Role of Wetlands in Reducing Phosphorus Loading to Surface Water in Eight Watersheds in the Lake Champlain Basin

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ABSTRACT / A landscape-level approach was applied to eight rural watersheds to assess the role that wetlands play in reducing phosphorus loading to surface waters in the Lake Champlain Basin. Variables summarizing various characteristics of wetlands within a watershed were calculated using a geographic information system and then compared to measured phosphorus loading through multiple regression analyses. The inclusion of a variable based on the area of riparian wetlands located along low- and medium-order streams in conjunction with the area of agricultural and nonwetland forested lands explained 88% of the variance in phosphorus loading to surface waters. The best fit model coefficients (P_{load} = 0.86Ag + 0.64For − 30Ripwet + 160) suggest that a hectare of riparian wetland may be many times more important in reducing phosphorus than an agricultural hectare is in producing phosphorus. These results provide additional support for the concept that protection of riparian wetlands is an important management strategy for controlling stream water quality in multiuse landscapes.

The role of wetlands in improving surface water quality is widely supported in the popular literature, but research on specific wetlands presents a less consistent view of wetlands as sinks for nutrients such as nitrogen and phosphorus (Peverly 1982, Howard-Williams 1985, Whigham and others 1988, Gehrels and Mulamoottil 1989, Clausen and Johnson 1990). Given the diversity of wetland types and positions in the landscape, it is not surprising that water-quality measurements show some wetlands acting as nutrient sinks, others as sources, and still others functioning inconsistently over seasons and varying hydrologic conditions. Because of the variability in individual wetland function, the cumulative role of wetlands in a landscape is still uncertain.

This study focuses on wetlands as components of the landscape and addresses how various attributes of wetlands within watersheds affect phosphorus loading from the watershed. Wetland attributes that may affect phosphorus loading include the areal extent, number, shape, type, and landscape position of wetlands relative to other watershed features. Although some of these characteristics have been examined in previous studies, much of that research has been limited to the scale of individual wetlands (Richardson 1985, Mitsch and Reeder 1991, Masscheleyn and others 1992). Surface waters are affected by activities within the entire basin that drains into them. Therefore, it is essential to consider the overall pattern of wetlands within the landscape, not just individual wetland sites. The quality of the water leaving a basin is a reflection of that water's interaction with all the various parts of the watershed. Accordingly, recent attention has focused on the effects of wetlands on water quality from a landscape perspective (Whigham and others 1988, Johnson and others 1990, Detenbeck and others 1992, Mitsch 1992, Chambers and others 1993).

For wetlands, the cumulative water-quality function in a watershed may be more that the simple sum of the contributions of the individual wetlands in that watershed (Johnston and others 1990, Detenbeck and others 1993). For example, one wetland along a tributary may itself retain little phosphorus, but its presence may decrease peak streamflow and facilitate the removal of larger amounts of phosphorus in another downstream wetland. Systematic surveys and evaluations of the ability of natural, hydrologically modified, and artifically created wetlands to remove phosphorus argue for a systems-wide evaluation of the potential of wetlands to reduce phosphorus export from drainage basins (Mitsch 1992, Chambers and others 1993).

In this study, we examined the distribution and characteristics of wetlands within watersheds through the use of a series of descriptive wetland variables quantified within a geographic information system (GIS). Each

KEY WORDS: Wetlands; Phosphorus; Landscape; Regression model; Riparian; Vermont

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variable captures particular spatial or functional characteristics of wetlands within a watershed. The potential that these wetland characteristics have to affect phosphorus exports from each watershed was examined by relating the wetland variables to measured phosphorus loads through multiple regression analyses.

Methods

Study Area

The study was conducted within the Lake Champlain Basin, a 21,326-km^2 drainage area including portions of Vermont, New York, and the Canadian Province of Quebec. This cool, temperate region has an average annual precipitation of 0.97 m. Topography and soils vary across the basin. Based on data availability, eight watersheds ranging in size from 3058 to 21,005 ha were chosen to assess the relationship between landscape features and phosphorus loading to Lake Champlain. The basins, Stevens Brook, Mill River, Stone Bridge Brook, Malletts Creek, Indian Brook, LaPlatte River, Lewis Creek, and Little Otter Creek are located in the Vermont portion of the Lake Champlain Basin (Figure 1). Land use among the watersheds varies from predominantly agricultural to mostly forested.

