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Research Article

Evaluating the relative roles of ecological regions and land-cover composition for guiding establishment of nutrient criteria

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Abstract

The continuing degradation of United States surface waters by excessive nutrient loads has motivated the establishment of nutrient criteria for streams, lakes, and estuaries as a means to protect aquatic resources. Nutrient criteria have been established based on ecoregional differences, recognizing that geographic variation in climate, topography, geology, and land use require use of different criteria values for different regions of the continental United States. Several studies have demonstrated that land-cover composition also strongly influences nutrient concentrations and yields. We examined the relative importance of ecoregions and watershed land-cover composition in explaining variability in nitrogen (N) and phosphorus (P) concentrations by re-analyzing the National Eutrophication Survey (NES) data reported by Omernik (1977). The variance of N concentrations among land-cover composition classes within ecoregions was six times larger than the variance among ecoregions. For P concentrations, land-cover composition within ecoregions accounted for three times more variance than ecoregions themselves. Variance across ecoregions was only weakly significant after accounting for variance in land-cover composition within ecoregions. The results suggest that the relationship between land-cover composition and nutrient concentrations in aquatic systems should also be used to help guide establishment of nutrient criteria.

Introduction

Elevated nutrient concentrations in aquatic systems have the potential to threaten numerous ecological goods and services, including consumption and recreation, biological diversity, and property values (Dodds and Welch 2000). Excessive nutrients are the third most frequently cited cause of water-quality degradation in the United States (http://oaspub.epa.gov/waters/national_rept.control). As part of its responsibilities under the Clean Water Act, CWA, (P.L 92-500 [1972], P.L. 100-4 [1987]), the U.S. Environmental Protection Agency has collapsed the 84 Level III ecological regions, originally developed by Omernik (1987), into 14 nutrient ecoregions (Rohm et al. 2002) to establish geographically variable, concentration criteria for nitrogen (N) and phosphorus (P) (U.S.

EPA 1998). The primary aim of setting ecoregion-based N and P criteria is to foster more informed management of nutrient over-enrichment (eutrophication) of the nation's surface waters. EPA's nutrient criteria are numerical values that are intended to serve as guidance to individual states as they develop their water-quality standards (U.S. EPA 1998)

Ecoregions (Omernik 1987; Bailey 1995) are a geographic partition of variance (Griffith et al. 1999). Climate, soils, geology, predominant land-use practices, and other factors are assumed to be more similar for two areas within the same ecoregion than for two areas in different ecoregions. The use of ecoregions to establish criteria assumes: (1) that baseline nutrient concentrations (i.e., largely free of anthropogenic influence) vary from one ecoregion to the next, and (2) nutrient concentrations indicative of water-quality degradation also vary from one ecoregion to the next. Some studies provide evidence supporting an ecoregional influence on nutrient concentrations and loads in surface waters. Halloway et al. (1998) found elevated N concentrations in streams with naturally high nitrate weathering rates, and Dillon and Kirchner (1975) found significant differences in P loads exported from forested watersheds due to geological differences. Lewis (2002) found a positive relationship between annual runoff and N loads for 19 minimally disturbed watersheds distributed throughout the U.S.

Part of the motivation for establishing baseline nutrient criteria is the well-documented influence of anthropogenic activities on nutrient concentrations (Carpenter et al. 1998). Numerous studies have shown a strong relationship between watershed land-cover composition and N and P loads (Beaulac and Reckhow 1982; Frink 1991; Panuska and Lillie 1995; Fisher et al. 1998; Jones et al. 2001; Wickham et al. 2003). For example, Beaulac and Reckhow (1982) report a three-fold increase in median N load as forest is replaced by agriculture, and Frink (1991) reports a five-fold increase in the maximum P load as forest is replaced by urban.

The purpose of this research is to gauge the relative importance of land-cover composition and nutrient ecoregions in explaining the variability of N and P concentrations. Establishment of ecoregion-based nutrient criteria recognizes the need to incorporate variance in environmental management strategies (Rohm et al. 2002). Gauging the relative importance of land-cover composition and nutrient ecoregions further informs these strategies. We used the National Eutrophication Survey (NES) data reported by Omernik (1977) to examine the relative roles of land-cover composition and ecoregions. The NES data include 928 observations that span the conterminous U.S.

