Importance of landscape variables and morphology on nutrients in Missouri reservoirs

J.R. Jones, M.F. Knowlton, D.V. Obrecht, and E.A. Cook

Abstract: The proportion of cropland cover in the catchments of Missouri reservoirs, a surrogate for non-point-source nutrient loss from agricultural watersheds, accounts for some 60%–70% of the cross-system variance in long-term averages of total phosphorus and total nitrogen (n = 126, ln transformation for nutrients and logit for cropland). The addition of dam height and an index of flushing rate improved r^2 values to ~77% for both nutrients. Even among reservoir catchments with >80% grass and forest cover, cropland accounted for most of the variation in nutrients. Reservoir nutrients showed a strong negative relation to forest cover. Relations between grass cover and nutrients were positive but weak, and grass had no significant statistical effect once cropland was taken into account. Residual analysis suggests that urban reservoirs would have about twice the nutrient level of reservoirs in non-cropland basins (forest and grass). The increase in nutrients with the proportion of cropland and the decrease with forest cover have previously been documented in Missouri streams.

Résumé : La proportion des terres agricoles dans les bassins versants des réservoirs du Missouri, une variable de remplacement pour les pertes diffuses de nutriments dans les bassins versants agricoles, explique environ 60 % – 70 % de la variances des quantités moyennes à long terme de phosphore total et d'azote total dans les bassins (n = 126, transformation ln des valeurs de nutriments et transformation logit dans le cas des terres agricoles). L'addition de la hauteur des barrages et d'un indice de vidange améliore les valeurs de r^2 à ~77 % pour les deux variables de nutriments. Même dans les bassins versants de réservoirs avec >80 % de couverture de prairie ou de forêts, les terres agricoles expliquent la plus grande partie de la variation des nutriments. Il y a une forte relation négative entre les nutriments dans les réservoirs et la couverture forestière. Les relations entre la prairie et les nutriments sont positives, mais faibles, et tout effet statistiquement significatif disparaît lorsqu'on tient compte des terres agricoles. Une analyse résiduelle indique que les réservoirs urbains auraient environ le double des concentrations de nutriments des réservoirs dans les bassins versants sans terres agricoles (donc de forêts et de prairies). L'augmentation des nutriments en fonction de la proportion des terres agricoles et leur diminution en fonction de la couverture forestière avaient déjà été démontrées dans les cours d'eau du Missouri.

[Traduit par la Rédaction]

Introduction

A central paradigm of modern limnology is that external nutrient loading, modified by morphology and hydrology, determines the trophic state of a lake (Edmondson 1961; Vollenweider 1975). Increased biological production resulting from nutrient enrichment is a major theme in freshwater ecology (Likens 1972; Smith 1998), and nutrient control to reduce excessive productivity is the principal focus of applied limnology (Sas 1989; Cooke et al. 1993). Anthropogenic activity has accelerated eutrophication, and lake management has typically addressed this problem by reducing excessive nutrient loading associated with point-source discharge from municipalities. This approach been successful in reversing eutrophication in Lake Washington (Edmondson 1994), in areas of the Laurentian Great Lakes (Nicholls et al. 2001), in several major European lakes (Sas 1989), and in other areas.

Recently, aquatic scientists have determined that non-point-source nutrient inputs from agricultural and urban sources are a leading cause of the nation's remaining water quality problems (Novotny and Chesters 1989; Soranno et al. 1996; Carpenter et al. 1998). Studies have quantified the interdependence of land cover and nutrient export coefficients from a variety of landscapes modified by human activity (Beaulac and Reckhow 1982; Frink 1991). It can be inferred from paleolimnological records and historic water-quality data that lake enrichment, by way of non-point-source mechanisms at the landscape level, has resulted from conversion of land from native cover to agriculture and urban use (Stoermer et al. 1993; Schelske and Hodell 1995;

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Reavie and Smol 2001). Specific studies have linked changes in lakes to intensified land-use practices within their catchments; in these examples the pathway for increased nutrient and organic-matter loading was from non-point sources (Mitchell and Galland 1981; Soranno et al. 1996; Carignan et al. 2000).

Limnological research in Missouri has demonstrated that stream nutrient levels are tied to land cover through non-point processes (Smart et al. 1985; Perkins et al. 1998; Lohman and Jones 1999). The general pattern is that nutrient levels increase in streams as a function of the proportion of cropland within the watershed and decline with forest cover. Relative to forest, row-crop agriculture represents a major disturbance to the landscape, with frequent tillage and fertilizer application (Turner and Rabalais 1991; Howarth et al. 1996). Missouri analyses suggest that these two contrasting cover types account for much of the measured variance in nutrient levels among streams within the state.

In this paper, we extend the land cover nutrient analysis to Missouri reservoirs, which vary from oligo- to hyper-eutrophic (Jones and Knowlton 1993). Few reservoirs in Missouri have point-source inputs, so quantifying the link between land cover (an indirect measure of external nutrient input from non-point-source anthropogenic activities) and large-scale patterns of reservoir trophic state is essential for interpreting factors regulating regional water quality (Jones and Knowlton 1993). Our objective was to determine whether land cover in the watershed, and measures of morphology and (or) hydrology, could account for among-system variation in reservoir nutrient levels within the state. Our approach is consistent with the concepts that underpin simple empirical loading models (Edmondson 1961; Vollenweider 1975). We use land cover as a surrogate for nutrient input, with the supposition that cropland will be the dominant source of external nutrients. In this large-scale comparative lake study we are identifying the influence of watershed characteristics on reservoir limnology (Jones et al. 1998), and the effects of unmeasured variables remain as residual error. Surprisingly, few studies have linked land cover to lake trophic state and there is only one study of this nature on reservoirs (Knoll et al. 2003).

