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Role of contemporary and historic vegetation on nutrients in Missouri reservoirs: implications for developing nutrient criteria

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Abstract

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Using vegetative survey records from the time of Euro-American settlement (circa 1815–1850) we found the proportion of historic prairie accounted for 42% of cross-system variation in total phosphorus (TP) and 48% of total nitrogen in 156 Missouri reservoirs. When combined with dam height (surrogate for lake morphometry) and hydraulic flushing rate (TP only), 56% of variation in nutrients was explained. Consistent with previous analyses, some two-thirds of variation in nutrients was accounted for by contemporary cropland, morphometry, and hydrology (TP only). Adding prairie or historic forest cover to models based on current cropland did little to increase explained variation. The relationship between reservoir nutrients and land cover is partly an artifact of past land conversion; most arable soils with inherent fertility sufficient to generate economically viable produce and suitable topography were former prairies. The cross-system analysis of Missouri reservoirs showed that nutrients in these anthropogenic ecosystems are largely determined by nonpoint input from current land use as modified by morphology and hydrology. Historic vegetation cover, however, was our best measure of baseline conditions in the reservoir catchments and contributes to the framework for developing nutrient criteria for these artificial lakes. No natural reference conditions exist for Missouri reservoirs, and we recommend setting site-specific nutrient criteria for these constructed systems.

Key words: historic land cover, Missouri reservoirs, nutrient criteria, prairies, vegetation

Reservoirs are created in valleys with suitable hydrology and morphology for a variety of beneficial uses that range from hydroelectric power and water supply to recreation. Most impoundments in the U.S. mid-continent have been constructed in the past 60 years, so they are relatively new landscape features. With Euro-American settlement during the previous century came rapid, region-wide conversion of prairies and forests to cropland and pastures that eventually would become catchments for future impoundments. Paleoreconstruction data from natural lakes in the agricultural Midwest (e.g., Stoermer *et al.* 1993) and sediment cores from the Mississippi Delta (Turner and Rabalais 1994), the terminus of drainage from this region, show increased nutrient loading from land use changes during that time. Reservoirs were constructed long after historic vegetation was altered and have received nutrient input from intensified agricultural practices from the time of dam closure. Studies of Midwest reservoirs show nutrient concentrations are directly correlated with contemporaneous land cover, exhibiting a positive relationship with cropland (a surrogate for nonpoint-source nutrient loss from agriculture) and a negative relationship with forest (Knoll *et al.* 2003, Jones *et al.* 2004). Including physical metrics representing morphology and hydraulic flushing rates into cross-system models accounts for additional variance in the reservoir nutrient data (Jones *et al.* 2004, Jones *et al.* 2008a). This outcome is consistent with the understanding that nutrient loading, depth and hydraulic residence time determine lake and reservoir nutrient levels (Welch and Jacoby 2004).

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Our research objective was to determine if any characteristic of historic vegetative cover from survey records at the time of Euro-American settlement (circa 1815–1850) explains variation in the nutrient levels of present day Missouri impoundments or accounts for residual variation in our contemporaneous land cover-nutrient models (Jones *et al*. 2004, Jones *et al*. 2008a). The analysis was based on an expanded data set (n = 156, Jones *et al*. 2008b). Historic vegetation cover summarized from early survey records provided our best metric of baseline conditions in the catchments of these artificial lakes and contributes to a larger framework for developing nutrient criteria in Missouri reservoirs. We outline how landscape data might be used for this purpose and recommend setting site-specific nutrient criteria for these constructed systems.

