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Spatial patterns in land cover of exurbanizing watersheds in southeastern Michigan

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Abstract

Recent research into landscape composition and configuration, or pattern, seeks to identify a core set of metrics and determine whether these describe unique gradients or dimensions of pattern across diverse settings. Prior work generally has examined relatively large units, and it is uncertain whether this approach will prove useful with small (50–100 km^2) landscape units such as the sub-catchment of headwater streams. We estimated 25 pattern variables for the 109 sub-catchment of the Huron and Raisin river basins in southeastern Michigan, which are similar in terrain but represent, respectively, urbanizing and agricultural conditions. Three principal components analyses (PCA) performed on sub-watersheds within the combined area, and for each basin separately, identified five axes that explained ~80% of the variation in landscape pattern. The first and strongest component described a fragmentation gradient ranging from landscapes dominated by a single land cover type to more diverse, patchy landscapes, and was similar in all three analyses. Variables quantifying variation in patch size were related to the second component in each analysis. Components three through five quantified different gradients in land cover pattern among the analyses, suggesting that gradients of variation in land cover spatial patterns quantified by later components are unique to each landscape. Pattern metrics were correlated with proportion of land in a land cover class, especially for proportion agricultural and proportion urban land, which exhibited the broadest land cover gradients in the study area. Moreover, a number of relationships were non-linear, indicating that the same value for a variable could occur in two different landscapes. Overall, we find that a suite of commonly used landscape metrics typically applied to large landscape units provides a similar basis for the quantitative description of the major gradients of variation in land cover spatial patterns when applied to small landscape units.

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Keywords: Landscape metrics; Spatial pattern; Land cover; Watershed; Michigan; Principal components analysis

1. Introduction

The spatial and temporal heterogeneity of ecological systems is widely assumed to influence ecological process, and measures of landscape pattern are commonly used to characterize this heterogeneity (Forman and Godron, 1986; Gustafson, 1998). However, there is considerable uncertainty regarding the appropriate scale for such analyses. For both theoretical and practical reasons, analyses often are carried out using large landscape units. On the other hand, land use planning and the activities of management agencies typically take place at the local level and address issues related to land use/cover over relatively small spatial extent. We wished to explore landscape pattern variability at this finer spatial scale, as part of an effort to investigate

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pattern, process and management opportunities within individual watersheds of moderate size.

A large number of indices can be used to quantify spatial heterogeneity, and many of these are correlated with one another, or respond to multiple components of spatial pattern and thus are difficult to interpret (Gustafson, 1998). For these reasons, a number of authors have attempted to identify a core set of metrics that can be generally employed as pattern indicators, and which can be grouped by factor analysis into a modest number of unique dimensions or axes to characterize landscapes (Riitters et al., 1995; Cain et al., 1997; Griffith et al., 2000). This prior research indicates that measures of diversity, texture, fractal dimension, patch size and shape, interspersion and nearest neighbor distance are likely contributors to a thorough quantification of land use/cover spatial patterns. However, the consistency of metrics and dimensions across different landscape conditions is uncertain, warranting further comparisons across landscape type and spatial scale.

A central premise of landscape ecology is that regional pattern constrains and often may determine ecological condition at a finer scale (Turner, 1989; Weins, 1989). Numerous studies of watersheds and the ecological condition of their river ecosystems provide strong support for this expectation (Hunsaker and Levine, 1995; Allan and Johnson, 1997). Studies that relate the condition of rivers to the landscape units they drain have examined both large watersheds (e.g. Jones et al., 2001) and small sub-watersheds (e.g. Castillo et al., 2000). Many assessments of stream condition focus on small streams in sub-catchments of less than a few hundred square kilometers, and often less than 50 km^2 (e.g. Roth et al., 1996; Wang et al., 2000). Thus it is of interest to ask whether the pattern indicators and unique dimensions of pattern identified in analyses of larger landscape units also are meaningful for more finely subdivided landscapes.

1.1. Related studies

Analyses of landscape pattern have investigated whether the same underlying aspects of pattern are identified in studies that differ in data resolution (Griffith et al., 2000) and diversity of landscapes included (Riitters et al., 1995; Cain et al., 1997). Indeed, a substantial degree of commonality appears to characterize these studies. Using a factor analysis approach, typically three to five components explain 80% or more of the variation in landscape patterns summarized by some 20–30 pattern variables. Some measures such as texture, defined as the frequency or organization of spatial changes or adjacencies in land cover types (often determined by contagion, diversity and dominance measures) are particularly consistent across landscapes, and the first several components tend to be similar, but not all metrics or components appear consistent.

Investigating 85 land use/cover maps across the USA and using factor analysis, Riitters et al. (1995) reduced 55 pattern variables to 26 variables and six factors interpreted as average patch compaction, overall image texture, average patch shape, patch perimeter-area scaling, number of attribute classes, and large-patch density area scaling. Cain et al. (1997) tested these factors for their stability across maps that differed in resolution, number of attributes, and method of delineating landscape unit boundaries. Although patch compaction and shape were not consistent indicators of land use/cover pattern in this analysis, diversity, texture and fractal dimension were consistent across different map types.

An investigation of a Kansas landscape (Griffith et al., 2000) identified five major factors necessary to characterize the spatial patterns of that region: overall landscape texture, patch shape and size, variables specific to the dominant land cover type, patch interspersion and nearest neighbor distance. Metrics emerging as most important in that study included measures of diversity, fractal dimension, and the interspersion and juxtaposition index. Unique to this investigation was the conclusion that class-specific variables for the most dominant land use/cover type explained a significant proportion of the variance among landscapes.

Each of these studies used landscape units of large spatial extent. Riitters et al. (1995) analyzed 85 US Geological Survey's land use data and analysis (LUDA) database maps, each approximately 21,600 km^2, selected to represent a rough comparison across physiographic regions of the USA. Griffith et al. (2000) analyzed 67 equal-area hexagons of a Kansas landscape, each 2560 km^2 in area. Focusing on the Chesapeake Bay and Tennessee River basins, Cain et al. (1997) used 1200 and 1800 km^2 equal-area sub-units, as well as 8-digit watersheds (hydrologic unit code, or HUC; Seaber et al., 1987) of the 180,000 km^2 Chesapeake Bay basin. In comparison, our study area encompasses just two 8-digit watersheds totaling approximately 5000 km^2, and as units we employed 109 small sub-catchments averaging 43 km^2 in area. These small sub-catchments, and their wadeable streams, constitute the spatial scale at which much stream assessment and management, as well as watershed planning, takes place. Changes in spatial extent may alter the analysis of landscape pattern (Turner, 1989) inviting an examination of prevailing land cover pattern metrics in smaller landscape units.

1.2. Objectives

This study investigates the small-scale spatial patterns in land cover within two river basins in southeastern Michigan. Our study region encompasses a wide range of conditions in land cover composition and configuration, including the city of Ann Arbor, suburban and exurbanizing areas, as well as highly agricultural areas. Twenty-five pattern variables were selected a priori, based on work described above, and we employed principal components analysis (PCA) to identify major gradients of variation in land cover patterns. Because one river basin contains more suburban and undisturbed land while the other is much more agricultural, we attempt to determine whether results vary depending upon the level of dominance in a landscape. We then explore the responses of spatial pattern metrics to variations in the proportions of four land use/cover classes: agriculture, urban, forest, and wetland. From this, we wish to understand the strength and nature of relationships between spatial pattern metrics and land use/cover proportions.