Methods

Limnology data

Limnology data used in this analysis come from 135 Missouri reservoirs that represent the range of reservoir resources within the state, including those used for water supply, recreation, and multipurpose Corps of Engineers reservoirs (Fig. 1). Reservoirs were sampled seasonally on three or four occasions during May–August from the surface layer at a site near the dam. Individual reservoirs were represented in the data set by collections ranging from 4 to 21 summer seasons during the period 1978–2002; most reservoirs were represented by data from ≥10 seasons. To limit the effects of temporal variation (Knowlton et al. 1984) on this analysis we confined our study to those reservoirs with four or more summer seasons' data. Samples were processed by standard methodology (Knowlton and Jones 1995). Analyses are based on lake means for total phosphorus (TP) and total nitrogen (TN) (Table 1). Lake means were calculated as nested averages over the period of record for each reservoir by calculating the geometric mean (ln-transformed) for each summer and then calculating the geometric mean across all summers to estimate the lake mean. Morphometric variables (volume and dam height) were provided by the Missouri Department of Natural Resources. Bathymetric maps were available for 26 reservoirs. For this subset, mean depth and dam height were strongly correlated (r = 0.96), with mean depth averaging about one-fourth of dam height. A hydrologic flushing index was estimated for each reservoir by using the regional runoff coefficient (Missouri Department of Natural Resources 1986), watershed area, and reservoir volume.

Watershed data

Geographic Information Systems and remote-sensing techniques were used to characterize cover types within the watersheds of Missouri reservoirs (forest, cropland, grass (which includes pastures), urban area, and water). Watersheds were digitized in a heads-up fashion using ESRI's Arc Info software (Environmental Systems Research Institute 1997) and United States Geological Survey 1:24 000 topographic maps in digital raster graphic format. Topology was built for each digitized watershed and a grid coverage (30 m × 30 m) was created using Arc Info software. Streams within the watersheds were digitized in the same fashion as the watersheds. The arcs depicting streams were buffered at two different distances, to create polygons around the streams that represented riparian zones of 75 and 150 m. Topology was built for the buffered streams and grid coverages were created (30 m × 30 m). Watershed and buffered-stream coverages were then imported into ERDAS IMAGINE software (Leica Geosystems GIS & Mapping 1997) and masked with a land-use coverage (1993 data) created by the Missouri Resources Assessment Program. A report was created for each masked coverage, providing the area classified in each cover-type category. The total area that was classified as water was divided into reservoir and non-reservoir categories.

Relations between landscape variables and nutrients were examined by least-squares methods of single and stepwise multiple regression with $p < 0.01$ unless otherwise stated. Data were transformed using ln or logit (adding 0.003 to cover types measured to avoid zero values) where appropriate. All analyses were performed with SPSS® for Windows version 11 (SPSS Inc. 2001).

Results

Reservoir and watershed characteristics

The median Missouri reservoir in this analysis is eutrophic, with 705 $\mu g \cdot L^{-1}$ TN and 39 $\mu g \cdot L^{-1}$ TP. Among the study reservoirs, however, nutrient values ranged 12- to 30-fold (Table 1), TP being more variable than TN (coefficient of variation = 73% vs. 44%).

The median watershed had 31% grass, 24% forest, 13% cropland, and <1% urban area, but individual proportions ranged from zero to >74% in each cover type (Table 1). Collectively, forest and agriculture (cropland plus grass) jointly composed >85% of the land area in most (80%) study basins (Fig. 2*a*), the remaining area being classified as water (median 5%) and urban area. Some 80% of the catchments had

Fig. 1. Map of Missouri, USA, showing the location of the 135 reservoirs considered in this study.

