Preliminary Comparison of Landscape Pattern–Normalized Difference Vegetation Index (NDVI) Relationships to Central Plains Stream Conditions

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ABSTRACT

We explored relationships of water quality parameters with landscape pattern metrics (LPMs), land use–land cover (LULC) proportions, and the advanced very high resolution radiometer (AVHRR) normalized difference vegetation index (NDVI) or NDVI-derived metrics. Stream sites (271) in Nebraska, Kansas, and Missouri were sampled for water quality parameters, the index of biotic integrity, and a habitat index in either 1994 or 1995. Although a combination of LPMs (interspersion and juxtaposition index, patch density, and percent forest) within Ozark Highlands watersheds explained >60% of the variation in levels of nitrite–nitrate nitrogen and conductivity, in most cases the LPMs were not significantly correlated with the stream data. Several problems using landscape pattern metrics were noted: small watersheds having only one or two patches, collinearity with LULC data, and counterintuitive or inconsistent results that resulted from basic differences in land use–land cover patterns among ecoregions or from other factors determining water quality. The amount of variation explained in water quality parameters using multiple regression models that combined LULC and LPMs was generally lower than that from NDVI or vegetation phenology metrics derived from time-series NDVI data. A comparison of LPMs and NDVI indicated that NDVI had greater promise for monitoring landscapes for stream conditions within the study area.

Over the past 200 years the freshwater resources of the USA have undergone the most significant transformation they have experienced since the Pleistocene glaciations (Williams et al., 1997). Agricultural activities are among the most frequently cited sources for degradation and pollution of aquatic resources, primarily due to nutrients and sediment (Cooper, 1993; Lenat and Crawford, 1994). The effects of these activities are of special interest in a predominantly agricultural region such as the U.S. Central Plains. For reviews of the general environmental impacts of agriculture from sediments, nutrients, organic contamination, and pesticides and/or metals see Cooper (1993), Matson et al. (1997), and Skinner et al. (1997), and for recent research on agroecosystems, see Carter (2001). In particular, problems stemming from agriculture in smaller streams of the Central Plains include sedimentation of previously clear streams and dewatering of streams due to intensive ground water mining for irrigation and conservation practices (e.g., farm ponds, conservation tillage).

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To address problems arising from agricultural nonpoint-source pollution, aquatic resource managers and fish ecologists must pay greater attention to large-scale spatial and temporal heterogeneity (Schlosser, 1991; O'Neill et al., 1997; Labbe and Fausch, 2000; Marsh-Matthews and Matthews, 2000). Consensus is forming that stream condition assessments must include both stream reaches and whole catchments (Sidle and Hornbeck, 1991; Roth et al., 1996; Johnson and Gage, 1997; Wiley et al., 1997). As a result of the strong linkages between stream biotic communities, water quality, and the surrounding landscape, land cover information is used extensively to support water quality studies (Zelt et al., 1995), especially as advances in remote sensing and geographic information systems (GIS) have made regional-level studies more feasible (Johnson and Gage, 1997; Herlihy et al., 1998).

LANDSCAPE–WATER QUALITY APPROACHES

Land Use–Land Cover and the Satellite-Derived Normalized Difference Vegetation Index

Traditionally, the relationships between terrestrial systems and aquatic systems have been studied by classifying aerial photography or satellite imagery into discrete LULC classes. Although the riparian buffer has great influence on water quality, aquatic biota, and habitat, many studies also show the importance of analyzing the entire watershed (Omernik, 1976; Osborne and Wiley, 1988; Johnson et al., 1997), with Johnson and Gage (1997) summarizing many of them. In contrast to relating simple land cover proportions to water quality conditions, however, Whistler (1996) used NDVI values. The premise behind its use is that vegetative cover (presence, density, and type) in a watershed has a strong influence on the water quality characteristics of runoff. Due to this relationship, multidate vegetation indices might better characterize the influence of land cover on nonpoint-source pollution than single-date general land cover maps. The NDVI has a long history of use in remote sensing, geography, and ecology to study characteristics of vegetation, including its presence, amount (biomass), type, and condition (Jensen, 1996; Rundquist et al., 2000). Because NDVI values are indicative of a watershed's biophysical condition, they provide advantages over LULC proportions. Even though the NDVI spatial resolution is relatively coarse, as a continuous variable

Abbreviations: AVHRR, advanced very high resolution radiometer; HI, habitat index; IBI, index of biotic integrity; IJI, interspersion and juxataposition index; LPM, landscape pattern metric; LULC, land use–land cover; NDVI, normalized difference vegetation index; USGS, United States Geological Survey; VPM, vegetation phenological metric.

it captures, to some extent, riparian condition. Whistler (1996), using NDVI values as a surrogate for biomass, found significant relationships between NDVI and selected water quality parameters that, in most cases, were stronger than relationships to land cover proportions. Derived from NDVI time-series datasets, vegetation phenological metrics (VPMs) have also been used to characterize landscapes and classify LULC (Reed et al., 1994; Loveland et al., 1995), but have yet to be fully explored for their potential in regional water quality monitoring and assessment.

Landscape Pattern

Another new research avenue for studying LULC–water quality relationships focuses on landscape pattern effects on water quality (Sharpe, 1994; Cairns and Niederlehner, 1996; Johnson et al., 1997; Schuft et al., 1999). The LPMs potentially affecting stream conditions include measures of fragmentation and connectivity, patch size and density, and the number of cover types (Jones et al., 1996). Mixed results have been reported from the few studies that have used LPMs in water quality studies. Wear et al. (1998) simulated landscape changes along an urban–rural gradient in the Southern Appalachians and suggested that different *landscape profiles*, including various LPMs, can have important implications for water quality. In southern Illinois, Hunsaker and Levine (1995) found that two landscape pattern metrics, dominance and contagion, did not explain as much variation in water quality as did LULC when analyzing full watersheds. When using other analysis units, however, such as stream corridors or hydrologic contributing areas, contagion was found to explain significant variation in conductivity and nutrient levels. In a study of several landscape parameters and water quality in Michigan streams, Johnson et al. (1997) and Richards et al. (1996) found that patch density had some bearing on water quality, but other factors such as geology or slope had equal or greater effect in most cases. Sharpe (1994) found little correlation between LPMs in grid cells of a runoff model and their nutrient output.

OBJECTIVES

As landscape pattern can be quantified using digital LULC data, it would be interesting to compare the utility of using both LPMs and LULC to explain variation in water quality with the results from using only NDVI-derived metrics (which do not require land cover data). Griffith (2000) showed that NDVI metrics were in many cases strongly correlated with water quality parameters. Using AVHRR NDVI removes the time-consuming step of classifying LULC.

The goal of this work is to seek methods that are able to characterize landscapes for regional assessment. Hence, we aim to explore screening indicators to identify watersheds that may be at risk of environmental degradation. This type of study is important for setting natural resource policy conducted at large scales. For example, Section 305(b) of the U.S. Clean Water Act mandates the assessment of water bodies, but a recent study found that about 80% of stream miles go unassessed (General Accounting Office, 2000). Thus, large-scale regional analyses are crucial. Our null hypothesis is that there is no difference between the relationships of NDVI and LPMs with the selected water quality parameters. Specifically, the focus of the research questions in this study are: (i) What are the relationships between landscape pattern metrics (LPMs) and selected water quality parameters? (ii) How much variation in the selected water quality parameters is explained by regression models using LULC and LPMs? (iii) How does the amount of variation explained by the combination of LULC and LPMs compare with that of the NDVI-derived metrics?

