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Research article

A method for the use of landscape metrics in freshwater research and management

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Abstract

Freshwater research and management efforts could be greatly enhanced by a better understanding of the relationship between landscape-scale factors and water quality indicators. This is particularly true in urban areas, where land transformation impacts stream systems at a variety of scales. Despite advances in landscape quantification methods, several studies attempting to elucidate the relationship between land use/land cover (LULC) and water quality have resulted in mixed conclusions. However, these studies have largely relied on compositional landscape metrics. For urban and urbanizing watersheds in particular, the use of metrics that capture spatial pattern may further aid in distinguishing the effects of various urban growth patterns, as well as exploring the interplay between environmental and socioeconomic variables. However, to be truly useful for freshwater applications, pattern metrics must be optimized based on characteristic watershed properties and common water quality point sampling methods. Using a freely available LULC data set for the Santa Clara Basin, California, USA, we quantified landscape composition and configuration for subwatershed areas upstream of individual sampling sites, reducing the number of metrics based on: (1) sensitivity to changes in extent and (2) redundancy, as determined by a multivariate factor analysis. The first two factors, interpreted as (1) patch density and distribution and (2) patch shape and landscape subdivision, explained approximately 85% of the variation in the data set, and are highly reflective of the heterogeneous urban development pattern found in the study area. Although offering slightly less explanatory power, compositional metrics can provide important contextual information.

Introduction

There is a growing demand for landscape-level freshwater monitoring and assessment methods (Griffith 2002; Mertes 2002), particularly in urban and urbanizing areas, where large-scale land transformation affects stream ecosystems in a variety of ways across numerous spatial and temporal scales (Morley and Karr 2002). Correspondingly, the wide range of anthropogenic impacts seen along urban–rural gradients provides an opportunity to address ecological questions across a greater variety of spatial scales than researchers would typically be able to produce (McDonnell and Pickett 1990). With growing levels of urbanization throughout the world, it is increasingly important that both research and management efforts take into account the effects of this widespread landscape alteration and its consequences for natural systems (Luck and Wu 2002).

Freshwater ecosystems are particularly sensitive to the effects of urbanization because they receive and transport water and materials from throughout watersheds (Knighton 1984; Paul and Meyer 2001; Morley and Karr 2002). Natural resource management agencies are faced with the challenge of developing monitoring and assessment tools that are both appropriate and cost-effective, and that provide a comprehensive survey of water resources (Barbour 1997). Although these efforts have often been local scale (i.e., reach and immediate riparian zone) in nature, managers are increasingly interested in acquiring and analyzing data that can be applied across broad geographic regions (Jones et al. 2000). Simultaneously, technical and conceptual advances continue to improve our ability to understand the linkages between landscapes and freshwater ecosystems at larger spatial scales (Johnson and Gage 1997; Griffith 2002; Mertes 2002).

The use of landscape metrics in particular provides the ability to quantify land use/land cover (LULC) pattern relatively quickly and easily (Herold et al. in press). However, many metrics have not been optimized for either urban or freshwater research and management applications. Although literally hundreds of landscape metrics have been developed, they fall into three general categories: (1) metrics of landscape composition, (2) metrics of spatial configuration (or pattern metrics), and (3) fractals (Turner et al. 2001). Each of these categories of metrics can be calculated for different landscape components: (1) patches, (2) classes (e.g., urban, forest), and (3) the entire landscape (McGarigal and Marks 1995). In general, metrics represent the spatial heterogeneity of a given landscape, and different patterns are observable at different scales (Herold et al. in press).

Caveats to the successful application of landscape metrics have been well documented. For example, because metrics are quantified based on highly related aspects of the landscape, there can be a great deal of redundancy (Riitters et al. 1995; Griffith et al. 2000), making it important to develop methods for choosing the most appropriate set of metrics to be used. In addition, many pattern metrics can be highly sensitive to changes in extent/area (Saura and Martinez-Millan 2001). This issue is particularly relevant to watershed studies because freshwater ecosystems are characterized by unidirectional flow that moves solutes, detritus, sediment, and organisms from upstream to downstream areas (Cooper et al. 1998). Therefore, delineation of the subwatershed area upstream of individual sampling sites, and subsequent landscape quantification within this reduced area, provides a spatially explicit landscape characterization that can be directly related to point sampled data. However, the consequence of this site-specific delineation is that many subwatersheds of differing extents result, making it critical that the landscape metrics used in comparisons be insensitive to variation in extent.

Previous studies using landscape metrics for water quality assessment purposes have resulted in mixed conclusions about the importance of local versus large-scale physical factors (Richards and Host 1994; Roth et al. 1996; Allan et al. 1997; Wang et al. 1998; Lammert and Allan 1999; Dovciak and Perry 2002; Roy et al. 2003). For example, Roth et al. (1996) explored the relationship between LULC and biotic communities at various spatial scales in an area dominated by agricultural land use. While they found large-scale land use to be the most effective predictor of biological community condition, in a similar study in the same region, Lammert and Allan (1999) found that local scale physical habitat variables explained more variation in freshwater communities.