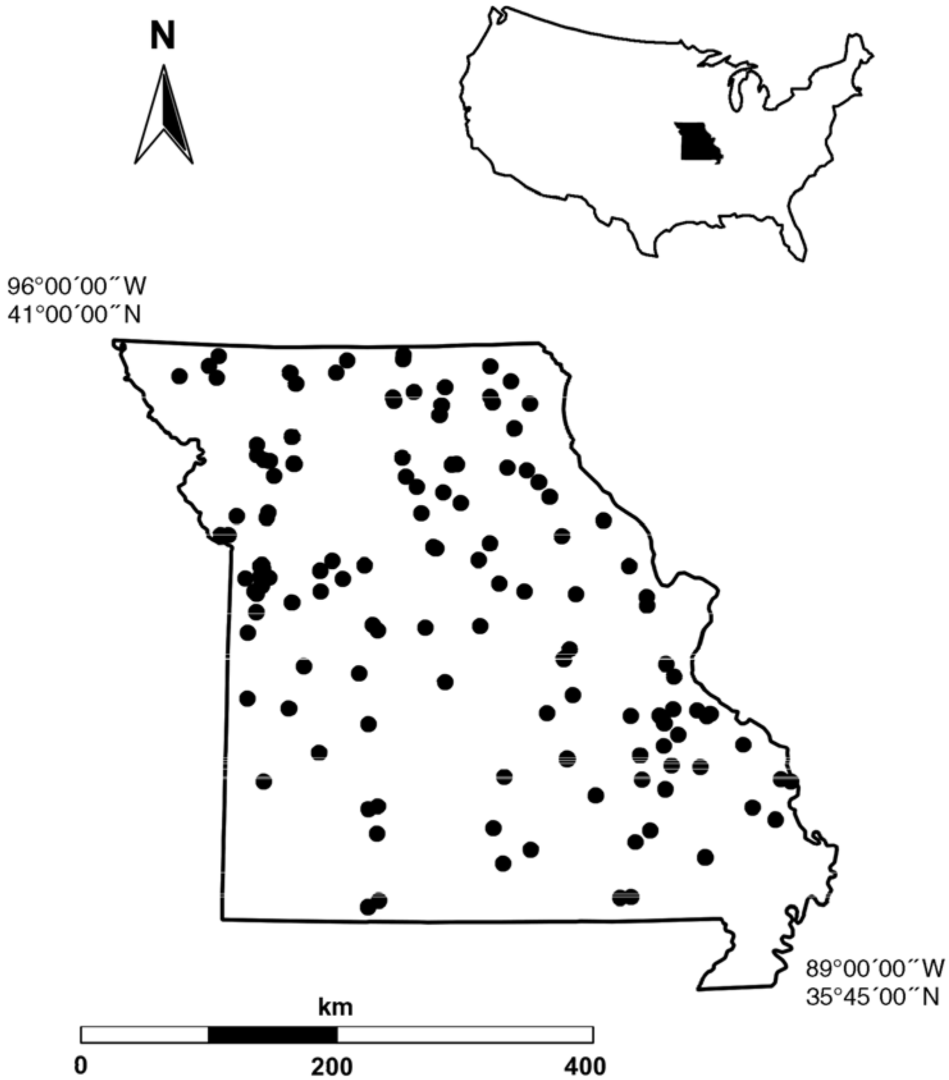
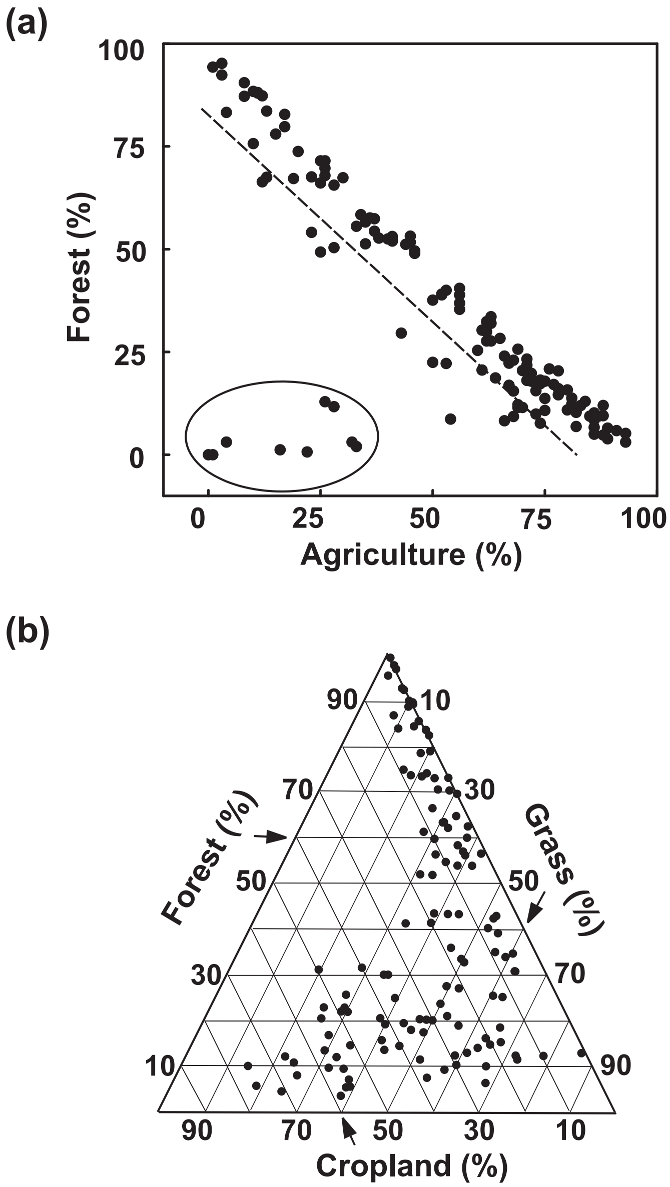


Table 1. Summary statistics for limnological data, land cover, and watershed–morphology data for Missouri reservoirs (n = 135).

	Median	Mean	Minimum	25%	75%	Maximum
Nutrient data						
Total phosphorus ($\mu g \cdot L^{-1}$)	39	45	6	21	58	182
Total nitrogen ($\mu g \cdot L^{-1}$)	705	725	200	500	920	2 330
Land cover (%)						
Forest	4	35	0	12	54	95
Grass	31	32	0	19	46	78
Cropland	13	19	0	5	32	74
Urban area	0	7	0	0	3	96
Water	5	6	0	3	8	25
Watershed–morphology data						
Reservoir area (ha)	42	750	2	17	114	21 787
Dam height (m)	14	16	5	10	19	77
Volume ($m^3 \times 10^4$)	208	7 787	6	67	509	333 319
Watershed area (ha)	1028	37 781	33	393	3857	1 875 178
Ratio of watershed to reservoir area	21	48	4	15	39	592
Flushing index ($year^{-1}$)	1.1	3.7	0.1	0.5	2.5	87.1

Fig. 2. (*a*) Plot of the proportion of forest cover in the catchments of 135 Missouri reservoirs against the proportion of the catchment in agriculture (cropland plus grass). The nine data points enclosed by an ellipse have >50% urban area in the catchment. The broken line represents 85% land cover jointly in forest and agriculture. (*b*) Ternary diagram showing the proportions of cropland, forest, and grass in the catchments of the Missouri reservoirs.