2. Methods

2.1. Study area

Both the Huron (2330 km^2) and Raisin (2780 km^2) are 8-digit watersheds draining into the western end of Lake Erie (Fig. 1). They are characterized by hilly to moderately undulating topography in their upper basins, consisting of moraines, till and outwash plains; and a relatively flat terrain in their lower basins, underlain by sands and clays from glacial Lake Erie (Knutilla and Allen, 1975). The upper basin is part of the eastern Corn Belt Ecoregion, whereas the lower basin falls within the Huron-Erie Lake Plain Ecoregion (Omernik, 1987). As of 2000, some 406,000 people resided within the boundaries of the Huron, and some 152,000 within the Raisin basin. The Huron contains larger urban centers (Ann Arbor, population 114,000; Ypsilanti, 22,000) than does the Raisin (Monroe, 22,000; Adrian, 22,000). In addition, the upper basin of the Huron is close to the spreading fringe of Detroit, whereas the Raisin watershed contains the largest proportion of agricultural land of any watershed in Michigan (Dodge, 1998). Thus, although these two watersheds are adjacent and share similar geologic features, their modern development pathways show marked differences.

Urban growth and suburban sprawl both are accelerating in southeastern Michigan, and it is predicted that 33% more land will be urbanized between 1990 and 2020 (SEMCOG, 1998). Two types of urban growth were evident in the period 1965–1995: denser urbanization adjacent to previously developed areas, and the scattering of new homes and sub-divisions in more rural areas. Exurban development refers to low-density residential development that occurs beyond incorporated city limits (Nelson and Dueker, 1990; Knight, 1999). The vast majority of projected development is expected to continue the trend toward scattered low-density development, and to take place in the development fringe and rural areas of the region.

2.2. Land cover data set

We used 1995/1998 land use/cover data for the landscape pattern analysis and sub-catchment boundaries to subdivide the landscape into 109 units. Land use/cover data for the northern two-thirds of the study area were compiled by Southeast Michigan Council of Governments (SEMCOG) using a 1978 Michigan Resource Inventory System (MIRIS) land use map as a template and aerial photography from 1995 to update areas that underwent urban development. Land use/cover data for the remaining area (Lenawee County, Michigan) was surveyed and compiled in 1998. These data have a positional accuracy of ±25 m and categorize land use to at least Anderson level 2 classification (see Anderson et al., 1976). We aggregated land use/cover into four major categories:

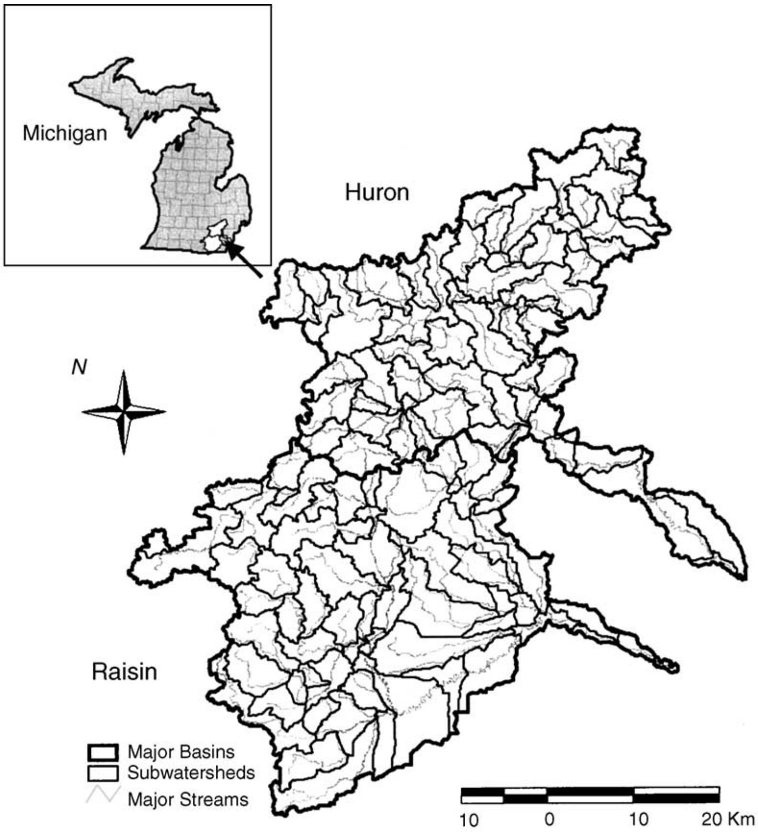

Fig. 1. The Huron and Raisin River basins are sub-divided into 109 sub-catchments averaging 43 km^2 in area. The two river basins combined comprise some 5000 km^2 in southeastern Michigan, and drain into western Lake Erie.

forest, agriculture, wetland, urban. These classes accounted collectively for 75–100% (mean 97.1%) of the land in each sub-unit. The 109 sub-catchments of the Huron and Raisin basins were delineated by the Michigan Department of Natural Resources and mostly delineate the basins of small tributaries, although a small number represent segments along the river mainstems (Fig. 1).

2.3. Landscape pattern metrics

Spatial pattern variables were derived using the vector version of Fragstats Spatial Pattern Analysis software (McGarigal and Marks, 1994). Fragstats computes both landscape-level variables, derived from all patches in a landscape irrespective of land use/cover class, and class-level variables, which are derived only from patches of a given land use/cover type (e.g. agricultural patch density). Twenty-five spatial pattern variables were selected, a priori, based on those variables that most consistently explained landscape spatial pattern in prior work. The variables are described in Table 1; for a more detailed description of each see McGarigal and Marks (1994). To quantify a fragmentation gradient, patch density and edge density metrics were selected. To characterize overall composition of the landscape, a dominance metric (1-Shannon's evenness index) was selected. Mean patch size and patch size coefficient of variation were used to account for variation in patch size. Patch interspersion was quantified using the interspersion and juxtaposition index, a metric similar to contagion but which can be computed from vector maps. Additionally, and where possible, we determined class-level variables for four land use/cover classes: urban, agriculture, forest, and wetland. Several metrics

Table 1
Description of land cover metrics selected for landscape analysis, their acronyms, and their units