A possible explanation for these varied results is that these studies have largely relied on compositional landscape metrics (e.g., percent agriculture versus percent urban cover). Indeed, the use of landscape metrics that quantify spatial configuration or arrangement may be more desirable than those that simply quantify landscape composition, particularly in urban and urbanizing watersheds. Because pattern metrics are more spatially explicit (Herzog and Lausch 2001; Turner et al. 2001; Gergel et al. 2002), they may be better able to account for the effects of land uses that differ in proximity and/or configuration in relationship to a specific water quality sampling location. Examples of spatial pattern metrics include the interspersion and juxtaposition index, a measure of landscape subdivision, and the mean shape index, which is reflective of patch–perimeter complexity.

In addition to providing ecological information, landscape pattern metrics may also give an important indication of the economic efficiency and social desirability of urban areas (Parker and Meretsky 2004). Although compositional metrics may offer a general assessment of urbanization, pattern metrics may be better able to capture the subtleties of increasingly important forms of urban expansion, such as agricultural and residential land conversion. Indeed, further fragmentation of urban and suburban communities has become a leading concern of decision-makers (Nagendra et al. 2004).

As it is now predicted that by 2008 more than half of the world population will be living in urban areas (World Bank 2004), understanding the relationship between pattern and process in urban communities is critical to successful natural resource management. Stream ecosystems, as a central and defining aspect of many cities, are particularly sensitive to the effects of urbanization (Paul and Meyer 2001). Therefore, optimizing landscape metrics for use in a metropolitan watershed context creates the opportunity to better understand both urban and freshwater system dynamics.

Here, using a freely available and downloadable LULC data set, we present a method for quantifying landscape composition and pattern in subwatershed units upstream of individual water quality sampling sites. Furthermore, we: (1) reduce the number of metrics based on those that are sensitive to changes in area/extent, (2) evaluate the redundancy of metrics using multivariate factor analysis, and (3) examine the explanatory power of compositional versus pattern metrics.

Methods

Study area

The study area is located in the Santa Clara Basin, which drains into the southern San Francisco Bay of California and includes the greater San Jose metropolitan area (Figure 1). The underlying geology of the area is largely volcanic in the upper basin with the lower basin consisting principally of alluvial deposits (McLaughlin et al. 2001). The basin is located in a Mediterranean-climate region, which is characterized by sequential, predictable, seasonal events of flooding and drying over an annual cycle, with wet winters and dry summers; streams in this area often go dry during the summer months under natural hydrological conditions (Gasith and Resh 1999). The current population is almost two million and the urbanized area covers almost 1000 km^2 of the total basin area of 2200 km^2 (Santa Clara Basin Watershed Management Initiative 2000).

We examined 84 subwatersheds in five major watersheds within the basin. All of the streams flow along an urban–rural gradient, beginning with headwaters in more pristine areas and becoming progressively more urbanized as stream size increases. Many of the streams begin in regional parks, are surrounded by moderately sized rural and suburban populations in the mid-sections, and become increasingly surrounded by high-density urban, commercial, and industrial land uses downstream. Although several of the streams might naturally go dry during the summer, each is regulated, with at least one major dam located in the upper to mid-section. This regulation largely eliminates the drying and wetting cycles that characterize Mediterranean-climate streams and results in flow in most of these streams throughout the year.

Spatial data

The first step in calculating landscape metrics was to delineate the subwatershed area upstream of each of the 84 sampling sites. Boundaries were hand digitized by Leila Gass of the US Geological Survey using 1:24,000 topographic quadrangle maps. Topographic-based boundaries were edited to reflect the influence of major stormwater drain systems on drainage patterns.

The National Land Cover Data Set (NLCD) 1992 for Northern California was then used to quantify landscape composition and configuration. This LULC data set was produced as part of a cooperative project between the US Geological Survey and the US Environmental Protection Agency to produce a consistent land cover data layer for the conterminous US based on 30-m