Landscape Analyses

Landscape analyses were performed to estimate the amount of agricultural and forest area in each watershed and to measure wetland characteristics through the calculation of various wetland variables. Data were manipulated in both vector and raster format using GIS software (ARC/INFO, Environmental Systems Research Institute, Redlands, California). The spatial data sets used in this study included watershed boundaries, land cover, and surface water. An individual digital coverage of the boundary of each of the eight basins was created from a US Geological Survey (USGS) data set of Vermont watershed boundaries. These boundary coverages were used repeatedly to pull out data from other data sets such as surface water and land cover.

The land-cover data used was based upon an 1988 Landsat Thematic Mapper (TM) image that was classified and provided by the Environmental Protection Agency (EPA). The imagery has a 30 × 30-m cell size. Land-cover mapping involved both unsupervised classification (cluster analysis) and supervised classification (maximum likelihood analysis). Sixteen modified Anderson level II/III classes (Anderson and others 1976) were used, including the following wetland categories: deciduous forested, coniferous forested, mixed forested, scrub shrub/emergent, scrub shrub, and emergent/open water. Based on an extensive field survey, an overall mapping accuracy of 80% was determined for this data set (unpublished data, EPA Region 1, Boston, Massachusetts). Wetland categories were selected out of the general land-use data to create a wetland coverage for each basin. Only wetlands of greater than six cells were included in this data set because of the questionable accuracy of classifications involving fewer than six cells.

Surface water networks for the watersheds were obtained from a number of different data sets. This inconsistency in source data is a result of both incomplete data sources and an effort to use the most detailed resolutions available. Data for the LaPlatte River, Lewis Creek, and Little Otter Creek basins were obtained from a merged 1:5000 and 1:20,000 scale data set created by the Vermont Center for Geographic Information (University of Vermont, Burlington, Vermont) from orthophotographs. Data for the Malletts Creek, Indian Brook, and Stone Bridge Brook basins were obtained from a 1:20,000 scale USGS data set. Data for the Stevens Brook and Mill River basins were obtained from a 1:5000 scale data set developed by the State of Vermont using orthophotographs. The use of both 1:5000 and 1:20,000 scales allow for the greatest amount of detail, but at the same time, it adds the inherent error associated with comparing data of different scales. Neither the USGS nor State of Vermont data sets have yet undergone complete editing and quality-control measures.

Wetland Variables

The role of wetlands in phosphorus loading to surface water was examined by calculating the amount of variance in measured phosphorus loading to Lake Champlain from each watershed that could be explained by introducing wetland data into a multiple regression that included agricultural and nonwetland forested areas as independent variables. While area-based measures for agricultural and forested land cover are routinely used to estimate phosphorus loading to surface water (e.g., Reckhow and others 1980, 1990, Rast and Lee 1983, Frink 1991), simple wetland area may not be the best surrogate measure of wetland function in the landscape. Thus, a series of wetland variables were developed that might more effectively capture wetland effects on phosphorus loading. Each of the wetland variables is a cumulative statistic that describes a particular feature of wetlands within a landscape (Table 1).

The wetland variables that were developed can be grouped into four categories: (1) quantity of wetland (area, number, perimeter); (2) wetland type (as assigned by EPA during image processing); (3) land use in the 30-m buffer zone around wetlands; and (4) the relationship of the wetlands to streams (area of wetlands within 30 m of streams, by stream order). The distance