METHODS

Study Area

This study was done for the United States Environmental Protection Agency (USEPA) Region VII, in cooperation with three states of the region. Iowa did not participate in the study, so for the purposes of this paper, we define the Central Plains as Kansas, Missouri, and Nebraska, even though southern Missouri contains distinct upland topography. Geology in the area consists of limestones and shales in central and eastern Kansas. Glacial episodes during the early Pleistocene spread glacial drift across northern Missouri, eastern Nebraska, and northeastern Kansas, whereas the Precambrian strata of the Ozark Uplands remained nonglaciated and rugged. Loess soils cover much of Nebraska, while alluvial sediments cover western Kansas and Nebraska (Williams and Murfield, 1977).

Precipitation ranges from 380 to 450 mm in westernmost Kansas and Nebraska, to 900 to 1000 mm in eastern Kansas, and to nearly 1200 mm on the Mississippi River in southeastern Missouri (Schroeder, 1982; Goodin et al., 1995). Native vegetation in the region consists of shortgrass prairie in westernmost Kansas and Nebraska, tallgrass and mixed-grass prairie in the Nebraska Sand Hills and central Kansas, a mosaic of bluestem prairie and oak–hickory forest in both eastern Kansas and northern Missouri, and dense oak–hickory forests in the Ozark Highlands. The central human transformation of the Great Plains has been the conversion of native grasslands to cropland. Currently, 90% of the area is in farms or ranches and 75% of the land area is cultivated (Riebsame, 1990). Chapman et al. (2001) provide a synopsis of the physical geography of Kansas and Nebraska.

Field Data

Water quality data were collected throughout the study area by USEPA Region VII during the late spring and summer of 1994 and 1995 as part of its Regional Environmental Monitoring and Assessment Program (REMAP) (USEPA, 1993). Stream sites (271) were randomly selected in Kansas, Nebraska, and Missouri to assess fisheries' health and stream condition, and to establish baseline data and methods usable for assessing long-term trends throughout the region (USEPA, 1994). At each stream sampling site, data on stream physical, biological, and habitat condition were collected. Field sampling was conducted once per site between June and September of 1994 or 1995 when flows were close to seasonal norms, which is generally low and when pollution stress is potentially high and the fish community is the most stable and sedentary (USEPA, 1994). Data collection techniques and water chemistry analytical methods followed USEPA Region VII Standard Operating Procedures (USEPA, 1994).

Four water quality parameters that are important determinants of water quality were included in this study: conductivity, turbidity, nitrite–nitrate nitrogen (NO_2–NO_3), and total phosphorus (TP). In addition, an index of biotic integrity (IBI) and habitat index (HI) were analyzed (Karr et al., 1986;

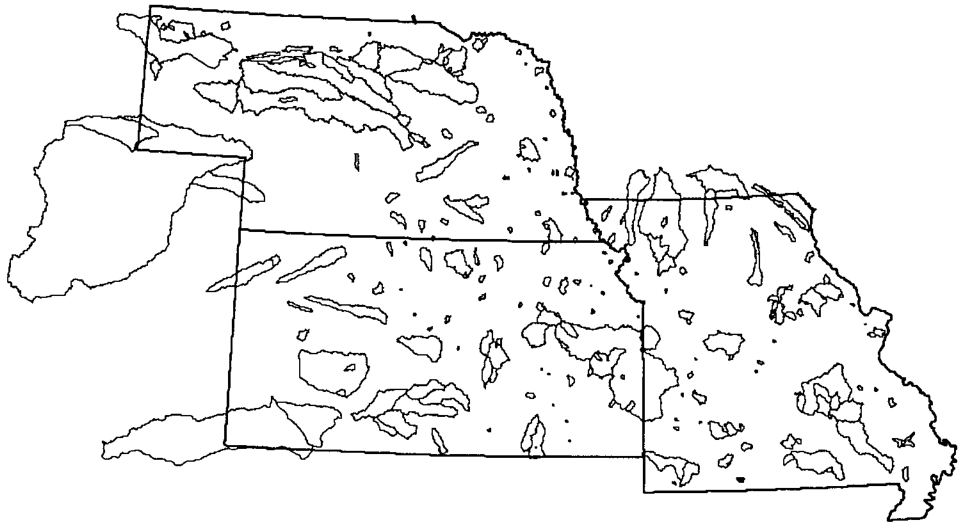


Fig. 1. Watersheds used in the study.

USEPA, 1994; Karr and Chu, 1998; Kaufmann et al., 1999). Appendix I lists metrics used to calculate these indices.

Landscape Data

For each stream sampling point, the watershed area was delineated and digitized (Fig. 1). The LULC data for the region were obtained from the United States Geological Survey (USGS) LULC Composite Theme Grid data set (United States Geological Survey, 1990), which was derived from aerial photography from the mid- and late-1970s with a spatial resolution of 200 m. The Anderson Level I classification was used;

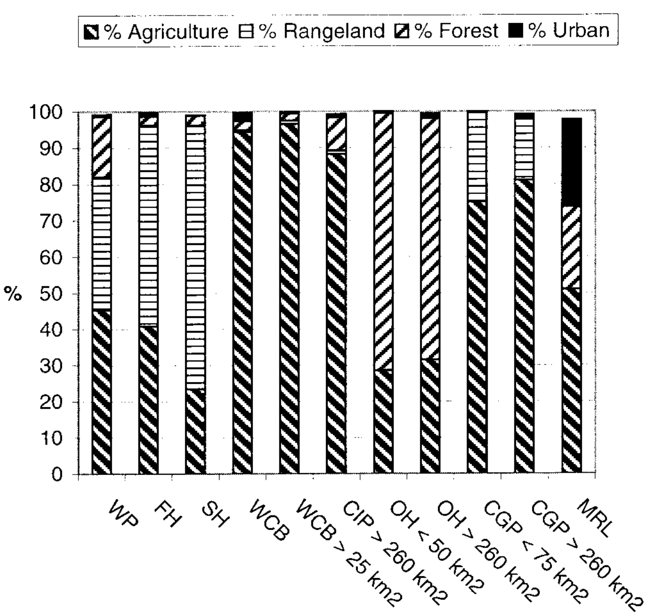


Fig. 2. Land use–land cover proportions in the watersheds stratified by ecoregion and/or size that are discussed in this study. WP, Western High Plains and Tablelands; FH, Flint Hills; GP, Glaciated Plains; SH, Nebraska Sand Hills; WCB, Western Corn Belt Plains; CIP, Central Irregular Plains; OH, Ozark Highlands; CGP, Central Great Plains; MRL, Mississippi River Lowlands. The proportions for some do not add to precisely 100% in some cases because not all of the possible eight land use–land cover types are shown.

eight LULC categories occurred in the study area. The LULC proportions for the watersheds are shown in Fig. 2. Areas within the watersheds were "clipped" from the land cover data and processed with FRAGSTATS 2.0 (McGarigal and Marks, 1995) to calculate 10 landscape pattern metrics (Table 1). Although there exists more recent land cover data at a finer resolution (30 m from 1992) (Vogelmann et al., 2001), it was not available at the start of this project. However, Herlihy et al. (1998) found that land cover–water chemistry regressions using 30-m data from 1992 produced no better results than did the USGS LULC data from the 1970s. Also, our preliminary work using a 30-m 1990 LULC dataset for Kansas (Whistler et al., 1995) produced mixed results. Therefore, although the USGS LULC dataset does not model the current landscape precisely, we believe it is adequate for our study. The LULC change that has occurred since the date of the USGS LULC data include an increase in grasslands due to the Conservation Reserve Program, an increase in center-pivot irrigation agriculture in western Kansas and Nebraska, and urban growth around the major cities.

