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Research article

Estimating the 'critical' distance at which adjacent land-use degrades wetland water and sediment quality

Jeff E. Houlahan[1,*] and C. Scott Findlay[1,2]

[1]*Dept. of Biology, University of New Brunswick at Saint John, P.O. Box 5050, Saint John, New Brunswick E2L 4L5, Canada;* [2]*Institute of Environment, University of Ottawa, 555 King Edward Street, Ottawa, Ontario, K1N 6N5, Canada;* [*]*Author for correspondence (e-mail: jeffhoul@unbsj.ca)*

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Abstract

Conversion of forested lands to agriculture or urban/residential areas has been associated with declines in stream and lake water quality. Less attention has been paid to the effects of adjacent land-uses on wetland sediment and water quality and, perhaps more importantly, the spatial scales at which these effects occur. Here we address these issues by examining variation in water and sediment nutrient levels in 73 southeastern Ontario, Canada, wetlands. We modeled the relationship between water and sediment nutrient concentrations and various measures of adjacent land-use such as forest cover and road density, measured over increasing distances from the wetland edge. We found that water nitrogen and phosphorous levels were negatively correlated with forest cover at 2250 meters from the wetland edge, while sediment phosphorous levels were negatively correlated with wetland size and forest cover at 4000 meters and positively correlated with the proportion of land within 4000 meters that is itself wetland. These results suggest that the effects of adjacent land-use on wetland sediment and water quality can extend over comparatively large distances. As such, effective wetland conservation will not be achieved merely through the creation of narrow buffer zones between wetlands and more intensive land-uses. Rather, sustaining high wetland water quality will require maintaining a heterogeneous regional landscape containing relatively large areas of natural forest and wetlands.

Introduction

The relationship between land-use and water quality has been clearly demonstrated over the last two decades (e.g., Herlihy et al. 1998; Benoit and Fizaine 1999; Cuffney et al. 2000; Berka et al. 2001). There is convincing evidence that watersheds dominated by agriculture and/or human settlement have significantly higher river, stream and lake nutrient levels (McFarland and Hauck 1999; Cuffney et al. 2000; Berka et al. 2001; Wang 2001). Increased surface water nutrient levels have been associated with surplus manure and chemical fertilizer application (Berka et al. 2001), high livestock density (McFarland and Hauck 1999), low forest cover (Benoit and Fizaine 1999), increased urbanisation (Wang 2001), reduced wetland density (Detenbeck et al. 1993) and increased row cropping (Johnson et al. 1997). However, there has been comparatively little research examining the relationship between land-use and *wetland* water or sediment quality (for exceptions see, Detenbeck et al. 1996; Schwarz et al. 1996; Crosbie and Chow-Fraser 1999) and even less examination of the scale of adjacent land-use effects; do adjacent land-uses only matter within a narrow strip bordering a waterbody or is water quality affected by land-uses, hundreds or perhaps thousands of meters from aquatic systems?

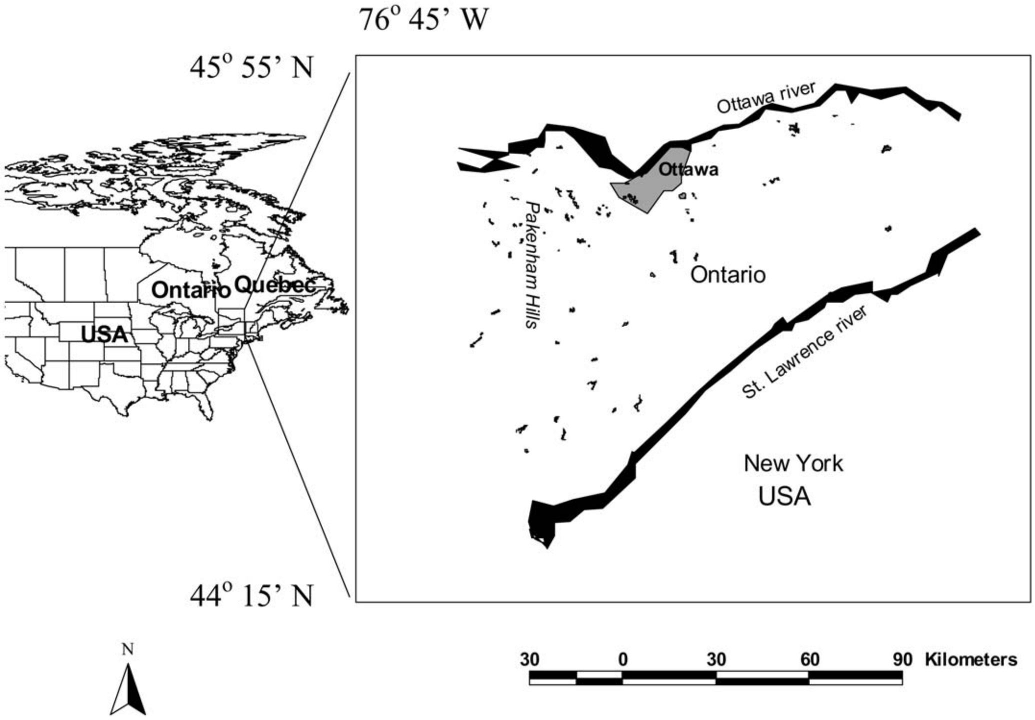

Figure 1. Map of the study area in southeastern Ontario, Canada.

