface waters result largely from the excessive application of inorganic and organic fertilizers in relation to nutrient removal in harvest, that is, surplus nutrient balances. Most of the manure N is lost from the agroecosystem by volatilization and leaching; however, P, with its lower mobility, largely accumulates in the surface soil (Sibbesen and Runge-Metzger 1995). When the input of P into the soil exceeds the removal of P in the crop, most of the surplus P will accumulate in the soil (Hooda *et al.* 2001). This accumulation increases the potential for P movement from soils through runoff and leaching to pollute surface water and groundwater (Elrashidi *et al.* 2005). The continuous accumulation of surplus P in the soil increases the total P content of the soil, much in readily exchangeable form, and the long-term risk of increasing P concentrations in land runoff and drainage to surface waters (Withers *et al.* 2001). Agricultural nutrient balances have, therefore, been used as indicators of the sustainability of farming practices (Parris 1998). Nitrogen and P budgeting methods are a useful tool in evaluating the impact of N and P cycling in agro-ecosystems on the quality of surface water (Nagumo and Hatano 2000; Smith *et al.* 2005). In some studies carried out over a drainage basin scale, significant positive correlations were found between the N concentrations in river waters and the proportion of common upland and grasslands in the drainage basins. The regression slopes or the impact intensities increased because of an increase in surplus N in farmlands (Woli *et al.* 2002, 2004). However, there is a lack of studies examining P concentrations in river water and P surpluses in farmlands. Therefore, the objective of the present study was to evaluate the relationship between upland proportion in drainage basins, the P concentration in river water and the P surplus in farmland estimated using P budgets in agricultural land.

MATERIALS AND METHODS

Study site and water sampling

All 212 cities, towns and villages of Hokkaido were selected for estimating P budgets in the agricultural land and for measuring P concentration in the outlet of major rivers and their tributaries.

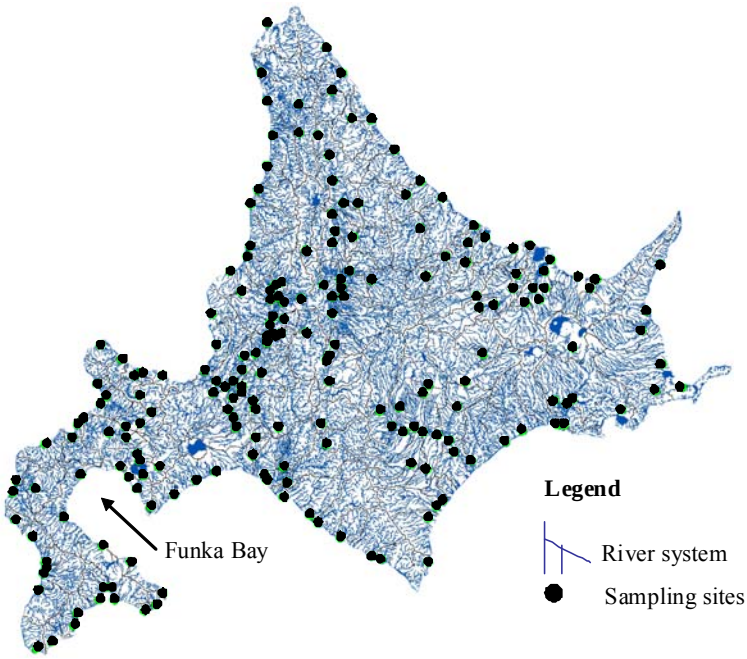

Figure 1 River system and the distribution of the sampling sites representing all cities, towns and villages in Hokkaido, Japan.

The outlet of major rivers flowing through most of the cities, towns and villages (Fig. 1) was chosen for taking water samples (Nagumo and Hatano 2001). Water sampling was carried out during the spring snowmelt in April 1998 by dividing the researchers into several groups to accomplish the sampling over a short duration of snowmelt and a similar timeframe, taking into account the snowmelting periods of the respective sites. For this reason, these data can not be representative of the sampling sites for the whole year; but are believed to be valid to analyze the relationship between river water quality during the snowmelt season and agricultural activity. The collected samples were brought to the university laboratory and put into the refrigerator (4°C) until the chemical analysis was done. Unfiltered samples were used to determine TP concentrations using persulfate digestion and the molybdate blue colorimetry method.