Methods

Summer monitoring data (1978–2007) were used to calculate the mean concentration of total phosphorus (TP) and total nitrogen (TN) in the 156 reservoirs included in this analysis (30 reservoirs have been added to the data base used in Jones *et al*. 2008a). Individual reservoirs are represented in the data set by collections from 4 to 27 summer seasons (described in Jones *et al*. 2008b). The median age of these reservoirs is 45 years (range 13–97 yr). Reservoir catchments were spatially determined in ArcInfo GIS based on 1-m resolution aerial photography and 10-m resolution digital elevation data. Dam structures were located and digitized into hydrologic cross-sections that were used to capture and delineate the areas of hydrologic flow into the dam locations; basin slope was estimated from this information. Current land use data for reservoir catchments were based on 30-m imagery from the LANDSAT thematic mapper developed by the Missouri Resource Assessment Partnership. Pre-settlement land cover was derived from original US Government Land Office survey notes and other historic sources in the Missouri Historic Landscape Project (James D. Harlan, Geographic Resources Center, University of Missouri). Current and historic cover summary statistics were calculated for each catchment along with statistics describing changes in land cover during the ~150-yr time period. The few largest reservoir catchments that extend beyond Missouri (i.e., Truman, Table Rock) were clipped at the current state boundary for lack of comparable historic land cover data in adjoining states. Prior to statistical analysis, land cover percentages were logit-transformed. To accommodate values of 0 and 1, 0.003 was added to values <0.5 and subtracted from values >0.5 before transformation. Flushing rate was transformed using a version of the Vollenweider equation (Jones *et al*. 2008a) to reflect the expected curvilinear response of nutrients to hydrology. Other variables were transformed to natural logs before analysis. Data were analyzed by simple and multiple regression. The regional limnology of Missouri reservoirs has been recently described using recognized ecological sections (Jones *et al*. 2008b). In this analysis we grouped reservoirs into the Plains (Osage and Glacial Plains) and the Ozarks (Ozark Highlands and Ozark Border) to simplify the presentation.

Results

Land cover – historic and contemporary

Within reservoir catchments, historic prairie, forest, and scrub cover each ranged from 0 to 100%. The median historic condition was 42% prairie, 28% forest, and 8% scrub (Table 1), with prairie negatively correlated with both forest and scrub (logit transformed, n = 156, r = −0.83 and −0.26, respectively). Vegetation cover showed a strong regional pattern, with prairie dominant in the rolling topography of the Plains and forests in the more rugged Ozarks (Table 1). Basin slope was positively correlated with forest cover (r = 0.63) and negatively correlated with historic prairie (r = −0.64).

Contemporary cropland cover in reservoir catchments ranged from 0 to 74% while forest cover ranged from 2 to 97% (Table 1). Across reservoir catchments cropland was strongly correlated with historic prairie (Fig. 1a; n = 156, r = 0.80, logit transformation). On average, 76% of current cropland in the Plains was historically prairie and 15% was forest. In the Ozarks the pattern is reversed; 72% of cropland was historically forest and 11% was prairie. Contemporary cropland was less extensive than historic prairie in most Plains catchments (89 of 100), but in most Ozarks catchments, cropland is larger than historic prairie cover (35 of 56). In reservoir catchments located statewide, cropland currently occupies about one-third of original prairie cover (limited to catchments with ≥1% historic prairie, median value 36%, n = 108).

Historic and current forest cover were also closely correlated in reservoir catchments (Fig. 1b; r = 0.73, logit transformation). Forest cover has changed over time, with some historically treeless catchments currently showing >50% coverage, as well as the opposite pattern. Among catchments with ≥1% historic forest (n = 115) the median present-day forest cover is 80% of its survey value. In the Plains, a median of 57% of current forest in the reservoir catchments is on former prairies. In the Ozarks, a median of only 9% of current forest is derived from other historic cover-types.

Cross-system patterns of reservoir nutrients with land cover, morphology, and hydrology

Reservoir nutrients in Missouri reservoirs span a range of >30-fold for TP (6–189 μg/L; Table 1) and >10-fold for TN

Table 1.-Summary of land cover and limnology data sets.