Many countries, states and provinces regulate land-use in narrow buffer zones adjacent to lakes, rivers and wetlands. Implicit in the designated width of buffer zones is the belief that only nearby adjacent land-uses affect water quality. Policy makers need to understand the distance at which adjacent land-uses affect water quality if riparian buffer zones are to be an effective management tool. Research examining the relationship between land-use and water quality has tended to focus on the watershed-scale (i.e., water quality in human-dominated versus more pristine watersheds) (Comoleo et al. 1996; Benoit and Fizaine 1999; McFarland and Hauck 1999; Jones et al. 2001) or the local scale (e.g., the effect of narrow vegetated buffer strips on water quality) (Brunet and Astin 1997; Patty et al. 1997; Hefting and De Klein 1998). By contrast, there are few studies comparing the relative importance of local versus water-shed level influences on wetland water quality (Hunsaker and Levine 1995; Tufford et al. 1998), and to our knowledge, none that have examined the relationship between land-use and water quality over several different spatial scales to identify the 'critical' distance at which adjacent land-uses show the strongest effects on water quality.

Effective management of wetland water quality requires the identification of land-uses that either degrade or enhance water quality and the determination of the distance over which such influences extend. Here we test the hypothesis that intense land-use (i.e., deforestation, increased urbanization) will degrade wetland water and sediment quality and estimate the distances over which such influences extend.

Methods

Study area

We sampled 73 wetlands from southeastern Ontario between 44′ 12′′ and 45′ 51′′ latitude and 74′ 34′′ and 76′ 30′′ longitude (Figure 1). This area is in the humid high cool temperate climatic region of Canada with a mean annual temperature of 4.2 °C, mean annual precipitation of ~ 800 mm and an average of 117 frost free days annually (Ecoregions Working Group 1989). About 60–70% of southeastern Ontario land area is forest covered and these forests are dominated by sugar maple (*Acer saccharum*), yellow birch

(*Betula lutea),* hemlock (*Tsuga canadensis),* and white pine (*Pinus strobus*). Almost all wetlands contained swamp and marsh habitat and nine contained some fen and/or bog habitat. The dominant swamp plants were silver maple (*Acer saccharinum*), cedar (*Thuja occidentalis*), dogwood (*Cornus sp*.), willows (*Salix sp*.), alder (*Alnus rugosa*), and ash (*Fraxinus sp*.). Some of the dominant marsh plants were cattails (*Typha sp*.), purple loosestrife (*Lythrum salicaria*), aquatic macrophytes (*Hydrocharis morsus-ranae, Nuphar, Nympheae, Potamogeton sp.)* and grasses and sedges (*Calamagrostis canadensis, Leersia oryzoides, Phalaris arundinacea, Carex sp., Scirpus sp*.). The bogs and fens were dominated by leatherleaf (*Chamaedaphneae calyculata*), blueberries and cranberries (*Vaccineum sp*.), sedges (*Carex sp*.) and cottongrass (*Eriophorum sp*.). Most of the sampled wetlands were in the St. Lawrence lowlands and are underlain by Paleozoic rock, but several of the wetlands in the northwestern corner of the study area are at the edge of the highlands and have Precambrian metamorphic bedrock (Fulton et al. 1987). Mean wetland size was 66.7 hectares and 55 wetlands were palustrine, 10 lacustrine and 8 riverine. The wetlands occurred along a wide gradient of land-use intensity from urban wetlands (located near the heart of Ottawa, Canada) to relatively remote wetlands in the Pakenham Hills ~ 80 km west of Ottawa).

Wetland sediment and water nutrients

Sediment and water samples were collected at 72 and 73 wetlands respectively during the period from 1997-1999. Each wetland was visited three times in 1997, 1998, or 1999 between the beginning of May and the end of August. One water sample was collected during each visit, yielding three water samples per wetland. For 14 wetlands there was no standing water on the last visit and for those wetlands we have only two water samples. Each water sample was a composite sample taken from 4 or 5 different points throughout the wetland. While composite sampling methods do not provide detailed information about spatial and temporal variability of water quality they have been identified as a cost and labor-efficient method of accurately estimating population means (Brown and Fisher 1972; Edland and van Belle 1994). Where possible we took samples for each visit from approximately the same locations; this was not always possible because areas with standing water changed from visit to visit. Water was sampled by holding the water bottle vertically 10–40 cm below the surface of the water column. All water samples were immediately acidified with sulfuric acid in the field to a pH < 2.0 (1 ml H_2SO_4 : 50 ml water) and then refrigerated. All samples were analysed within 3–6 months for total phosphorus (TP) and Total Kjeldahl Nitrogen (TKN) using standard colorimetric methods (APHA 1995). We then calculated mean TP and TKN values in mg/L for each wetland.

Four sediment samples were collected in each wetland on the second visit to the wetland , usually in late June or July. We attempted to sample from a wide range of vegetation communities so as to span the full range of sediment nutrient values found in each wetland. Approximately the top ten centimeters of sediment was scooped into a plastic baggie and all sediment samples were immediately frozen upon returning to the lab. All sediment samples were analysed within 3-18 months of the sampling period. Seven samples were lost in transit between the freezer and the sediment analysis laboratory so 7 of the wetlands have only three samples. Soils were dried at 35 °C for 24 hours in a forced air oven. Extremely wet samples were dried for an additional 24 hours until completely dry. Samples were then crushed with a wooden rolling pin and sieved through a 2-mm stainless steel sieve. All sediment samples were analysed for total extractable phosphorus (TEP) (sodium bicarbonate extraction), ammonium (NH_4) (KCl extraction), nitrate (NO_2) (KCl extraction), potassium (K) (ammonium acetate extraction), and magnesium (Mg) (ammonium acetate extraction) (Carter 1993; see Appendix 1 for a detailed description of sediment analyses). We then estimated mean TEP, K, and Mg in mg/L and mg/kg, and mean NH_4 and NO_3 in mg/kg for all wetlands.