Estimating P budgets

A simple P budget model proposed by Baker and Richards (2002) was slightly modified and used for estimating soil surplus P in agricultural lands (Fig. 2). The original model included river export as one of the outputs associated with non-point loads from farmland and direct point source loads resulting from sewage sludge as the input. As we did not have data either on the P flux from the sewage sludge or on its application to farmlands, and we did not quantify the export of P to rivers because of lack of data on river velocity, these items were omitted from the budget estimation. Instead, we have added three components: farmland surplus, disposed excreta and municipal waste P, assuming that these have potential for leaching, loss through surface runoff or directly mixing into surface water. The farmland surplus P was estimated by subtracting outputs through crop

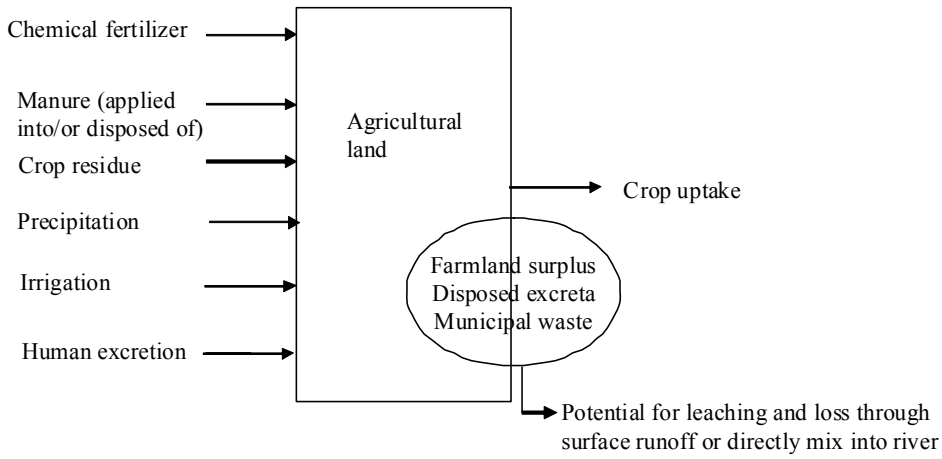

Figure 2 Phosphorus inputs to and outputs from the agricultural land.

uptake from inputs such as chemical and manure fertilizers, human excretion, crop residue, precipitation and irrigation. The quantity of P in livestock excreta not utilized on farmland was assumed as disposed P. The contribution of municipal waste to P discharge into rivers was evaluated based upon the TP removal efficiency (61% as proposed by Kunimatsu and Muraoka 1997) of the sewage treatment plants. The municipal waste was calculated on the basis of P content in human excrement, which was estimated by multiplying the number of people by the excretion rate 0.26 kg P person^{-1} as recommended by Matsuzaki (1979). As information on the use of human excreta on farmland was not available, the proportion of communities using self-treatment to the total was calculated by using the number of communities and the treatment practice (Ministry of Agriculture, Forestry and Fisheries 1990). The proportion of human excreta used on farmland ranged from 0 to 15.4%, which was estimated only for farming families and was apportioned between agricultural use and disposal. For non-farming families, the whole human excretion P was considered to be disposed, resulting in input to the sewage treatment plant. The database on human population, livestock and agricultural land was compiled by referring to the Hokkaido Statistics and Information Office (2003). The database compiled by Mishima *et al.* (2004) was referred to for estimating the P content in different crop products and its residues for various upland and lowland crops, vegetables, fruits and grasses. Chemical P fertilizers applied to the farmland were estimated based on the fertilizer recommended rate for various crops by the Hokkaido Department for Agropolicy (2002). The P content in applied livestock manure was calculated based on a report that 93% of livestock excreta are used for manure in Hokkaido (Hokkaido Government, 1993). The total livestock excrement was estimated by multiplying the number of livestock by the rate of excretion recommended by Nyukantori (1976). For dairy as well as beef cattle and pig, P content in the excrement was apportioned between agricultural use and disposed quantity by using the proportion of agricultural use of the excrement to the total in Hokkaido (Hokkaido Statistics and Information Office 1993). All poultry feces were assumed to be disposed of based on the study by Kaku *et al.* (1993). For horses, raised mainly by grazing, we assumed that all the excrement was applied to croplands, including that directly deposited on grasslands (Nagumo and Hatano 2000). The P concentration in precipitation was calculated by multiplying the annual mean precipitation and P content (1.18 kg ha^{-1} yr^{-1}), whereas the concentration in irrigation was calculated by multiplying the