		Statewide (n = 156)	**Plains (n = 100)**	**Ozarks (n = 56)**
Historic Land Cover				
% prairie	mean	43.8	65.7	4.8
	median	41.9	73.5	0
	range	0–100	0–100	0–74.9
% forest	mean	40.9	21.5	75.5
	median	28.0	6.6	90.2
	range	0–100	0–100	0–100
% scrub	mean	15.3	12.8	19.7
	median	7.7	7.9	7.7
	range	0–100	0–92.6	0–100
Contemporary Land Cover				
% crop	mean	17.5	25.3	3.5
	median	13.3	25.4	1.0
	range	0–74.0	0.4–74.0	0–40.9
% grass	mean	34.4	38.2	27.7
	median	33.7	36.0	25.7
	range	0.6–76.7	5.3–76.7	0.6–57.8
% forest	mean	32.7	19.7	57.2
	median	23.1	15.1	55.0
	range	1.7–97.4	1.7–84.2	12.9–97.4
% urban	mean	7.3	8.5	5.2
	median	3.3	3.4	2.8
	range	0–70.5	0.3–70.5	0–34.0
Nutrients				
TP (μg/L)	mean	46.5	57.8	26.2
	median	38.2	47.9	20.9
	range	6.0–188.9	13.8–188.9	6.0–90.4
TN (μg/L)	mean	750	880	510
	median	740	860	490
	range	200–2200	380–2200	200–1060
Physical Features				
flushing rate (1/year)	mean	4.3	1.4	9.5
	median	1.1	0.9	1.5
	range	0.1–142.2	0.1–6.0	0.2–142.2
dam height (m)	mean	15.5	14.0	18.2
	median	13.4	12.7	14.3
	range	4.6–76.8	6.1–38.4	4.6–76.8

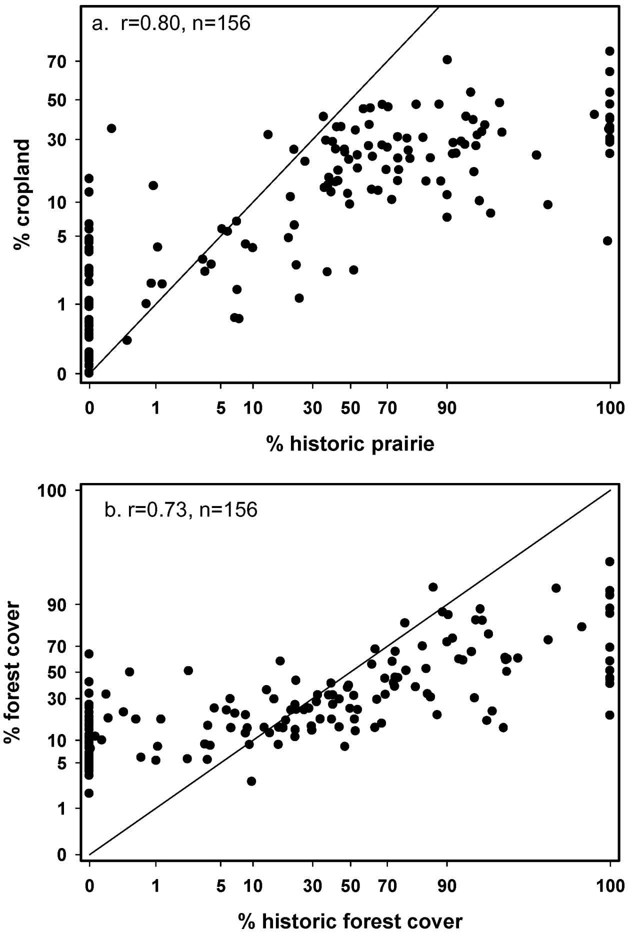

Figure 1.-Relations of current and historic cover types in catchments of 156 Missouri reservoirs. (a). Contemporary cropland versus historic prairie. (b). Contemporary forest versus historic forest. Reference lines show 1:1 ratios.