Land-use data

For all 73 wetlands, the data fell into two broad categories; data describing characteristics of the wetland proper (i.e., area, latitude, longitude, streams, presence of permanent ponds, and percentage of wetland that was marsh/swamp/bog/fen) and data describing adjacent land-uses (i.e., road density, forest cover, building density, proportion of lakes/rivers, proportion of wetlands, and distance to nearest wetland). These data were extracted using Arcview 3.2 and digital 1:10000 Ontario Base Maps from the Ontario Ministry of Natural Resources that were created from 1991 aerial photos. Because one of our goals was to estimate the distance at which adjacent land-uses affect wetland water quality we needed to sample at multiple scales. To obtain fine-scale estimates of land-use effects and be reasonably certain that we had land-use data out beyond which land-use has little effect we needed to sample at small to large scales. The largest scale (i.e., 5000 meters) was chosen because recent work suggests that land-use out to 2000 meters and beyond can affect water quality and because exploratory analyses suggested that, in most cases, the relationship between water quality and land-use diminished at distances beyond 3000 meters. Thus, values for each variable were estimated for a series of overlapping contours spanning distances 0–100 meters, 0–200 meters, 0–250 meters, 0–300 meters, 0–400 meters, 0–500 meters, 0–750 meters, 0–1000 meters, 0–1250 meters, 0–1500 meters, 0–1750 meters, 0–2000 meters, 0–2250 meters, 0–2500 meters, 0–3000 meters, 0–4000, and 0-5000 meters from the wetland edge.

In addition, indices related to agricultural practices (i.e., fertilizer application, amount of cropped land, manure application, number of cattle) were obtained from the 1996 Statistics Canada Census of Agriculture database. The data are provided only at the level of enumeration areas (EA), (EA's are geographic areas canvassed by one census representative and are the smallest geographic area for which census data are reported. They are delineated by number of dwellings rather than physical size) and where there were fewer than 15 farms in a single EA, EA's were combined so that (for reasons of data confidentiality) information was not given out in blocks of fewer than 15 farms. The average size of the enumeration areas used in this study was 6406 ha. (1388–46592 ha.). To estimate the amount of cropped land, chemical application etc. we calculated the proportion of the EA that fell within the distance contour of interest (i.e., 2000, 3000, or 4000 meters) and multiplied that proportion by the total amount cropped land, chemicals applied etc. in the entire EA. Clearly, this will introduce some (exactly how much is unknown) measurement error in these variables, as the calculation assumes that chemicals and fertilizers are applied uniformly across the EA.

Statistical analyses

We used Systat 8.0 to do all statistical analyses. Simple linear regressions were used to examine the bivariate relationships between water and sediment nutrients, and each of the independent variables. Multiple regression models were developed by including all independent variables that had bivariate relationships with $p < 0.2$ and removing variables that were not statistically significant at the $\alpha = 0.05$ level.

The effects of forest cover, road density, building density, and agricultural intensity on water and sediment nutrient levels were tested using one-tailed hypothesis tests because we expected the relationship to be in a specific direction. Tests of all other independent variables were 2-tailed.

For spatially delimited ecosystems (e.g., surface water courses, forest patches, wetlands), an important issue in conservation land-use planning is the distance beyond which putative land-use stressors have no significant effect on the ecosystem attribute in question. This can be determined by assessing changes in model fit with distance from the defined boundary of the ecosystem (Hunsaker and Levine 1995; Findlay and Houlahan 1997). For example, if forest cover on lands beyond a certain critical distance from a wetland has no significant impact on TKN levels, then inclusion of information about forest cover beyond that critical distance should not improve the fit of a model that predicts TKN levels based on forest cover. In fact, when using spatially cumulative measures of land-use, including land-use information beyond the critical distance may well reduce model fit, as the additional information contributes only statistical noise. On the other hand, for distances smaller than the critical distance including information about land-use at greater distances should increase model fit.

The Type I error rate for individual hypotheses was set at 0.05 despite the comparatively large number of comparisons. The intent of multiple comparison corrections is to reduce the experiment-wise probability of making a Type I error. But by reducing the Type 1 error rate, the Type 2 error rate is increased. It is not clear, in this context at least, that the negative consequences of committing a Type II error are less dramatic than those of committing a Type I error. In fact, one might argue that a Type I error (finding a significant effect where none exists) implies the short-term financial cost of taking action when none is necessary, while a Type II error (missing a significant effect when one exists) implies the potential long-term and irreversible impacts of not taking action when it is required.

We have included sediment phosphorus and nitrogen as independent variables in regression models

Table 1. Mean and range of nutrient concentrations across all wetlands. * mg/kg.

Nutrient	Mean (mg/L)	Range (mg/L)
Total Kjeldahl Nitrogen (in H_2O)	1.62	0.61–5.15
Total Phosphorous (in H_2O)	0.15	0.02–0.68
TKN:TP (in H_2O)	13.65:1	4.89:1–39.07:1
Total Extractable Phosphorous (in sediments)	10.53	2.00–30.67
Nitrate (in sediments)	1.85*	0.00–34.92
Ammonium (in sediments)	70.39*	5.36–276.10
Potassium (in sediments)	34.67	9.5–82.00
Magnesium (in sediments)	274.62	25.5–667.75

predicting water nutrient levels because it is well known that sediment nutrient levels buffer water nutrient levels (Reddy et al. 1996). More importantly, by including sediment nutrient levels in the models we can assess the effects of adjacent land-uses on water nutrient levels *independent* of land-use effects on sediment nutrient levels.

All road density and distance from the wetland variables and all sediment and water nutrient variables were log transformed to stabilize the variance and linearize relationships. The proportion of land covered by wetland and building density were square root transformed. Partial regression plots were used for graphical representation of multiple regression results (Draper and Smith 1981). This allows the graphical representation of bivariate plots when the independent variable is part of a multiple regression model (e.g., Kerr and Currie 1995; Findlay and Houlahan 1997).