total area of paddy fields by the irrigation water volume of 15,000 m^3 ha^{-1} and a P content of 0.13 kg ha^{-1} yr^{-1} in irrigated water as recommended by Sekiya (1987).

Calculating topographic factor

We used corrected topographic factors (CTF) to tentatively explain the stream TP concentrations. Using the Universal Soil Loss Equation (USLE: Wischmeir and Smith 1978 and MAFF 1992), the topographic factor (TF) is calculated as follows:

$$TF = (I/20.0)^{0.5} (68.19\sin 2\theta + 4.75\sin\theta + 0.068)$$

where I is the field slope length (m) and θ is the slope (°). In our study, the CTFs were estimated by setting I at 20.0 m and using the statistical data (acreage for three categories of farmland slope, Ministry of Agriculture Forestry and Fisheries 1994). The values (68.19sin2θ + 4.75sinθ + 0.068) were calculated with acreage-weighted averages for all cities, towns and villages in Hokkaido (Imai and Ishiwata 2006).

RESULTS AND DISCUSSION

Total P concentrations and their relationship with the proportions of upland and urban area and municipal waste P

A distribution of the TP concentration in the outlets of major rivers of Hokkaido is presented in Fig. 3. Forty two percent of the sampled sites had TP concentrations above 0.05 mg L^{-1}, which shows

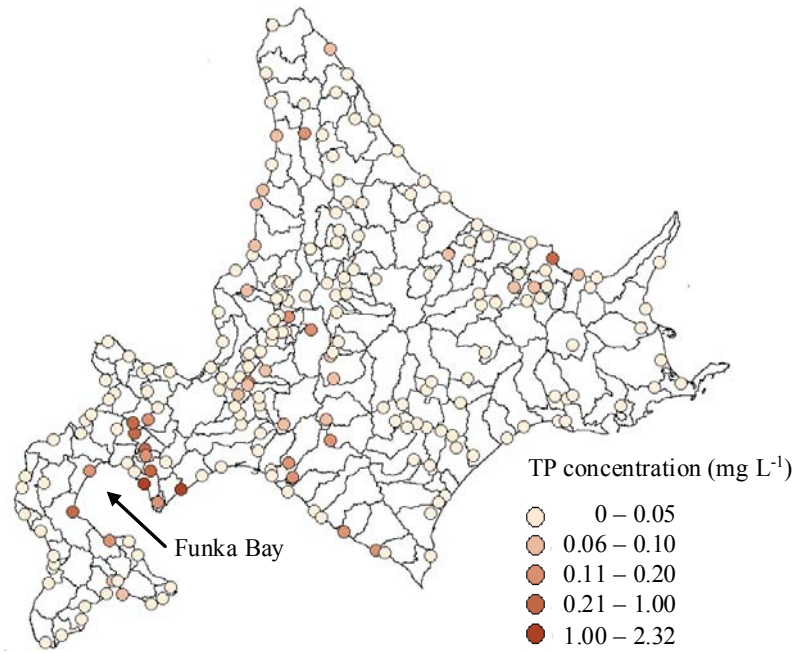

Figure 3 Distribution of total phosphorus (TP) concentrations in river water.