The normalized difference vegetation index and vegetation phenological metrics were derived from the National Oceanic and Atmospheric Administration's (NOAA) advanced very high resolution radiometer (AVHRR) satellite sensor. Twenty-six periods of biweekly NDVI composites for 1995 were used. Each composite is composed of the maximum NDVI value for every 1-km^2 pixel over a two-week period (Eidenshink, 1992). The NDVI is a ratio of near-infrared (NIR) and red solar reflectance and has been shown to be correlated with leaf area index and thus photosynthetic activity and plant biomass (Jensen, 1996). The equation for calculating NDVI is: (NIR $-$ Red)/(NIR $+$ Red) with values ranging from -1 to 1, and with high values indicating dense, healthy, green vegetation; values close to zero indicating bare ground or sparse vegetation; and negative values indicating water, clouds, or snow.

In addition to the NDVI values, a series of derived metrics describing vegetation phenology were developed using algorithms modified from Reed et al. (1994). The VPMs used were maximum NDVI, date of onset of greenness, NDVI value at onset of greenness, number of growing days, growing season duration, and rate of green-up (growth rate). We used NDVI values from biweekly Periods 7 to 22 (late March through early November). Loveland et al. (1995) found that VPMs

Table 1. The FRAGSTATS metrics used in the analysis. Full descriptions of these metrics, and equations for their calculations, are provided in McGarigal and Marks (1995).

Abbreviation	Metric name (units)	Description
AWMPFD	area-weighted mean patch fractal dimension	Patch shape complexity measure, weighted by patch area; AWMPFD approaches 1 for shapes with simple perimeters (e.g., circles), and 2 for complex shapes.
AWMSI	area-weighted mean shape index	Mean patch shape complexity, weighted by patch area; equals 1 when all patches are circular and increases as patches become noncircular.
CONTAG	contagion (%)	Approaches 100 when the distribution of adjacencies of individual cells among unique patch types becomes increasingly uneven. Equals 0 when all patch types are equally adjacent to each other. Larger values denote a landscape composed of larger, more clumpy patches. Smaller values denote a landscape composed of many, small patches.
ED	edge density (m/ha)	Sum of length of all edge segments divided by total area.
IJI	interspersion and juxtaposition index	Approaches 0 when distribution of adjacencies among patch types becomes increasingly uneven; IJI equals 100 when all patch types are equally adjacent to all other patch types.
MPS	mean patch size (ha)	Total landscape area divided by the total number of patches.
MSIDI	modified Simpson's diversity index	Diversity measure; increases with number of patch types and as the proportional distribution of area among patch types becomes more equitable.
PD	patch density (no./100 ha)	Number of patches divided by total landscape area.
PR	patch richness	The number of land use–land cover types.
SHDI	Shannon diversity index	Diversity measure; equals minus the sum, across all patch types, of the proportional abundance of each patch type, multiplied by that proportion.

were helpful in classifying LULC for the conterminous USA. For each watershed, GIS overlay techniques were used to extract LULC proportions and to calculate mean NDVI values for each biweekly period and mean and standard deviations of VPM values. The U-index (human use index) (USEPA, 1994), which equals the proportion of agriculture plus urban land, was also calculated to gauge the level of total anthropogenic disturbance in regional landscapes.

The data were stratified by USEPA ecoregions, or in some cases, groupings of ecoregions (Omernik, 1987). While using the entire data set without stratification may be useful, based on statistical analysis, we found it necessary to stratify by ecoregion, because differences in general agricultural crops and land cover between ecoregions tended to cancel out any relationships. We also stratified by watershed area when adequate sample size existed. Details of the watershed selection process and variable transformations are explained in Griffith (2000).

Pearson product–moment correlation coefficients (Davis, 1986) were calculated to quantify relationships between stream condition variables and the LPMs, NDVI, and VPMs. To examine the effect of watershed size on the LPMs, partial correlation analyses that controlled for the effect of watershed size were also performed. Multiple regression was performed using the stream condition parameters as dependent variables, and LPMs and LULC as independent variables. Input variables for the regression models were determined by checking for instances where both an LULC and an LPM were significantly correlated with a stream condition parameter, and where both retained this significant correlation even after watershed size was factored out. Regression models were built only for ecoregions in which there were significant separate bivariate correlations between water quality parameters and the LPMs or LULC. The rationale behind this was because maps of LULC are needed to calculate LPMs. If LULC proportion adds additional information to variation explained along with LPMs, we wondered whether using them in conjunction might better explain water quality variation than simply using NDVI, which does not require LULC data. In most cases, when comparing LPMs alone versus NDVI, the NDVI metrics were more strongly correlated to the selected parameters than were the LPMs. Only the AVHRR data are needed to produce the NDVI–VPMs, and we wished to compare LPMs and LULC together as a unit with the NDVI metrics alone.

To assess the robustness of the multiple regression models, the condition index (CI), and the variance inflation factor (VIF) were used. Condition indices are the square roots of the ratios of the largest eigenvalue to each successive eigenvalue (Montgomery and Peck, 1992). The VIFs measure how much the variances of the estimated regression coefficients are inflated as compared to when the predictor variables are not linearly related (Neter et al., 1996). Condition indices in most cases were kept at 10 or below, and if the index was higher, both it and the VIF were used to decide which variables to eliminate from the model. Thus, because some condition indices were higher than 10, variable collinearity could not be fully eliminated. Finally, histograms of the regression standardized residuals or plots of the regression standardized vs. standardized predicted values were used to assess the regression models.

RESULTS AND DISCUSSION

Table 2 lists descriptive statistics for sizes of watersheds used within each ecoregion, and Table 3 shows the correlation between the LPMs and the selected stream condition parameters. Not all ecoregions or size stratifications are shown due to length considerations. Instead, we focus on the ecoregions and size stratums having the highest correlations and providing the clearest examples of LPM or NDVI relationships to water quality. Tables 4a and 4b show the correlations of the NDVI values and VPMs with the selected water quality parameters. In ecoregions for which watersheds were also stratified by size, there were generally stronger correlations for the larger watersheds. Part of this result may be caused by small watersheds restricting the range of spatial patterns of LULC. Small watersheds may have also been more sensitive to potential human error in delineating and digitizing the watershed boundary.

Landscape diversity measures, landscape texture mea-

Table 2. Mean and range of watershed sizes in each ecoregion.

Ecoregion	Mean watershed area	Minimum	Maximum
	km^2		
Western Plains and Tablelands	1 831	10.1	17 415
Flint Hills	228	0.5	1 067
Sand Hills	2 212	9.6	13 499
Western Corn Belt Plains	126	1.6	1 836
Central Irregular Plains	571	2.3	14 688
Ozark Highlands	452	3.6	3 929
Central Great Plains	587	3.9	5 970
Mississippi River Lowlands	379	2.8	3 447

sures (e.g., interspersion and juxtaposition index [IJI] and contagion), and patch measures (density or richness) were most often correlated with the water quality parameters. In particular, the IJI may prove beneficial in watershed condition monitoring as it was strongly correlated with water quality parameters in the Ozark Highlands, Flint Hills, and Central Irregular Plains. Patch density was also strongly correlated (r = 0.92) with the habitat index in the Mississippi River Lowlands. Each stream condition parameter had roughly the same number of significant correlations with an LPM, with the exception of turbidity, which had the fewest. A comparison of Tables 3 and 4a,b shows that an NDVI date or VPM was more frequently correlated to stream conditions than were the LPMs.