Results

General

These wetlands spanned a wide range of nutrient conditions from relatively oligotrophic to very eutrophic (Table 1). The bivariate relationships between water/sediment nutrient levels and many of the land-use variables were statistically significant (Figure 2). However, many of these land-use variables are correlated with each other and thus, often land-use variables that are statistically significant in simple linear regression models are not statistically significant when included in multiple regression models with other key independent variables. We have focused on those independent variables that remained statistically significant when included in models incorporating other important land-use variables. These key independent variables are i) wetland area, ii) forest cover, iii) proportion wetland, iv) total centerline roads, v) % marsh, vi) total extractable phosphorous (Table 2). In addition, we found for some nutrients that there was a significant difference in nutrient levels across years even when we controlled for key land-use variables. When this was true we have constructed separate regression models for each year (see Table 2).

Wetland characteristics

Water nutrient levels (Figure 2) were negatively correlated with wetland size, number of inflow/outflow streams and percent marsh, although when the effects of year, forest cover and proportion wetlands were statistically controlled, both the effect of streams and wetland area become non-significant.

The correlations between wetland characteristics and sediment nutrient concentrations varied among nutrients. Both TEP and K showed significant negative correlations with wetland area, but no such relationships were detected for NO_3, NH_4 or Mg. There was a statistically significant positive relationship between Mg and % marsh but this relationship was not detected for TEP, NH_4, NO_3 and K (Figure 2). When forest cover and year were statistically controlled, TEP still showed a significant relationship with wetland area (Table 2).

Land-use

There were statistically significant bivariate relationships between water and sediment nutrient concentrations and many land-use variables, including forest cover, road density, building density, proportion wetland (Figure 2). All nutrients except NO_3 showed a negative relationship with forest cover, with the relationships for TKN, TP, K and TEP being particularly

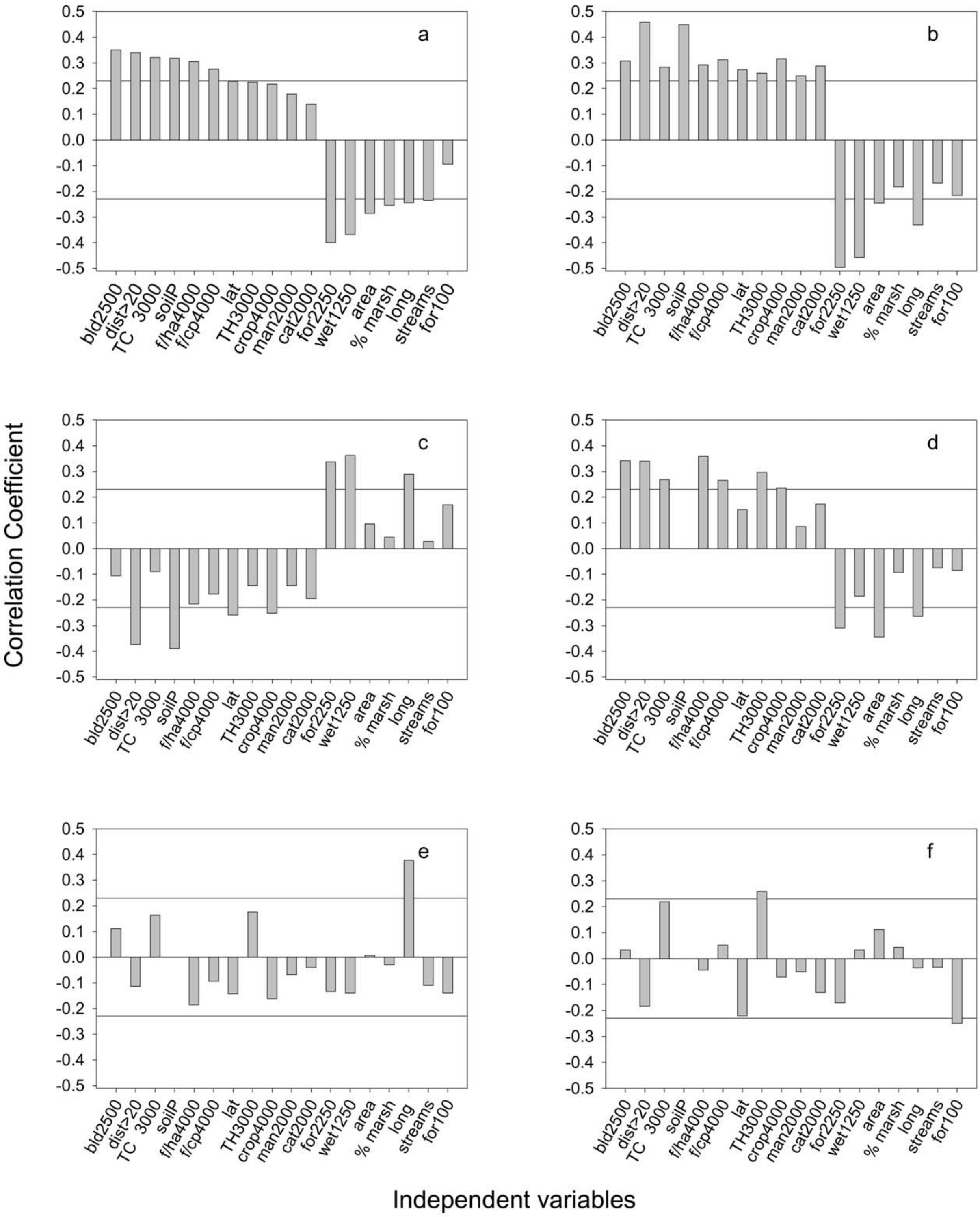

Figure 2. Histogram of correlation coefficients for bivariate relationships between water and sediment nutrients, and key independent variables: a) total kjeldahl nitrogen (TKN), b) total phosphorus (TP), c) total Kjeldahl nitrogen to total phosphorous ratio (N:P), d) total extractable phosphorus (TEP), e) ammonium (NH_4), f) nitrate (NO_3), g) potassium (K), and h) magnesium (Mg). Building density$_{2500m}$ (bld2500), distance to nearest wetland > 20 hectares (dist > 20), total extractable soil phosphorous (TEP), fertiliser/hectare$_{4000m}$ (f/ha4000), fertiliser/cropped hectare$_{4000m}$ (f/cp4000), latitude (lat), total highway$_{3000m}$ (TH3000), cropped land$_{4000m}$ (crop4000), manure applied$_{2000m}$ (man2000), cattle$_{2000m}$ (cat2000), forest cover$_{2250m}$ (for2250), proportion wetland$_{1250m}$ (wet1250), wetland area (area), percent of wetland that is marsh (% marsh), longitude (long), number of stream inputs/outputs (streams), forest cover$_{100m}$ (for100). The solid horizontal lines indicate the threshold for statistical significance (n = 73).