favorable conditions for eutrophication in the receiving estuaries. The areas surrounding the Funka Bay typically had higher TP concentrations, ranging from 0.5 mg L^{-1} to as high as 2.3 mg L^{-1}. There were two sites with a TP concentration exceeding 1 mg L^{-1} that were at the outlet of rivers flowing through urban areas. The river outlets of most of the cities had TP concentrations exceeding the recommended limit of TP concentration (0.05 mg L^{-1}) to avoid eutrophication. Various studies also reported that P losses to the surface water relate more to urban land use rather than agricultural and

forested land use (Beaulac and Reckhow 1982; Clesceri *et al.* 1986; Smart *et al.* 1985). Phosphorus loads from various land-use types can be affected by physical basin characteristics, such as drainage, geology, soil type and physiography (Clesceri *et al.* 1986). Comparing P loads from 21 watersheds with mixed land uses in the Missouri Ozark Plateau Province, USA, Smart *et al.* (1985) found that an urban watershed lost twice as much P as pastures. Beaulac and Reckhow (1982) and Clesceri *et al.* (1986) also reported that P loads are generally greatest from urban land, with lower loadings from agricultural land, and the lowest loading from forests. However, the TP concentrations in river water in our study correlated neither with the proportion of urban area (Fig. 4a) nor with the municipal waste P (Fig. 5a). The reason for this could be a lack of uniformity in the criteria used to select the sampling sites at the outlets of rivers flowing through the urban areas because evaluating the effect of municipal wastes on P loading to river water was not taken into account when sites were selected for taking grab samples from all over the Hokkaido region. Sampling sites selected above or below the points at which the outlet of sewage treatment plants is drained determine whether or not the effect of municipal wastes on P loading to river water can be assessed. The results indicated that TP concentration did not correlate with the proportion of upland fields (Fig. 4b), which was unlike the case of NO_3-N. Several studies have reported that NO_3-N concentrations are correlated with the proportions of upland fields (Hayakawa *et al.* 2006; Tabuchi *et al.* 1995; Woli *et al.* 2002, 2004) pasture land (Buck *et al.* 2004; Smart *et al.* 1985) and agricultural cropland (Cronan *et al.* 1999; McFarland and Hauck 1999; Nagumo *et al.* 2004). Jordan *et al.* (1997) also reported that unlike N concentration, P concentration did not correlate with any land use, but differed among watersheds. As P discharge is related to the transport of suspended particles (SP), the influence of agriculture on P discharge may be outweighed by the effects of the geochemistry and erodibility of sediments in the watersheds (Grobler and Silberbauer 1985; Vighi *et al.* 1991). A very rare case was found that both N and P concentrations increased with an increase in farmland area, but the area was characterized by the application of dairy waste as manure (McFarland and Hauck 1999). Phosphorus fluxes are difficult to quantify because P is strongly associated with suspended particles transported mainly during episodic high flows (Kronvang *et al.* 1992). Jordan *et al.* (1997) found that P concentration correlated with the concentration of SP, which differed greatly among watersheds in different regions. However, we could not evaluate the relationship between the SP and the TP concentrations in river water because we could not measure the SP because of unavoidable circumstances.

Estimated surplus P in farmland

The estimated P budget showed that 76% of the total towns had surplus P in farmland ranging from negative values to 30 kg ha^{-1} of farmland (Fig. 6), and areas with mixed farmland and livestock husbandry had higher surplus values ranging from 31 to as high as 72 kg ha^{-1}, indicating that the source of the residual P was the applied chemical and manure fertilizers. The towns with some of the highest surplus values (kg ha^{-1} of farmland) were the intensive livestock farming areas such as Sawara (71.9), Mori (63.9), Shiranuka (61.3) and Shiraoi (57.6), which had a comparatively low agricultural land base. This result is consistent with that of UK agricultural land (Withers *et al.*