Acronym	Description	Units
Land cover percentage metrics		
Agriculture	Agricultural land cover within a sub-catchment	%
Urban	Urban land cover within a sub-catchment	%
Forest	Forested land cover within a sub-catchment	%
Wetland	Wetland land cover within a sub-catchment	%
Landscape-level spatial pattern metrics		
PD	Patch density	#patches/100 ha
PSCV	Patch size coefficient of variation	%
ED	Edge density	m/ha
DOM	Dominance	None
IJI	Interspersion and juxtaposition index	%
Class-level spatial pattern variables		
ub_PD	Patch density of urban patches	#patches/100 ha
ag_PD	Patch density of agricultural patches	#patches/100 ha
fo_PD	Patch density of forested patches	#patches/100 ha
wt_PD	Patch density of wetland patches	#patches/100 ha
ub_MPS	Mean patch size of urban patches	ha
ag_MPS	Mean patch size of agricultural patches	ha
fo_MPS	Mean patch size of forested patches	ha
wt_MPS	Mean patch size of wetland patches	ha
ub_PSCV	Patch size coefficient of variation of urban patches	%
ag_PSCV	Patch size coefficient of variation of agricultural patches	%
fo_PSCV	Patch size coefficient of variation of forested patches	%
wt_PSCV	Patch size coefficient of variation of wetland patches	%
ub_ED	Density of urban edges	m/ha
ag_ED	Density of agricultural edges	m/ha
fo_ED	Density of forested edges	m/ha
wt_ED	Density of wetland edges	m/ha
ub_IJI	Interspersion and juxtaposition index for urban patches	%
ag_IJI	Interspersion and juxtaposition index for agricultural patches	%
fo_IJI	Interspersion and juxtaposition index for forested patches	%
we_IJI	Interspersion and juxtaposition index for wetland patches	%

identified as important in prior work could not be applied in this study because of limitations of scale and differences in the format of the original land cover data from which the variables were derived. Fractal dimension and other shape metrics were not included in this analysis, because the small spatial extent of the sub-catchments limits the sample number of patches available, making these metrics subject to spurious results (McGarigal and Marks, 1994). Mean patch size and patch density are redundant measures at the level of the landscape but account for different aspects of pattern at the class-level (McGarigal and Marks, 1994); therefore, mean patch size was omitted from the list of landscape-level variables but retained at the class-level.

2.4. *Statistical analysis*

Variables were transformed to achieve a normal distribution when possible. All percentage data were arcsine-square root transformed. To ensure that variables chosen were not strongly redundant, pair-wise correlation coefficients were calculated. No variables had Pearson correlations greater than 0.90, the criterion for data reduction used by Riitters et al. (1995); all were retained for principal components analysis. We used PCA to group our 25 variables into a series of components in metric-group space representing high within-group correlation among metrics and low between-group correlation. We then identified variables that had the highest loadings (the correlation between a variable and a component) on each component and examined them to determine whether they could be associated with a particular aspect of landscape pattern.

PCA was used to identify major gradients of variation in land cover pattern for three different geographical extents. The combined basin analysis ordinates 109 sub-catchments located within the adjacent Huron and Raisin River basins. Then separate analyses were performed on each of the two basins, using the 54 sub-catchments within the Huron River basin and the 55 sub-catchments within the Raisin River basin. To assess similarities and differences among components of all three analyses, Spearman rank correlation coefficients were determined between the component loading patterns for each PCA.

We then used regression analysis to explore the response of spatial pattern metrics to changes in the proportion of land cover types within the sub-catchments of the Huron and Raisin River basins. Pattern variables were regressed against land use/cover proportion data. Best fit was determined using a visual assessment of the biplot and residuals plot, and by comparison of r^2 values between a linear fit and a second-order polynomial fit. We anticipated that spatial autocorrelation, the tendency for observations in close proximity to have similar values and a common obstacle in the analysis of data derived from a contiguous landscape unit, would influence our regression results. Therefore we used a spatial autoregressive model, which adjusts the linear regression model to account for the influence of neighboring values and results in less biased tests of significance, to test for possible biases resulting from spatial autocorrelation. The simultaneous autoregressive (SAR) model (Kaluzny et al., 1998), implemented in the S-PLUS extension for Arcview 3.2, was used for this test.

3. Results

3.1. Basic landscape description

A wide range in land use/cover is seen within the combined area of the two basins. Area occupied by natural land cover types occurs over a limited range, with minimum values near zero and maximum values of 27.3% for wetland and 28.6% for forest. In contrast, the range of values for agricultural land (0.1–91.8%) and urban land (3.3–71.6%) is great. The 25 spatial pattern variables also show a considerable range in values across the 109 sub-catchments of these two basins (Table 2).

Land use/cover composition differs significantly between the Huron and Raisin River basins (Table 3). Land use/cover in the Raisin basin is predominantly agricultural (average of 55 sub-catchments = 62.6%), and urban land is relatively low at 12.1%. In contrast, agriculture comprises just 24.6% of land use/cover within the Huron River basin, and urban averages 28.3%, more than twice the value for the Raisin. Huron sub-catchments have, on average, considerably more area occupied by natural land cover types (24.2% forest and wetland), compared with the Raisin (16.0% forest and wetland).

3.2. PCA components and their associated variables

Principal components analysis of pattern variables found that the first five components together explained approximately 80% of the variation in the 25 landscape variables for the Huron and Raisin basins combined (hereafter, combined basin analysis), and also for each basin alone (Table 4). Components were rotated using a varimax rotation to aid in interpretation. All retained components had an eigenvalue greater than one. Variables retained for component interpretation were those variables associated with a particular component which explained at least 30% of the variance in that component (i.e. rotated component loading ≥ 0.55 or ≤ -0.55) and had a greater loading with that component than with any other.

In the combined basin analysis, the first five components in the ordination explained 78.7% of the variance in the landscape pattern variables. Metrics highly correlated with the first component included most of the patch density and edge density variables (Table 4). Additionally, dominance and agricultural mean patch size exhibited strong negative loadings with this component. This component can be summarized as a fragmentation gradient ranging from landscapes dominated by a single land use/cover type, generally with large patches of agriculture, to more diverse, patchy landscapes. The second component summarizes patch size variation within a landscape. Variables with high

Table 2
Summary statistics and transformation information for spatial pattern metrics determined from a combined analysis of 109 sub-catchments of the Huron and Raisin River watersheds

Variable	Minimum	Maximum	Mean	S.D.	Transformation	Normal after or without transformation
Agriculture	0.1	91.8	43.4	26.3	arcsin sqrt	No
Urban	3.3	71.6	20.3	15.5	arcsin sqrt	No
Forest	0.7	28.6	10.2	5.6	arcsin sqrt	Yes
Wetland	1.2	27.3	9.9	6.6	arcsin sqrt	No
PD	3.9	25.8	12.9	4.7		Yes
PSCV	196.6	2381.1	660.6	496.0	log 10	No
ED	20.8	102.2	66.1	17.8		No
DOM	0.1	0.8	0.4	0.2	ln	Yes
IJI	41.5	84.4	60.3	7.6		Yes
ub_PD	1.2	8.9	4.6	1.4		Yes
ag_PD	0.1	4.2	1.3	0.8	sqrt	Yes
fo_PD	0.2	4.1	1.7	0.9		Yes
wt_PD	0.2	5.1	1.8	1.0	sqrt	Yes
ub_MPS	0.9	25.3	4.4	3.4	ln	Yes
ag_MPS	1.1	573.3	59.2	95.6	log 10	Yes
fo_MPS	1.9	52.0	6.4	5.1	log 10	Yes
wt_MPS	1.5	26.0	6.0	3.6	ln	Yes
ub_PSCV	86.1	627.0	247.8	100.5	ln	Yes
ag_PSCV	0.0	853.9	352.6	186.9	ln	Yes
fo_PSCV	65.1	416.7	159.8	55.3	ln	Yes
wt_PSCV	34.3	412.7	160.8	72.5	ln	Yes
ub_ED	9.8	59.3	29.9	11.1		No
ag_ED	0.4	53.6	29.3	12.8		No
fo_ED	1.7	41.6	18.9	9.4		No
wt_ED	2.5	46.1	18.2	10.2	sqrt	Yes
ub_IJI	10.6	83.5	55.9	16.3	arcsin sqrt	No
ag_IJI	0.0	88.9	66.3	9.7	arcsin sqrt	Yes
fo_IJI	22.0	92.5	63.0	12.3	arcsin sqrt	No
wt_IJI	16.0	85.9	60.8	11.3	arcsin sqrt	No