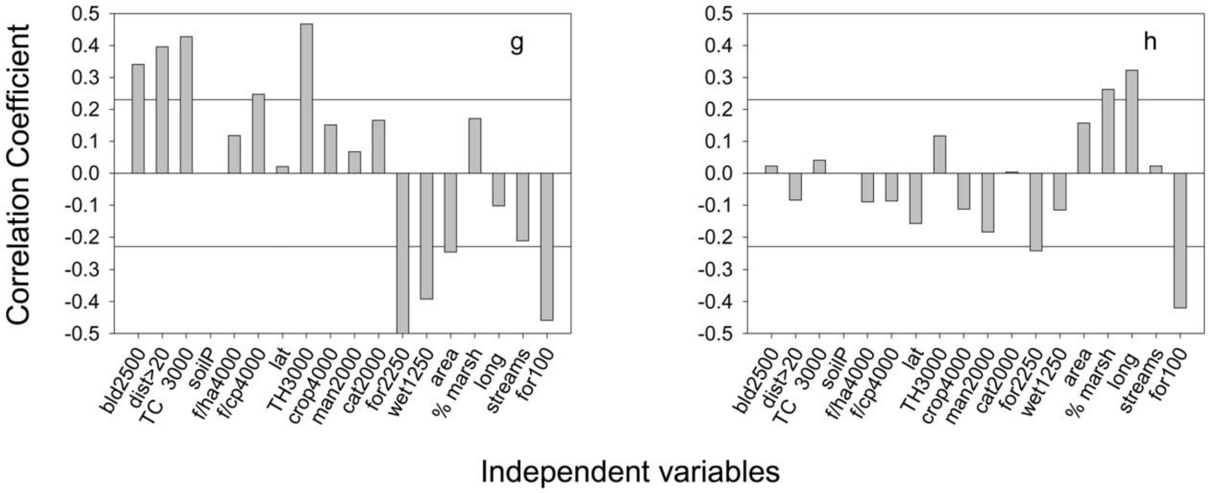

Figure 2. Continued.

Table 2. Multiple regression coefficients and coefficients of determination (R^2). of models relating wetland nutrient concentrations to adjacent land-uses, nutrient levels and wetland characteristics. Where year (i. e. 1997, 1998, or 1999) was a statistically significant predictor of nutrient concentrations we have estimated regression coefficients separately for each year (the significance level is for the overall model containing Year as a categorical variable). Log_{10}total Kjeldahl nitrogen (TKN), log_{10}total phosphorous (TP), total Kjeldahl nitrogen to total phosphorous ratio (TKN:TP), log_{10}total extractable phosphorous (TEP),– log_{10}nitrates (NO_3),– log_{10}potassium (K),– log_{10}magnesium (Mg).

Nutrients	Year	Forest Cover	Proportion wetland	Area	% Marsh	Total Extractable Phosphorous	Total Centreline Roads	R^2
TKN	***	*** 1. − 0.58 2. − 0.20 3. − 0.45	ns	ns	** 1. − 0.08 2. − 0.25 3. − 0.31	ns	ns	0.365
TP	**	*** 1. − 0.40 2. − 0.54 3. − 0.46	ns	ns	** 1. 0.40 2. − 0.35 3. − 0.39	** 1. 0.44 2. − 0.15 3. 0.28	ns	0.487
TKN:TP	***	** 1. 15.23 2. 8.20 3. 4.63	* 1. 29.49 2. − 1.65 3. 16.76	ns	ns	ns	ns	0.362
TEP	ns	− 0.27 **	− 0.55**	− 0.11**	ns	ns	ns	0.253
NO_3	***	ns	ns	ns	ns	ns	*** 1. − 0.05 2. 0.15 3. 0.38	0.423
K	ns	− 0.28***	ns	ns	ns	ns	0.16 **	0.278
Mg	ns	− 0.54***	ns	ns	ns	ns	ns	0.165

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$, ns – $p > 0.10$.

strong (Figure 2). These relationships persisted even when other important land-use variables and year were statistically controlled (Figure 3, Table 2). The distance at which forest cover showed the strongest effect was 2000 − 2250 meters for TKN, TP, K and TKN:TP ratios; 4000 meters for TEP; 1500 meters for NH_4 and 100 meters for magnesium (an example of the relationship between distance and rms is given for TKN in Figure 4).