<5% urban area, but nine reservoirs located within metropolitan Kansas City had 50–96% urban area (mostly residential; Fig. 2*a*); this unique subset is treated separately in the land cover – nutrient analysis. Forest and grass jointly composed 75–99% of the catchment area in half of the basins (Fig. 2*b*); within this subset these two cover types were negatively correlated (r = –0.96, n = 66) and across the continuum of possible combinations, forest and grass were well represented (low, high, and equal proportions of each type). Grass and cropland jointly composed 75–93% of the catchment area in ~20% of the basins (Fig. 2*b*) in combinations of 20–70% of either cover type, which were negatively correlated (r = –0.95, n = 32). Forest showed a hyperbolic relation to cropland (r = –0.86, logit-transformed, urban reservoirs excluded); with the exception of a few highly forested catchments, combinations of these two cover types did not dominate the study basins.

Among catchments with >5% cropland (n = 82) the proportion of cropland within the 75-m corridor consistently averaged about 20% less than within the overall watershed. Similar minor differences were found among catchments such that cropland within the 75- and 150-m corridors was highly correlated with cropland in the entire drainage basin ($r \geq$ 0.89, n = 108). Comparisons also showed that the proportion of each cover type in the riparian zone was similar to its proportion in the entire basin (grass, forest, and urban area, $r \geq$ 0.85). These strong correlations limit the suitability of the data set to test the role of riparian land cover on reservoir nutrients at this scale of analysis.

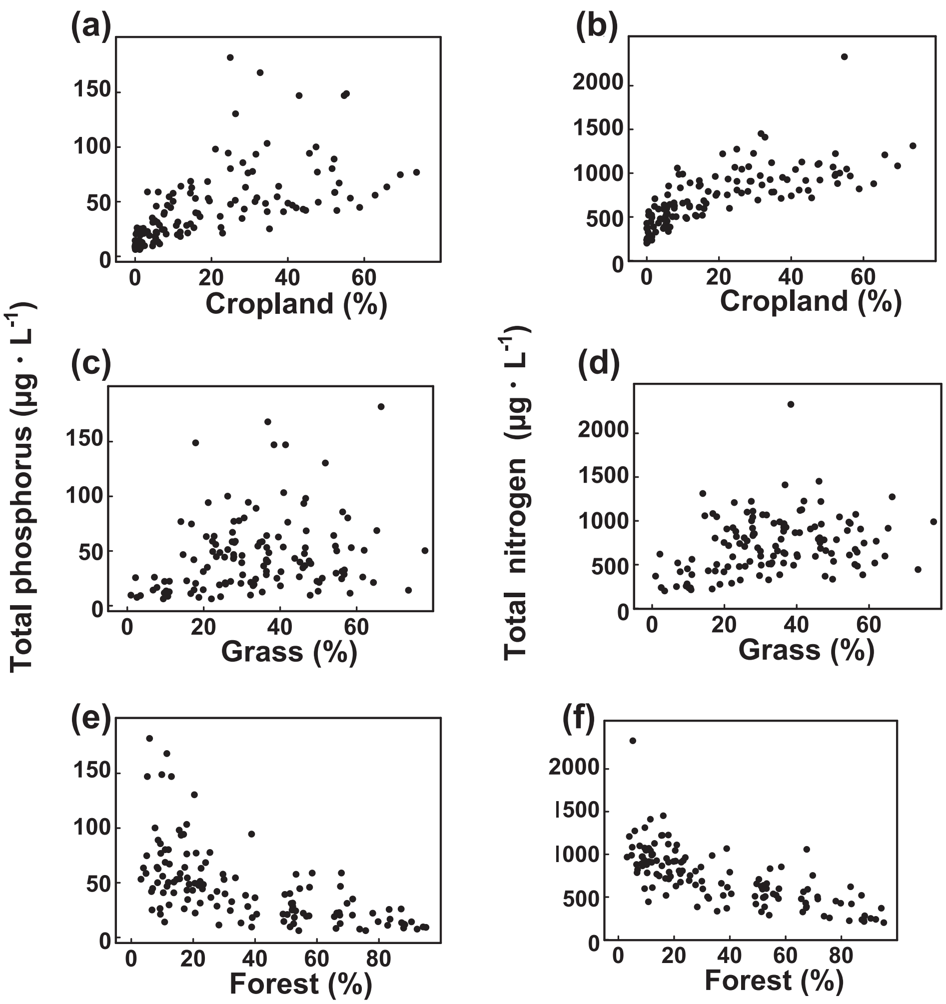
There are strong correlations among the physical features of reservoirs and their watersheds (ln-transformed, n = 135; Table 1). Dam height was significantly correlated with reservoir surface area (r = 0.71), volume (r = 0.83), and watershed area (r = 0.57). Reservoir surface area was correlated with both watershed area (r = 0.89) and storage volume (r = 0.96). The ratio of watershed area to reservoir surface area (both in hectares) ranged from 4 to 592, with a median of 21 and an average of 48. The flushing index, expressed as the ratio of average inflow volume to reservoir volume, ranged from 0.1 to 87, with a median of 1.1 and mean of 3.7 (year^{-1}).