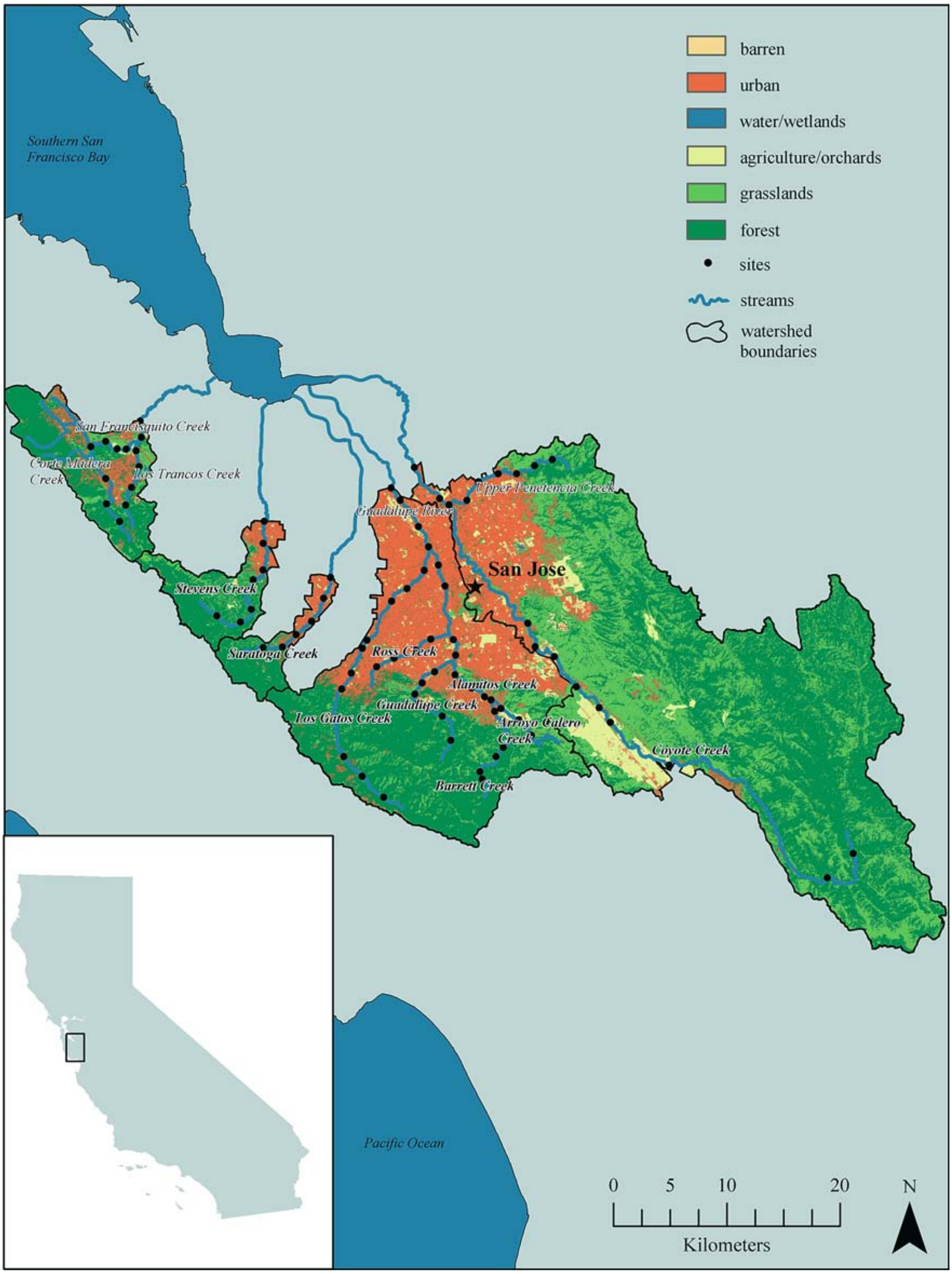

Figure 1. Map of the study area showing the basin and watershed boundaries, stream and sampling site locations and surrounding LULC. Data provided by the NLCD.

Landsat thematic mapper (TM) data. The base data set for this product was winter (leaf-off) TM data, nominal-1992 acquisitions, and ancillary data, including leaf-on TM, digital elevation data and derived slope, aspect, and shaded relief; US Bureau of the Census population and housing density data; and National Wetlands Inventory data (US Geological Survey 2000).

The accuracy assessment for the NLCD product is not complete for the study area. However, the accuracy assessment completed for other regions in the eastern United States show an overall accuracy at the patch level ranging from 61–81% (Vogelmann et al. 2001). A more detailed description is available on the NLCD website (http://landcover.usgs.gov/natllandcover.html).

The original coverage contained 20 cover classes, which were aggregated into eight, more general, and functionally related LULC classes for the purposes of this investigation (Table 1). The aggregation was based on the original hierarchy used for the LULC classification. For example, the deciduous, evergreen, and mixed forest classes were all aggregated to a more general "forest" class.

Table 1. The original NLCD LULC classification for northern California contained 20 cover classes.

Classes used in analysis	Original cover classes
Water	Open water
	Perennial ice/snow
Urban	Low intensity residential
	High intensity residential
	Commercial/industrial/ transportation
Barren	Bare rock/sand/clay
	Quarries/strip mines/gravel pits
	Transitional
Forest	Deciduous forest
	Evergreen forest
	Mixed forest
Orchards	Orchards/vineyards/other
Grasslands	Grasslands/herbaceous
Agriculture	Pasture/hay
	Row crops
	Small grains
	Fallow
	Urban/recreational grasses
Wetlands	Woody wetlands
	Emergent herbaceous wetlands

Based on the NLCD hierarchy, the classes were aggregated into eight more general cover classes.

Landscape metric calculation

Because previous studies linking landscape-level variables with water quality indicators have largely relied on compositional metrics, and resulted in contradictory outcomes, we were interested in comparing the explanatory power of compositional versus spatial configuration metrics in the most spatially explicit manner possible. Compositional metrics calculated included percent urban, forest, and agriculture. For the pattern metrics, we were most interested in landscape-level pattern metrics that quantify spatial configuration, a category that includes metrics such as patch area and perimeter, contagion, and connectivity (McGarigal and Marks 1995). Furthermore, within the general category of spatial pattern metrics, we were most interested in metrics that would be least sensitive to changes in landscape area, or extent, as well as non-redundant. Although hundreds of metrics have been developed, based on the above criteria, we were able to narrow the field to a smaller group of specific metrics (Table 2).

The subwatershed polygon layers were used to clip the NLCD LULC grid using the Spatial Tools extension for ArcView™ 3.2 (ESRI, Inc., Redlands, CA). Landscape metrics were calculated within each subwatershed area using ArcGrids exported to Fragstats 3.2 (McGarigal and Marks 1995). An

Table 2. Landscape metrics calculated in this study.