Both NO3 and K show significant positive correlations with road density, even when other land-use variables and sampling season are statistically controlled (Table 2), with road density showing the

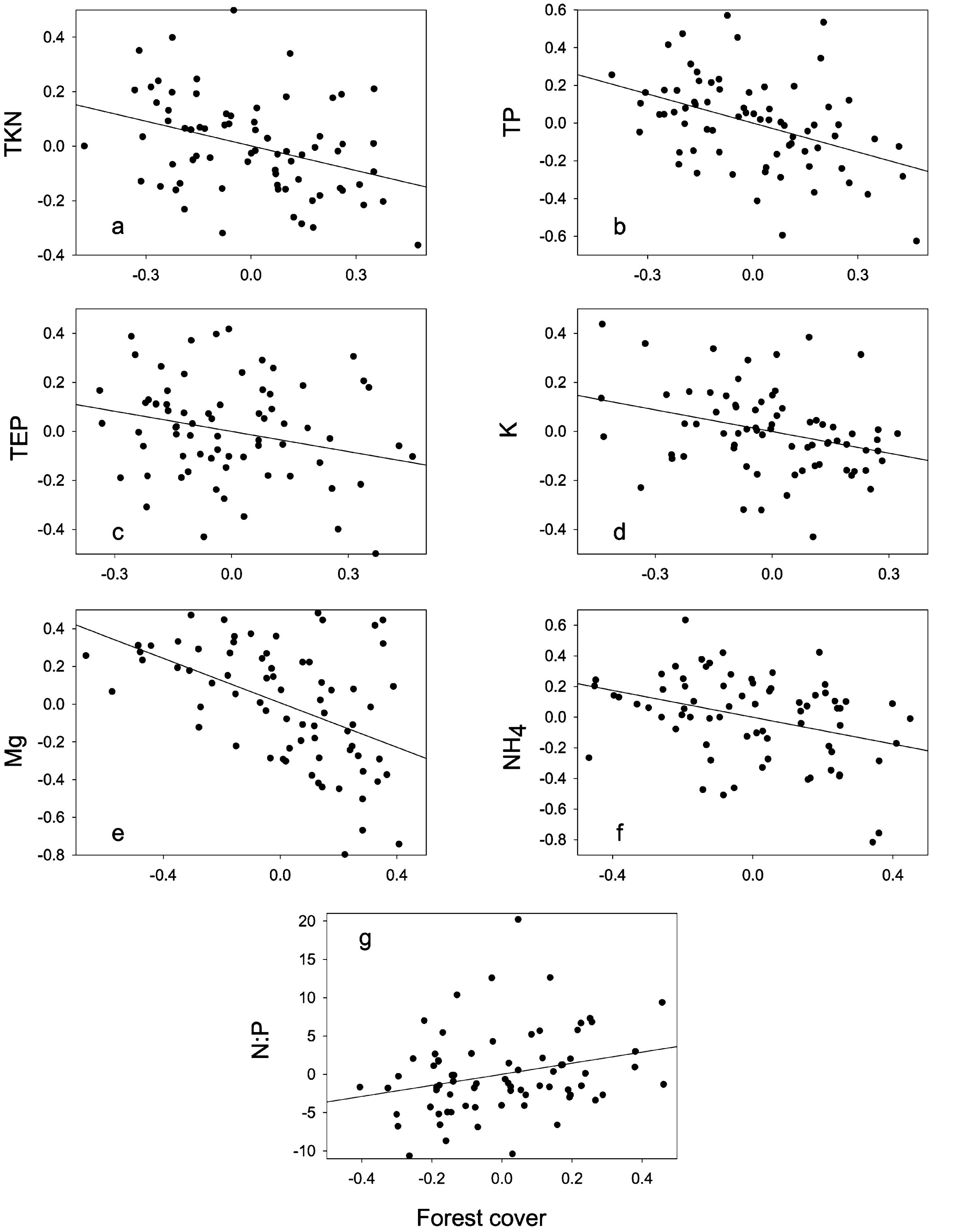

Figure 3. Partial-partial plots of the relationships between a) TKN, b) TP, c) TEP, d) K, e) Mg, f) NH_4, g) N:P and forest cover$_{2000m}$ (for2000) (corrected for all other variables in the respective multiple regression models).

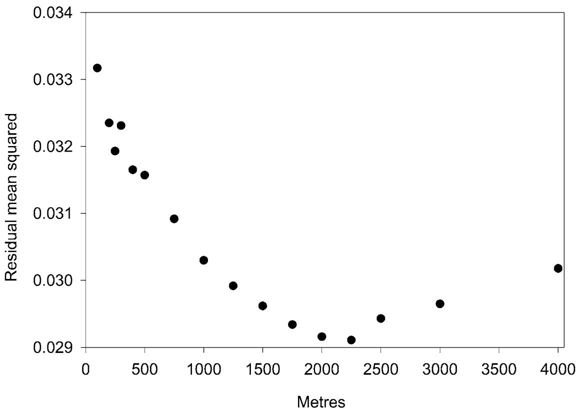

Figure 4. Plot of model fit (residual mean square, RMS) of the regression models: log_{10} TKN = a + $b_1 log_{10}$A + b_2M + b_3FC_i, where A is wetland area, M is % marsh, FC is forest cover, i = contour distance (100 m, 200 m,...,4000 m), and a, b_1, b_2, and b_3 are fitted coefficients.

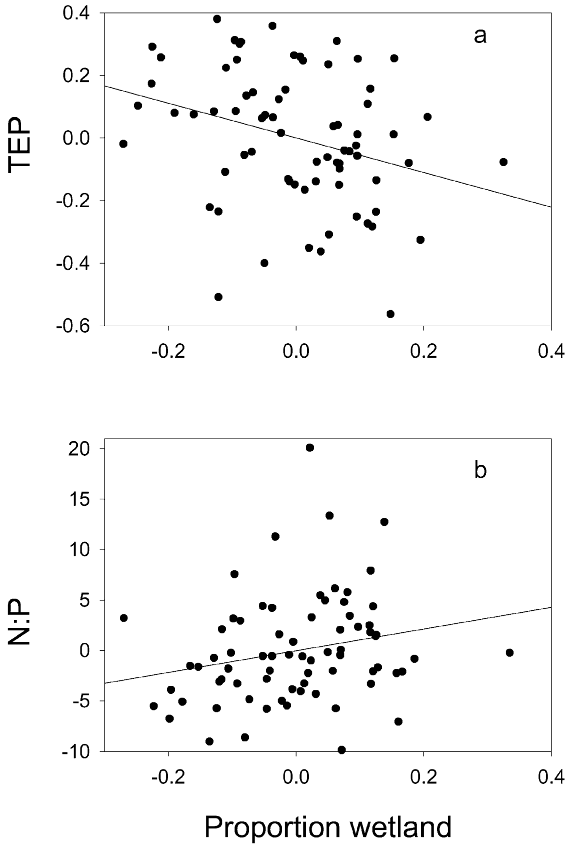

Figure 5. Partial-partial plots of the relationships between a) TEP and b) N:P, and proportion wetlands at 3000 m and 2250 m (wet3000 and wet2250), respectively, corrected for forest cover at 4000m and 2250m (for4000 and for2000), respectively.

strongest effect at 500 and 2000 m for NO3 and K respectively.