Limnological characteristics and land cover

As expected, both TP and TN in Missouri reservoirs were positively related to the proportion of cropland within their watersheds (r > 0.61, n = 126, which does not include the nine reservoirs with >50% urban area; Figs. 3*a* and 3*b*), with a pattern of increasing variance with increasing cover. Minimum nutrient levels were strongly influenced by cropland; reservoirs with >50% cropland had minimum TP and TN of 43 and 830 μg·L^{-1}, respectively. Nutrient concentrations were also weakly correlated with grass (Figs. 3*c* and 3*d*), but minimum values were low over the entire range in the data set. Both nutrients were negatively correlated with forest (r > –0.59; Figs. 3*e* and 3*f*), and variation declined with increasing forest. For reservoirs with >90% forest, TP and TN were less than 15 and 335 μg·L^{-1}, respectively, with little among-system variation. These results parallel the pattern seen in Missouri streams, where cropland tends to be the largest source of nutrients and forest the smallest (Perkins et al. 1998). Grass is an intermediate nutrient source, but is more similar to forest than to cropland, at least in terms of minimum observed concentrations. Neither nutrient showed a significant correlation with the proportion of urban area; reservoirs with >50% urban area had nutrient levels of 16–55 μg·L^{-1} TP and 390–900 μg·L^{-1} TN, which rank low to intermediate within the overall data set.

When transformed variables (ln for nutrients and logit for land cover) were used, cropland accounted for 62% and 71% of the variation in TP and TN, respectively (n = 126, not including reservoirs with >50% urban area; Fig. 4, Table 2). Multiple regression showed that the inclusion of dam height (ln-transformed), a surrogate term for lake morphometry and

Fig. 3. Linear plots of total phosphorus and total nitrogen against the proportions of cropland, grass, and forest in the catchments.



a correlate of watershed physiography, improved the r^2 values to 73% for TP and 76% for TN (Table 2).

The addition of the flushing index (ln-transformed) improved the explanation of among-system variation in TP to 77% (Table 2) but was not significant in the TN analysis. Among these independent variables, only dam height and flushing index were significantly correlated (r = 0.38, p < 0.0001). Analysis of multicollinearity showed that parameter estimates were not adversely affected in regressions that included both dam height and flushing index. Given the intercorrelation among the physical and morphological features of these systems, watershed area (ln-transformed, r^2 = 0.78) or the ratio of watershed to reservoir surface area (ln-transformed, r^2 = 0.77) performed similarly to the flushing index in the TP analysis.

Collectively, morphology variables, and for TP, hydrology variables, accounted for ~20%–40% of the variance not accounted for by non-point-source features of cropland (Table 2). Adding other land-use categories to these models did not appreciably reduce the residual variance (only ~1% improvement in r^2 values) and were not always significant over just cropland and morphology. Even among reservoir systems dominated by grass and forest (<20% cropland, n = 75), cropland accounted for >50% of the variation in TP (52%) and TN (57%), and adding dam height improved the models to ~70% for both nutrients.

Reservoir nutrients were negatively related to proportion of forest (logit-transformed, r^2 = 0.49–0.62; Fig. 4), and with dam height and watershed area included, multiple regression explained ~70% of the among-system variation in nutrient content of the Missouri reservoirs (models not shown). Relations of grass (logit-transformed) with nutrients were positive but much weaker (r^2 = <0.2) than those with cropland or forest, and multiple regressions using the proportion of agricultural land in the watershed (cropland plus grass) explained less variance than did cropland alone. Relations with the proportion of urban area were not significant.

For the nine reservoirs with >50% urban area, the statewide regression models consistently underpredicted TP and TN. Residuals (observed minus predicted) were nearly all positive (Fig. 5) and were strongly correlated with the proportion of urban cover (r = ~0.9 for models 3 and 5 from Table 2). This result suggests that urban catchments export proportionately more TP and TN than other non-cropland cover types (forest and grass).

For non-urban catchments with cover-type measurements in the riparian corridor (n = 99), residuals from the statewide models were only weakly related to land use in the 75- and

Fig. 4. Total phosphorus and total nitrogen plotted against the proportions of cropland and forest. Nutrients are ln-transformed and cover type was logit-transformed.