The following discussion focuses on several notable issues and findings with respect to the use of LPMs for regional watershed monitoring: (i) problems in calculating a full suite of landscape pattern metrics, (ii) the lack of many significant correlations between the LPMs and stream condition, (iii) the sensitivity of the LPMs to watershed size, (iv) counterintuitive results, and (v) inconsistent patterns of correlations. The regression results will then be discussed, as will the comparison of these regressions with the amount of variation in water quality explained using NDVI metrics only.

Although a wider range of LPMs was initially tested, only a subset was able to be used to analyze all or most of the watersheds. This situation occurred because the 200-m resolution of the LULC data and small size of some watersheds resulted in several watersheds having only a single patch, or only one or two patches each of certain cover types. These circumstances prevented the calculation of some landscape-level metrics, or class-level metrics that focused on one land cover class such as grassland or forest. Metrics that focus on grassland in this region may be more useful to understanding water quality processes, but in parts of the study area some watersheds had very little grassland or none at all.

Most of the time an LPM was not correlated with water quality or stream condition parameters (Table 3). With 17 ecoregions or stratifications within ecoregions (by watershed size) in the study area, and six stream condition parameters, a total of 102 possible opportunities for a significant correlation with any of the LPMs existed. Not all stratifications are shown on Tables 3 and 4a,b because, as stated earlier, they had few or no significant correlations. For example, the Central Irregular Plains was considered one stratification, as were three watershed size groups for this ecoregion. There were only 48 times out of a possible 102 when a stream condition parameter had a significant relationship with any LPM.

Besides having relatively few significant correlations to the selected stream parameters, LPMs are affected by watershed size. This problem affected many correlations and was especially severe for the patch shape metrics. This situation resulted in part because the size and shape of LULC patches are constrained to some extent by watershed size. In particularly small watersheds, patches have only a limited number of shape configurations. While some of these metrics can be standardized, preliminary analysis including principal components analysis showed little effect on the outcome.

Some of the correlations between LPMs and stream parameters in larger watersheds (>25 km^2) of the Western Corn Belt Plains revealed counterintuitive relationships, especially to those persons not familiar with the study area. In this predominantly agricultural landscape, lower edge density, lower landscape diversity, and a landscape with land cover patches in larger aggregations (higher contagion) were all associated with increased habitat quality (Table 3). Figures 3 and 4 show graphs of these conditions. Considering that these same landscape patterns are also associated with greater amounts of agriculture in the watersheds (Table 5), these results seemed surprising, initially. One might expect that patches of forest or grassland in an agricultural matrix would add edge amount and increase landscape diversity with land covers that are intuitively associated with better stream conditions. Probable reasons for this arise from the importance of other factors besides landscape pattern or LULC that influence water quality. A closer examination of the five watersheds with the lowest HI scores and the five with the highest scores proved instructive. Two of the watersheds with the lowest scores straddled the loess-derived bluffs that flank the Missouri River floodplain. This environmental setting may be significant because of the enhanced erosion resulting from the higher slopes and erodible material found there. These bluffs are partially forested, which helps to explain the negative (albeit not statistically significant) relationship between percent forest and habitat index (Table 6). One of the subcomponents comprising the habitat index is substrate quality. Figure 4 shows that in the watersheds having the lowest HI scores, the substrate quality index is extremely low, supporting the occurrence of increased erosion from these bluffs. To

Table 3. Pearson correlations ($\alpha = 0.05$) between selected landscape pattern metrics and stream variables. These metrics were significant even after controlling for watershed size using partial correlation analysis. Additional stratifications of the data included nine extra categories in the Western Corn Belt Plains, Central Irregular Plains, Ozark Highlands, and Central Great Plains. These were not shown because there were either few significant correlations or very low correlations. The number of samples sites n is denoted as (n) for the interspersion and juxtaposition index (IJI), which could not be calculated for some watersheds due a lack of adequate patch numbers. Also, n varies among parameters, because in some cases a specific parameter measurement was not collected.†

Ecoregion‡	Conductivity	Turbidity	NO_2–NO_3	TP	IBI	HI
Western Plains and Tablelands§	% agriculture: 0.46; $n = 24$	log % urban: 0.50; $n = 21$		% agriculture: 0.71, U-index: 0.73; $n = 25$		
Flint Hills		PR: 0.47 $n = 19$	IJI: 0.63; $n = 21$			
Sand Hills	% grassland: −0.59, SHDI: 0.65, MSIDI: 0.64; $n = 19$			log % agriculture: 0.54; $n = 20$		
Glaciated Plains¶					SHDI: 0.53; $n = 15$	SHDI: 0.64; $n = 15$
Western Corn Belt Plains, >25 km²				log % urban: 0.48	IJI: 0.74 ($n = 13$)	log % agriculture: 0.6, U-index: 0.65, ED: −0.55, SHDI: −0.63, MSIDI: −0.64, CONTAG: 0.51; $n = 17$
Central Irregular Plains, >260 dm²	log % forest: 0.45; $n = 18$	log % forest: −0.27, U-index: 0.27; $n = 15$; IJI: 0.63 ($n = 14$)				SHDI: 0.60, MSIDI: 0.51, PR: 0.53, CONTAG: −0.50; $n = 17$
Ozark Highlands, 50–500 km²	IJI: 0.79 ($n = 11$), PD: 0.62; $n = 12$	log % grassland: 0.47; $n = 13$	% forest: −0.43, PD: 0.68, SHDI: 0.63; $n = 15$; IJI: 0.58 ($n = 13$)	% urban: 0.66; $n = 15$		log % grassland: −0.36; $n = 15$
Central Great Plain, >260 km²	log % grassland: 0.49, SHDI: 0.51; $n = 18$		PR: −0.50; $n = 18$	% grassland: −0.31, SHDI: −0.54, log % urban: 0.36; $n = 18$		
Mississippi Valley Lowlands#				% forest: −0.69, U-index: 0.71; $n = 11$	log % urban: −0.73, $n = 11$	PD: 0.92; $n = 11$

† CONTAG, contagion; ED, edge density; HI, habitat index; IBI, index of biotic integrity; MSIDI, modified Simpson's diversity index; PD, patch density; PR, patch richness; SHDI, Shannon diversity index; TP, total phosphorus; U-index, human use index.
‡ Some of the regions consist of aggregation of several ecoregions to increase the sample size.
§ Consists of the Western High Plains, Southwestern Tablelands, and Northwestern Great Plains ecoregions.
¶ Consists of the Northern Glaciated Plains and the Northwestern Glaciated Plains ecoregions.
# Consists of the Interior River Lowlands and Mississippi Alluvial Plains ecoregions.