Landscape aspect quantified	Metrics calculated
Patch size distribution and density	Patch density
	Mean patch size
	Mean radius of gyration
	Landscape shape index
Patch shape complexity	Mean fractal dimension index
	Mean shape index
Isolation/proximity	Similarity index
Contrast	Contrast-weighted edge density
Contagion and interspersion	Contagion
	Percentage of like adjacencies
	Interspersion and juxtaposition index
Subdivision	Landscape division index
	Splitting index
	Effective mesh size
Landscape composition	Percent urban
	Percent forest
	Percent agriculture

Metrics were chosen to represent as many different aspects of spatial pattern as possible.

example of the subwatershed areas for which landscape pattern metrics were calculated is shown in Figure 2.

Although there is always error associated with using multiple spatial data layers, in this case, given the coarse level of the LULC data used, the effect of any error on the final results should be small. However, it should be noted that using the vector-based subwatershed layers to clip the NLCD raster grid could cause greater differences in the perimeter calculations of smaller compared to larger subwatershed areas.

The contrast-weighted edge density metric was calculated using an edge-weight file that maximized the distance between dissimilar land cover types (e.g., the urban cover class is most different from the forest cover class) (Table 3). In addition, the similarity index metric was calculated using a similarity-weight file that assigned higher weights to more similar cover classes, and was calculated with a search radius of 90 m. Both the edge and similarity-weight values were assigned to reflect hypothesized aquatic macroinvertebrate habitat functions, including connectivity, structure, dispersal, and refugia. For example, water and wetlands were assigned high similarity weights because they provide more similar macroinvertebrate habitats, than, for example, the water versus

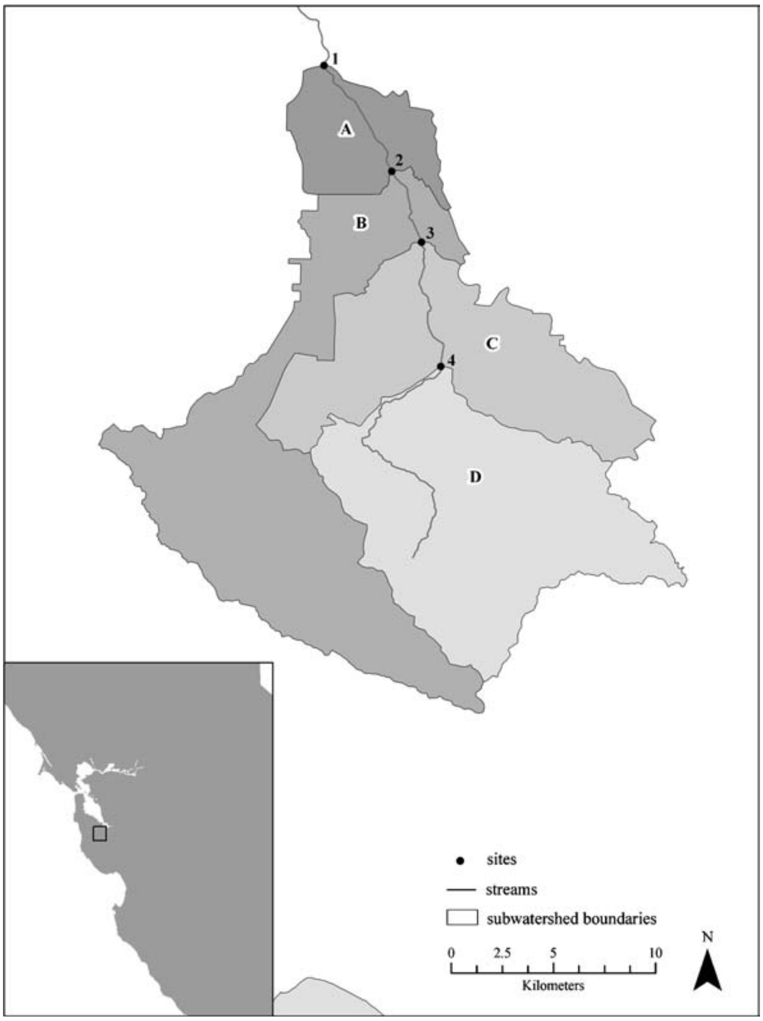

Figure 2. The Guadalupe watershed grid, showing subwatershed areas delineated upstream of each water quality sampling site. Moving downstream, each subwatershed area contains the entire upstream area (e.g., the subwatershed area for sampling site 2 contains areas B, C, and D).

Table 3. Values used for calculating the contrast-weighted edge density and similarity indices.