(200–2200 μg/L, Table 1). In regression analysis the proportion of historic prairie accounted for 42% of cross-system variation in reservoir mean TP and 48% of TN variation (Table 2; Fig. 2). When combined with dam height (surrogate for lake morphometry) and hydraulic flushing rate (TP only), some 56% of the variance in nutrients was explained (Table 2). No other category of historic vegetation explained more than 2% of residual variation unless prairie was excluded. Without prairie, historic woody cover explained 31% of TP variation (partial r^2, model not shown) and historic scrub an additional 5% (negative coefficients for both) in a model that included dam height (11%) and flushing rate (2%). For TN, forest cover explained 39% and scrub 4% (both negative coefficients) of variation in a model including dam height (7%).

Consistent with previous analyses (Jones *et al.* 2004, Jones *et al.* 2008a), some two-thirds of cross-system variation in reservoir nutrients was accounted for by contemporary cropland in the catchments, dam height, and hydraulic flushing rate (TP only; Table 2). Adding reservoir age to the models did not significantly increase explained variation, which suggests construction date does not appreciably influence the cross-system pattern. Given the strong correlation between historic prairie and cropland (Fig. 1), predictions of TP and TN based on the two cover types were strongly correlated (Fig. 3; r > 0.85), but current cropland was the stronger predictive variable. Adding historic prairie to the cropland regressions increased explained variation by only 1% for TP and none for TN. Including historic forest cover increased

Table 2.-Simple and multiple regressions for TP and TN using current and historic cover metrics (n = 156 reservoirs) where %crop is percentage of current crop land (logit-transformed), % prairie is percentage of historic prairie (logit-transformed), Z_{ln} the natural log of dam height (m) and FI_{ln} is the flushing index (Jones *et al.* 2008a).

		r^2	RMSE
1	$TP_{ln} = 4.224 + 0.276 \times \%crop$	0.46	0.545
2	$TP_{ln} = 5.654 + 0.254 \times \%crop - 0.569 \times Z_{ln}$	0.60	0.469
3	$TP_{ln} = 5.801 + 0.270 \times \%crop - 0.447 \times Z_{ln} + 0.633 \times FI_{ln}$	0.65	0.444
4	$TP_{ln} = 3.692 + 0.124 \times \%prairie$	0.42	0.566
5	$TP_{ln} = 5.078 + 0.111 \times \%prairie - 0.537 \times Z_{ln}$	0.54	0.503
6	$TP_{ln} = 5.172 + 0.115 \times \%prairie - 0.440 \times Z_{ln} + 0.503 \times FI_{ln}$	0.57	0.489
7	$TN_{ln} = 6.964 + 0.194 \times \%crop$	0.57	0.307
8	$TN_{ln} = 7.698 + 0.183 \times \%crop - 0.292 \times Z_{ln}$	0.67	0.272
9	$TN_{ln} = 6.588 + 0.084 \times \%prairie$	0.48	0.337
10	$TN_{ln} = 7.292 + 0.078 \times \%prairie - 0.272 \times Z_{ln}$	0.56	0.311