Table 4a. Pearson correlation coefficients (significant at $\alpha = 0.05$) in selected ecoregions. Listed are the two most strongly correlated normalized difference vegetation index (NDVI) values or vegetation phenologic metrics (VPMs). If a land use–land cover (LULC) type was significantly correlated to a water quality or stream condition variable, it was listed; if none is shown there were no LULC types significantly correlated at $\alpha = 0.05$. In general, NDVI and VPMs were as highly correlated as LULC. In many cases, while an NDVI or VPM was significantly correlated to a stream variable, an LULC type was not.†

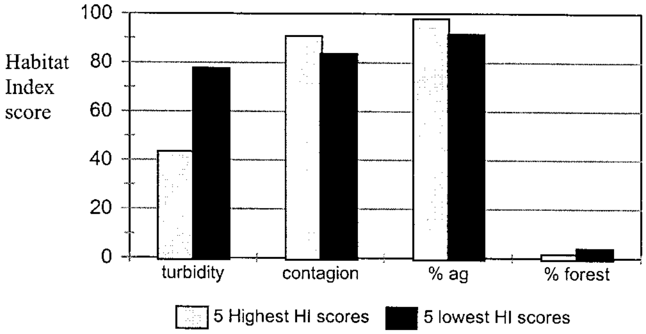
Ecoregion	Conductivity	Turbidity	NO_2–NO_3	TP	IBI	HI
Western Plains and Tablelands‡	% agriculture: 0.46, onset NDVI s.d.: 0.65, date of max. NDVI s.d.: 0.57; $n = 24$	log % urban: 0.50, P22 NDVI: 0.57; $n = 21$		% agriculture: 0.71, U-index: 0.73, mean onset date: −0.74, P8 NDVI: 0.71; $n = 25$		Date of max. NDVI: 0.47; $n = 25$
Flint Hills		mean onset date: −0.76, P18 NDVI: −0.70; $n = 19$	mean onset date s.d.: 0.65, onset NDVI s.d.: 0.53; $n = 21$			
Sand Hills	% grassland: −0.59, mean onset NDVI: 0.70, P14 NDVI; 0.69; $n = 19$		mean growth rate: −0.48, mean growing days: 0.47; $n = 20$	log % agriculture: 0.54, P11 NDVI: 0.57, P8 NDVI: 0.53; $n = 20$		
Western Corn Belt	% grassland: −0.59, P22 NDVI: 0.41, P11 NDVI: 0.35; $n = 33$	log % agriculture: −0.47, U-index: −0.50, P14 NDVI: 0.49; $n = 29$	P10 NDVI: −0.69, P8 NDVI: −0.66; $n = 34$	U-index: −0.5; $n = 34$	mean growth rate: −0.65, P15 NDVI: −0.64; $n = 34$	mean onset date: −0.49, P10 NDVI: 0.48; $n = 34$
Mississippi Valley Lowlands§	onset NDVI s.d.: −0.72; $n = 9$	P18 NDVI: −0.78, date of max. NDVI: −0.66; $n = 10$	mean growing days: −0.62, $n = 11$	% forest: −0.69, U-index: 0.71, onset NDVI s.d.: −0.70; $n = 11$	log % urban: −0.73, P18 NDVI: 0.79, P16 NDVI: 0.78; $n = 11$	

† HI, habitat index; IBI, index of biotic integrity; P, period; s.d., standard deviation; TP, total phosphorus; U-index, human use index.
‡ Consists of the Western High Plains, Northwestern Great Plains, and Southwestern Tablelands ecoregions.
§ Consists of the Interior River Lowlands and Mississippi Alluvial Plains ecoregions.

Table 4b. Pearson correlation coefficients (significant at $\alpha = 0.05$) in selected ecoregions which were also stratified by size. Listed are up to two most strongly correlated normalized difference vegetation index (NDVI) values or vegetation phenologic metrics (VPMs). If a land use–land cover (LULC) type was significantly correlated to a water quality or stream condition variable, it was listed; if none is shown there were no LULC types significantly correlated at $\alpha = 0.05$. In general, NDVI and VPMs were as highly correlated as LULC. In many cases, while an NDVI or VPM was significantly correlated to a stream variable, an LULC type was not. Correlations were generally stronger for larger watersheds in the Western Corn Belt Plains and Central Irregular Plains. In the Ozark Highlands and Central Great Plains, each watershed size group had a variable which had the strongest correlations.†

Ecoregion	Conductivity	Turbidity	NO_2–NO_3	TP	IBI	HI
Western Corn Belt, >10 mi^2 (25 km^2)	P20 NDVI: 0.54; $n = 16$		mean onset date: 0.75, P10 NDVI: −0.73, mean growth rate: 0.71; $n = 17$	log % urban: 0.48; $n = 17$	P15 NDVI: −0.66, max. NDVI: −0.61; $n = 17$	log % agriculture: 0.60, U-index: 0.65, mean onset date: −0.55; $n = 17$
Central Irregular Plains, >100 mi^2 (260 km^2)	mean growing days: 0.60, P19 NDVI: 0.68, $n = 18$	onset NDVI s.d.: −0.87, P8 NDVI: −0.73, mean onset date s.d.: −0.79; $n = 15$	P20 NDVI: 0.67; $n = 18$		onset date s.d.: 0.64, onset NDVI s.d.: 0.59, P14 NDVI: −0.57; $n = 18$	onset date s.d.: 0.71, P14 NDVI: −0.70, onset NDVI s.d.: 0.68; $n = 17$
Ozarks, <20 mi^2 (50 km^2)	P9 NDVI: −0.55; $n = 14$	log % agriculture: 0.53; $n = 15$	P18 NDVI: −0.52; $n = 15$	P8 NDVI: −0.56, onset date: 0.52; $n = 15$	onset NDVI s.d.: −0.82, P8 NDVI: −0.59; $n = 14$	log % agriculture: −0.64, mean onset NDVI: 0.66, mean growing days: −0.59; $n = 15$
Ozarks, >100 mi^2 (260 km^2)			date of max. NDVI s.d.: 0.77, P13 NDVI: −0.67; $n = 10$			
Central Great Plains, <30 mi^2 (75 km^2)			P14 NDVI: 0.60, P18 NDVI: 0.55, $n = 20$	date of max. NDVI s.d.: −0.62, mean onset date s.d.: −0.52; $n = 20$		date of max. NDVI s.d.: 0.60, onset NDVI s.d.: 0.54; $n = 20$
Central Great Plains, >100 mi^2 (260 km^2)	log % grassland: 0.49, P11 NDVI: 0.64, mean onset date: −0.56; $n = 18$			log % grassland: −0.55, date of max. NDVI s.d.: −0.77, onset NDVI s.d.: −0.63; $n = 18$	mean onset NDVI s.d.: 0.65, mean onset NDVI: 0.64; $n = 19$	log % urban: −0.51, onset NDVI s.d.: 0.54; $n = 19$

† Hi, habitat index; IBI, index of biotic integrity; P8, late April; P10, mid-May; P14, mid-July; P18, early September; P20, early October; s.d., standard deviation, TP, total phosphorus; U-index, human use index.

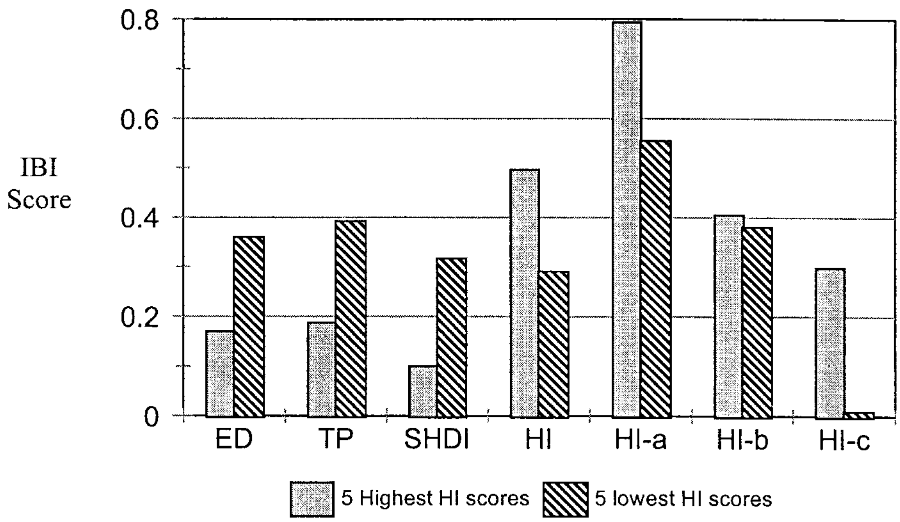


Western Corn Belt Plains (watersheds > 25 km^2)