Summary statistics show untransformed values (see Table 1 for units).

loadings on component two include landscape-level and agricultural patch size coefficient of variation, as well as agricultural edge density. Urban mean patch size is negatively correlated with this component. Landscape-level interspersion and juxtaposition index and agricultural IJI were positively correlated with component 3, indicating that this component summarizes a patch interspersion gradient. Additionally, forest mean patch size loaded highest on component 3. The fourth component summarizes spatial patterns in urban land cover. A second interspersion gradient is also contained within this component, correlating strongly with the interspersion and juxtaposition index for urban land cover and the natural land cover categories, forest and wetland. The fifth component summarizes wetland patch size.

Of the five retained components, component one (the fragmentation gradient) and component two (patch size gradient) best separate the sub-catchments by their respective basins (Fig. 2). Sub-catchments of the Huron River basin tend to occupy the positive end of component 1 and the negative end of component 2, indicating a highly fragmented landscape with relatively homogenous patch sizes. Sub-catchments of the Raisin River basin tend to occupy the negative end of component 1 and the positive end of component 2 indicating a more dominant, contiguous landscape with greater patch size heterogeneity. However, there are many exceptions to the above generalities, signifying overlap in spatial patterning between the two catchments. Further components do not separate sub-catchments based on their membership in a given basin.

Table 3
Percentages of four land cover classes for the sub-catchments of the Huron River basin, the Raisin River basin, and the two basins combined

Land cover	Statistic	Huron	Raisin	Combined basins
Agriculture	Maximum	67.5	91.8	91.8
	Mean	24.6	62.6	43.4
	Minimum	0.1	21.9	0.1
Urban	Maximum	71.6	42.0	71.6
	Mean	28.3	12.1	20.3
	Minimum	4.0	3.3	3.3
Forested	Maximum	28.6	21.9	28.6
	Mean	12.1	8.3	10.2
	Minimum	2.7	0.7	0.7
Wetland	Maximum	27.33	25.22	27.33
	Mean	12.11	7.74	9.94
	Minimum	2.21	1.2	1.2

Kruskal–Wallis tests revealed means for each land cover class to be significantly different between the sub-catchments of the Huron and Raisin River basins ($P \le 0.001$).

3.3. Basin comparisons

When principal components are derived for the sub-catchments of each basin separately (Table 4b and c), comparisons reveal strong similarities in the first two components although there are some differences in which variables load on these components and the magnitude of their loadings. The first component explained a lower fraction of variance for the Huron analysis than it did for either the Raisin or for the combined basin analysis. Subsequent components deviate further when compared between analyses.

For the Huron River basin, 77.2% of the variance in the spatial pattern variables was explained in the first five components. Several patch density and edge density variables were most highly correlated with component one, and forest mean patch size was negatively correlated with this component (Table 4b). Component one can be summarized as a fragmentation gradient with larger contiguous forest patches characterizing one end of the gradient, and with high density of patches and edges at the other extreme. The second component describes the spatial patterning of the developed land use/cover types. Patch size and variability variables of agriculture and urban patches, as well as the edge density of these land use types, loaded on component two. Component three summarizes the interspersion of land use/cover types within

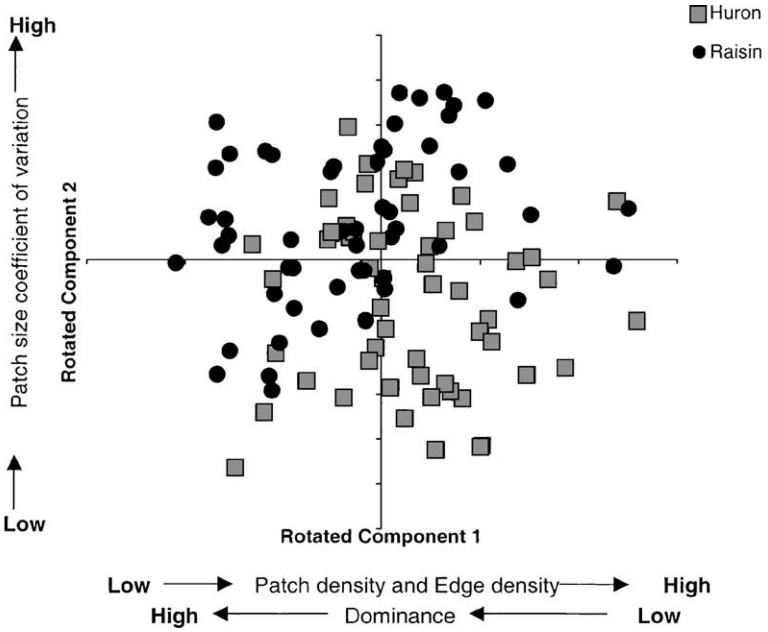

Fig. 2. Biplot of rotated principal components 1 and 2 from the combined basin PCA shows some differentiation between sub-catchments of the Huron and Raisin basins. Components are labeled with the metrics that had high loadings on each axis, and the direction of the correlation.

Table 4
Varimax rotated factor pattern for principal component analysis of the (a) combined basin analysis; (b) Huron; and (c) Raisin River basins