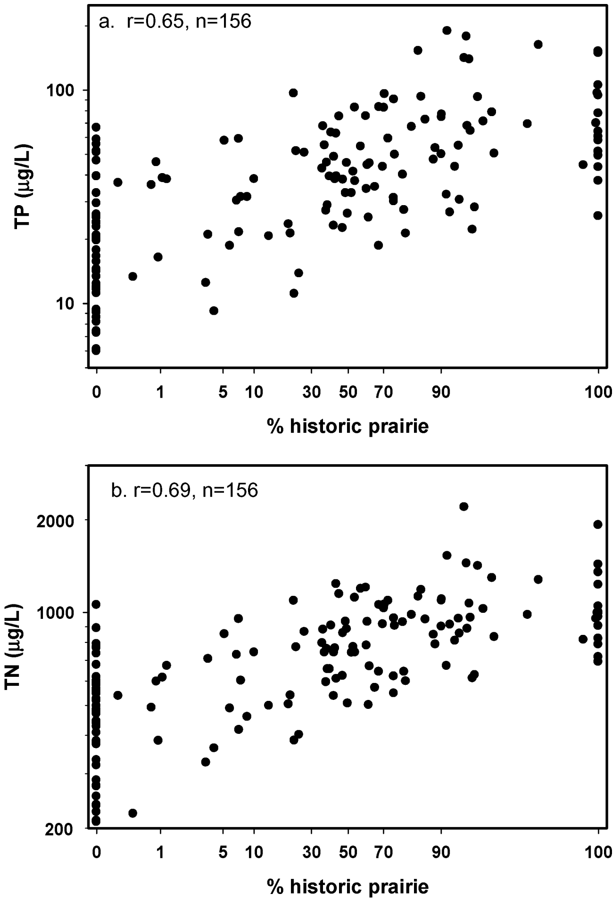

Figure 2.-Relations of reservoir mean TP (a) and mean TN (b) to historic prairie cover.

the r^2 for the TN model by 2%. None of the other historic land cover variables added significantly to the models, and residual analysis showed no obvious regional differences in the influence of historic cover type.

These results indicate reservoirs with watersheds previously dominated by prairie had no tendency toward higher or lower nutrients relative to current cropland than those previously in forest, and vice versa. Residuals from the nutrient regressions indicated that the proportions of cropland created by plowing prairies versus that created by clearing forest or scrub did not influence reservoir TP. Among Plains reservoirs, residuals from the TN–cropland–dam height regression (equation 8, Table 2) showed a weak negative correlation ($r = -0.23$, $p = 0.023$) with the proportion of cropland derived from former forests. This trend was not evident among Ozark reservoirs. Overall, these results imply current land use is much more important than historic cover in determining reservoir nutrients and that any current influence of historic conditions is subtle.

Characteristics of low phosphorus Missouri reservoirs

As expected from cross-system regression models (Table 2), Plains reservoirs with the lowest TP (median = 16 μg/L for the bottom fifth percentile, n = 5 of 101; Table 3) are deep water bodies with low flushing rates, located in catchments with less than a quarter of the median cropland found in the region (6% vs. 25%). Not surprisingly, historical survey data show the catchments of reservoirs in this group had modest prairie cover (with one exception) and an order of magnitude more forest than most Plains catchments. These reservoirs supported about one-third the TP found in the median Plains reservoir and about one-tenth of the value of shallow, nutrient-rich reservoirs situated on historic prairies (Table 3). These five reservoirs with low TP values are similar to impoundments in the Ozarks (Jones *et al.* 2008b).

The same cross-system pattern held among Ozark reservoirs; TP increased with cropland and flushing rate and was inversely tied to historic forest cover and depth. Low TP reservoirs were deep with low flushing and located in wooded valleys. Ozark reservoirs with high TP were mostly rapidly flushed, riverine impoundments or had more cropland than typical for the region.