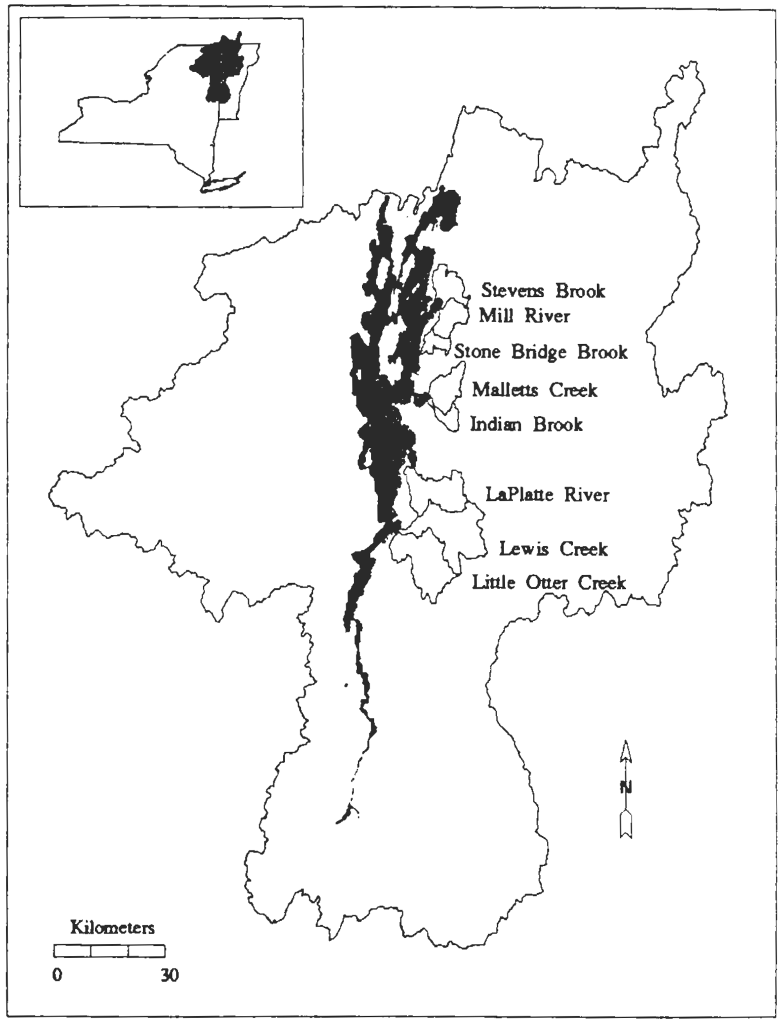

Figure 1. The locations of the eight watersheds within the Lake Champlain Basin. The shaded area is Lake Champlain. The insert box shows the location of the Lake Champlain Basin relative to the states of New York and Vermont.

of 30 m was chosen for use in category 3 and 4 based on the 30-m cell size of the source coverage. Stream orders for the surface water networks were assigned according to the Strahler stream order method (Strahler 1957). In category 4, the amount of riparian wetland was broken down by stream order to explore the relationship between stream size and wetland function. Four different variables were created to sum the areal extent of riparian wetlands located near different orders of streams. These variables are cumulative summations, so, for example, the area of riparian wetlands located along third-order streams could be obtained by subtracting the area along first- and second-order streams from the area along first, second, and third order streams.

Phosphorus Loading Estimates

Estimates of phosphorus loading to Lake Champlain from the eight watersheds were obtained from the State of Vermont (Smeltzer 1994). These estimates are based on stream sampling from March 1990 to April 1992 during periods of low, moderate, and high flow conditions and application of the FLUX program (Walker 1987, 1990). Point-source loading of phosphorus was subtracted from the total annual load to provide an estimate of nonpoint-source loading. Point-source loads ranged from 0 to 28% of the total annual loading. The nonpoint-source loading estimate (kilograms per year per watershed) was used as the dependent variable in all the statistical analyses.