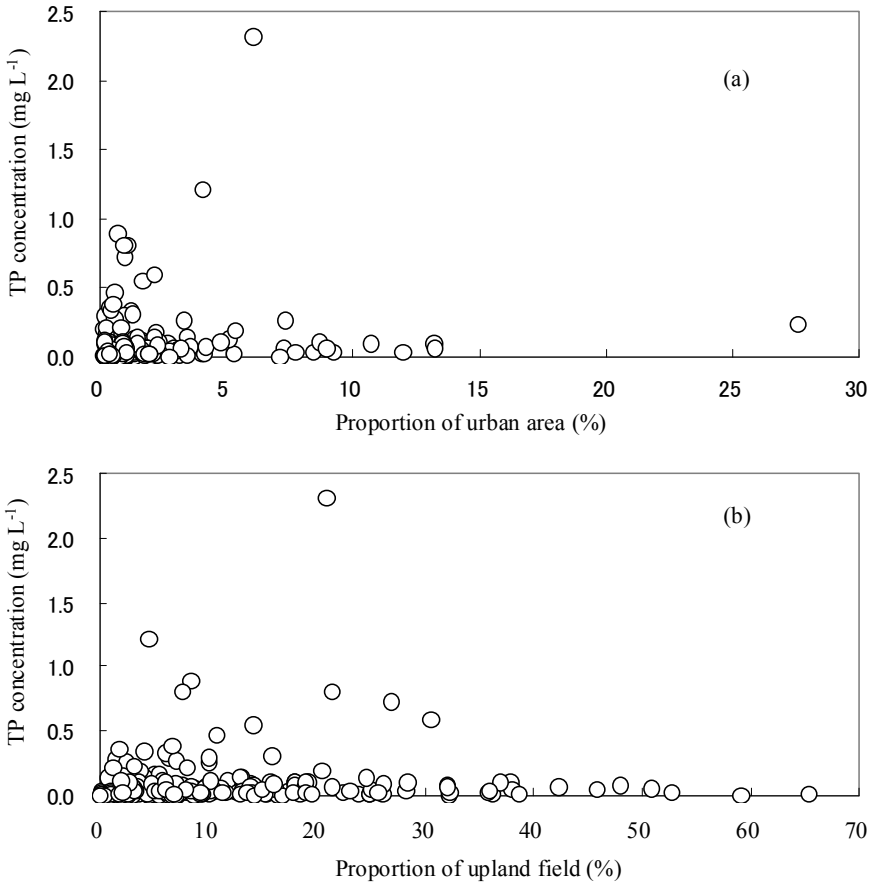

Figure 4 Relationship between the proportion of urban area (a) and upland field (b) and the total phosphorus (TP) concentration in the river water.