Cover class	Water	Urban	Barren	Forest	Orchards	Grasslands	Agriculture	Wetlands
Water	0.0	*0.8*	*0.8*	*0.2*	*0.7*	*0.5*	*0.8*	*0.1*
Urban	**0.2**	0.0	*0.2*	*1.0*	*0.5*	*0.6*	*0.4*	*1.0*
Barren	**0.2**	**0.8**	0.0	*1.0*	*0.6*	*0.6*	*0.4*	*1.0*
Forest	**0.5**	**0.1**	**0.1**	0.0	*0.6*	*0.3*	*0.8*	*0.2*
Orchards	**0.3**	**0.5**	**0.4**	**0.4**	0.0	*0.6*	*0.3*	*0.8*
Grasslands	**0.5**	**0.4**	**0.4**	**0.7**	**0.4**	0.0	*0.6*	*0.6*
Agriculture	**0.2**	**0.6**	**0.6**	**0.2**	**0.7**	**0.4**	0.0	*0.8*
Wetlands	**0.9**	**0.1**	**0.1**	**0.8**	**0.2**	**0.4**	**0.2**	0.0

Edge values are italicized, and the similarity values are in bold. Edge values maximized the distance between dissimilar land cover types and the similarity values assigned higher weights to more similar cover classes.

urban classes. All metrics were calculated in a batch file format including all 84 subwatersheds using eight-pixel rules in a standard window.

Statistical analysis

Descriptive statistics were used to determine if any of the landscape pattern metrics behaved erratically or had low variance, indicating an inability to discriminate between subwatersheds. All metrics were then tested for normality using the Shapiro–Wilk W test with a p-value of less than 0.05. After testing for normality, all metrics were square root transformed to improve normality, except for patch density, which required a log transformation, and contrast-weighted edge density, which required a cube root transformation.

Spearman rank correlation analysis was used to determine if any of the landscape metrics were highly correlated with changes in area/extent. Any landscape pattern metrics that were not useful in discriminating between subwatersheds, or were highly correlated with area, were not carried forward for subsequent multivariate analyses. All descriptive analyses were completed using Analyze-it™ software (Analyze-it™ Software Ltd., Leeds, UK).

A multivariate factor analysis, principal components analysis (PCA), was used to determine if a reduced set of factors could be used to explain the variation in the landscape metrics. In general, factor analysis techniques can be used to explore interrelationships among many different variables to determine if there is an underlying set (the factors) that explains the correlation between variables. This technique has been successfully used in previous landscape ecology research. For example, Riitters et al. (1995) used multivariate factor analysis to find a group of six landscape pattern metrics out of an original group of 26 that explained most of the variation in their data. For our research, a correlation matrix was used to derive the factor analysis components. For graphical display, the scaling of the axes is represented as a proportion of the maximum values. All multivariate analyses were completed using the statistical package PC-ORD™ Version 4 (MjM Software Design, Glenden Beach, OR, US).

Results

An analysis of the distribution of landscape metrics was done to determine which metrics should be removed (Table 4). The results indicated that similarity index and effective mesh size pattern metrics had high standard errors, and these metrics were eliminated from further analyses. In addition, the fractal dimension index showed little variability, making it less useful for discriminating between subwatersheds, and it was also removed from further analyses.

Spearman rank correlation analysis between the landscape metrics and extent indicated that the landscape shape index ($r = 0.97$, $p < 0.05$) and percent agriculture ($r = 0.60$, $p < 0.05$) were highly correlated with changes in subwatershed area (Table 5). The landscape division index and landscape splitting index were somewhat correlated with changes in extent ($r \sim 0.40$, $p < 0.05$), but, because the correlations were relatively low, the variables were not removed. Subwatershed areas ranged in extent from 5 to 800 km^2 (mean = 135 km^2).

Table 4. The distribution of landscape pattern metrics used for the study area (mean, standard error, and 95% confidence interval).

Landscape pattern metric	*n*	Mean	SE	95% CI of mean	
Patch density	84	22.50	0.87	20.78	24.23
Mean patch size	84	4.93	0.17	4.58	5.27
Radius of gyration	84	35.03	0.53	33.97	36.09
Landscape shape index	84	26.39	2.25	21.91	30.87
Fractal dimension index	84	1.05	0.00	1.05	1.05
Mean shape index	84	1.29	0.01	1.28	1.30
Similarity index	84	36,685.57	4811.07	27,116.53	46,254.60
Contrast-weighted edge density	84	43.30	2.13	39.06	47.53
Contagion	84	67.05	1.00	65.05	69.04
Percentage of like adjacencies	84	84.48	0.44	83.61	85.36
Interspersion and juxtaposition index	84	30.02	1.68	26.68	33.36
Landscape division index	84	52.08	2.30	47.50	56.65
Landscape splitting index	84	2.61	0.15	2.32	2.90
Effective mesh size	84	4769.09	614.37	3547.13	5991.05
Percent urban	84	11.40	1.69	8.03	14.76
Percent forest	84	66.49	1.96	62.59	70.39
Percent agriculture	84	1.25	0.19	0.88	1.60

The similarity index and effective mesh size pattern metrics had high standard errors, and were removed from further analyses. In addition, the fractal dimension index showed little variability, and was therefore not useful for discriminating between subwatersheds.

Factor analysis results showed that only the first two axes extracted were significant (using the general rule that axes with eigenvalues lower than one are not significant). These axes explained 85% of the variation in the landscape metric data (Table 6). The relationship between specific landscape metrics and the first two PCA axes indicated that axis 1 was highly correlated with landscape metrics related to patch size, density, and distribution, i.e., patch density, mean patch size, contrast-weighted edge density, and contagion. The compositional metrics – percent urban and percent

Table 5. Spearman rank correlations calculated between landscape metrics and subwatershed extent/area (n = 84, asterisk indicates significance at $p < 0.05$).