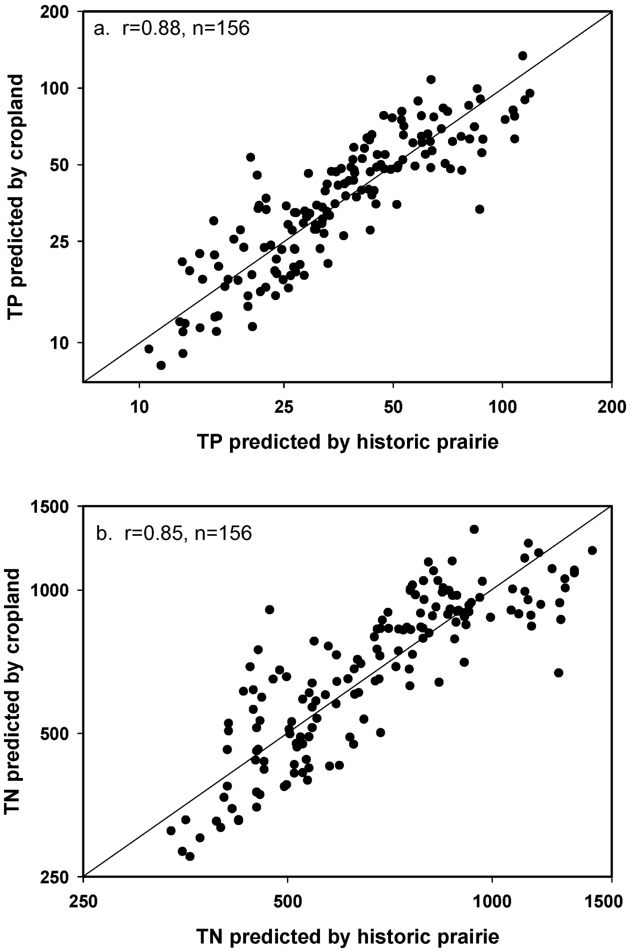

Figure 3.-Comparison of predictions of TP and TN by regression models based on current cropland and historic prairie cover. Values in (a) are from equations 3 and 6 in Table 2; values in (b) are from equations 8 and 10.

Discussion

Reservoir nutrients and human influences, past and present

The Missouri landscape has a long history of anthropogenic influence, with evidence of human populations for many thousands of years (O'Brien and Wood 1998), and by the early 16th century, large populations in the region modified landscapes with roads, fields, and settlements (Denevan 1992). Prairie vegetation in the Plains was likely maintained by fire at an interval of about 5–15 years (Schroeder 1982), and anthropogenic fire constituted the major influence on Ozark vegetation (Guyette *et al.* 2002).

By any measure, alteration of the Missouri landscape resulting from Euro-American settlement was drastic compared to modifications by indigenous humans. Available evidence suggests broad-scale plowing of native prairies and clearing of forests for high-intensity agriculture greatly increased nutrient loss from watersheds (Smith *et al.* 2003, Turner and Rabalais 2003). Consequently, the streams impounded by Missouri reservoirs currently export far greater loads of nitrogen and phosphorus than previously. Conversion of prairie to cropland in the Plains probably resulted in a several-fold increase in nutrient export. An early experimental plot study in Missouri showed conversion of prairie vegetation to continuous wheat increased N and P loss about 50-fold and continuous corn increased values about 100-fold (Miller and Krusekopf 1932). Runoff information from agricultural watersheds in the Midwest suggests soluble P loss from corn is about 10-times that from prairie (Miller and Daniel 1981). Stream nutrient data from a prairie reference site in the Kansas Flint Hills conformity showed averages of about 7 μg/L TP and 223 μg/L TN (Dodds and Oakes 2004); these values are considerably lower than currently measured in Missouri's agricultural streams (Perkins *et al.* 1998). The

Table 3.-Features of the five least enriched and most enriched reservoirs in the Plains region and regional medians. Units follow Table 1.

	TP	Dam Height	Flushing Rate	% Historic Prairie	% Historic Forest	% Crop Land
Nehai Tonkeia	14	19.8	0.11	24.3	39.5	1.2
Marie	14	15.2	0.18	0.0	87.9	6.4
Lincoln	16	21.0	0.46	0.0	99.7	2.1
Weatherby	16	25.9	0.14	0.9	95.8	13.6
Fox Valley	18	15.9	0.33	0.0	84.9	12.0
Regional median	49	12.8	1.0	74.8	6.9	25.5
Ray County	152	6.1	2.1	100	0	39.6
Montrose	152	10.1	6.0	84	8.6	30.7
Maysville	162	6.1	4.2	99	0	9.4
Cameron #1	178	10.1	3.6	94	0.6	39.2
King	189	12.1	4.1	91	1.1	28.4

difference between current and pre-settlement nutrient export is probably less for the Ozarks than in the Plains. While only fragments of unbroken prairie remain in the Plains and do not constitute an entire reservoir basin, altered forests still cover much of the Ozarks (Table 1). Agricultural grasslands are a major secondary cover type in the Ozarks (Table 1) and are associated with nonpoint nutrient loss (Smart *et al.* 1985). Export coefficients consistently show plant nutrient loss from cropland is many times that from either forests or pasture (Reckhow *et al.* 1980, Alexander *et al.* 2004).