Methods

Analysis of variance techniques were used to evaluate the relative importance of land-cover composition and nutrient ecoregions in explaining variability in the NES data. Land cover was nested within nutrient ecoregions in a general linear model. Nutrient ecoregions and land-cover composition were both considered to be random effects, such that solving the equations for expected values of mean squares provides variance components for nutrient ecoregions (σ^2_{r}), land-cover compositions ($\sigma^2_{\mathrm{l(r)}}$), and error (σ^2_{e}) (Searle et al. 1992). The statistical significance of land-cover composition was tested by the usual *F*-test ratio (mean square for land-composition divided by the mean square for error). The statistical significance of nutrient ecoregion was tested by the *F*-test ratio of mean square for land-cover composition, with appropriate adjustments for unequal sample sizes (Satterthwaite 1946). This analysis enabled us to evaluate the relative contributions of within- and between-ecoregion sources of variance to the observed total variance in nutrient concentrations.

The NES data were collected between 1972 and 1974 to quantify relationships between stream nutrient concentrations and watershed characteristics (Omernik 1977). The NES data included the relative proportions of the land-cover classes, and used these proportions to assign a land-cover classification to each watershed. Land-cover percentages were identified for forest (F), cleared (C), agriculture (A), urban (U), range (R), wetland (W), and other (O), using thresholds of 50, 75, and 90% to assign a land-cover classification label. For example, the land-cover classification was F50 where the percentage forest was greater than or equal to 50 but less than 75. There were no watersheds where wetland or other equaled or exceeded 50%, and the percentage thresholds were not applied to urban. Urban was assigned as the land-cover classification when its percentage in the watershed exceeded 44. The NES data are dominated by watersheds where forest or agriculture are greater than or equal to 50%. Range was the dominant land-cover class (R50, R75, R90) for only 41 watersheds, and only 23 watersheds had the cleared land-cover classifications as their assignment (C50, C75, C90). Like urban, we did not distinguish among the different percentage thresholds for range and cleared, and simply used 'Range' and 'Cleared' as the land-cover classifications for those 64 watersheds. 'Mixed' was the land-cover classification assignment when urban was less than 45% and no land-cover class was at least 50% of the watershed.

Geographic coordinates were not supplied for the individual watersheds in the NES data (Omernik 1977). The primary locative information supplied was the lake name for the watershed, and there were often several watersheds associated with a single lake. We used the Geographic Names Information System (GNIS) (http://geonames.usgs.gov/stategaz/index.html) to acquire geographic coordinates for the lake names associated with the NES watersheds to incorporate the sample locations into a Geographic Information System (GIS). GNIS-based identification of NES locations was corroborated using American Automobile Association road maps, Internet searches, and visual comparison with the sample site location maps in Omernik (1977, p. 13) and Rohm et al. 2002, p. 228). The GNIS-based coordinates were then used to assign each NES watershed to a nutrient ecoregion (Figure 1). Nutrient ecoregions and NES land-cover classifications (e.g., F50) provided the two classification variables for analysis of variance (Table 1).

Our identification of NES watershed locations was based on the lake name assigned to each since the geographic coordinates of the individual watershed outlets were not reported by Omernik (1977). Because it was not possible to determine the precise location of each NES watershed or the precise location of ecoregion boundaries (e.g., digitizing error), our GNIS-based NES locations were inspected for their proximity to a nutrient ecoregion boundary, and an alternate nutrient ecoregion was assigned to samples that could not be confidently assigned to a single ecoregion.

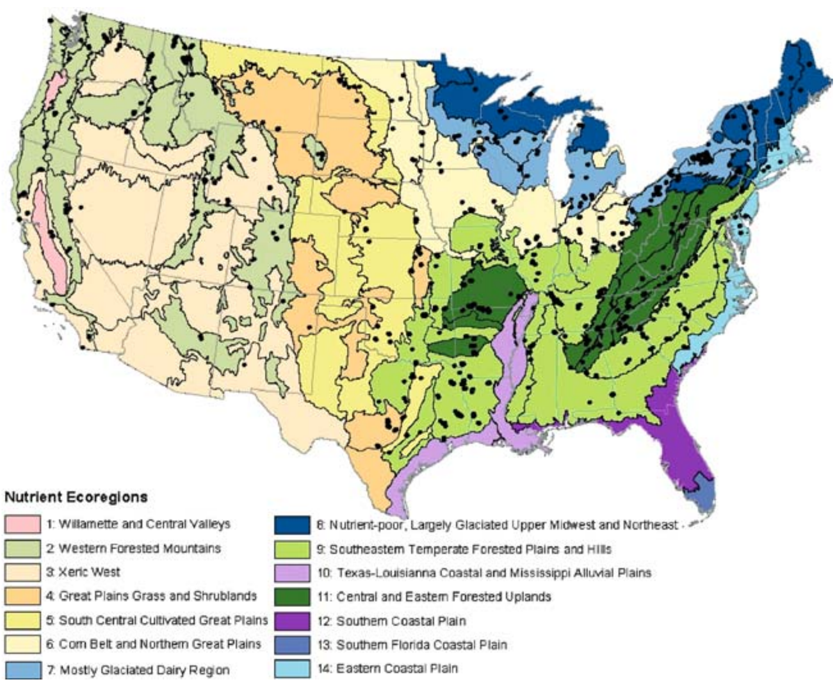

Figure 1. Location of NES sample sites overlaid on nutrient ecoregions.