Landscape pattern metric	Correlation with extent
Patch density	−0.05
Mean patch size	−0.07
Radius of gyration	*−0.23
Landscape shape index	*0.97
Mean shape index	−0.11
Contrast-weighted edge density	−0.01
Contagion	*−0.23
Percentage of like adjacencies	−0.20
Interspersion and juxtaposition index	−0.12
Landscape division index	*0.43
Landscape splitting index	*0.34
Percent urban	0.02
Percent forest	*−0.30
Percent agriculture	*0.60

The metrics of percent agriculture and landscape shape index were highly correlated with changes in extent, and were removed from further analysis.

Table 6. Factor analysis results indicated that the first two axes extracted explained 85% of the variation, with the third axis providing relatively little explanatory power.

	Component number	
	1	2
Eigenvalue	7.47	2.69
Cumulative percent variance	62.27	84.68
Landscape metric		
Patch density	−0.34	0.16
Mean patch size	0.33	−0.13
Radius of gyration	0.23	−0.35
Shape index	0.17	−0.42
Contrast-weighted edge density	−0.34	0.01
Contagion	0.33	0.20
Percentage of like adjacencies	0.28	0.33
Interspersion and juxtaposition index	−0.22	0.35
Landscape division index	−0.29	−0.32
Landscape splitting index	−0.23	−0.39
Percent urban	−0.31	0.28
Percent forest	0.32	0.23

Results of the principal components factor analysis indicate that axis 1 was most correlated with metrics related to patch size and density, as well as percent urban and percent forest to a slightly smaller degree, while axis 2 was most correlated with metrics related to patch shape ($n = 84$).

forest – were correlated with axis one to a slightly smaller degree. Axis 2 was most correlated with landscape metrics related to shape and intermixing of cover classes, i.e., radius of gyration and the mean shape index, as well as the interspersion and juxtaposition and landscape splitting indices.

The distribution of subwatersheds reflects similarities in landscape pattern, with subwatersheds along the first axis grouped by metrics related to patch size and density, while subwatersheds along the second axis were most related to patch shape metrics and the landscape subdivision metrics (Figure 3). These results indicated that several of the metrics were measuring highly related aspects of landscape, making it possible to reduce the number of different metrics while still retaining the ability to explain a good deal of variation in the data set.

Spearman rank correlation analysis revealed high levels of correlation among many of the landscape pattern metrics, confirming the results of the factor analysis (Table 7). For example, many of the patch-based variables were highly correlated. In addition, the composition metrics were correlated with many of the pattern metrics, with some exceptions. For example, the percent urban metric was least correlated with the percentage of like adjacencies and the landscape division and splitting indices, while percent forest was least correlated with the shape, interspersion and juxtaposition, and landscape division indices.

Discussion

In urban and urbanizing areas, land cover change significantly influences the structure, function, and dynamics of ecological systems (Luck and Wu 2002). The condition of freshwater ecosystems in particular reflects the cumulative impacts of such landscape alteration because streams connect and concentrate the effects of land use activities (Hynes 1975; Wear et al. 1998). Historically, the tools needed to analyze the effects of landscape-scale variables on water quality indicators were unavailable (Johnson and Gage 1997). However, the increased accessibility of remotely sensed data and geographic information and computing technologies has made large-scale analyses of freshwater ecosystems possible (Griffith 2002; Mertes 2002).