Artificial lakes in Missouri were constructed in physically favorable locations more than a century after vegetation was removed for agricultural production. Our cross-system analysis suggests the nutrient status of these mostly eutrophic (60%; Jones *et al.* 2008b) and mesotrophic (20%) impoundments is determined mainly by human influences. Cropland serves as a metric of nonpoint source nutrient loading from human-altered landscapes and stands out as the foremost explanatory factor in our reservoir models (Table 2; Jones *et al.* 2004, Jones *et al.* 2008a). Reservoir depth and flushing rate are a function of design and site location in the catchment and strongly influence nutrients (Jones *et al.* 2008a). Note that the amount of variation explained and the model parameters for this expanded data set (24% larger) are quite similar to previous analyses (Jones *et al.* 2004, Jones *et al.* 2008a), suggesting the analysis is a robust generalization of nutrient patterns in Missouri reservoirs. Nutrient levels in some reservoirs presumably have varied over time in response to changes in land use (Jones *et al.* 2004) and with the intensity of farming practices. Even so, impoundments in predominantly agricultural catchments have likely been fertile from the time of dam-closure. Reservoir age was not a factor in the cross-system analysis; recently constructed reservoirs fit the statewide nutrient pattern (Table 2) equally as well as those decades older. The trophic status of an individual Missouri reservoir is, in effect, determined by the decisions of choosing a location within a valley catchment and designing a dam.

Historic vegetation explained little residual variation in the nutrient–cropland regressions, suggesting that contemporary land use is the primary determinant of nutrient loss from these watersheds. Past land use can influence nutrient saturation and current loss from landscapes (Aber *et al.* 1998) and may account for the weak signal in our data, suggesting that historic forests in the Plains yield less nitrogen when converted to cropland than other cover types. But at the resolution of our analysis, historic conditions did not broadly account for variation in reservoir nutrients. This result was not surprising given that ~150 years have passed since plowing of prairies and forest clearing remade these watersheds.

Nutrients in Missouri reservoirs were related to historic prairie cover in the same general pattern, though somewhat less strongly, as they were to present-day cropland (Table 2; Fig. 3). A likely explanation is that lands most suitable for cultivation, with favorable basin slope and arable soils having inherent fertility to generate economically viable produce, were largely former prairies (Fig. 1). Within the catchments of our study reservoirs, some 76% of cropland was prairie at the time of Euro-American settlement. The relationship between reservoir nutrients and historic prairie is partly an artifact of past land conversion. Soil quality and basin topography are integral features that initially influenced cropland conversion; more recently, these same characteristics influenced which lands remained in cultivation or were converted to grasslands (including conservation reserves) and forests.

Natural reference conditions, as described by Gibson *et al.* (2000) for natural lakes, represent the least impacted conditions and typify ambient background or baseline nutrients. Analogous reference conditions do not exist for Missouri reservoirs. Reservoirs were built long after vegetation was altered for agriculture so that nutrient loads were in place prior to creating these artificial lakes. Human design and intentional positioning of impoundments in valleys with established land cover suggests site-specific nutrient criteria are appropriate. Site-specific assessment avoids making untenable comparisons between impoundments with different hydro- and morphology features. With other factors held equal, deep impoundments with long hydraulic retention will consistently have lower nutrients than shallow, rapidly flushed water bodies (Welch and Jacoby 2004, Jones *et al.* 2008a). Data from Plains reservoirs (Table 3) illustrate this fact; reservoirs with the lowest TP have physical features atypical of the region and are not examples of the nutrient condition readily achievable in most impoundments.