TKN, TP, K and TEP were all negatively correlated with the proportion of adjacent land that is wetland, while TKN:TP was negatively correlated. The proportion of wetland continued to explain a statistically significant proportion of the variation in TEP and TKN:TP when other land-use variables and year were included in the model (Figure 5, Table 2). Because the proportion of land covered by wetland was correlated with forest cover (r = 0.42, df = 75, p < 0.01) it dropped out of models that also include forest cover. The critical distances for the effect of adjacent wetlands on TEP and TKN:TP ratio were 1250 meters and 2250 meters respectively.

Nutrients

There were statistically significant correlations between a number of nutrient variables, with the correlation between TKN and TP (r = 0.84) being especially strong. Nutrients were not significant independent predictors in any regression models with the exception of TEP, which is an important predictor of TP in models including key land-use variables and sampling season (Table 1).

Discussion

The 'critical distance' of forest cover

Forest cover effects on TKN and TP levels, and proportion wetland and forest cover effects on TKN:TP ratio were detectable out to 2250 meters. There are several possible explanations for this result: (1) forest cover is a surrogate measure of agricultural activity, such that extensive forest cover reflects generally reduced fertiliser and animal waste inputs; (2) adjacent forests act as sinks for surface/subsurface nutrient inputs; (3) forests anchor the soil and lower erosion rates into wetlands; or (4) areas having fertile soils (and naturally higher water and sediment nutrient levels) are more likely to be farmed and hence, have reduced forest cover.

Certainly forested buffer strips can improve water quality (Phillips 1989; Kuusemets and Mander 2002; Uusi-Kamppa et al. 2000). Most studies suggest that buffers should be at least 15 meters wide (Castelle et al. 1994), that vegetated strips of 15–100 meters wide can remove more than 80% of nitrogen and/or phosphorus inputs (Schultz et al. 1995; Kuusemets and Mander 1999), and that even buffers of < 15 meters may significantly reduce nutrient inputs (Hubbard and Lowrance 1994). These studies suggest that relatively narrow strips of vegetation can remove most nutrients in run-off. Thus it seems unlikely that the effect we find (i.e., out to 2000 m) is due solely to forest cover acting as a nutrient sink.

It has also been well documented that there is a positive relationship between watershed land-use practices and soil erosion. In particular, loss of forest cover is associated with increased soil erosion (Bormann and Likens 1979; Currier 1980) and diminished water quality. Again, it seems unlikely that this effect would persist out to 2000 m.

It is difficult to test the hypothesis that the negative relationship between forest cover and wetland nutrient levels is due to intensive agriculture occurring in areas of greater soil fertility because we have no historical wetland water and sediment nutrient data. However, within our study area there are regions of relatively intensive (St. Lawrence lowlands) and modest (Pakenham Highlands) agricultural activity. Sediment nutrient levels in wetlands with $> 60\%$ forest cover within 2000 m do not differ significantly between the two regions suggesting that areas of intensive farming have not been selected based on soil fertility. Whether this result would hold at a smaller scale, between high-intensity and low-intensity agriculture areas within the St. Lawrence lowlands, is unknown.

Unlike nutrient levels, TKN:TP ratios showed a positive relationship with forest cover. This suggests that intense agricultural activity increases phosphorus levels more than nitrogen levels, that forests absorb nitrogen more efficiently than phosphorus, and/or that wetlands are more able to buffer nitrogen inputs (through denitrification and subsequent volatilization or increased nitrogen sedimentation) than phosphorus inputs. Agricultural soils tend to be nitrogen-limited and fertiliser and manure application rates have historically been based on crop nitrogen requirements and soil nitrogen content (Sharpley et al. 1994) so it is likely that excess phosphorus application is more common than excess nitrogen. As well, forest buffers may be more efficient at scavenging nitrogen because nitrates (and to a lesser extent, ammonia) are mobile and thus tree roots are able to absorb nitrogen from a large soil volume while phosphorous is relatively immobile (Giles 1996) in soils, and trees absorb phosphorus from a relatively small soil volume (Owens and Johnson 1996). This shift in N:P levels could have enormous implications for aquatic plant communities if it converts the aquatic environment from nitrogen-limited to phosphorus-limited (Stelzer and Lamberti 2001).

The critical distance for forest cover effects varies among sediment nutrients, ranging from 4000 and 2000 meters for phosphorous and potassium respectively, to 500–1500 m for NH_4 and NO_3 to about 100 m for Mg. This may reflect the relative degree to which fertiliser applications drive sediment nutrient levels. For phosphorus and potassium, which are important components of most commercial fertilizers (Nijhoff 1983; Uri 1999), the detection of forest effects at larger spatial scales may well be because forest cover correlates negatively with agricultural activity and it is not surprising that fertilizer runoff from fields 2–4 kilometers from a wetland will affect downstream sediment nutrient levels. For magnesium, which is not usually a component of commercial fertilizers but is often found in high concentrations in groundwater, the effect of forest cover occurs over relatively short distances because effects are due only to nutrient uptake. This is ancillary evidence that fertilizer application is part of the explanation for increased phosphorous, nitrogen and potassium in wetlands with little surrounding forest cover. Nitrogen is an important component of commercial fertilizers (Uri 1999) but because we only have measures of two relatively small and dynamic compartments of the nitrogen cycle it is difficult to interpret distance effects.