Component	(a) Factor loadings					CV	(b) Factor loadings					CV	(c) Factor loadings					CV
	1	2	3	4	5		1	2	3	4	5		1	2	3	4	5	
PD	**0.82**	−0.28	−0.05	0.35	−0.22	0.92	**0.73**	−0.48	0.12	−0.09	−0.20	0.82	**0.80**	0.03	0.04	0.22	0.18	0.73
PSCV	−0.45	**0.79**	−0.20	−0.21	−0.12	0.92	−0.31	**0.85**	−0.12	0.10	0.00	0.85	−0.35	**0.83**	−0.28	0.01	−0.26	0.95
DOM	−**0.58**	0.37	−0.38	−0.51	−0.14	0.90	−0.37	0.18	−**0.75**	0.33	−0.14	0.87	−0.46	0.49	−0.31	−0.26	−0.52	0.89
IJI	0.47	−0.01	**0.66**	0.49	0.02	0.90	0.12	0.10	**0.92**	−0.18	0.03	0.90	0.44	−0.15	0.03	0.24	**0.82**	0.94
ED	**0.83**	−0.20	0.14	0.41	−0.01	0.92	**0.67**	−0.30	0.25	−0.35	0.18	0.76	**0.82**	−0.13	0.20	0.28	0.28	0.88
ub_PD	0.43	−0.21	−0.19	0.41	−0.43	0.62	0.27	−0.35	0.02	0.43	−0.49	0.62	0.34	0.05	0.04	0.11	0.02	0.13
ub_MPS	−0.01	−**0.69**	−0.08	0.54	0.15	0.79	−0.20	−**0.69**	0.05	0.13	0.00	0.54	0.10	−0.41	**0.85**	−0.01	0.08	0.90
ub_PSCV	−0.08	−0.28	−0.21	**0.72**	0.17	0.68	−0.23	−0.18	0.27	−0.13	0.01	0.18	−0.11	0.06	**0.87**	0.20	−0.09	0.81
ub_IJI	0.54	−0.36	0.22	**0.67**	0.08	0.93	0.23	−0.54	**0.68**	−0.16	0.06	0.84	0.49	−0.23	0.46	0.36	0.46	0.85
ub_ED	0.26	−0.54	−0.24	**0.63**	−0.22	0.86	0.02	−**0.70**	0.05	0.45	−0.25	0.76	0.36	−0.16	**0.52**	0.06	0.01	0.43
ag_PD	**0.81**	0.15	0.03	0.19	−0.02	0.72	**0.81**	0.28	0.03	0.05	−0.05	0.75	**0.89**	−0.05	0.16	0.12	0.20	0.87
ag_MPS	−**0.70**	0.49	−0.02	−0.40	0.04	0.89	−0.40	**0.82**	0.04	0.10	−0.04	0.85	−**0.81**	0.21	−0.30	−0.21	−0.26	0.91
ag_PSCV	−0.12	**0.90**	−0.12	0.09	−0.01	0.86	−0.02	**0.89**	0.00	0.08	0.09	0.80	0.10	**0.93**	0.05	0.15	−0.10	0.91
ag_IJI	0.07	0.09	**0.83**	0.08	0.04	0.71	−0.37	0.18	**0.56**	−0.06	0.24	0.54	0.24	−0.12	−0.27	−0.17	**0.77**	0.77
ag_ED	0.15	**0.80**	0.18	−0.19	0.00	0.72	0.19	**0.92**	0.00	0.11	−0.01	0.89	**0.82**	0.34	−0.02	−0.08	0.18	0.83
fo_PD	**0.83**	−0.12	−0.08	0.10	−0.16	0.74	0.57	−0.24	−0.05	−**0.66**	−0.08	0.82	**0.82**	0.14	−0.14	0.31	0.09	0.81
fo_MPS	−0.08	−0.10	**0.74**	−0.06	0.05	0.58	−**0.55**	0.23	0.21	−0.43	−0.05	0.59	0.10	−0.37	0.16	0.09	0.52	0.45
fo_PSCV	0.42	−0.07	0.08	0.29	0.03	0.28	0.06	−0.03	0.02	−**0.80**	0.09	0.66	0.30	0.10	0.22	**0.70**	0.19	0.68
fo_IJI	0.43	−0.03	0.28	**0.76**	−0.01	0.85	0.05	−0.07	**0.90**	0.20	0.01	0.85	0.33	0.01	0.23	**0.59**	0.51	0.77
fo_ED	**0.75**	−0.05	0.29	0.07	−0.08	0.65	0.21	−0.12	0.13	−**0.87**	−0.03	0.83	**0.74**	−0.15	−0.09	0.47	0.29	0.88
wt_PD	**0.90**	0.06	0.03	0.08	0.02	0.82	**0.82**	−0.13	0.10	−0.22	0.24	0.81	**0.85**	0.14	−0.06	0.35	0.18	0.89
wt_MPS	−0.17	−0.33	0.14	−0.03	**0.83**	0.84	−0.05	0.06	0.00	0.02	**0.90**	0.81	−0.38	−**0.70**	0.16	0.11	−0.04	0.68
wt_PSCV	0.39	0.25	−0.15	0.24	**0.57**	0.62	0.23	0.00	0.10	−0.01	**0.76**	0.64	0.25	−0.04	0.02	**0.84**	−0.12	0.79
wt_IJI	0.39	0.04	0.26	**0.77**	−0.08	0.82	−0.03	−0.01	**0.91**	0.06	−0.07	0.83	0.33	0.23	0.21	0.51	0.52	0.73
wt_ED	**0.81**	−0.03	0.11	0.07	0.43	0.86	**0.68**	−0.03	0.10	−0.26	0.56	0.86	**0.71**	−0.21	0.01	0.50	0.21	0.84
Eigenvalue	10.7	3.5	2.3	1.7	1.5		6.8	4.5	3.7	2.3	2		11.7	3.7	2.5	1.7	1.1	
Variance explained (%)	42.8	14	9.4	6.6	5.9		27.3	18.1	14.7	9.2	7.9		46.9	15	10	6.8	4.5	
Cumulative variance (%)	42.8	56.8	66.2	72.8	78.7		27.3	45.4	60.1	69.3	77.2		46.9	61.9	72.0	78.8	83.3	

The highest loading for each variable is shown in bold and was used in component interpretation unless the absolute value of that loading was <0.55 (i.e. less than 30% of variance in that component explained). Communality values (CV) represent the proportion of the total variance explained by a spatial pattern variable.

the sub-catchments. It represents a gradient from a landscape dominated by a single land use/cover type where patches are not well interspersed to a more diverse landscape in which the land use/cover types are highly interspersed. All interspersion and juxtaposition indices were most highly correlated with this component. Dominance was negatively correlated with component three. Components four and five describe the two natural land cover types, forest and wetlands, respectively.

For the Raisin River basin, 83.3% of the variance in spatial pattern variables was explained by the first five components. Again, most of the patch density and edge density variables correlated with the first component (Table 4c). Component one is a fragmentation gradient, very similar to that seen in the combined basin analysis. Component two can be summarized as the variation in patch sizes in the landscape, and is highly correlated with the variation in the size of agricultural patches. Additionally, the mean patch size of wetlands is inversely correlated with this component. Unlike the other two analyses, agricultural edge does not load strongly on component 2 in the Raisin basin. The third component represents a summary of urban patch size. Component four describes the variation in the patch sizes of two natural land cover categories, forests and wetlands. Component five describes an interspersion gradient.

Similarities among the components of the combined basin analysis and those of the basins considered separately are further documented by Spearman rank correlations among components (Table 5). The first component, the fragmentation gradient, is highly correlated among all three analyses. The second component, representing a gradient in patch size variation, is moderately correlated among analyses also. This provides evidence that these gradients consistently account for the majority of variation in spatial patterns throughout the study area. The remaining components lack consistency among all three analyses although similarities between analyses are evident.