Statistical Analyses

Previous research has demonstrated that the amount of agricultural and forested area within the Lake Champlain Basin has a direct relationship to the amount of phosphorus exported from each watershed (Budd and Meals 1994). Agriculture is generally recognized as an important nonpoint source of phosphorus and contri-

Table 1. Wetland variables[a]

Wetland quantity
Wetland area (ha)
Number of wetlands
Wetland perimeter (km)
Wetland types
Deciduous wetland area (ha)
Coniferous wetland area (ha)
Mixed forest wetland area (ha)
Scrub shrub/emergent wetlands area (ha)
Land uses within a buffer zone around wetlands
Forested area (ha)
Agricultural area (ha)
Wetlands and streams
Area of wetlands near first-order streams (ha)
Area of wetlands near first- and second-order streams (ha)
Area of wetlands near first-, second-, and third-order streams (ha)
Area of wetlands near first-, second-, third-, and fourth-order streams (ha)
Area of all riparian wetlands (ha)

[a]Each variable describes characteristics of wetlands in eight watersheds

butes a large amount of the phosphorus produced by a rural watershed (Omernick 1976, Gilliland and Baxter-Potter 1987, Owens and others 1991, Tim 1992). Nonwetland forest is a smaller source of phosphorus, but given the large extent of forested area in some watersheds, it has an important cumulative effect on the phosphorus produced. Urban land uses in the eight basins we studied were small in extent and not considered to be a major nonpoint-source contributor of phosphorus.

Because the opportunity of wetlands to influence phosphorus export from watersheds is tightly linked to the land use occurring within the watershed, statistical analyses focused on regressing wetland variables as independent variables in conjunction with the agricultural and forested land area. Although the watersheds differed in other characteristics as well (e.g., soils, specific topography), land use is probably the largest factor affecting phosphorus dynamics and loading. A basic agricultural and nonwetland forested area regression was modified with the addition of the wetland variables to evaluate the contribution of the wetlands in explaining variation in the annual phosphorus load. Although each of the wetland variables captures important and often different functional characteristics of wetlands, limitations in the degrees of freedom prevented the addition of more than one wetland variable to the regression model at a time. Furthermore, because only one wetland variable was entered into the regression at a time, correlation between wetland variables was not considered. Independence of the wetland variables from the area of agricultural and forested land was examined through correlation analysis.

The statistical package JMP (SAS Institute, Cary, North Carolina) was used for all analyses. All models were contrasted using an adjusted R^2 to account for the degrees of freedom in the model and the change in the number of parameters; therefore, models with different degrees of freedom are directly comparable. The significance of the independent wetland variable was evaluated using an F statistic. Given the small sample size, no attempt was made to quantify statistically significant differences among the R^2s of the various models.

Results and Discussion

The eight Lake Champlain watersheds showed substantial variation in land cover (Table 2); some were dominated by forested land, while others were dominated by agriculture. In no case was there significant urban land use.

Agricultural and forested land area was fairly successful in predicting the estimated annual export of phosphorus. The basic regression model using just agricultural and forested land area as independent variables accounted for more than 60% of the variation in phosphorus load (adjusted $R^2 = 0.63$, $P > F = 0.04$).

In all cases, a change in the adjusted R^2 values from the 0.63 obtained with just the inclusion of forested and agricultural areas occurred when each wetland variable was added to the model (Table 3), but not all wetland variables improved the model. Wetland variables in general were independent of area of forested and agricultural land, thus providing an additional source of variation to "explain" the dependent variable (phosphorus load). However, the total wetland area and riparian wetland area did correlate with forested area ($r = 0.92$, $r = 0.90$, respectively.) In addition, as might be expected, the area of both forested and agricultural land within a 30-m buffer zone of a wetland correlated well with the total amount of these land uses in each watershed ($r = 0.99$ for forested land and forested buffers, $r = 0.90$ for agricultural land and agricultural buffers). Therefore, these buffer zone variables did not add much to the initial two-variable forested and agricultural land area model.

The effects of the wetland variables in each category are discussed below.

