Taylor & Francis
Taylor & Francis Group

Quantifying landscape pattern and its change in an estuarine watershed using satellite imagery and landscape metrics

XIAOJUN YANG* and ZHI LIU
Department of Geography, Florida State University, Tallahassee, FL 32306, USA

Degradation of estuarine ecosystems caused by human-induced stressors justifies finding efficient ways to manage and protect these environments. This study demonstrates the utilities of satellite remote sensing, landscape metrics and multivariate statistical analysis for quantifying landscape pattern and its change in a highly sensitive estuarine watershed. The objective of this study was to identify the appropriate method for landscape pattern characterization in the Pensacola estuarine drainage area (PEDA) as part of an interdisciplinary effort to develop environmental indicators for integrated estuarine ecosystem assessment in the Gulf of Mexico. The study has several components. First, two land-use and land-cover maps were produced from satellite imagery by using hierarchical classification and spatial reclassification techniques. Then, 56 metrics of landscape composition or configuration were computed from the two maps for different spatial observational units, including the PEDA, four sub-watersheds, and three predefined buffer areas. Because some of the landscape metrics may be correlated with each other, landscape ecology principles, principal component analysis and Spearman's rank correlation analysis were used to eliminate redundant metrics. This resulted in a parsimonious set of core metrics which were not redundant but spanned the important dimensions of landscape structure and pattern. These core metrics were finally used to quantify landscape pattern for different spatial observational units at the two different years. Landscape structure has been found to be more fragmented in the Pensacola Bay watershed, around the city centres and along the coastlines, where urbanization and human economic activities are more concentrated. Over time, the landscape mosaics became more heterogeneous while the classes of patches tended to be more fragmented. Results of this study should help coastal managers in the PEDA target those areas in need of conservation and protection.

1. Introduction and research objectives

Estuaries as the receiving basins for major river systems belong to the most dynamic ecosystems on Earth. Large coastal populations and intense development have greatly accelerated environmental pressure on downstream estuaries, exacerbating degradation of estuarine ecosystems ((Basnyat *et al*. 1999, EPA 1999, Bowen and Valiela 2001, Dojiria *et al*. 2003, Finkl and Charlier 2003). Therefore, there is a strong need for environmental monitoring and assessment in order to manage and protect these highly sensitive ecosystems more effectively (Hobbie 2000). To assess environmental conditions in estuarine ecosystems, a suite of indicators, spanning the full spectrum of biological organization from generic markers to entire

*Corresponding author. Email: xyang@fsu.edu

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160500219273

ecosystems, is needed (Niemi *et al*. 2004). An assessment of landscape patterns at the ecosystem level can help identify some of the most important aspects of environmental changes, which emerge from lower-level disturbances due to complex interactions between social and environmental processes (Turner 1989, Forman 1995).

Recent innovations in the theories of landscape ecology and the technologies of remote sensing and Geographic Information Systems (GIS) offer a promising framework for a quantitative assessment of landscape structure and pattern (Turner 1990, McGarigal and Marks 1995, Turner *et al*. 2001, McGarigal 2002). Landscape ecology as the forefront of ecology and land management emphasizes the interaction between spatial pattern and ecological process (Turner *et al*. 2001). Interest in measuring landscape pattern has been driven by the promise that there are strong links between ecological pattern and ecological function and process (Gustafson 1998). Landscape metrics as quantitative indices to describe structure and pattern of a landscape can be extracted from a land-use and land-cover map derived mostly from remotely sensed imagery. They can be used to assess ecosystem health or as variables for models that support environmental assessment and planning efforts (e.g. Cain *et al*. 1997, Ravan and Roy 1997, Griffith *et al*. 2000, Fuller 2001, Herzog *et al*. 2001, Patil *et al*. 2001, Gergel *et al*. 2002, Leitao and Ahern 2002, Liu *et al*. 2003).