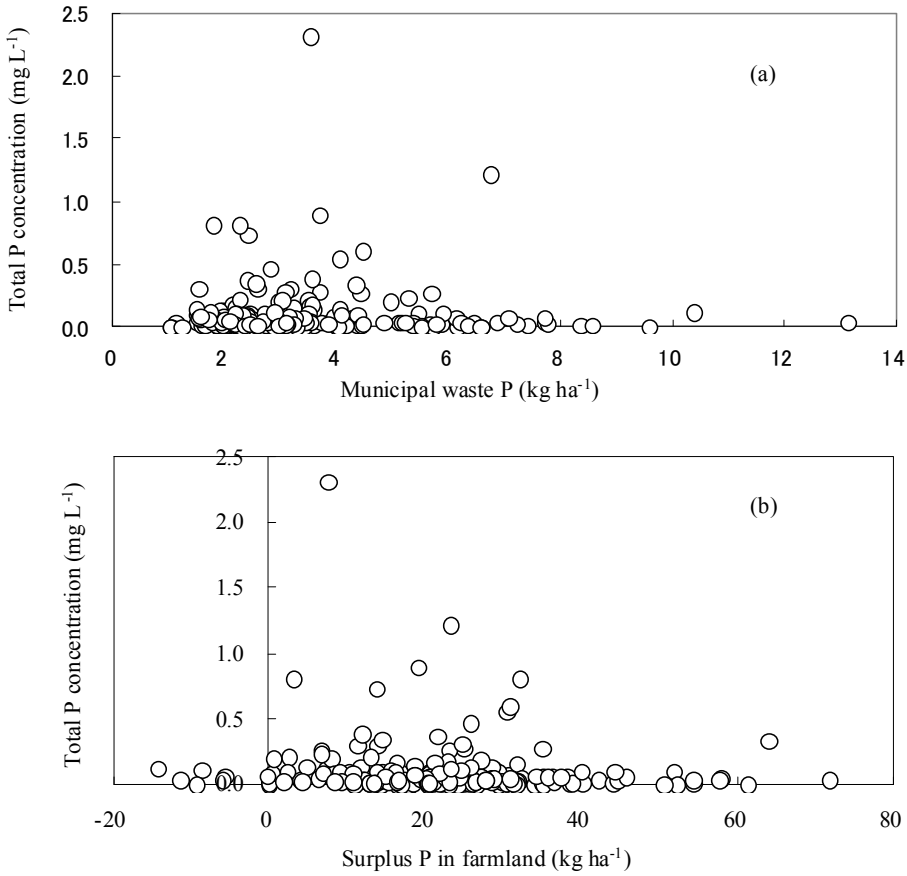

Figure 5 Relationship between municipal P (a) and surplus P in farmland (b) and the total phosphorus (TP) concentration in the river water

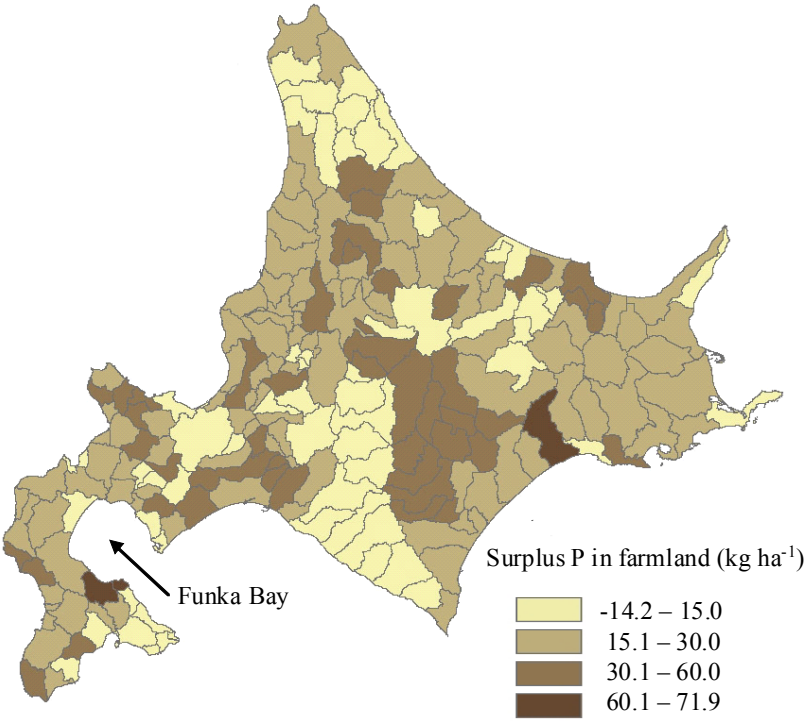

Figure 6 Distribution of surplus phosphorus (P) in farmland (kg ha^{-1}) estimated Using P budgets.