Variables of wetland quantity

Wetland area, number of wetlands, and wetland perimeter were all closely related and generally associated with the size of the watershed. For example, Lewis Creek, the largest basin, had both the largest area (1946

Table 2. Variables used in multiple regression analyses for each of eight watersheds[a]

	Indian Brook	LaPlatte River	Lewis Creek	Little Otter Creek	Malletts Creek	Mill River	Stevens Brook	Stone Bridge Brook
Dependent variable								
Phosphorus loads (kg/yr)	900	7,600	5,200	5,400	1,700	3,500	3,400	800
Independent variables								
Land cover								
Agricultural area (ha)	1,219	7,027	6,197	10,123	3,103	3,816	4,954	1,340
Forested area (ha)	1,321	4,821	12,082	5,885	3,444	1,542	1,167	1,445
Wetland indices								
Wetland quantity								
Wetland area (ha)	205	1,286	1,946	1,672	593	458	278	177
Wetlands (N)	135	449	814	684	345	152	139	118
Perimeter (km)	94.95	410.8	724.9	611.7	256.6	152.6	109.3	81,350
Wetland type (ha)								
Deciduous forest	147	1,041	1,440	1,224	371	319	155	124
Coniferous forest	24	183	322	325	78	115	41	30
Mixed forest	34	29	14	101	37	14	44	2
Scrub shrub/emergent	0	6	109	21	17	4	17	0.8
Land use in buffer zones around wetlands								
Forest (ha)	106	398	777	408	318	138	83	126
Agriculture (ha)	72	490	652	762	265	185	136	80
Wetlands and streams								
Wetland area (ha):								
Near first-order streams	8	37	97	78	62	18	10	23
First and second order	15	62	129	133	78	29	17	28
First, second, and third	20	76	189	186	100	39	22	47
First, second, third, and fourth	24	83	256	234	111	50	22	62
Total Riparian Wetlands	24	89	268	241	111	71	23	62

[a]The dependent variable was phosphorus load. The independent variables were the area of agricultural and forested lands in the watershed and a series of variables summarizing the spatial characteristics of wetlands in the watershed.

ha) and the largest number of wetlands (814). Stone Bridge Brook and Indian Brook, the two smallest basins, have the least area (~200 ha) and the fewest wetlands, with 118 and 135, respectively. The simple quantity of wetland in a watershed could account for a proportional uptake of phosphorus in surface waters, and thus explain variation in phosphorus export. In addition, greater wetland edge (or perimeter) might be associated with shallower waters, greater vegetative mass, and a longer contact time between runoff, stream water, and the wetland. These factors might facilitate phosphorus retention through plant uptake and sedimentation.

When each of the three measures of wetland quantity were added into the regression model, they produced similar adjusted R^2s (Table 3). None of them increased the value dramatically, suggesting that variables of simple quantity do not explain more of the variation in phosphorus loading than do agricultural and forested land area alone.

Wetland type

Wetland types are based on the vegetation present. Forested wetlands, particularly deciduous forested wetlands, account for the majority of wetlands in all of the basins (Table 2). Scrub–shrub and emergent wetlands generally covered the smallest areal extent in each watershed. Similar to the amount of edge, the presence of vegetation can increase the potential for phosphorus retention by plant uptake, as well as by decreasing water flow and increasing retention time, both of which facilitate sedimentation.

Only the area of mixed wetland forest substantially increased the fit of the model (adjusted $R^2 = 0.83$). The area of mixed forested wetland is relatively small, and thus it is unlikely that this particular wetland type would account for so much more phosphorus uptake or release than the other wetland forest types. We can offer no process-oriented explanation for the strength of this relationship; however, this variable did not correlate strongly with other wetland variables, so it seems to reflect an independent source of variation to the model.

Land Use Surrounding Wetlands

The opportunity of wetlands to function as sources or sinks of nutrients is, in part, a reflection of the land use surrounding them. For example, agricultural uses

Table 3. Adjusted R^2 values and associated probability of greater F from linear regressions[a]

Model	Adjusted R^2 values	$P > F$ wetland coefficients
Agricultural and forested areas alone	0.63	
Agricultural and forested areas with wetland variables		
Wetland quantity		
Wetland area (ha)	0.57	0.64
Wetlands (N)	0.70	0.23
Total perimeter (km)	0.62	0.67
Wetland type		
Deciduous forest (ha)	0.65	0.32
Coniferous forest (ha)	0.58	0.59
Mixed forest (ha)	0.83	0.06
Scrub–shrub/emergent (ha)	0.57	0.61
Land use in buffer zones around wetlands		
Forest (ha)	0.59	0.51
Agriculture (ha)	0.59	0.52
Wetlands and streams		
Wetlands near first-order streams	0.76	0.13
Wetlands near first- and second-order streams	0.79	0.10
Wetlands near first-, second-, and third-order streams	0.85	0.05
Wetlands near first-, second-, third-, and fourth-order streams	0.88	0.03
Wetlands near second-, third-, fourth-, and fifth-order streams	0.78	0.10
Total area of riparian wetlands	0.84	0.05