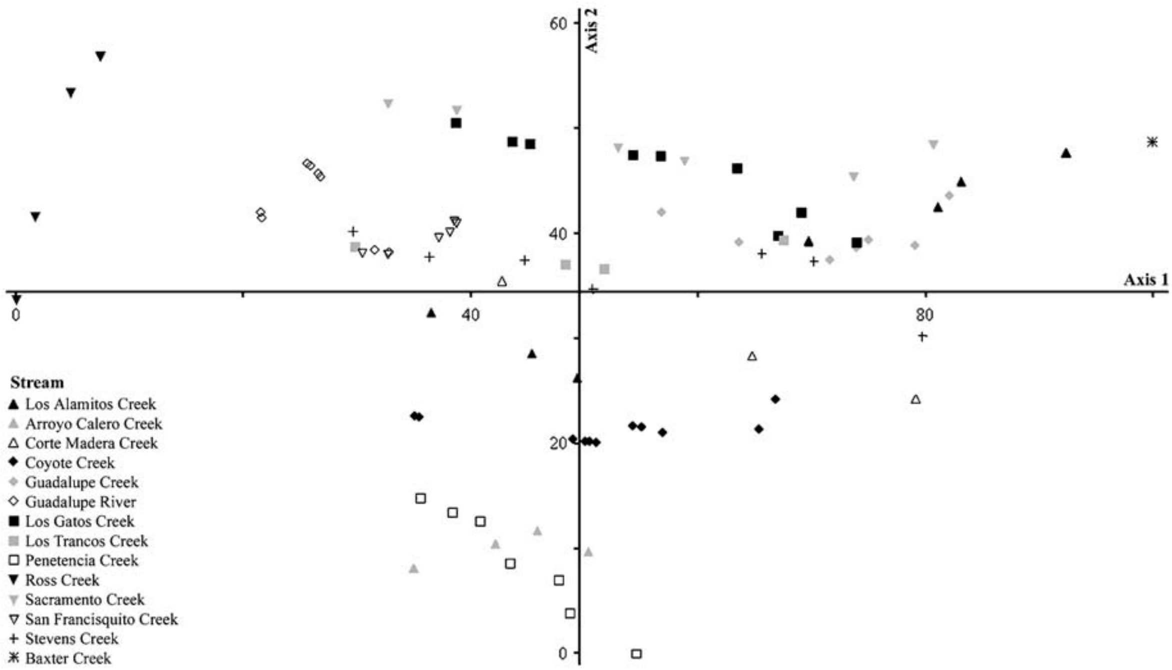

Figure 3. Graphical representation of the factor analysis results showing the distribution of subwatersheds in ordination space and the relationship of the subwatersheds to the first two ordination axes, or factors ($n = 84$).

Table 7. Spearman rank correlation analysis was used in combination with the factor analysis results to determine redundancy between landscape metrics ($n = 84$, all values except those in italics were significant at $p < 0.05$).

Landscape pattern metrics	PD	MPS	ROG	MSI	CWD	CON	PLA	IJI	DIV	SPL	%UR	%FO
Patch density	1.00											
Mean patch size	−0.99	1.00										
Radius of gyration	−0.70	0.69	1.00									
Mean shape index	−0.49	0.44	0.84	1.00								
Contrast-weighted edge density	0.91	−0.91	−0.52	−0.31	1.00							
Contagion	−0.74	0.74	0.33	*0.21*	−0.84	1.00						
Percentage of like adjacencies	−0.63	0.64	*0.19*	*−0.07*	−0.76	0.86	1.00					
Interspersion and juxtaposition index	0.70	−0.68	−0.49	−0.52	0.62	−0.39	*−0.08*	1.00				
Landscape division index	0.54	−0.58	*−0.26*	*−0.07*	0.68	−0.88	−0.83	*0.18*	1.00			
Landscape splitting index	0.32	−0.35	*−0.11*	*−0.04*	0.47	−0.77	−0.74	*0.02*	0.91	1.00		
Percent urban	0.85	−0.82	−0.72	−0.72	0.79	−0.64	−0.34	0.84	0.43	0.27	1.00	
Percent forest	−0.65	0.65	0.37	0.26	−0.74	0.94	0.83	−0.29	−0.09	−0.86	−0.60	1.00

Landscape metrics provide one promising avenue for quantifying the impact of human activities on freshwater ecosystems. Landscape metrics have been applied in a variety of research and management efforts. However, pattern metrics in particular have been underutilized in urban areas (Herold et al. in press). Although it is clear that urban form can be characterized by specific landscape patterns, identifying clear linkages with process has proven elusive (Parker and Meretsky 2004). Ecologically, this may be because although a great deal of remotely sensed data exists for urban areas, field data has tended to be more sparse. However, with the increasing focus on the expansion of urban areas, this is changing, allowing new opportunities to observe and test the relationship between pattern and process in urban and urbanizing landscapes. Because pattern metric results may also reflect the socioeconomic functioning of urban areas (Parker and Meretsky 2004), these types of urban studies may allow for increased understanding of the interplay between ecological and social systems.

The application of landscape metrics in freshwater systems has demonstrated the difficulty in linking pattern and process. For example, in similar, predominately agricultural areas, Roth et al. (1996) found watershed scale land use to be an effective predictor of fish and benthic macroinvertebrate metrics, while Lammert and Allan (1999) found local scale physical habitat variables explained more variation in freshwater communities. In the urban southeastern United States, Roy et al. (2003) found biotic indices were better predicted by local habitat variables, although urban land cover was significantly correlated with both an index of biotic integrity and an invertebrate community index.

In addition to differences that may be caused by varying study designs and geographic regions, previous research in this field has largely relied on compositional landscape metrics. Although the common application of compositional landscape metrics (e.g., percent urban) can give an indication of general land cover transformation, the arrangement or configuration of spatial pattern, an aspect of the landscape hypothesized here to be particularly important to the integral nature of freshwater systems, is largely neglected.

One approach that has been used to make landscape-level assessment more spatially explicit, as well as more applicable to freshwater systems, is to quantify landscape composition at several different spatial scales within a study area (e.g., riparian corridors at 200, 1000, and 2000 m, and upstream watershed area (Sponseller et al. 2001)), or by defining 'contributing zones' based on a combination of watershed variables such as drainage area, flow, soil type, and slope (Basnyat et al. 1999, 2000). Although these studies identified relationships between landscape-level factors and water quality indicators, to be appropriately quantified, these types of efforts can require finer resolution data than is feasible or cost-effective to acquire (L.B. Johnson, personal communication). In addition, intensive spatial data processing often makes these approaches less practical for large-scale monitoring and assessment programs. The use of landscape pattern metrics to quantify spatial pattern over large geographic areas without having to delineate riparian corridors or purchase additional data provides the potential to be more easily integrated into freshwater management efforts.

Comparing the explanatory power of compositional versus spatial pattern metrics quantified at the landscape level within the subwatershed area upstream of individual water quality sampling sites, we used a combination of descriptive and multivariate statistical methods to determine if any of the metrics were highly correlated with changes in extent, or were highly redundant. Our results indicate that there are two factors, interpreted as: (1) patch density and distribution, and (2) patch shape and landscape subdivision, that explain 85% of the variation in the data set. Although offering slightly less explanatory power, both the percent urban and percent forest metrics can add contextual, as well as potentially mechanistic, information when combined with pattern metric results.