With development of GIS software technology, measurement of landscape metrics seems to be unlimited. However, there are several major issues which need to be addressed before these quantitative indices can be meaningful for landscape pattern analysis. First, the choices of landscape metrics seem to be quite rich, but some may be partially or perfectly correlated with each other because they are actually derived from a few primary measurements that can be made from patches (McGarigal and Marks 1995). This results in redundancy. On the other hand, a large number of metrics would be troublesome to interpret and analyse. Clearly, a small set of metrics that are not redundant but can capture the major properties of a landscape are preferred. Selection of core landscape metrics can be accomplished by using landscape ecology principles described by McGarigal (2002) and examples of using this approach of selection for landscape pattern analysis can be found in Zhang *et al*. (1997), Fuller (2001) and Li *et al*. (2001). However, this may work well for reducing inherent redundancy but not for empirical redundancy. Statistical methods (e.g. principal component analysis) can be used to reduce data redundancy and select a parsimonious suite of independent metrics for landscape pattern analysis (e.g. Riitters *et al*. 1995, Cain *et al*. 1997, Griffith *et al*. 2000, Herzog and Lausch 2001). Although recent studies indicate that landscape pattern can be characterized by using several core indicators, consensus has not been reached on the choice of individual metrics (McGarigal 2002).

Choice of appropriate spatial observational units is another critical issue because landscape metrics are sensitive to the extent over which they are calculated (Hunsaker *et al*. 1994). Thus, spatial observational units may affect the pattern–process relationship established by using landscape metrics. On the other hand, a spatial observation unit is needed before any landscape metrics can be computed. The current landscape ecology literature, however, does not provide much guidance on how to choose spatial observational units. Further effort is needed to design spatial observational units which could explicitly reflect some hypotheses related to major processes acting upon the landscape under investigation.

The objective of this study was to develop the appropriate method for landscape pattern characterization in the Pensacola estuarine drainage area (PEDA). The study area has historically supported a rich and diverse ecosystem, productive fisheries and considerable recreational opportunities in north-western Florida (EPA 1999). During the past decade, this area has witnessed significant population and economic growth, resulting in point- and non-point-source pollution, hydrologic alterations and direct habitat destruction throughout the watershed. These changes have provoked concerns over the degradation of ecosystem health in Pensacola Bay. Since 2001, the authors have been involved in an interdisciplinary research project – CEER-GOM (Consortium for Estuarine Ecoindicator Research for the Gulf of Mexico) funded by the US Environmental Protection Agency (EPA) through the Estuarine and Great Lakes (EaGLe) Program. The objective of CEER-GOM has been to develop environmental indicators for integrated estuarine ecosystem assessment in the Gulf of Mexico. Pensacola Bay, as one of the three exemplary large-scale river-driven estuarine systems across the northern Gulf of Mexico, has been targeted for co-ordinated research by Project CEER-GOM. This article examines landscape pattern and its changes in the PEDA by using remote sensing and landscape metrics. Specifically, the objectives were to identify and apply a set of independent core metrics for quantifying landscape pattern and the changes in landscape pattern over time among various spatial observational units.

2. Research methodology

The research had several major components (figure 1): (i) land-use and land-cover classification; (ii) spatial observational unit design; (iii) computation of landscape metrics; (iv) selection of core metrics; and (v) interpretation and analysis. This section provides the technical details for the first four procedures, along with a brief description of the study area.

2.1 *Study area*

The geographical coverage of Pensacola estuarine drainage area (PEDA) includes the majority of Escambia, Santa Rosa and Okaloosa counties, the north-western part of Walton County in Florida, as well as portions of Conecuh, Covington, Escambia and Monroe counties in Alabama (figure 2). The PEDA is defined according to National Oceanic & Atmospheric Administration (NOAA)'s Coastal Assessment Framework (CAF). CAF is a GIS-based digital spatial framework designed for managers and analysts to organize information on the nation's coastal, near-ocean and Great Lakes' resources (NOAA 1999). The PEDA is the estuarine portion of the Pensacola Bay drainage basin and comprises approximately 50% of the total watershed (NFWMD 1997). The entire basin discharges into the Gulf of Mexico through a narrow pass at the mouth of Pensacola Bay. The PEDA has a total area of 9119 km^2. This represents 8643 km^2 of upstream watershed and 476 km^2 of bays, fitting within a whole scene (34 225 km^2) of Landsat imagery.