[a]These regressions relate watershed characteristics to measured phosphorus loads from each watershed. Agricultural and forested area established the initial regression equation. Wetland variables were added individually to the regression.

of the land around wetlands could, over many years, result in large accumulations of nutrients in the wetland. The gradual release of these nutrients over the duration of most surface water studies might suggest that wetlands surrounded by agriculture are sources of nutrients. On the other hand, if wetlands act as sinks, then the location of agriculture in the buffer area of wetlands would reduce the contribution of agricultural phosphorus to the overall watershed loading. Much less reduction would occur if forests were adjacent to wetlands because forests are generally considered small contributors of watershed phosphorus.

Because the areal extent of forested land and agriculture in buffer zones closely followed the extent of these land uses in the watershed as a whole, the use of these variables did not improve the model fit over that based on total agricultural and forest land use alone (Table 3).

Wetlands and streams

Several variables were designed to approach the issue of connectivity between wetlands and other surface water features. A wetland's proximity to the surface water network is important because a wetland can only be effective in improving water quality if the water has the opportunity to come in contact with that wetland. If wetlands located close to the stream network have a greater impact on phosphorus loading than isolated wetlands located far from the stream network, then the variables in this category should result in greater improvement in the fit of the model than the simple wetland quantity variables.

For all eight basins, the greatest areas of riparian wetlands are located along first-order streams (Table 2). The linear extent of first-order streams is also greater than that of other stream orders. This relationship is typical of most stream networks. Thus, for the most part, the area of riparian wetlands decreases as the order of the streams increase. Exceptions to this can be seen in the Lewis Creek basin, which has a large wetland complex near its mouth and, thus, shows an increase in the area of wetlands along high-order streams as compared to along some of its lower order streams.

The largest improvements in the phosphorus loading model occur with the addition of riparian wetlands (Table 3; an adjusted R^2 value of 0.84 for all riparian wetlands and 0.88 for first- through fourth-order streams). These results are consistent with published hypotheses that riparian wetlands have the greatest potential to improve water quality because their location close to the stream network results in extensive interaction with both stream water and surface water runoff (Brinson 1988). Because a higher percentage of water in the narrower lower order streams comes in contact with wetlands than that in the larger highest order

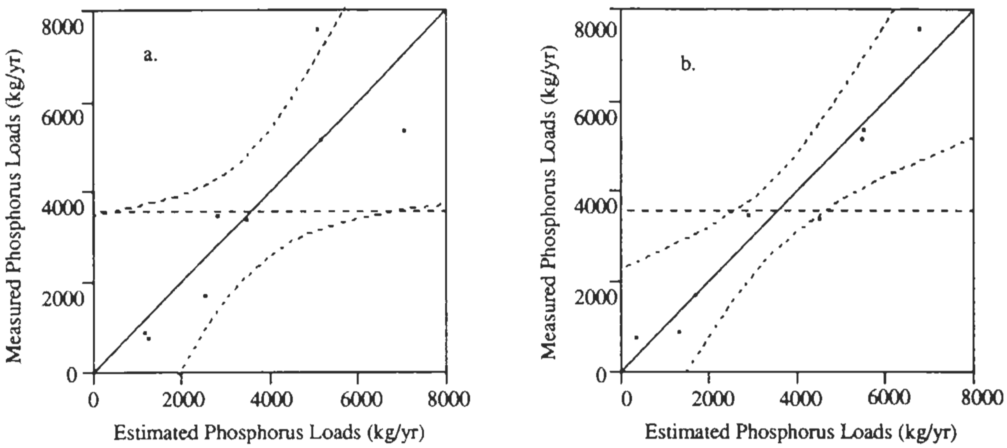

Figure 2. Estimated and measured phosphorus loading to surface water. **(2a)** The regression line and confidence bounds (95%) that occur when two independent variables, the area of agricultural lands and the area of nonwetland forested lands, are regressed against measured phosphorus loads. **(2b)** The regression line and confidence bounds that result when a third independent variable, the area of riparian wetlands located along first- through fourth-order streams, is added to the regression.