Table 1. Number of NES observations by land-cover classification and nutrient ecoregion, and means and standard errors (SE) for N and P by nutrient ecoregion and land-cover classification. There were no NES observations in nutrient ecoregions 1, 12, and 13.

Land-cover classification[a]	Nutrient ecoregions												N		P	
	2	3	4	5	6	7	8	9	10	11	14	Sum	Mean	SE	Mean	SE
A50	1	1	11	9	6	42	1	41	0	31	2	145	1.82	0.06	0.089	0.008
A75	5	1	5	6	15	25	0	15	0	4	1	77	2.69	0.12	0.145	0.010
A90	3	2	0	3	59	1	1	9	0	1	1	80	5.41	0.31	0.190	0.018
Cleared	11	8	2	0	0	1	0	1	0	0	0	23	1.02	0.09	0.058	0.011
F50	40	13	4	0	0	19	10	80	1	36	4	207	0.86	0.03	0.037	0.002
F75	37	5	0	0	0	2	14	39	0	35	2	134	0.73	0.03	0.027	0.002
F90	31	3	0	0	0	0	21	18	0	33	0	106	0.63	0.03	0.019	0.001
Mixed	10	10	10	1	1	17	3	33	0	15	4	104	1.23	0.06	0.053	0.006
Range	4	8	16	7	0	0	0	6	0	0	0	41	1.32	0.11	0.081	0.012
Urban	0	0	0	0	0	2	0	4	0	5	0	11	1.18	0.11	0.092	0.026
Sum	142	51	48	26	81	109	50	246	1	160	14	928				
N: Mean	0.78	1.51	1.69	1.89	4.97	1.93	1.03	1.15	0.56	1.09	1.92					
N: SE	0.07	0.22	0.14	0.11	0.31	0.10	0.14	0.05		0.06	0.48					
P: Mean	0.041	0.099	0.097	0.133	0.180	0.070	0.026	0.062	0.127	0.031	0.059					
P: SE	0.004	0.025	0.014	0.015	0.015	0.006	0.005	0.004		0.002	0.017					

[a]A and F refer to agriculture and forest and 50, 75, and 90 refer to the minimum percentage thresholds, e.g., A75 identifies watersheds where agriculture occupies at least 75% of the area but less than 90%. Omernik (1977) also split cleared and range into three groups each using the 50, 75, and 90% thresholds, but we aggregated them into a cleared group and a range group because of the small number of observations. Watersheds identified as urban had at least 44% of their area as urban. Watersheds were assigned the label mixed when urban was less than 44% and all other land-cover classes were less than 50%.

Analysis of variance was run for each ecoregion assignment. About 20% (168 of 928) of the NES watersheds were assigned alternate ecoregions.

Results and discussion

Land-cover composition within nutrient ecoregions accounted for about six times more variance in N and about three times more variance in P than variance among nutrient ecoregions (Table 2). Nutrient ecoregions were only weakly significant after accounting for differences in land-cover composition within nutrient ecoregions. The same results were obtained for the second analysis that used an alternate nutrient ecoregion assignment for the 168 'border' NES sites.

The small proportion of variance explained by nutrient ecoregions suggests that they should not account for much difference in N and P concentrations for subsets of the NES data where land-cover composition can be treated as constant. For the subset of NES watersheds that had at least 75% forest (F75, F90), nutrient ecoregions were significant but had little explanatory value, and not all ecoregions had significantly different N and P concentrations (Table 3). For the subset of NES sites that had at least 75% agriculture (A75, A90), nutrient ecoregions were significant for N but there were not significant differences between all nutrient ecoregions, and results for P were not statistically significant. Dodds et al. (2002) also found that ecoregions were not a significant factor for explaining variance in phosphorus.