Physiographically, the PEDA lies within the Coastal Plain province, which is underlain mainly by beds of sand, silt, and clay that dip gently seaward (Marsh 1966). The estuarine embayments are within the Gulf Coastal Lowlands subdivision and contain a series of parallel terraces rising from the coast in successively higher levels. Much of the area is less than 30 m above sea level. The PEDA includes three

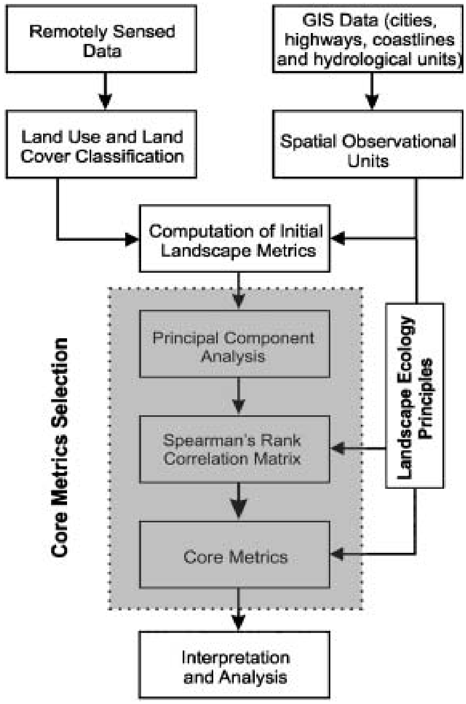

Figure 1. Flowchart of the procedure used in this study.

major river systems – Escambia, Blackwater and Yellow rivers. The climate is humid subtropical with generally warm temperatures.

2.2 *Land-use and land-cover classification*

In order to compute landscape metrics and analyse landscape pattern changes, two different dates of land-use and land-cover maps were produced. For this purpose, a predominantly cloud-free scene of Landsat Thematic Mapper (TM)/Enhanced Thematic Mapper Plus (ETM+) imagery was acquired from USGS EROS Data Center for 1989 and 2002, respectively. A modified version of the Anderson land-use and land-cover scheme (Anderson *et al.* 1976) was developed (table 1). The TM/ETM+ data were radiometrically normalized and then classified through the use of hierarchical classification and spatial reclassification techniques (Yang and Liu 2005). Accuracy assessments indicate that the overall classification errors for the two maps (figure 3) were less than 10%. Detailed discussion about the classification procedures is presented by Yang and Liu (2005). Before the actual computation of landscape metrics, a 5×5 modal filter was applied to the two raster maps to remove isolated pixels resulting from boundary errors (Yang and Lo 2002). This should help improve the speed in the computation of landscape metrics.

2.3 *Spatial observational units*

Spatial observation units must be determined before landscape metrics can be computed. Choosing appropriate spatial observational units is critical for landscape pattern analysis. Previous research reported the use of hexagons to sample the