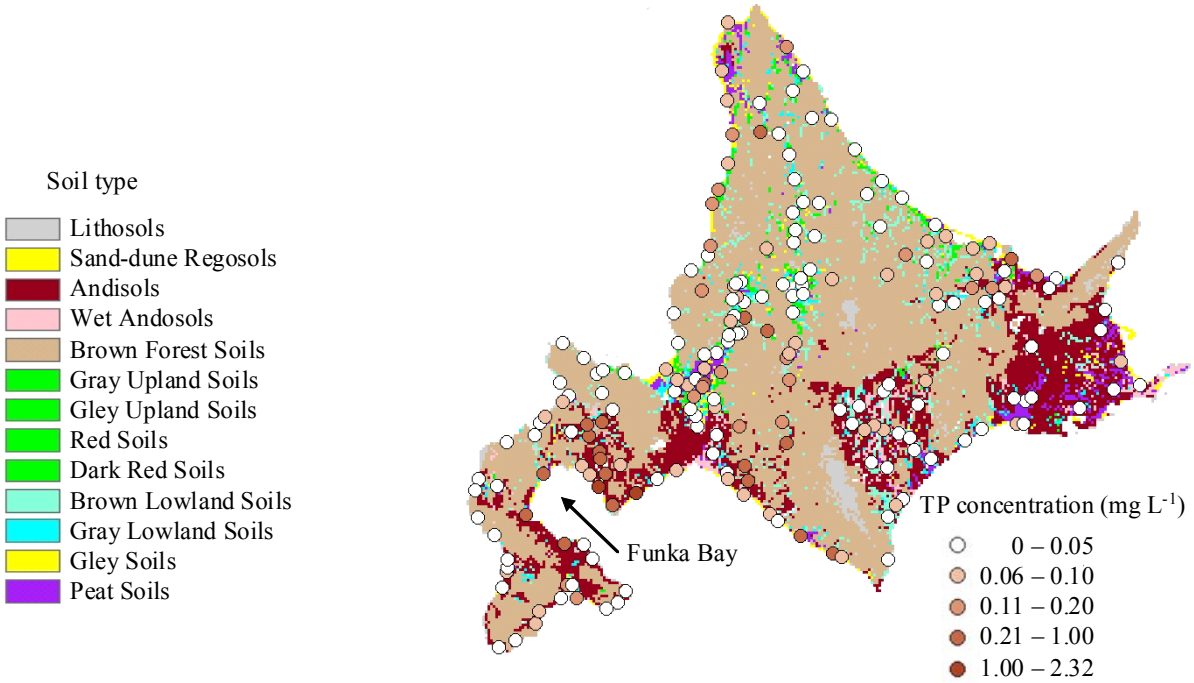

Figure 7 Distribution of total phosphorus (TP) concentrations in river water and soil types.

2001), where the largest P surplus occurred in the relatively limited areas of arable soils that received manure from intensive pig and poultry units. The values of surplus P in farmland in most of the cities, towns and villages of this study are quite high compared with previously reported values (less than 20 kg ha^{-1} of agricultural land) of farmland surplus P in Europe (Oenema *et al.* 2005. Withers *et al.* 2001) and in Australia (McKee and Eyre 2000), where the reported values ranged from negative to 17.5 kg ha^{-1}. However, the P surplus value of our study is small compared with that of the UK, where values up to 200 kg P ha^{-1} yr^{-1} were recorded (Hooda *et al.* 2001).

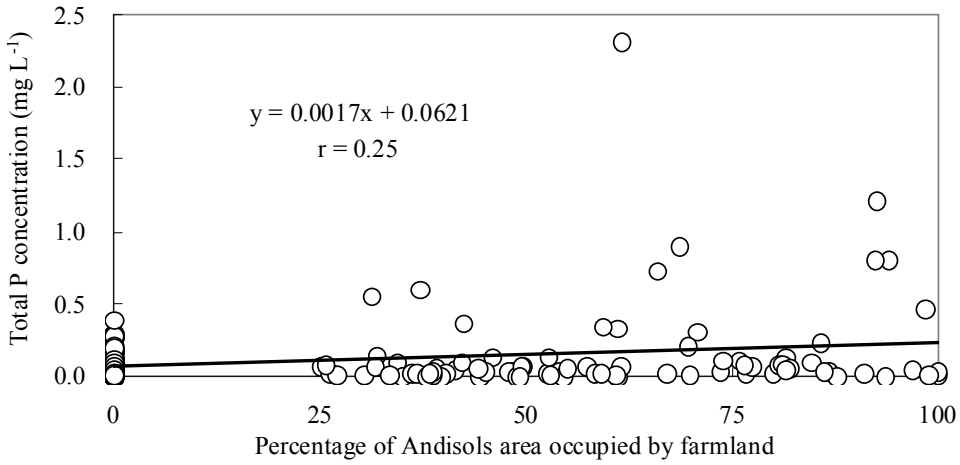

Figure 8 Relationship between the Andisols area occupied by farmland and the total phosphorus (TP) concentration in the river water.