Fig. 3. Graphs of landscape measures for the five watersheds in the Western Corn Belt Plains (watersheds > 25 km^2) with the highest habitat index (HI) scores and the five lowest. The graph shows what at first appear to be counterintuitive relationships: Watersheds with more agriculture, a landscape in which cover types are more aggregated, and less forest have better habitat conditions and lower turbidity. Turbidity is measured in nephelometric turbidity units (NTUs) and contagion is measured in percent with higher values indicating a more clumped or aggregated land cover.

test this hypothesis, we examined soils on eight watersheds having low HI scores that straddled the bluffs of the Loess Hills, and compared them with the five upland watersheds having the highest HI scores. We used digital STATSGO soils data (USDA, 1994) to estimate the percentage of watersheds covered by silt loam, which is highly erodible when wet due to lack of an adequate number of clay particles, which normally bond soils together. The mean percentage of silt loam in the watersheds on the bluffs was 59.5%, compared with 12.4% for the upland watersheds having high habitat index scores and substantially more silty clay loam, loam, silty clay, and clay soils. These results support the claim that erosion of fine silt sediments (especially given the increased slopes on the bluffs) might be contributing to the observed relationships in Fig. 4.

The five watersheds with the highest HI scores were all on the fringes of the ecoregion; none were in the more intensively cultivated Missouri River floodplain. Of these five watersheds, two had no urban lands within them, and for a third, the sampling point was located in a state park. In contrast, for the five watersheds with the lowest HI, all contained some urban lands, and one watershed had an interstate highway bisecting it. Although forest and urban lands comprise a small percentage of the watershed, their presence adds edge length to the landscape. While greater amounts of edge in a predominantly rural and agricultural area might intuitively be associated with greater amounts of forest or grassland, and in turn with conditions more conducive to higher-quality habitat, the presence of forest in this case may be indicative of enhanced erosive conditions, because the forested areas occur on the loess-covered bluffs that have heavy agriculture in their upstream reaches. Thus, although these watersheds may have forest vegetation that might be typically associated with



Western Corn Belt Plains (watersheds > 25 km^2)

Fig. 4. Graphs of landscape measures for the five watersheds in the Western Corn Belt Plains (watersheds > 25 km^2) with the highest habitat index (HI) scores and the five lowest. ED, edge density ([m/ha]/10); TP, total phosphorus (mg/L); SHDI, Shannon diversity index, ranging from 0 to 1 with higher values indicting a watershed with a relatively greater balance of land use–land cover (LULC) types; HI, habitat index ranging from 0 to 1 with higher scores indicating higher quality habitat; HI-a, riparian vegetation quality; HI-b, lack of disturbance in riparian zone; HI-c, substrate quality. This graph shows what at first appears to be counterintuitive relationships: Watersheds with higher quality habitat have a lower edge density and lower landscape diversity. In a rural, predominantly agricultural area, edge density might intuitively indicate more forest and hence lower turbidity and better substrate, and a higher Shannon diversity index might intuitively indicate more forest or grassland. But urban areas also add edge, and the presence of forest might be indicative of erosion from bluffs along the Missouri River. The correlation tables (Tables 5 and 6) indicate that, in fact, higher turbidity is associated with percent forest and percent urban.

Table 5. Pearson product–moment correlations between landscape pattern metrics and land use–land cover (LULC) proportions in the Western Corn Belt Plains (>25 km^2) (n = 17) (α = 0.05). This table shows the strong correlations of landscape pattern metrics with LULC proportions, except for the interspersion and juxtaposition index, which had no statistically significant correlations with LULC. Table 1 describes the landscape pattern metrics.

Landscape metric†	log % agriculture	log % forest	log % urban	log U-index
PD	−0.57	0.56	ns‡	−0.54
ED	−0.92	0.84	0.52	−0.91
AWMSI	−0.66	0.58	0.48	−0.68
AWMPFD	−0.75	0.68	0.49	−0.77
SHDI	−0.99	0.77	0.58	−0.99
MSIDI	−0.97	0.76	0.54	−0.995
CONTAG	0.92	−0.77	ns	0.88
IJI	ns	ns	ns	ns
PR	ns	ns	ns	ns

† AWMPFD, area-weighted mean patch fractal dimension; AWMSI, area-weighted mean shape index; CONTAG, contagion (%); ED, edge density (m/ha); IJI, interspersion and juxtaposition index; MSIDI, modified Simpson's diversity index; PD, patch density (no./100 ha); PR, patch richness; SHDI, Shannon diversity index.
‡ Not significant.

soil anchoring capability, in this case erosion remains a problem, and in particular gully erosion occurs on some of these bluffs. Moreover, the presence of even small urban areas may increase the probability of point sources of pollution or human disturbance of riparian habitat. There is probably a huge and complicated interaction between human effects and underlying natural (geologic and terrain) variation. Because logistics prevented detailed geological site analyses, this aspect is not examined more fully here.

The relationship described above contrasts with that when using a VPM. The mean date of onset of greenness had a negative relationship with HI (Table 4b; $r = -0.55$). In other words, a later onset date (indicative of watersheds having a greater percentage of late-season crops such as corn or soybean) was associated with poorer habitat conditions, which might be expected in watersheds with more intensive agriculture. Although watersheds having higher HI scores had more agriculture than the watersheds in worse condition, the difference was small. Moreover, in the USGS LULC data, pasture land is classified as agriculture as opposed to grassland. With a dataset that did not have a more detailed classification, there was no means to assess how much of the agricultural area was row crop and how much was pasture. Thus, in contrast to LULC, the VPM is reflective of biophysical data and is not categorized, and it seemed to provide a more intuitive relationship in this example. Comparing Tables 3 and 4a,b, there were fewer moderate or strong correlations between LPMs and water quality than there were between NDVI and water quality. Finally, examining the correlations for all ecoregions (Table 3) does not show any consistent patterns across stream measures or across ecoregions with respect to which LPMs were correlated with water quality. We believe that this result derives from basic differences in landscape pattern and composition that occur across the different ecoregions.

Multiple Regression Models

Based on the condition requirements for creating regression models described at the end of the Methods section, there were a limited number of times a regression model was built because there were few times when both an LPM and an LULC proportion were significantly correlated to a stream parameter (Table 3). The condition indices (CIs) or variance inflation factors did not indicate severe violations of assumptions for the regressions, although in certain instances the CI was higher than ideal. Although for two of the models, scatterplots of standardized residuals and predicted values were not perfectly randomly distributed, histograms of the standardized residuals did not reveal severe departures from normality. Midsized watersheds in the Ozark Highlands (50–500 km^2) provided one instance where a combination of LULC and landscape pattern performed better than the NDVI variables (Tables 4a,b, 7) at explaining variation in water quality. Using percent forest,

Table 6. Correlations between selected water quality parameters, landscape pattern matrics (LPMs), and land use–land cover (LULC) in the Western Corn Belt Plains (>25 km^2). This table shows some counterintuitive results but also helps to explain them. Although the correlations were not significant (α = 0.05), the directions of the relationships suggests that the greater the agriculture the lower the turbidity and total phosphorus (TP), and the higher the substrate quality. Although not significant, the direction of the signs shows that the greater the forest area the greater the phosphorus and turbidity and lower substrate quality. However, also note the directions of the signs for edge density. Note that although percent forest is related to edge, so is percent urban. Percent urban is also related to total phosphorus. This shows that the environmental setting must be considered when observing counterintuitive relationships with LPMs. n = 17, except for turbidity (n = 14) and contagion (n = 16).