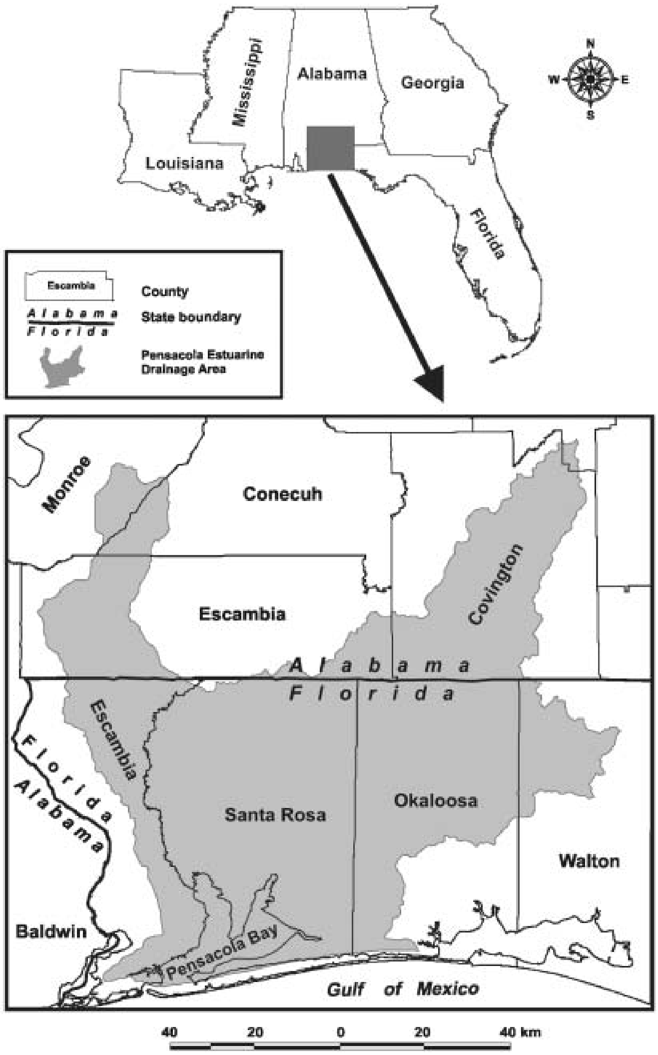

Figure 2. Location of the study area.

landscape (e.g. Hunsaker *et al.* 1994, Griffith *et al.* 2000), but also noted the significant discrepancy of pattern metrics between the hexagon sampling landscape and the complete landscape (Hunsaker *et al.* 1994). In this study, a different strategy was adopted. The spatial observational units used here are related to either a hydrological unit or a predefined buffer zone. They are associated with different levels or types of biophysical and human dimension stressors, which are likely to impact landscape pattern.

In total, eight spatial units were considered. They include the entire PEDA, four major sub-watersheds, and three predefined buffer areas (figure 4). The boundaries of PEDA and its four sub-watersheds – Escambia River, Blackwater River, Yellow River and Pensacola Bay, were extracted from USGS 1 : 250 000 hydrological unit boundaries (USGS 2004). PEDA was used for comparison. The four sub-watersheds were compared to examine the variation of landscape pattern across the watershed.

Table 1. Land-use and land-cover classification scheme used.

No.	Class name	Definition
1	Low-density Urban (LDU)	Approximately 40–70% (impervious) construction materials; mostly residential development including single/multiple family houses and public rental housing estate as well as local roads and small open (transitional) space as can be always found in a residential area; with a various amount of vegetation cover
2	High-density Urban (HDU)	Approximately 70–100% (impervious) construction materials, e.g. asphalt, concrete, etc.; typically com mercial and industrial buildings with large open roofs as well as large open transportation facilities, e.g. large airports, parking lots and multi-lane interstate/state highways; contain military bases, tourism and recreational facilities, and a low percentage of residential development residing in the city cores
3	Agricultural Land (AGL)	Mainly crops, pastures and other herbaceous vegetation, including lands that are regularly mowed for hay and/or grazed by livestock and regularly tilled and planted cropland; may contain small parks and golf courses
4	Evergreen Forest (EGF)	Mostly coniferous forests (including vegetative species such as pine and cedar)
5	Mixed Forest (MXF)	Neither evergreen nor deciduous species dominate; often mixed with a various amount of shrubs and brushes
6	Woody Wetlands (WWL)	Mostly hardwood, mixed forest and shrubs; distributed along rivers and bays
7	Emergent Herbaceous Wetlands (EHW)	Mainly tall grasses such as black needle rush; also called swamp, salt marsh and brackish marsh
8	Barren Land (BCH)	Areas of sparse vegetation cover (less than 20%), including beaches, clearcuts, and transactional lands that are likely to change or be converted to other uses in the near future; may contain fallow land
9	Water (WTR)	All areas of open water, generally with greater than 95% cover of water, including streams, rivers, lakes, reservoirs and bays

The other three units considered are highway buffers, city buffers and coastline buffers. The highway buffers were derived from the ESRI 2002 highway data (ESRI 2003). The size of highway buffers was weighted according to highway types, with Interstate highways receiving the highest score, followed by US highways, state highways and the other unclassified roads. Highway buffers occupy 5402 km^2 or 59.21% of the total PEDA. City buffers were weighted by a city's 2002 population size (ESRI 2003), occupying a total area of 611 km^2. Coastline buffers consist of the area within 1 km of the coastline (NOAA, 1999), representing 661 km^2 of the PEDA.