The 'critical distance' of road density

Potassium and maximum nitrate levels were positively correlated with surrounding road density at 2000 and 500 metres, respectively. There is evidence that increased potassium levels are found downstream of road salt applications because the sodium found in road salts displaces potassium in the soils allowing the displaced potassium to runoff to downstream water-bodies (Mason et al. 1999; Pugh et al. 1996). However, the distance effects are counter-intuitive because potassium is less mobile in soil than nitrate (Havlin et al. 1998) and thus we would expect the longer distance effects for nitrate.

The 'critical distance' of adjacent wetlands

The literature is inconclusive as to the effect of surrounding wetlands on water quality with some studies showing improved water quality (Detenbeck et al. 1993; Johnston et al. 1990) , others showing diminished water quality (Prepas et al. 2001; Prentki et al. 1978). In our sample, TEP and TKN:TP were negatively correlated with the proportion of wetlands on adjacent lands at 1250 and 2250 metres, respectively. As with forest cover, it is difficult to distinguish effects that are due to wetlands serving as sinks for nutrients and those that are due to wetlands being an index of agricultural intensity.

Wetland characteristics

Wetland size and type were important correlates of nutrient levels for some nutrients. One possible explanation is that water and sediment quality at the centre of large wetlands is better buffered against external inputs than smaller wetlands simply by virtue of the greater distance between the core and input sources and the larger vegetation sink for incoming nutrients (Detenbeck et al. 1996; Zheng et al. 2002). Another is that the vegetation communities, and therefore an important component of the nutrient cycle in wetlands, along wetland size gradients (Moorhead 1999).

Sediment versus water nutrient levels

Unlike previous research that had not demonstrated any obvious relationship between land-use and sediment nutrient levels (Schwarz et al. 1996), our results show a negative relationship between forest cover and sediment phosphorous, potassium and magnesium levels. However, the predictive power of land-use models was greater for water than sediment nutrient levels. One explanation is that water nutrient levels reflect primarily recent land-use patterns and subsequent nutrient inputs from lands adjacent to a wetland. Sediment nutrient levels, on the other hand, reflect sedimentation patterns and deposition of nutrients that have occurred over several decades, as well as factors such as soil exchangeable cation capacity (Bendell-Young and Pick 1997). As such, any modeling of water and sediment nutrient levels using recent land-use data is likely to show stronger relationships with water than sediment nutrient levels. We still find significant relationships between recent land-use patterns and sediment nutrient levels because sediment nutrient levels are, in part, a reflection of recent land-uses and there is a strong correlation between current and historical land-use patterns.

We want to emphasize that simple measures of adjacent land-use will not capture the entire wetland nutrient story. There is still a great deal of unexplained variation in wetland nutrient levels that may be explained by factors such as topography and soil type (Poiani et al. 1996).

Management implications

While recent decades have seen the development of wetland protection policies at international, national, state or provincial and municipal levels, few explicitly regulate adjacent land-use. Canadian federal wetland policy takes as a guiding principle that 'Wetlands and wetland functions are inextricably linked to their surroundings, particularly aquatic ecosystems, and therefore, wetland conservation must be pursued in the context of an integrated systems approach to environmental conservation and sustainable development' (Government of Canada 1991), but there are no recommendations for implementing such a philosophy. US wetland policy centers on a 'no-net loss' policy with no mention of adjacent lands (Lewis 2001) and while there are state and provincial policies (e.g., Ontario, Massachusetts, and New Jersey) that explicitly address buffer zones, the width of regulated buffers are from 30–120 meters, far narrower than our results suggest are necessary to protect wetland water quality. In fact, for many sediment and water nutrients the effects of adjacent land-uses are detected at distances up to 4000 meters and perhaps beyond. This implies that small-scale solutions alone (e.g., narrow buffers around individual wetlands) will almost certainly be ineffective.

Our results suggest that current US and Canadian wetland conservation policy and regulations are highly unlikely to sustain wetland water and sediment quality, even if implemented and scrupulously enforced. By contrast, sustaining the quality of wetland water requires maintaining a heterogeneous regional landscape containing significant proportions of natural forest and wetlands, as well as crop and pasture-lands; regulating agricultural activities such as irrigation and fertiliser application; and maintaining comparatively large forested wetland buffers.

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Appendix

Potassium and Magnesium:

1. Add 25 ml of 1.0 N ammonium acetate extractant to 2.5 cc of prepared soil.
2. Shake for 15 minutes ensuring that soil is kept in suspension.
3. Filter through a Whatman #2 filter paper.
4. Dilutefiltrate with distilled water (1:9).
5. Read on atomic absorption spectrophotometer. Potassium is read at 766.5 nanometers and magnesium at 285.2 nanometers.

Sodium Bicarbonate Extractable Phosphorous:

1. Add 50 ml of 0.5 N sodium bicarbonate extractant to 2.5 cc of prepared soil.
2. Shake for 30 minutes ensuring that soil is kept in suspension.
3. Filter through a Whatman #5 filter paper.
4. Read on Colorimetric Autoanalyzer.

Note: A series of 5 standards was used to check calibration on chart, the wave length of the analysis was 820 nanometers, and a known sample was included in each tray of 40 samples.

Nitrate and Ammonium:

1. Add 25 ml of 2.0 M potassium chloride extractant to 5.0 grams of soil.
2. Shake for 30 minutes ensuring that soil is kept in suspension.
3. Filter through a Whatman #42 filter paper.
4. Read on Colorimetric Autoanalyzer.

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