Factors explaining the river TP concentration

Figure 5b shows the relationship between surplus P in farmland and the TP concentration in the river water. The result indicated that the TP concentration was not correlated with the farmland surplus P, and suggests that P loss from farmlands is not attributed to the P cycling in an agro-ecosystem. Several studies have reported that the loss of P from farmlands is linked more with topography and sediment loss resulting from soil erosion (Baker and Rechards 2002; Sibbesen and Runge-Metzger 1995; Vighi *et al.* 1991). Our study showed that river water in the areas with most of the Andisols (characterized by volcanic soils) had low concentrations of TP, except for the area surrounding Funka Bay (Fig. 7) even when the soil surplus P was high. However, the proportion of Andisol area occupied by farmlands showed a significant positive correlation ($r = 0.25$, $P < 0.01$) with TP concentrations (Fig. 8). We also evaluated the impact of topographic factors on TP concentration by dividing the Hokkaido region into two groups: areas covered by above 50% of Andisols occupied by farmlands (group A) and all areas possessing Andisols of varying proportions (group B). The result showed that topographic factors were positively correlated ($r = 0.49$, $P < 0.01$) with TP concentration for group A (Fig. 9). Using the TP concentration as a dependent variable and the disposed excreta per unit of land area**,** application rate of chemical fertilizer per unit of farmland, application rate of manure fertilizer per unit of land area, Andisol area occupied by farmland, and topographic factor as independent variables, we carried out multiple regression analyses. The results showed that TP concentration was best explained by a combination of all these variables ($r^2 = 0.21$,

$P < 0.001$, n = 211) as illustrated in Eq. 1:

$$\text{TP concentration} = -0.071 + (0.028 * \text{disposed excreta} + 0.0018 * \text{Andisol area occupied by farmland} + 0.0019 * \text{application rate of chemical fertilizer} + 0.036 * \text{topographic factor}) \quad (1)$$

These results indicated that TP export would occur in Andisol regions, although they have a high P absorption capacity, when a high amount of P fertilizers is applied in sloping areas. It should be noted that there is a limitation in the application of this result as the samples used for measuring TP concentrations were taken during the snowmelt season, which does not represent the whole year or the other seasons in Hokkaido.

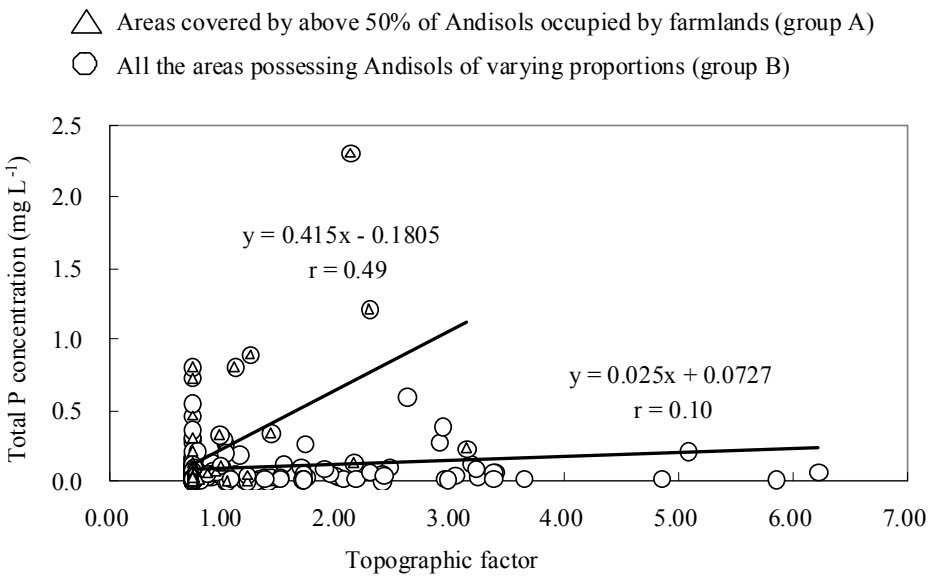

Figure 9 Relationship between topographic factors and the total phosphorus (TP) concentration in the river water

Conclusions

Total P concentration in river water was not correlated with the proportion of upland field and urban area or with the farmland surplus P and the municipal waste P that mix into the river water. Although the areas containing Andisol had a high P absorption capacity, total P export would occur in such areas when a high amount of fertilizer was applied in sloping fields and animal excreta was disposed of. Thus, P losses from farmlands to river water during the snowmelt season could be attributed to fertilizer management and soil type along with topographic conditions and rainfall events inducing soil erosion.

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