Comparing the combined basin analysis to the Huron basin analysis, component 2, a patch size variation gradient, and component 5, a wetland gradient, respectively, are highly correlated. Component 3 is an interspersion gradient in both analyses; however, the combined basin analysis draws solely on the landscape-level and agricultural IJI to characterize the gradient whereas the Huron analysis includes the landscape-level and all class-level IJI variables. Component 4 is not significantly correlated between the two analyses. In several cases, correlations did occur between non-corresponding components. Huron component 4, a forest gradient, weakly correlates to combined analysis components 1 and 3. Huron component 2 is negatively correlated to the combined component 4. This relationship illustrates that high values for most agricultural patterns variables correspond to low values for urban pattern variables and low IJI for urban, forest, and wetland patches.

The similarities between the combined basin analysis and the Raisin River basin alone are fewer. Component 2 is moderately correlated, quantifying patch size variation in both but deviating in the importance

Table 5
Spearman rank correlations between factor loadings of principal components from each of the three analyses

Component		Huron					Raisin				
		1	2	3	4	5	1	2	3	4	5
Huron and Raisin	1	0.91	−0.51	–	−0.51	–	0.92	–	–	0.62	0.51
	2	–	0.85	–	–	–	–	0.69	−0.64	–	–
	3	–	–	0.62	−0.47	–	–	–	–	–	0.88
	4	–	−0.65	0.60	–	–	–	–	0.79	0.49	–
	5	–	–	–	–	0.74	–	−0.46	–	–	–
Huron	1						0.89	–	–	0.55	–
	2						–	0.44	−0.50	–	–
	3						–	–	–	0.41	0.74
	4						–	–	–	−0.53	−0.46
	5						–	–	–	–	–

Dashes (–) indicate non-significant correlations ($P > 0.05$).

of the loadings of several other variables. Component 4 is weakly correlated, sharing only a high loading for forest IJI. Again, correlations occurred between non-corresponding components. Raisin component 3 is most similar to combined analysis component 4, sharing a description of variation in patterns of urbanization. Raisin component 5 is highly correlated to combined analysis component 3, illustrating that though IJI metrics do account for variation in both landscapes, when the Raisin River sub-catchments are considered alone this metric declines in importance.

3.4. Influence of land cover on spatial pattern metrics

Spatial pattern metrics were influenced by changes in the proportion of land cover classes to varying degrees as detected by regression analysis (Table 6). Spatial pattern metrics were determined to be spatially autocorrelated by the Geary's C and Moran's I (except for wt_PSCV and ag_IJI), therefore the results from a spatial regression analysis of the same data were used to determine if regressions remained significant after correcting for spatial autocorrelation. All significant regressions remained significant when adjusted for autocorrelation except for the relationship between IJI and proportion of agriculture land cover and between IJI and the proportion of urban land cover. To simplify presentation and interpretation of results and to permit comparison of the standard r^2 measure of regression fit, which is not relevant in spatial regression models (Kaluzny et al., 1998), the traditional regression results are reported. Table 6 can, therefore, be used to

Table 6
The r^2 values between land cover proportions and spatial pattern metrics

Metric	Forest	Wetland	Agriculture	Urban
Landscape-level spatial pattern metrics				
PD	0.32	0.22	−0.56	0.24
PSCV	−0.21	−0.28	0.68	−0.42
DOM	−0.41	−0.41	**0.74***	0.48*
IJI	0.38	0.21	0.41*	0.23*
ED	0.45	0.38	**0.73***	0.18
Class-level spatial pattern variables				
ub_PD	–	–	−0.23	0.29
ub_MPS	–	–	−0.53	**0.76**
ub_PSCV	–	–	−0.25	0.33
ub_IJI	0.33	0.32	**0.84***	0.59*
ub_ED	–	–	−0.56	**0.84**
ag_PD	0.17	0.19	0.42*	–
ag_MPS	−0.34	−0.30	**0.83**	−0.44
ag_PSCV	–	–	0.35	−0.27
ag_IJI	–	–	–	–
ag_ED	–	–	**0.78***	−0.39
fo_PD	0.46	0.22	−0.29	–
fo_MPS	0.38	–	–	–
fo_PSCV	0.42	0.14	−0.22	–
fo_IJI	0.23	0.15	0.46*	0.28*
fo_ED	**0.78**	0.23	−0.22	–
wt_PD	0.31	0.46	−0.20	–
wt_MPS	–	0.25	–	–
wt_PSCV	–	0.25	–	–
wt_IJI	0.21	–	0.41*	0.14
wt_ED	0.26	**0.84**	−0.22	–
Total number of significant relationships	16	16	21	15
Total number of non-linear relationships	0	0	8	4

Significant ($P < 0.01$) values are shown: dash (–) indicates non-significant relationships. Values >0.70 are shown in bold. Asterisks ($*$) indicate where second-order polynomial was used to achieve best fit.

determine only the general patterns of relationships, which was our goal.

Consistent with previous simulation studies (Gustafson and Parker, 1992; Hargis et al., 1998), most of the landscape-level pattern variables showed some sensitivity to variations in the proportion of the four land use/cover types, especially agriculture and urban. Edge density and dominance were the two metrics most likely to exhibit such sensitivity. Though the specific set of metrics exhibiting non-linear relationships may be affected by the type of regression model used (i.e. ordinary least squares versus spatial regression) and the range of land use/cover proportions exhibited within the data set, it is clear that several metrics exhibit non-linear relationships that can be approximated with second-order polynomials.

Several metrics consistently showed a non-linear response to change in agricultural land cover, the anthropogenic land cover class that occurred over the broadest range of values across sub-catchments (Table 2). Dominance and edge density at both the landscape-level and the class-level (Fig. 3) exhibited highly significant relationships with proportion agriculture. However, significant responses of pattern variables to variations in proportion of land use/cover were less frequent when forest or wetland was used as the predictor variable. The proportions of these land use/cover types occur over a relatively small range in values within our data set (Table 2), which limits the opportunity to display more complex relationships.

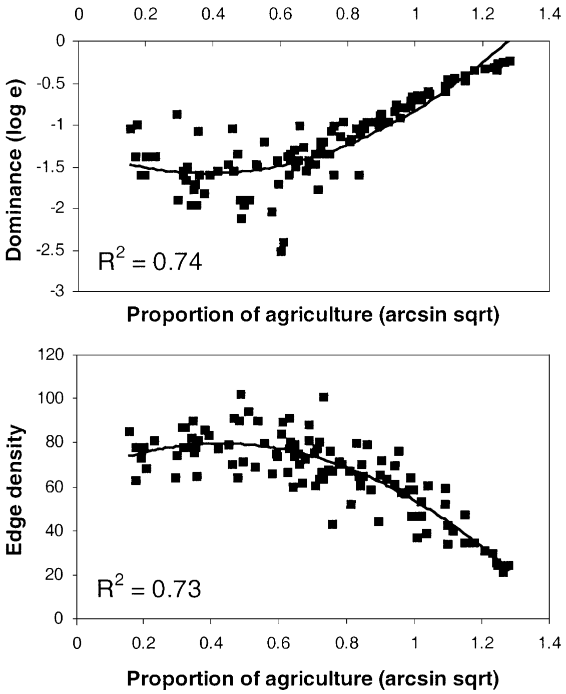

Fig. 3. Pattern metrics showed both linear and non-linear relationships with proportion land cover. Non-linear relationships were most common in relation to proportion agricultural land, which exhibited the greatest range of any land cover. The non-linear response of dominance (top) and edge density (bottom) are illustrated.