	Turbidity	TP	HI†	Substrate quality	Edge density	Contagion	SHDI‡
Percent log agriculture	−0.38 (ns)	−0.21 (ns)	0.6	0.34 (ns)	−0.92	0.92	−0.99
Percent log forest	0.43 (ns)	0.24 (ns)	−0.39 (ns)	−0.27 (ns)	0.84	−0.77	−0.77
Percent log urban	0.29 (ns)	0.48	−0.31 (ns)	−0.15 (ns)	0.52	−0.42	0.57
Edge density	0.33 (ns)	0.11 (ns)	−0.55	−0.31 (ns)	–	−0.91	−0.91
Contagion	−0.27 (ns)	−0.07 (ns)	0.51	0.36 (ns)	−0.93	–	−0.88
SHDI	−0.45 (ns)	0.28 (ns)	−0.63	−0.35 (ns)	0.91 (ns)	−0.88	–

† Habitat index.
‡ Shannon diversity index.

Table 7. Multiple regression models chosen for instances where there were significant correlations for both landscape pattern metrics (LPMs) and vegetation phenological metrics (VPMs) with a stream condition parameter. An examination of correlations with the dependent variable was used to select the input variables to the model.†

Ecoregion (stream parameter)	R^2	Adjusted R^2	p value
Sand Hills (conductivity) (n = 19)			
log conductivity = 2.17 − 9.69 × 10^{-4} % grassland + 0.383 SHDI	0.43	0.36	0.011
Western Corn Belt Plains, >25 km^2 (habitat index) (n = 16)			
HI = −1.2 + 0.0191 U-index − 0.00286 CONTAG	0.44	0.35	0.006
Central Great Plains, >260 km^2 (total phosphorus) (n = 18)			
log TP = 1.01 − 0.21 log % grassland − 0.332 SHDI	0.30	0.21	0.066
Ozark Highlands, 50 to 500 km^2 (conductivity) (n = 12)			
log conductivity = 2.02 − 0.00118 % forest + 0.0172 IJI + 1.7 PD	0.86	0.80	0.002
Ozark Highlands, 50 to 500 km^2 (NO_2–NO_3) (n = 15)			
log NO_2–NO_3 = −1.145 − 0.014 % forest + 3.56 PD + 0.0258 IJI	0.72	0.64	0.004
Mississippi River Lowlands (TP) (n = 11)			
log TP = 0.315 + 0.00219 U-index − 0.012 AWMSI	0.53	0.41	0.051

† AWMSI, area-weighted mean shape index; CONTAG, contagion; HI, habitat index; IJI, interspersion and juxtaposition index; PD, patch density; SHDI, Shannon diversity index; U-index, percent agriculture + percent urban.

IJI, and patch density in regression models produced coefficients of variation (adjusted R^2) of 0.64 and 0.80 using NO_2–NO_3 and conductivity, respectively, as dependant variables. In a highly forested environment, one might expect higher patch density to be associated with poorer water quality conditions because the other LULC types in this area, urban or agriculture, are typically detrimental to water quality conditions. In a more simple landscape, mechanisms may be easier to surmise. Forest is associated with less erosion in these cases, and more patches would indicate that the forest cover had been fragmented, leading to situations where increased erosion could occur. Although there is some degree of correlation between the LPMs (especially the diversity indices) and the LULC (Table 8), the IJI appears to explain unique information, as it is not correlated with LULC.

In several cases, the regression models did not explain as much variance as did a single VPM. The regression model for the Sand Hills ecoregion (Table 7) provides one example of this situation, and also demonstrates the interrelatedness of the LULC proportions with the landscape diversity indices (SHDI, MSIDI). This interrelationship arose because the diversity metrics are derived from LULC proportions, so a strong relationship with LULC and some collinearity are inevitable. Table 7 shows the results of the regression models with conductivity levels (R^2 = 0.43). This regression model did not explain as much variance as mean NDVI at the onset of greenness value by itself (r = 0.7, r^2 = 0.49; Tables 4a and 7). In the Central Great Plains (watersheds > 260 km^2), the Shannon diversity index is moderately correlated to TP levels (r = −0.54; Table 3), but in a regression model with both it and percent grassland, only 21.1% of the variation was explained. The low adjusted R^2 value resulted in part because the two metrics are correlated with each other. In comparison, the standard deviation of the date of maximum NDVI (r = 0.77, r^2 = 0.59) by itself explained more variation (Table 4b). The collinearity between LPMs and LULC noted above occurs for other regions as well, and is perhaps best represented in Table 7 by the decline in the multiple correlation coefficients after adjustment (adjusted R^2).

Landscape Pattern and Processes Affecting Water Quality

An analysis of significant correlations between an LPM and a water quality parameter leads to the question of the mechanisms by which landscape pattern affects water quality. For example, in the Western Corn Belt Plains, a higher IJI value was associated with higher (better) IBI scores (r = 0.74; Table 3). This correlation coefficient was higher than that for any of the VPMs (Table 4b), but how interpretable is this? What is the process, if any, behind the connection of interspersion and juxtaposition of LULC patches to IBI? Complicating matters is a contrasting situation in the Central Irregular Plains, where higher IJI values represented the opposite condition, in other words, a more degraded condition (higher turbidity) (Table 3). Several criteria of good ecological indicators (Griffith, 1998) are not met by several landscape pattern metrics studied here including sensitivity to changes in environmental variables, reliability in response, and ease of understanding.

As Haines-Young (1999) states, landscape pattern has little intrinsic meaning or significance until it is placed in the context of problems or processes. Regarding water quality, the mechanisms connecting many landscape pattern metrics and stream conditions have yet to be

Table 8. Correlations (α = 0.05) between landscape pattern metrics and land use–land cover (LULC) proportions in midsized watersheds (50–500 km^2) of the Ozark Highlands. The strong relationship of the landscape diversity indices to LULC proportions is shown, whereas the interspersion and juxtaposition index (IJI) seems to explain unique information.

Landscape pattern metric	Percent agriculture	Percent forest	U-index	Percent urban
Patch density	0.42 (ns†)	−0.44 (ns)	−0.40 (ns)	ns
Shannon diversity index	0.91	−0.86	0.92	0.73
Modified Simpson's diversity index	0.93	−0.83	0.96	0.59
Patch richness	ns	ns	ns	ns
Interspersion and juxtaposition index	ns	ns	ns	0.50 (ns)

† Not significant.

established. For ecoregions that have more diverse LULC patterns or highly human-impacted landscapes, it may not be clearly associated with mechanisms that have deleterious effects on water quality. Contrasting this is the simpler landscapes, such as the forested Ozarks. In this case, increased interspersion and patch density can logically be associated with the fragmentation of the forest, which would potentially be associated with increased erosion or point sources of pollution. The NDVI (e.g., Period 15 NDVI with IBI in Table 4a,b, Western Corn Belt Plains) provides a more intuitive feel for what that metric represents. Higher NDVI values at this time of year (late July) probably represent greater amounts of corn-based agriculture, which would strongly influence water quality through runoff containing fertilizers and through increased vulnerability to erosion resulting in increased sedimentation of streams, which in turn would affect biotic communities.

Implications of Findings for Regional Watershed Monitoring

Jones et al. (1996) stated that "correlations between landscape pattern and certain levels of ecological process are generally lacking." This study provides further direction to LPM–water quality studies by providing an account of the relationships between LPMs and empirical stream data across a multistate region. Although LPMs have frequently been suggested as tools to study water quality, the few studies that examined them have had mixed results. Hunsaker et al. (1992) found that contagion explained 20% of conductivity levels in southern Illinois watersheds, but in a later study determined that land cover proportions explained more variance. Johnson et al. (1997) and Richards et al. (1996) found that patch density explained variation in water quality in Michigan in some seasons, but other landscape factors (geology, LULC, slope) generally were more important. Sharpe (1994) found no correlation between LPMs and water quality in a nutrient runoff model.