Both the strength of the axis and the distribution of subwatersheds across the first factor indicate that many subwatersheds are differentiated based on patch density and distribution, as represented by the pattern metrics of patch density, mean patch size, contrast-weighted edge density, and contagion. Based on our results, we reduced the specific metrics related to the first factor to (1) patch density (mean patch size and patch density are directly correlated, although the choice of which to retain is essentially arbitrary), and (2) contagion (the contagion and the contrast-weighted edge density are highly correlated, but the edge density computation relies on a fairly subjective weighting, making contagion more reliable). Patch density is simply a measure of the number of patches of a given class per unit area, while contagion is a pixel-based (versus patch-based) measurement of land cover class adjacencies that gives an indication of overall spatial aggregation (McGarigal and Marks 1995).

In our study area, the subwatersheds most closely correlated with high patch density are those in highly to moderately populated suburban to urban areas, while subwatersheds in more rural locations with high forest cover and lower density housing where fewer classes occupied the landscape are most closely related to high levels of contagion. Both the percent urban and percent forest metrics are additionally correlated, to a lesser degree, with this first factor. Indeed, the first factor seems to be capturing the strong urban–rural gradient that characterizes much of the study area.

The distribution of subwatersheds across the second factor indicates that some subwatersheds are additionally differentiated based on patch shape and landscape subdivision, as represented by the pattern metrics of mean shape index, radius of gyration, and the landscape splitting and interspersion and juxtaposition indices. Again, it is possible to further reduce this group of metrics. For example, because the landscape splitting index has a higher standard error, it can be removed. Furthermore, the radius of gyration and mean shape index were highly redundant; because the radius of gyration metric was more highly correlated with changes in extent, it can also be removed.

The mean shape index is based on patch perimeter and provides a measure of patch shape complexity (McGarigal and Marks 1995). Although previous research using simulated landscapes of varying pixel areas has indicated that the mean shape index is sensitive to changes in extent (Saura and Martinez-Millan 2001), this was not the case in our study area. The interspersion and juxtaposition index is somewhat conceptually similar to the contagion metric, but provides a measure of the extent to which patch types of different classes are interspersed, versus overall landscape 'clumpiness' (Gustafson 1998).

The distribution of subwatersheds across this second axis indicates the importance of landscape subdivision and shape complexity in certain watersheds. For example, subwatersheds along the Guadalupe River, which is located in a highly urbanized watershed largely occupied by a diversity of intermixed LULC classes, are differentiated by the interspersion and juxtaposition index. In addition, the shape index can be used to distinguish subwatersheds in the San Francisquito watershed, an area dominated by an increasingly pervasive form of suburban growth, particularly in the western US: 'ranchette' style housing, which can be characterized by sizeable single family homes on relatively large (between one and five acres), homogenous parcels.

Our results support those of Cifaldi et al. (2004), who compared landscape metric results for agricultural and urban basins in the mid-western US to determine the suitability of landscape metrics in smaller versus larger subwatershed units. Although the purpose of their study was different, it is interesting to note that they also found basins were best described by a fragment gradient ranging from landscapes dominated by large, single-class patches to smaller, more diverse patch areas. Additionally, they also found that different combinations of both compositional and pattern metrics characterized landscape pattern within basins. In urban areas in particular, the interspersion and juxtaposition index was similarly found to be an important secondary descriptor of landscape pattern.

Heterogeneity in urban landscape pattern is increasingly common throughout the world as cities areas spread into rural and agricultural communities (Nagendra et al. 2004), and may require researchers to develop new methods and language that go beyond the urban–rural dichotomy to better reflect the complexities of land use conversion (Theobald 2004). Understanding diverse growth patterns may be useful for understanding both the ecological and socioeconomic functioning of urban and urbanizing landscapes, which has implications for planning and management (Croissant 2004; Parker and Meretsky 2004).

Although specific landscape patterns may differ, the approach that we have outlined is applicable across regions, and particularly well suited to urban areas. An important next step in this research is to link landscape metrics with indicators of water quality, such as aquatic macroinvertebrate communities, to test the relationship between landscape pattern and ecological process. Research addressing social and economic drivers, as well as the impact of planning decisions, would also give a more complete understanding watershed dynamics in urban areas.

In summary, we have presented a method for quantifying landscape pattern in an urban watershed context. We used a readily available LULC data set, compared composition and pattern metrics quantified in site-specific subwatershed areas, and removed those metrics sensitive to changes in extent, as well as those that were highly redundant. Two factors (patch density and distribution, and patch shape and landscape subdivision) were found to explain 85% of the variation in the data, and are highly representative of the heterogeneous urban growth pattern in the study area. We further identified a reduced set of pattern metrics most related to these factors: patch density, contagion, mean shape index, and the interspersion and juxtaposition index. Although offering slightly less explanatory power, compositional metrics can provide important contextual information to watershed studies. When quantified in a manner relevant to freshwater dynamics, metrics have the potential to provide data about landscape transformation that is directly applicable to watershed research and management efforts.

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