Class-level edge density showed a tight relationship with changes in the proportion of the corresponding land cover type (Fig. 3). Urban, wetland and forest edge density increased linearly as urban, wetland and forest land cover, respectively, increased. Edge density of agriculture patches displayed a non-linear response to increases in agricultural land. Some other metrics, including patch density and patch size coefficient of variation, were only moderately influenced by, or not influenced by, changes in the proportion of the four land use/cover types.

4. Discussion

This analysis of spatial pattern in land use/cover, applied to small sub-catchment units of two adjoining watersheds in southeastern Michigan, identified a number of components and their associated variables that explain much of the variance in land use/cover spatial pattern. Similar to the findings of others (Riitters et al., 1995; Cain et al., 1997; Griffith et al., 2000), five principal components captured the principal gradients in land use/cover patterns. Because our analysis focused at a smaller spatial extent, used a smaller number of land use/cover categories and attempted to differentiate between patterns in land use/cover where development type differed, our results confirm generalities that can be drawn from, as well as identify the limitations of, previous work. The first two components, fragmentation and variation in patch size, were strong descriptors of land use/cover patterns for both an agricultural landscape and a suburbanizing landscape. Sub-catchments of the Huron River basin tended to have greater edge density and patch density with less variation in patch size, whereas the Raisin River basin was a landscape with high dominance, lower edge and patch density, and greater variation in patch size. Further components deviated between the two basins likely due to a shift from a homogeneous landscape dominated by a single land use/cover type to a more heterogeneous and diverse landscape. Additionally, spatial pattern in land use/cover exhibited both linear and non-linear relationships with changing amounts of the proportion of a given land use/cover type. Non-linear relationships may more commonly be encountered when the land use/cover type in question exhibits a large range of values. Understanding these relationships is necessary for accurate interpretations of spatial patterns and their relationship to ecological processes.

Nearly 80% of the spatial variation in land cover in this analysis was explained by five factors of a PCA. Each component represents a gradient in land cover patterns that can be visualized from examples of extreme conditions (Fig. 4). The first encompasses a fragmentation gradient with sub-catchments having high patch and edge densities at the positive end of the component. These occur predominantly just outside town centers where agriculture and natural lands are being converted to urban, creating a heterogeneous patchy landscape. The exception is Ann Arbor, the most populous city within the study area, and can be attributed to the dominance of urban development there. Sub-catchments at the negative end of the component are characterized by having a high dominance value and larger mean size of agricultural patches. Most of these sub-catchments occur in the lower reaches of the Raisin River basin, where agricultural development is most extensive.

Components 2–5 cumulatively accounted for less variation than the first component alone, illustrating the relative importance of the fragmentation gradient

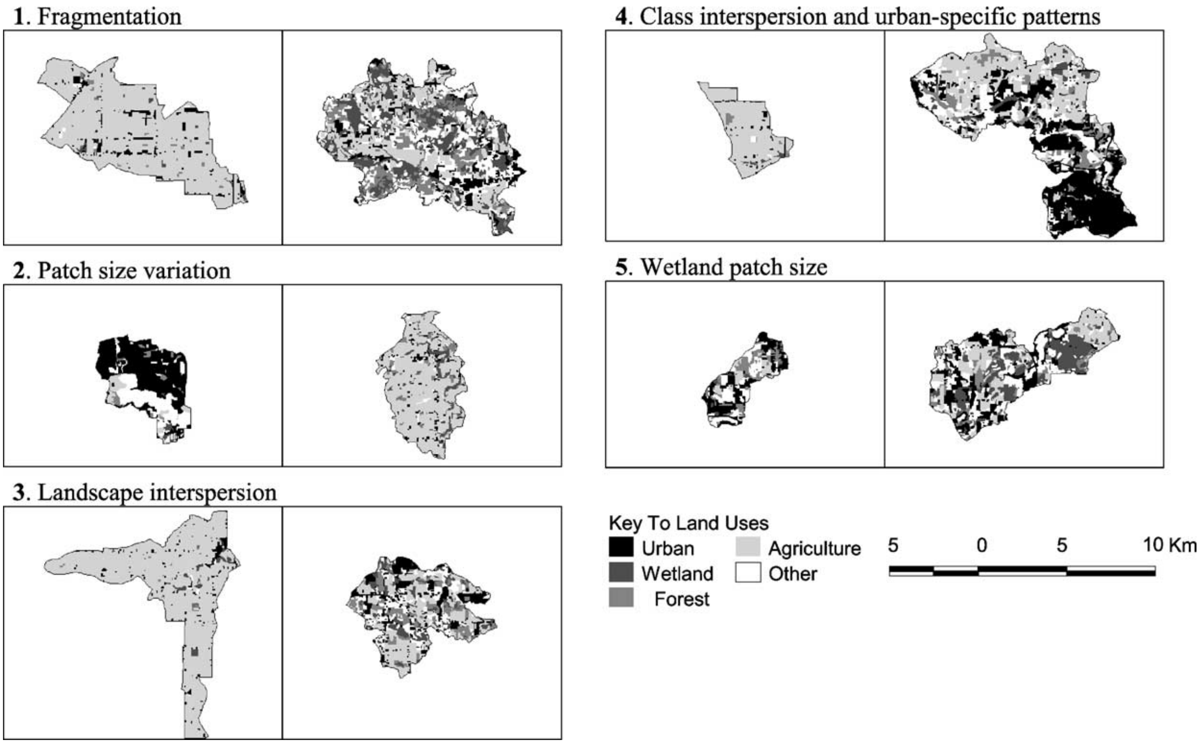

Fig. 4. A comparison of sub-catchment maps which had relatively high and low factor scores for the five factors from the combined basin analysis (see Table 4). Map pairs illustrate range of condition among sub-catchments showing examples of extreme condition of a given factor. Catchments with low factor scores are on the left and high values on the right of the (A) fragmentation gradient (factor 1); (B) variation in patch size (factor 2); (C) variation in patch interspersion (factor 3); (D) an urban land cover and interspersion gradient (factor 4); and (E) variation in wetland patch size (factor 5).

in quantifying variation in land cover spatial patterns. The second component identified a gradient in variation in patch size, with the narrowest range in variation occurring throughout the Huron and upper Raisin, and the widest range occurring in a limited area of the lower Raisin where agricultural land is greatest. Agricultural patch size drives the relationship between PSCV and component 2. Interestingly, high urban mean patch size values occur only where variation in patch size is low showing that, in this landscape, larger urban areas do not occur in highly agricultural areas. Component three reflects a patch interspersion gradient. High landscape interspersion values are most often associated with a more even distribution of land cover types. In this study agricultural interspersion and juxtaposition index was the variable most highly correlated with component 3, and low IJI values were associated with sub-catchments with either a very high or very low percentage agriculture. Both scenarios, though very different in land use/cover composition, limit the interspersion potential of a land use/cover type.