Our results are consistent with those found by Smith et al. (2003). Smith et al. (2003) used N and P loads from 63 baseline sites to estimate average concentrations by nutrient ecoregion. Of the 63 sites, 42 (67%) were located in nutrient ecoregions 2 (Western Forested Mountains), 8 (Nutrient Poor Largely Glaciated Upper Midwest and Northeast), and 11 (Central and Eastern Forested Uplands) (see Figure 1). We found that nutrient ecoregions were not a significant explanatory factor for these 42 sites (Table 4), and thus all pairwise comparisons of means among the three ecoregions were not significant. The differences found by Smith et al. (2003) in estimated baseline N and P concentrations among these three ecoregions were small, as were differences across all ecoregions. Regional differences related to other model factors, such as differences in in-stream N and P decay rates (Alexander et al. 2000; Peterson et al. 2001) may explain part of the regional variation

Table 2. Variance components and ANOVA results.

Source	Expected mean square		Term	N	P
Nutrient ecoregion	$\sigma^2_e + 3.2071\,\sigma^2_{l(r)} + 22.78\,\sigma^2_r$		σ^2_r	0.1371 (8%)	0.001010 (12%)
Land-cover composition	$\sigma^2_e + 11.518\,\sigma^2_{l(r)}$		$\sigma^2_{l(r)}$	0.8575 (47%)	0.003254 (41%)
Error	σ^2_e		σ^2_e	0.8216 (45%)	0.003732 (47%)
	DF	Sum of squares	Mean square	*F*-value	*p*-value
Nitrogen					
Model	71	1794.6750	25.2771	30.76	< 0.0001
Ecoregion	10	69.4320	6.9432	1.94[a]	0.0496
Land cover	61	652.5974	10.6983[a]	13.02	< 0.0001
Error	856	703.3623	0.8216		
Corrected total	927	2498.0373			
$R^2 = 0.72$					
Phosphorus					
Model	71	3.9428	0.0555	14.88	< 0.0001
Ecoregion	10	0.3613	0.0361	2.75[b]	0.0050
Land cover	61	2.2860	0.0378[b]	10.04	< 0.0001
Error	856	3.1946	0.0037		
Corrected total	927	7.1374			
$R^2 = 0.55$					

[a]As the denominator for the *F*-test for ecoregion, the adjusted mean square for land cover is 3.5718 and the adjusted degrees of freedom is 87.5.
[b]As the denominator for the *F*-test for ecoregion, the adjusted mean square for land cover is 0.0131 and the adjusted degrees of freedom is 96.1.

in nutrient ecoregion baseline concentrations found by Smith et al. (2003).

Our results are also consistent with the concentrations recommended by EPA for each nutrient ecoregion (Table 5). Overall, differences in recommended concentrations for N and P are small. For example, five of the 14 nutrient ecoregions have nearly identical values for P (0.008–0.010) for the water body type lakes and reservoirs. Three anomalous exceptions are the much higher N concentrations in nutrient ecoregions 6 (Corn Belt and Northern Great Plains [rivers and streams]) and 13 (Southern Florida Coastal Plain [lakes and reservoirs]), and the much higher P concentration in nutrient ecoregion 10 (Texas-Louisiana Coastal and Mississippi Alluvial Plain [rivers and streams]). Nutrient ecoregion 13 is the Lake Okeechobee and Everglades region of southern Florida. Nearly all the samples used to develop the recommended concentration for the lakes and reservoirs water body type in this nutrient ecoregion were in Lake Okeechobee (U.S. EPA 2000, p.10), which is surrounded by considerable agricultural and urban development. Likewise, both the Corn Belt (nutrient ecoregion 6) and the Mississippi River Valley (nutrient ecoregion 10) are dominated by agriculture, and the anomalous values for these nutrient ecoregions may be due to the existence of few locations that are not surrounded by the agricultural land characterizes these regions. It is possible that a lack of sites in these nutrient ecoregions whose concentration values are not influenced by anthropogenic land uses partly explains the anomalous values

The results reported here suggest that the broad-scale factors that define nutrient ecoregions (Rohm et al. 2002) are not sufficient for detecting geographic trends in N and P concentrations. There is considerable variability in land-cover composition within nutrient ecoregions. Watersheds with at least 50% forest or 50% agriculture occurred in most nutrient ecoregions, and many of the nutrient ecoregions included almost all of the NES land-cover classifications (Table 1). Our results suggest that variability in land-cover composition from watershed to watershed within a nutrient ecoregion is an important driver of variability in N and P concentrations, and that the broad-scale factors that differentiate nutrient ecoregions obscure well-documented relationships between land-cover composition and nutrients

Table 3. Anova results and difference of means tests for NES data versus nutrient ecoregions for forest-dominated (F75, F90) and agriculture-dominated (A75, A90) subsets.