Despite the limitations of LPMs demonstrated here, a few significant relationships may be helpful in monitoring watershed conditions. The LPMs were more understandable in "simpler" landscapes or where a strong urban–rural gradient existed. Examples are the IJI in the Ozark Highlands, and diversity indices in the Sand Hills. In the Sand Hills, the mechanism behind the relationship with land cover diversity is easy to understand. In this contiguous grassland region, the presence of even small agricultural areas (especially on the fringes of the ecoregion) increases land cover diversity and thus probably negatively affects stream condition due to enhanced erosion potential and/or chemical applications. In the Mississippi River Lowlands, higher patch density was strongly correlated with higher habitat index scores ($r = 0.92$; Table 3) because several mid-sized watersheds in the St. Louis area had relatively large, but few, patches of urban land. Based on this research, it is recommended that, if analyzing relatively small watersheds (about <50 km^2), LULC data resolution should be at least 30 m to allow a high probability that a full range of land cover types would occur, and so that class-level metrics can be used. This research also demonstrated the need to further refine the use of LPMs with respect to water quality applications. Basic differences in landscape structure probably caused different landscape metrics to be related to different parameters in different ecoregions. The same metric will probably not work for every ecoregion or for every water quality parameter. Due to this result, using a suite of metrics to evaluate conditions is appropriate (Qi and Wu, 1996; Jones et al., 1996, 2000). For most ecoregions, there were stronger correlations with NDVI or VPMs than there were with LPMs. When using LPMs, it may be useful to stratify watersheds into size classes so as to reduce the effect that size of the watershed or other unit has on patch shape variables (Turner et al., 1989; O'Neill et al., 1996). One must also be aware of site-specific factors when interpreting LPMs. As demonstrated, other factors influencing water quality besides LPMs can cause counterintuitive relationships. Implications of our results indicate that, for the purposes of watershed condition monitoring, simpler metrics such as patch density or diversity may be more useful than the more esoteric metrics such as fractal dimension or shape indices.

Study Limitations and Future Research

We have provided possible and reasonable explanations of the results from a landscape perspective, but the explanations are not meant to be exhaustive. Certainly, we acknowledge that some instream processes not discussed here could be affecting the results and would be interpreted differently by aquatic biologists or water chemists. Moreover, there are other important factors that determine water quality besides landscape pattern or vegetation condition as represented by NDVI. This fact is reflected in some cases by the relatively low or moderate r and R^2 values. Using the random sampling framework by which stream sites in this study were located, there was no control on geology, soils, slope, ground water hydrology, or point sources of pollution. Additionally, hydrometeorological conditions may not have been ideal at the time of summer sampling. During low flow periods, ground water typically supplies most of the flow. In these situations, water quality may be less affected by landscape surface features (Wang, 1997). Taylor et al. (1996) and Frenzel and Swanson (1996) have also stressed the importance of hydrologic events to stream biotic assemblages in the Central Plains. They found that discharge-related disturbances and other changes in environmental parameters were associated with varying fish assemblages (Taylor et al., 1996). Because the time from a rainfall or flow disturbance event was not necessarily controlled for during sampling, results pertaining to the IBI could have been affected. There can also be bio–physico–chemical differences between headwater and downstream sites (Harding et al., 1999). Other factors potentially affecting results include the use of 1995 AVHRR data, which in some cases did not match the 1994 sampling of streams. Additionally, for many small watersheds, besides containing only a few pixels (especially the NDVI data), a small amount of positional error in drawing or digitizing watersheds may have resulted in a large variation in the land cover proportions and landscape pattern.

For future research, it would be helpful to isolate specific watersheds, particularly in the dynamic urban–rural fringe of metropolitan areas, and examine how LPMs change over time in correspondence with changes in stream conditions. Manipulation of experimental watersheds to understand the effects of landscape pattern might also shed insight into the mechanisms by which landscape pattern affects stream conditions. Other potentially useful research might involve pattern analysis of NDVI as opposed to LULC (Keane et al., 1999). Finally, we attempted to simplify the analysis in this study by using many individual correlations and regression analyses. Some multivariate statistical procedures may have also shed insight into some of the problems, such as discriminant analysis or regression tree analysis, but practical constraints precluded their use here.

CONCLUSIONS

In a comparison of the utility of LULC and landscape pattern with NDVI and VPMs to explain variation in selected water quality parameters, the NDVI or VPMs in most cases had stronger correlations. This study provides new information by being among the first to examine empirical relationships between LPMs and water quality across a multistate region. Several concerns using the LPMs were noted. For patch shape metrics, watershed size greatly affected the results. Some LPMs could not be calculated for very small watersheds because there were inadequate numbers of patches. Finally, there was little consistency in correlations between stream conditions and the LPMs. Although these results were generally negative, this does not mean that future work cannot demonstrate their usefulness. Most other studies have also reported mixed results using LPMs. However, negative results can be as useful as positive ones in illustrating the issues that need attention and problems to avoid. It appears that NDVI may be as important to pursue as LPMs. In particular, the variables associated with onset of greenness appear to have the most promise to monitor watersheds. Generally, NDVI appears to work best when stratified by ecoregions, and especially where there is a distinct contrast in phenology between agricultural fields and the natural vegetation. Certain LPMs such as IJI, patch density, or patch richness may be most important in simple landscapes where one can more easily identify mechanisms that affect water quality. Or, it may be better to use metrics such as those used by Jones et al. (2000) (e.g., roads, bridge crossing, adjacent land use, etc.) than more esoteric LPMs.

The fact that in several cases a VPM explained the largest proportion of variance in IBI scores was surprising since there is no direct connection between vegetation indices and fish communities. Indirect correlations are still helpful, however, because NDVI and VPMs reflect conditions to which factors that negatively affect stream water quality are associated (Frenzel and Swanson, 1996). The VPMs are in some cases very strongly correlated with land cover, but apparently reveal additional information as well, such as crop type and vegetation condition. There also may be a connection between NDVI and agricultural intensity, which Harding et al. (1999) say has been ignored, but could be an indicator of agricultural effects in streams. The LPMs have been very useful in terrestrial applications and have been shown to have some bearing on water quality. However, compared with 200-m LULC data and LPMs derived from them, NDVI-derived metrics showed more promise in monitoring stream conditions in the U.S. Central Plains. Smith et al. (2000) discussed the development of environmental indicators to estimate environmental trends, conditions, and the sustainability of agroecosystems. Findings presented here are important in the quest to identify broad-scale indicators of watershed condition for use in monitoring and assessment programs.

APPENDIX I

Component Indices or Variables for the Index of Biotic Integrity and Habitat Index

Index of Biotic Integrity

- Total number of fish species
- Number and identity of darter species
- Number and identity of sunfish species
- Number and identity of sucker species
- Number and identity of intolerant species
- Proportion of individuals as green sunfish, carp, bullheads, goldfish
- Proportion of individuals as omnivores
- Proportion of individuals as insectivorous cyprinids
- Proportion of individuals as piscivores (top carnivores)
- Number of individuals in sample
- Proportion of individuals with anomalies

Habitat Index, Comprised of Eight Subindices

- Riparian vegetation quality
- Lack of riparian human disturbance
- Substrate quality
- In-channel disturbance and deviance from expected channel morphology and substrate
- Habitat volume
- Spatial complexity
- Instream fish cover
- Stream power and velocity

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