Components 4 and 5 are class-specific gradients accounting for variation in urban and wetland land use/cover types, respectively, illustrating that class-level variables account for variation in the data left unaccounted for by landscape-level variables. Additionally, component four quantifies a second interspersion gradient. The component correlates highly with urban, forest and wetland IJI. The IJI variables loaded highest on two different components, a result that can be seen throughout the component loading pattern with other metrics. The land use/cover type with the highest proportion of total land area is likely driving the relationship between landscape-level IJI and a principal component. Generally, the landscape-level variable and corresponding agricultural variable correlated most strongly with the same component, with the exception of the edge density metric.

The suite of spatial pattern metrics chosen for this study explained similar proportions of variance and identified a similar number of components in comparison with previous studies attempting to summarize spatial variability in land cover. Riitters et al. (1995) explained 82.7% of the variance in five significant components for 26 land cover pattern variables. Griffith et al. (2000) explained between 81 and 89% of the variance in five components of 27 pattern variables. This study explained between 77 and 83% of the variance in the same number of components for 25 land cover pattern variables. Metrics defining significant components common to all of the above analyses were those quantifying diversity, contagion, and edge and patch density related metrics. Likewise, Cain et al. (1997) found measures of diversity and image texture to consistently account for large portions of variation in land cover patterns when tested among maps varying in resolution, number of attributes and method of delineating landscape unit boundaries. Patch size metrics also were strong correlates with factors in each of the three studies. Common between Griffith et al. (2000) and this study were the importance of the interspersion and juxtaposition index and of class-level pattern variables, particularly when derived for the dominant land cover type (e.g. grassland and cropland in Griffith et al., and agriculture in this study). Interestingly, the lack of patch shape and nearest neighbor distance metrics in this study did not reduce the variation explained, indicating that these metrics may not be accounting for variance that cannot be accounted for by other pattern metrics.

Land use/cover pattern indices have been shown to be sensitive to the spatial extent of a landscape and the number of land cover types used to derive the indices (Turner et al., 1989; Cain et al., 1997), which may account for some differences in factor pattern interpretation between this study and previous work. This analysis used much smaller landscape units than prior work, and four possible land cover categories, versus six categories used by Griffith et al. (2000) and 37 used by Riitters et al. (1995). Additionally, the importance of components determined using a factor analysis will be influenced, in part, by the metrics included in the analysis and what aspect of landscape structure those metrics quantify (Cain et al., 1997). While we chose metrics to closely match the aspects of landscape structure captured in prior studies, we were unable to use fractal dimension metrics because the small number of polygons in each sub-catchment could lead to spurious results. The vector format of the land use/cover data excluded the use of contagion and nearest neighbor distance metrics. Details of the analysis and comparisons with other studies likely would be altered if these metrics were incorporated.

Separate principal components analyses of the Raisin and Huron River basins revealed considerable additional complexity in land use/cover pattern. While the major landscape gradient, fragmentation, was identical in the two basins, the remaining components exhibited rather pronounced differences in factor patterns. Evidently the shift from a landscape with high dominance in land use/cover (Raisin) to a landscape with more diversity in land cover (Huron) alters the secondary gradients in landscape patterns.

A landscape that shows high dominance by a single land use/cover is likely to differ from a more heterogeneous land cover in a number of pattern metrics. On the other hand, there is rarely a one-to-one relationship between metric values and landscape configuration (Gustafson, 1998). Both linear and non-linear relationships might be expected depending upon the nature of the landscape and the extent of variation in proportion of a land cover.

Proportion of agriculture in a basin explained the most variance in spatial pattern (Table 6). Variance explained by the proportion of urban land exceeded variance explained by the natural categories, although natural land cover types had a similar number of significant relationships to spatial patterns. These two classes showed the widest range in values, which may also account for the occurrence of non-linear responses of metrics with increasing proportions of agriculture and urban. Non-linear responses occurred with the landscape-level variables DOM, IJI and ED, and most class-level IJI and ED variables also showed a non-linear response to variations in land use/cover. Metrics with consistently linear responses included PD, PSCV and MPS. Variables showing a non-linear response to variations in the proportion of a given land use/cover type illustrate that the same value for that variable can occur in two very different landscapes.

Though most variables used in these regressions exhibited conspicuous patterns of spatial autocorrelation, with only a few exceptions traditional regression models matched autoregressive models in the determination of significance. We used results from the traditional regression to facilitate qualitative comparisons of the strength of relationships between land use/cover proportions and pattern metric values. The general patterns in our empirical results agree with previous simulation studies (e.g. Gustafson and Parker, 1992), showing that there are significant relationships between the proportion of a landscape in a given land cover type and the pattern of that landscape. However, as in other actual landscapes (e.g. Coppedge et al., 2001), relationships between pattern and proportion are not as clean as those produced in simulated landscapes. These findings provide further evidence for the need for research that seeks to identify an independent ecological effect of landscape configuration, above and beyond the effects of landscape composition (i.e. proportion data). Our results also confirm that some of these relationships are non-linear, suggesting that, in order to interpret metrics of spatial configuration one also needs to know something about land use/cover composition. Spatial configuration metrics should, therefore, not be used in isolation.

5. Conclusion

In summary, this analysis supports prior efforts to identify a sufficient set of measures of landscape pattern that will be effective in quantifying land cover across a wide range of landscapes and spatial scales. Pattern metrics that accounted for variation in larger landscape units (2000–20,000 km^2) also were effective with units averaging <50 km^2. A primary dimension of fragmentation appears to be common to most studies, although subsequent axes may be landscape-specific. Nonetheless, our results agree with the findings of others (Riitters et al., 1995; Cain et al., 1997; Griffith et al., 2000) that the metrics employed here describe variation in land use/cover and are useful in identifying three to five independent components of landscape pattern.

Whether all of the landscape heterogeneity that can be mapped and quantified is of relevance to the ecological process under investigation is often uncertain (Turner, 1989; Gustafson, 1998). The proportion of a land use/cover type may be as effective in predicting a variable of interest as are the many measures of heterogeneity one can calculate (Gustafson, 1998). In our study, the proportion of land in agriculture exhibited the greatest range of any single land cover category, and was predictive of a number of pattern measures. Hence, it remains to be determined whether variation in stream habitat and biota are better explained by configuration metrics than simple proportions (i.e. composition). However, pattern variables have improved statistical relationships between land cover and in-stream variables in several cases (Hunsaker and Levine, 1995; Cifaldi, 2001). Additionally, preliminary findings suggest that our ability to predict fish assemblage metrics from landscape and habitat data is improved by dis-aggregating the Huron and Raisin watersheds (Diana, 2002), a finding that accords with the marked differences in landscape pattern that this study reveals between the two basins.

Aquatic systems integrate the terrestrial landscape and hence reflect its condition. Ultimately, research into land use/cover quantification should culminate in the knowledge necessary to determine the mechanistic links between the way humans have shaped the landscape and the implications for ecological communities and processes. The pattern variables identified in other studies, and echoed here at a scale where the majority of aquatic studies occur, should be used to improve our predictive capacity of land use impacts upon the integrity of these systems.

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