	DF	Sum of squares	Mean square	*F*-value	*p*-value
Nitrogen: F75, F90					
Ecoregion	3	0.897	0.299	3.19	0.0244
Error	224	20.970	0.094		
Corrected total	227	21.867			
Model R^2: 0.04					
Phosphorous: F75, F90					
Ecoregion	3	0.0091	0.0030	11.75	< 0.0001
Error	224	0.0581	0.0003		
Corrected total	227	0.0672			
Model R^2: 0.14					
Nitrogen: A75, A90					
Ecoregion	2	165.095	82.547	15.47	< 0.0001
Error	121	645.750	5.337		
Corrected Total	123	810.845			
Model R^2: 0.20					
Phosphorus: A75, A90					
Ecoregion	2	0.0483	0.0241	2.08	0.1289
Error	121	1.4022	0.0116		
Corrected Total	123	1.4505			
Model R^2: 0.03					
Difference of means					
F75, F90			A75, A90		
Ecoregions	N	P	Ecoregions	N	P
2 versus 8	**	**	6 versus 7	**	NS
2 versus 9	NS	NS	6 versus 9	**	NS
2 versus 11	NS	**	7 versus 9	NS	NS
8 versus 9	NS	**			
8 versus 11	**	NS			
9 versus 11	NS	**			

Nutrient ecoregions with sufficient sample sizes included 2, 8, 9, and 11 for forest-dominated sites and 6, 7, and 9 for agriculture-dominated sites (see Table 1). For the forest subset, sample sizes for nutrient ecoregions 2, 8, 9 and 11 were 68, 35, 57, and 68, respectively. For the agriculture subset, sample sizes for nutrient ecoregions 6, 7, and 9 were 74, 26, and 24, respectively. Bonferroni *t*-tests ($\alpha = 0.10$) were used for difference of means testing. A double asterisk (**) denotes significantly different means.

Table 4. Anova results for USGS reference data versus nutrient ecoregion reported in Smith et al. (2003, Table S1).

	DF	Sum of squares	Mean square	*F*-value	*p*-value
Nitrogen					
Ecoregion	2	46831.06	23415.52	0.91	0.4099
Error	39	1000722.79	25659.56		
Corrected total	41	1047553.85			
R^2 = 0.045					
Phosphorus					
Ecoregion	2	145.96	72.98	0.44	0.6476
Error	39	6477.05	166.08		
Corrected total	41				
R^2 = 0.022					

Nutrient ecoregions with sufficient sample sizes included 2, 8, and 11. Sample sizes for nutrient ecoregions 2, 8, and 11 were 23, 10, and 9, respectively.

when nutrient ecoregions are used as the sole explanatory factor (Rohm et al. 2002). Land-cover composition appears to provide useful information to further guide establishment of nutrient criteria as states set more specific standards to augment EPA's national guidance.

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Table 5. EPA recommended N and P criteria by nutrient ecoregion for the water body type lakes and reservoirs and the water body type rivers and streams.

Ecoregion	L/R	R/S	L/R	R/S
	N	N	P	P
1. Willamette and Central Valleys	NR	0.31	NR	0.047
2. Western Forested Mountains	0.10	0.12	0.009	0.010
3. Xeric West	0.40	0.38	0.017	0.022
4. Great Plains Grass and Shrublands	0.44	0.56	0.020	0.023
5. South Central Cultivated Great Plains	0.56	0.88	0.033	0.067
6. Corn Belt and Northern Great Plains	0.78	2.18	0.038	0.076
7. Mostly Glaciated Dairy Region	0.66	0.54	0.015	0.033
8. Nutrient-Poor, Largely Glaciated Upper Midwest and Northeast	0.24	0.38	0.008	0.010
9. Southeastern Temperate Forested Plains and Hills	0.36	0.69	0.020	0.037
10. Texas-Louisiana Coastal and Mississippi Alluvial Plains	NR	0.76	NR	0.128
11. Central and Eastern Forested Uplands	0.46	0.31	0.008	0.010
12. Southern Coastal Plain	0.52	0.90	0.010	0.040
13. Southern Florida Coastal Plain	1.27	NR	0.018	NR
14. Eastern Coastal Plain	0.32	0.71	0.008	0.031

L/R and R/S are abbreviations for lakes and reservoirs and rivers and streams, respectively. Values are reported in milligrams/liter (mg/l). Values for phosphorus are rounded to three significant digits. NR (not reported) is used to denote that criteria are not yet available for some water body types in some ecoregions.
Source: http://www.epa.gov/waterscience/criteria/nutrient/ecoregions (viewed January 28, 2005).

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