2.4 *Computation of landscape metrics*

The two raster maps of land use and land cover were converted into vectors and landscape metrics were then computed by using Fragstats*ARC (McGarigal and Marks 1995). A total of 56 metrics (table 2) were considered in the context of the research objective and the landscape ecology principles (e.g. Turner 1989, Forman 1995, McGarigal 2002). These metrics are related to either landscape composition (e.g. proportional abundance of each class) or landscape configuration (e.g. patch

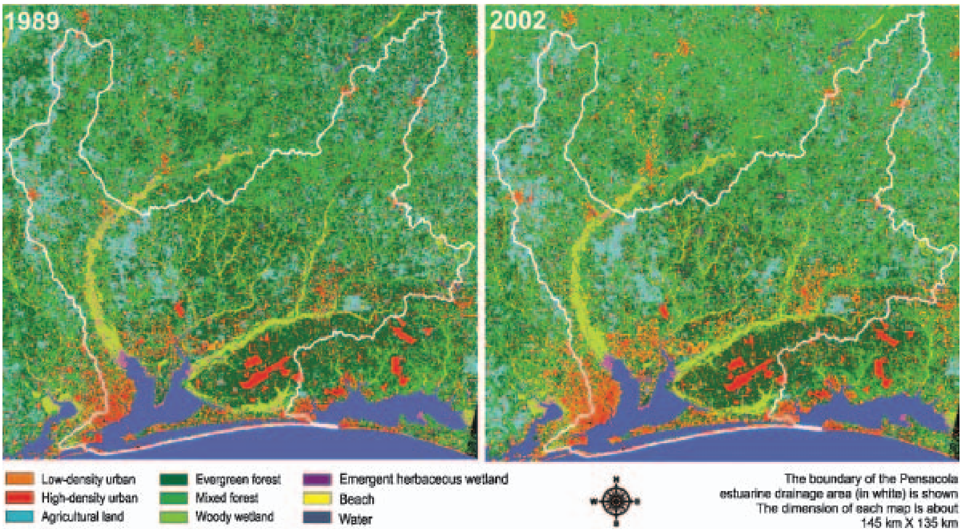

Figure 3. Land-use and -cover maps derived from Landsat TM/ETM+ data for the Pensacola estuarine drainage area (PEDA).

size distribution and density, patch shape complexity and interspersion). They are grouped into six major structural categories: area, patch, shape, core area, diversity and configuration. At the class level, there are a total of 25 metrics, falling within five of the six major structural groups. At the landscape level, there are a total of 31 metrics. These metrics were computed for each spatial unit using the 1989 and 2002 land-use and land-cover data.

2.5 *Selection of core metrics*

Principal component analysis (PCA) and Spearman's rank correlation analysis (SRCA) were used to help identify a set of metrics that best described characteristics of the landscape units. PCA is a multivariate method that linearly combines the original variables into several uncorrelated and independent variables known as principal components (Ramsey and Schafer 1997). Most of the variability in the original variables is captured in the first few principal components. PCA was used here to identify a smaller set of metrics from the initial list which were highly correlated with the first few components. Variables that were not strongly correlated with the first few principal components were excluded from further analysis.

SRCA was conducted after PCA. As a non-parametric method, SRCA uses the ranks of the data, rather than the actual data, to compute a correlation coefficient known as r_s:

$$r_s = 1 - \frac{6\sum d^2}{n(n^2-1)} \tag{1}$$

where Σd^2 is the sum of the squared differences between the pairs of ranks, and n is the number of pairs (Walford 1995). With SRCA, a correlation coefficient matrix was created at the landscape and class levels, respectively.

Finally, a few core metrics that are ecologically critical were included in the context of the research objective and landscape ecology principles (e.g. McGarigal