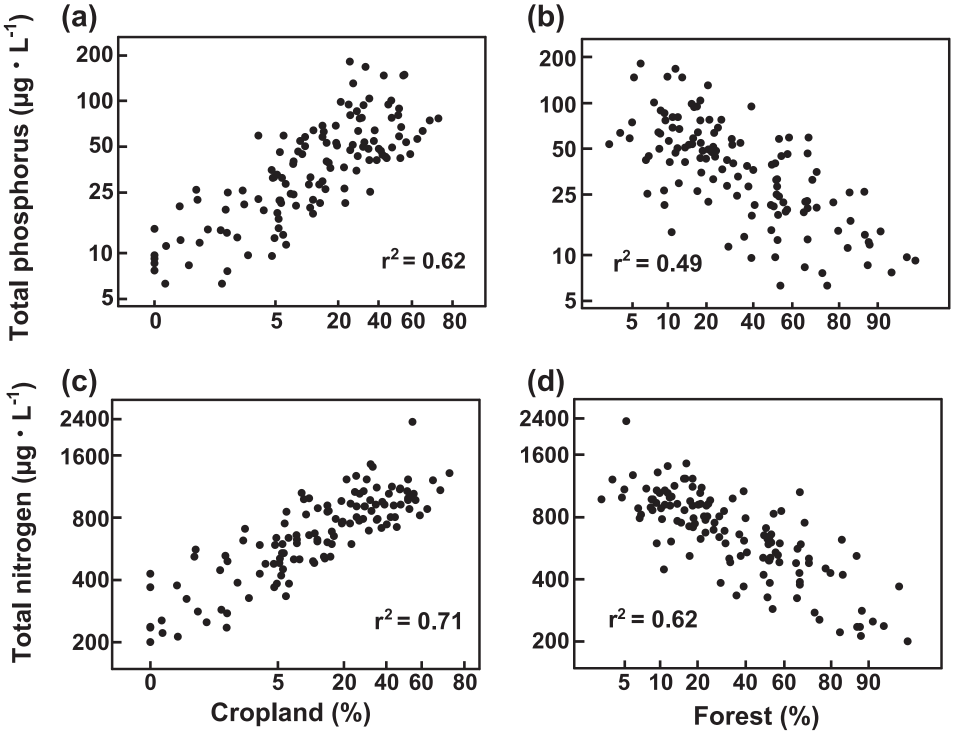


Table 2. Regression models for total phosphorus and total nitrogen (TP and TN, respectively, ln-transformed) based on the proportion of cropland (%crop, logit-transformed), morphology (dam height, DH), and hydrology (flushing index, FI).

Relation	r^2	SE
1: TP = 4.27 + 0.36 %crop	0.62	0.47
2: TP = 5.53 + 0.33 %crop – 0.50 DH	0.73	0.40
3: TP = 5.20 + 0.35 %crop – 0.37 DH + 0.12 FI	0.77	0.37
4: TN = 6.96 + 0.24 %crop	0.71	0.26
5: TN = 7.51 + 0.23 %crop – 0.22 DH	0.76	0.23

Note: Model number, standard error (SE), and coefficient of determination (r^2) are provided for each regression. Units are shown in Table 1.

150-m corridors. Residuals from the TP and TN models (models 3 and 5 from Table 2) were positively correlated with grass in the 150-m corridor (r = 0.27–0.31, $p < 0.05$), residuals from the TN model (model 5 from Table 2) were also correlated with grass in the 75-m corridor ($r = 0.26$, $p < 0.05$), and residuals from the TP and TN models were correlated with urban cover in the 150-m corridor (model 5 from Table 2, $r = 0.2$, $p < 0.05$). Proportions of forest and cropland in the riparian corridor had no significant influence on residuals from any of the models.

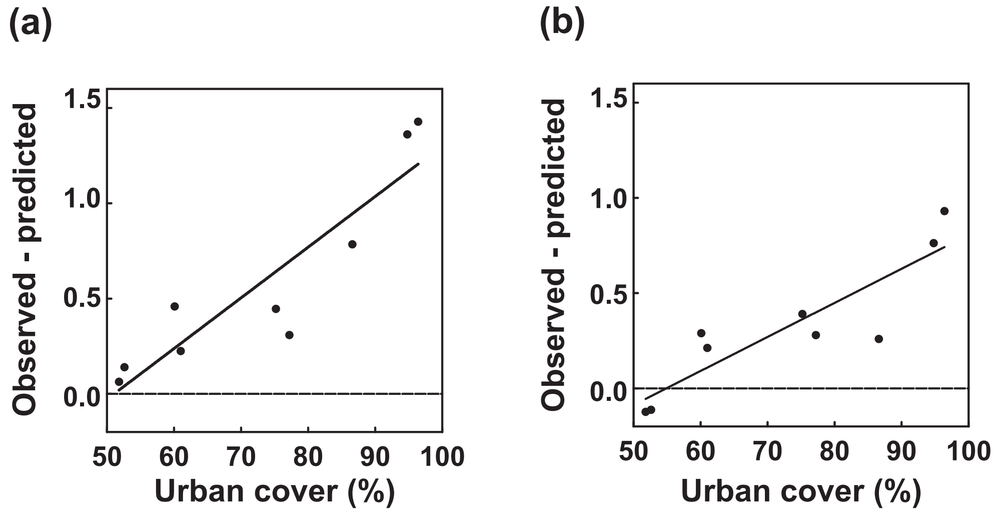
Discussion

Collectively, these empirical analyses specific to Missouri reservoirs support limnological theory in that nutrient concentrations are largely determined by external inputs as modified by morphology and hydrology (Edmondson 1961; Vollenweider 1975). In this statewide analysis, cropland accounts for some 60–70% of the variance in reservoir nutrient concentration. These relations with cropland were expected, but are surprisingly powerful given that they are limited to a single catchment feature, a surrogate of the degree of nonpoint-source loading. The models presented herein ignore nutrient contributions from non-cropland cover, which account for >75% of the land area considered in this study. The pattern, however, directly parallels findings that cropland was highly correlated with nutrients in Missouri streams (Perkins et al. 1998).