In estimating site-specific reservoir nutrient levels, the cross-system, nutrient-cropland regression (Table 2) provided a quantitative framework within the context of the statewide continuum (Jones *et al.* 2008b) and the broader regional context (Jones *et al.* 2008a). The proportion of historic prairie cover could be used as a surrogate term for nutrient loading, with about the same outcome (Table 2). Prairie cover closely matched the intent of establishing a baseline conditions by representing indigenous vegetation in reservoir catchments (Gibson *et al.* 2000); it also provided a quantitative basis for estimating nutrient loss from the landscape at the time of Euro-American settlement. Regardless, it would be straightforward to compare nutrient levels in a given reservoir by predicting expected values based on unique design specifications (depth and volume) and edaphic features (land cover and watershed size; Table 2). Impoundments with low long-term nutrient levels or levels below the cross-system pattern might be identified for protection, consistent with the EPA antidegredation policy (Gibson *et al*. 2000). Reservoirs with nutrients in excess of the regional expectation, where nutrient-related water quality problems clearly impair designated use, might be candidates for nutrient reduction.

Several approaches have been taken to establish nutrient criteria to protect designated uses for lake water, such as water supply, recreation and aquatic life (Reckhow *et al*. 2005; Dodds *et al*. 2006; Soranno *et al*. 2008). Ideally, nutrient criteria should be tied to designated-use statements for specific impoundments. An early example was the work of Dillon and Rigler (1975) linking nutrients in boreal lakes to algal chlorophyll and recreation potential (swimming, fishing, and aesthetics). An extensive analysis of Minnesota lakes has resulted in threshold values of phosphorus, and the response variables chlorophyll and transparency, to protect use classes in the diverse ecoregions of that state (Heiskary and Wilson 2005). A similar analysis of nutrient-caused impairment is not available for Missouri reservoirs.

Designated use should reflect societal values; implementation of criteria should be technically attainable and provide a favorable ratio of water quality benefit to cost. Major nutrient reduction would not necessarily benefit reservoirs designated for warmwater recreational fisheries where production and harvest are closely tied to nutrients (Yurk and Ney 1989). About one-fourth of the impoundments in our data set were built with conservation funds and are managed with stocking and harvest regulation for recreational fishing (recreational swimming is not permitted in these impoundments). In contrast, groundwater in some areas of the Plains is naturally saline, and communities rely on surface water supplies. Several water supply reservoirs are located in valleys historically in prairie vegetation (70–100%), and cropland currently dominates their catchments (Knowlton and Jones 2007); they are eutrophic, and some samples have measurable algal toxins (Graham *et al*. 2004). In these nutrient impaired systems, land retirement from cropland to prairie vegetation or forest may be an appropriate tool for drastically reducing nutrient loads from agricultural catchments (Ribaudo *et al*. 1994).

Interestingly, implementation of stream criteria can directly improve nutrient related water quality problems in reservoirs (Dodds and Oakes 2004), which are considered major anthropogenic alterations of the landscape (Nilsson *et al*. 2005). Nonpoint nutrient loads from agriculture can be reduced using best management practices, which broadly include fertilizer, manure, and tillage management along with vegetating riparian zones and critical source areas (Pionke *et al*. 2000, Sharpley *et al*. 2001, Vidon and Smith 2007). Nutrient reductions can protect designated use in streams and, by extension, reduce eutrophication in reservoirs; therefore, a broad-scale nutrient reduction effort aimed at streams would likely reduce the slope and/or intercept of the empirical fit between reservoir nutrients and cropland (Table 2). Broad implementation of best management may represent the most readily attainable conditions in these artificial lakes without major changes in agricultural production.

Our analysis describes why nutrients differ in reservoirs statewide and provides an historical context for the cross-system pattern. Vegetation structure from the survey at the time Euro-American settlement is our best measure of early landscape characteristics in the region and is a metric of baseline historic conditions in valleys recently impounded for the benefits that reservoirs provide society. Not surprisingly, low-nutrient reservoirs are located in deep valleys that were historically forested and remain so, while high-nutrient reservoirs are in shallow valleys that were once prairie, now converted to cropland. Once adopted, nutrient criteria enforcement will rely on the principles of applied limnology to manage nutrients or, where appropriate, improve water quality (Welch and Jacoby 2004, Cooke *et al*. 2005). Empirical relationships for these purposes have been developed specifically for Missouri reservoirs, including expectations for bloom frequency and summer maximum algal biomass (Jones *et al*. 2008b).

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