streams (Whigham and others 1988), the water-quality improvement resulting from wetlands in these locations may be particularly important in influencing the amount of sediment and nutrients entering streams from nonpoint sources (Gilliam 1994). However, the R^2 values associated with using different combinations of stream orders in this study are too close to suggest any significant difference between higher and lower order streams.

In order to see how the addition of the area of riparian wetlands improved the relationship to phosphorus loading, regression lines were plotted (Figure 2). The plots show how the additional variable improved the model, with the movement of the points closer to the regression line. The regression equation that describes this best fit is $P_{load} = 0.86Ag + 0.64For - 30Ripwet + 160$ (Ag is the area of agricultural land use, For is the area of forest, Ripwet is the area of riparian wetland adjacent to first-, second-, third-, and fourth-order streams). The model coefficients would seem to indicate that 1 ha of riparian wetland is about 35 times more important in phosphorus reduction than a hectare of agricultural land is in phosphorus production. However, because of the small sample size, the standard errors associated with the regression coefficients are substantial (the Ripwet coefficient = 30 ± 8.8, the Ag coefficient = 0.86 ± 0.14). Acknowledging, however, that regression coefficients do not demonstrate causality, the magnitude of the negative wetland coefficient in comparison to the smaller positive agriculture coefficient does provide additional support for a hypothesis that riparian wetlands can affect phosphorus loading.

Conclusions

This paper represents an initial attempt to address the role that wetlands play in reducing phosphorus loading to surface waters. We took a landscape perspective by focusing on the overall pattern of wetlands in the watershed. The wetland variables that appeared to improve the fit of the model the most included the amount of mixed forested wetlands and the areal extent of riparian wetlands. The addition of each of these variables increased the adjusted R^2 values above what could reasonably be attributed to chance. Therefore, the results of these analyses are consistent with the idea that wetlands retain phosphorus in watersheds. In addition, these findings support the hypothesis that riparian wetlands connected directly to the surface water reduce the amount of phosphorus exported from the basin. The proximity of wetlands to the basin's stream network probably affects phosphorus loading by allowing wetlands to interact with the stream water and acting as a buffer zone through which surface runoff entering the stream must flow.

There may be relationships that exist between wetlands and phosphorus loading that were not identified in this study because of the small sample size (eight watersheds). A small sample size increases the possibility that outlying points will drive the results and obscure relationships. The model we present should be reiterated on a larger number of basins when the land-use data that make such analyses possible become available for the Lake Champlain basin. A larger sample size would clarify the presence of outlying points and, thus, increase the precision of the model and the confidence in predicted relationships. In addition, the eight basins we evaluated have fairly similar wetland characteristics and distributions. Because informative comparisons using regression rely on the existence of variations, additional analyses with a broader array of watersheds would also contribute to a better understanding of the role of wetlands in landscapes.

Although wetlands are a relatively small areal component in most landscapes, this study strongly suggests that riparian wetlands do influence phosphorus loading. The inclusion of riparian wetland information in a landscape-level multiple regression analysis explained a considerable amount of the variance in phosphorus exports. If these observations are confirmed through additional and broader-scale studies, nonpoint-source management strategies should recognize the important role that riparian wetlands play in reducing phosphorus loading and seek to preserve these critical landscape elements.

Acknowledgments

We thank the Environmental Protection Agency, Region 1 in Boston, Massachusetts, for providing the wetlands data base used in this study and Robert Gagliuso and the Vermont Center for Geographic Information for assistance with various aspects of the project. We also thank Don Meals, David L. Stites, Robert France, and one anonymous reviewer for their helpful comments.

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