Undoubtedly, cropland is a greater relative source of nutrients than the other dominant cover types in our analysis, grass and forest. Even among reservoirs where cropland composed <5% of the basin (n = 32, urban reservoirs excluded), variation in cropland was a much stronger correlate of TP and TN than variation in other cover types. Row-crop agriculture represents a continuous disturbance to the landscape that is intensively managed by tilling, harvest, and application of nitrogen-rich fertilizers (Turner and Rabalais 1991; Howarth et al. 1996). Researchers have consistently found nutrient export from cropland to be several times that from grass and forest (Beaulac and Reckhow 1982; Frink 1991), and our analysis supports this pattern. Among Missouri reservoirs, TP and TN increased strongly with cropland and decreased with forest, resulting in about a 7-fold minimum difference in nutrients between a reservoir dominated by forest and one dominated by cropland. Regression equations based on forest cover and morphology were slightly more variable than those based on cropland but suggest that this land cover type was the smallest nutrient source in our catchments.

The influence of grass on reservoir nutrient levels was less apparent. Reservoirs in catchments dominated by grass had

Fig. 5. Effect of the proportion of urban cover on residuals (observed – predicted, ln-transformed data) from models 3 (*a*; $r = 0.91$) and 5 (*b*; $r = 0.89$) in Table 2 calculated for nine urban reservoirs not included in the statewide land cover – nutrient analysis. Solid lines were fitted by least squares.



about triple the TN and less than double the TP of those dominated by forest, suggesting that exports from grass were intermediate between those from forest and cropland. The literature suggests that nutrient flux from grass is not necessarily uniform. Losses are much greater from intensively fertilized and grazed pastures relative to grass fields set aside for conservation (Sharpley et al. 1994; Watson and Foy 2001). This entire continuum of grassland management is known to occur within Missouri, but data from specific basins are not available. In our analyses, variation in grass had no significant statistical effect once cropland was taken into account. This finding suggests that nutrient export from grass is consistently low relative to that from cropland or that loss rates from grass are strongly correlated with those from cropland among the various catchments. Cropland in Missouri is predominantly located in regions of rich soils (Jones and Knowlton 1993), and nutrient flux from agricultural areas (cropland plus grass) in a given basin may be highly influenced by ambient soil fertility; however, we cannot test this viable hypothesis with our data set.

Nutrient export from urban catchments often equals or exceeds that from agriculture (Beaulac and Reckhow 1982; Frink 1991), and impervious surfaces increase runoff relative to other cover types. Most of our catchments had <5% urban area, but nine reservoirs in metropolitan Kansas City were unique, with >50% urban cover, and were excluded from the statewide analysis. Compared with models based on the proportion of cropland in the catchment these reservoirs had higher TP and TN than predicted, the difference increasing directly with the proportion of urban cover. Residual analysis suggests that a reservoir in an urban catchment (zero cropland) would have twice the nutrient level of a reservoir in a non-cropland basin (forest and grass) represented in our statewide regressions (e.g., ln residual >0.69). Data from Missouri streams support this pattern (Smart et al. 1985). This preliminary analysis suggests that there are strong effects of urbanization on reservoir nutrients, but most Missouri impoundments are in rural regions where urban cover is a minor component of land cover.

In this analysis the percentage of cropland is a surrogate for nutrient concentration in the inflowing streams (Perkins et al. 1998). In steady-state models, lake nutrient concentrations are a function of inflow values minus sedimentation (Vollenweider 1975). Sedimentation is governed by several physical processes such as settling velocity, settling distance (mean depth), time available for settling to occur (flushing rate), and several biological processes such as zooplankton feeding and resuspension by bottom-feeding fish. In this presentation dam height serves as a surrogate for mean depth and is a correlate of reservoir volume, stratification potential, and hydrology. Flushing index is inflow volume relative to reservoir volume and is correlated with watershed area and the ratio of watershed area to lake surface area. In all cases these physical metrics explained additional variance in reservoir nutrients not accounted for by cover type.

Loss of nutrients as a result of sedimentation should decrease with increasing flushing rates, making flushing a positive influence on in-reservoir nutrient levels. Consistent with this expectation, the coefficient for the flushing index is positive (Table 2, model 3). For a given flushing rate and inflow concentration, the expected effect of increasing lake depth is also positive (Cooke et al. 1993). With increasing water-column depth there is a decreasing probability that sedimenting particles will reach the bottom before water exits the lake. In our regression models, however, the coefficients for depth (dam height) differ by being negative. For example, based on model 3 the median Missouri reservoir (13% cropland, dam height 14 m, and flushing index 1.1) would have 36 $\mu g \cdot L^{-1}$ TP, but when other features are held constant, a reservoir with half that dam height would have 46 $\mu g \cdot L^{-1}$ TP and a reservoir with twice the dam height would have 28 $\mu g \cdot L^{-1}$ TP. Internal nutrient loading is an inverse function of mean depth (Nürnberg 1984) and may contribute to this apparent disparity between our results and convention. Also, inputs to reservoirs are often affected by plunging inflows, yielding interflow or underflow currents that deliver incoming nutrients to subsurface strata with little effect on the surface conditions reflected in our data (Knowlton and Jones

1995). The phenomenon is likely of greater consequence in deeper water bodies relative to shallower ones, and this inflow pattern likely contributes to the large coefficients used to describe sedimentation processes in reservoirs relative to natural lakes (Jones and Bachmann 1978; Canfield and Bachmann 1981). We cannot quantify the role of either process with these data, but nearly all Missouri reservoirs develop subsurface anoxia during stratification, thereby increasing the potential for internal loading, and plunging inflows are common.

Several landscape-level factors, outside the scope of this analysis, likely contributed to unaccounted-for variation in our relations. Among these, variation in rates and timing of fertilizer application and tillage practices, all major factors in determining yields (Howarth et al. 1996; Baker and Richards 2002; Richards et al. 2002), would have contributed to non-uniform losses from agricultural fields (both cropland and grass). Changes in land use during the study period would also have contributed to residual error. In addition, the spatial pattern of land cover within the catchments, referred to by Johnson et al. (1997) as patch density, would be a source of additional variation in chemical flux from catchments (Soranno et al. 1996).

Land use within the riparian zone can be a critical factor in determining nutrient export from a watershed. Land away from the stream channel is thought to have less impact on stream nutrients, and hence flux of materials to downstream reservoirs, than land close to the channel (Osborne and Wiley 1988). We had expected that our characterization of land use within the riparian zone of these basins would be a significant factor in our models. Our data, however, are not well suited for quantifying the effects of vegetated buffers because of the strong correlation between the major cover type in the entire catchment and that found in the riparian zone. Although most watersheds had a larger proportion of forest and grass relative to cropland in the riparian corridor (median values within the 75-m corridor were 42% forest, 31% grass, and 10% cropland), the range of conditions in our data set was too narrow to provide a strong test of riparian buffers. Others have quantified the attenuation of nutrient export by vegetated buffers (Osborne and Kovacic 1993), whereas in some large-scale studies there is no evidence of reduction (Omernik et al. 1981).

Volatilized nitrogen from fertilizers and animal-waste facilities within the state could be an unmeasured atmospheric source of nitrogen to the basins and directly to the reservoirs (Howarth et al. 1996). Biotic factors may also influence among-system variance though sediment-feeding fish (Michaletz 1997; Schaus et al. 1997) that would contribute to internal loading. In two reservoirs, known introductions of grass carp (*Ctenopharyngodon idella*) have reduced littoral vegetation, with concurrent increases in pelagic nutrients and algal biomass (J. Jones, unpublished data) during a period when the proportion of cropland in both catchments decreased. Several reservoirs were intentionally fertilized to improve the fishery, but removing these systems from the analysis resulted in only small improvements in cover type – nutrient relations. Several reservoirs receive inputs from municipal effluents, but this information did not improve the models. Lastly, our limnological collections are from the down-lake zone of these impoundments, near the dam. They represent conditions after in-reservoir processes such as sedimentation, uptake, and dilution have altered the chemistry and suspended-solids content of inflow from the catchment (Jones and Knowlton 1993), thereby blunting the relation between nutrient flux from the catchment and reservoir measurements. Surrogate measures of morphology and hydrology, dam height, and flushing accounted for variance attributed to these processes in our models.

Our land cover – nutrient relations, modified by physical features, match or exceed the level of explanation provided by similar cover-type relations in Connecticut lakes (Field et al. 1996), where relations were negative with forest and positive with urban cover and agriculture, Ontario (Dillon and Molot 1997), where peatlands explained among-lake variation in TP, Quebec (Carignan et al. 2000), where forest harvest was important in determining TP, Alberta (Prepas et al. 2001) where wetlands were correlated with TP, and Ohio (Knoll et al. 2003), where agriculture explained variation in maximum TP among 12 reservoirs. Similarly, Meeuwig and Peters (1996) successfully used empirical land-use models based on catchment characteristics and morphometry to model chlorophyll in a broad suite of lakes. Predictions of coastal eutrophication from land use account for about the same amount of variation as our analogous reservoir relations (Meeuwig 1999).

About 90% of all Missouri reservoirs were constructed in the past 50 years and many are half that age. Land-use practices have not been constant over this period, but pre-impoundment land cover was undoubtedly similar to current conditions, being dominated by forest or cropland with interspersed grass. These land-use patterns would have directly influenced stream water quality (Perkins et al. 1998) and, beginning with impoundment, determined reservoir water quality. In this respect, Missouri reservoirs differ from many temperate lakes that have experienced cultural eutrophication resulting from post-settlement changes in land use (Field et al. 1996; Soranno et al. 1996). Land-cover data from a subset of the catchments (n = 29) that coincide with the period of our water-quality information (ca. 1980 – present) show virtually no change in the proportion of forest (a median increase of 2%) but a small decline in cropland and a concurrent increase in the proportion of grass (median changes of –8% and +12%, respectively). This shift in cover type is consistent with changes in agricultural policy over the period. The inference is that in the near term, cropland will not expand but large-scale declines in row-crop agriculture are also unlikely. Our analysis suggests that efforts to improve reservoir water quality in the state should focus on minimizing non-point nutrient sources. Research on nutrient loss from agriculture has shown that small "hot spots" often account for most nutrient export (Gburek et al. 2000) and that measures such as riparian-zone management can decrease nutrient loss (Osborne and Kovacic 1993; Soranno et al. 1996). The full potential for what are called best management practices (e.g., Mostaghimi et al. 2001) to control non-point-source nutrients has not been realized. When technological nutrient management is routinely practiced, the importance of cropland to nutrient levels in Missouri reservoirs will likely diminish.

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