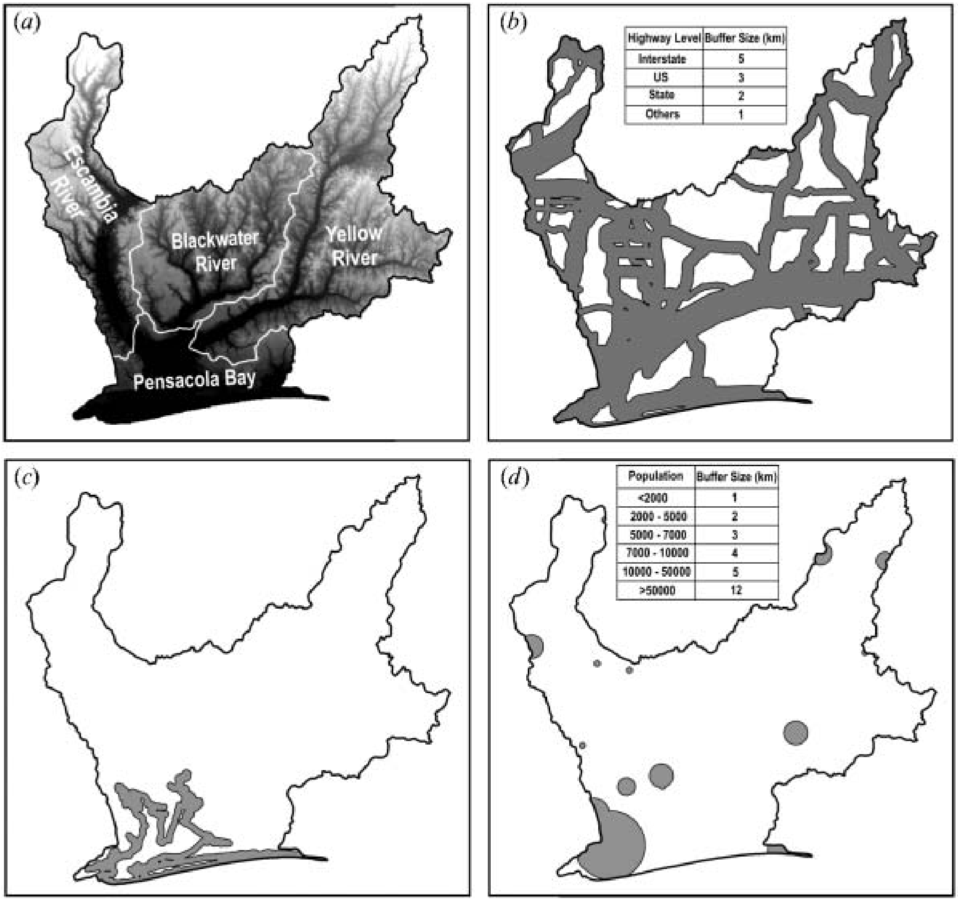

Figure 4. Spatial units used in the study. (*a*) The entire Pensacola estuarine drainage area (PEDA) and its four sub-watersheds: Blackwater River, Escambia River, Pensacola Bay and Yellow River. (*b*) Weighted highway buffers. Note that buffer distance for each type of highways is given. (*c*) Coastline buffers. The buffer distance is 1 km. (*d*) Weighted city buffers according to population.

and Marks 1995, Turner *et al*. 2001). While any number of metrics could be eliminated after PCA and SRCA, it was decided to include at least one core metric for each structural group (see table 2). This was to ensure that each structural group could be addressed in the further analysis. If no metrics were left for any structural group after PCA and SRCA, at least one critical metric for that group would have to be added back into the list. In this way, a final list of the core metrics was created at the landscape and class levels, respectively.

Table 3 summarizes the outcome of the PCA at the landscape level. In this computation, all 31 metrics at the landscape level were considered for eight spatial units at two different years. Thus, there were 16 'samples' used in the PCA. To increase interpretability, an orthogonal varimax rotation, which perceives the relative orientation, was used on the resulting component scores. Note that the first four components explain approximately 96% of the variability in the entire dataset. Metrics that were weakly correlated with the first four principal components were excluded from further analysis. This resulted in the elimination

Table 2. List of initial and final landscape metrics at the class and landscape levels, respectively.

Structural feature	Index (Acronym)	Full name (Unit)*	Class level		Landscape level	
			Initial	Final	Initial	Final
Area	CA	Class Area (ha)	Yes			
	LPI	Largest Patch Index (%)	Yes	Yes	Yes	Yes
	PLAND	Percent of Landscape (%)	Yes	Yes		
	TA	Total Area (ha)			Yes	
Patch	MPS	Mean Patch Size (ha)	Yes	Yes	Yes	Yes
	NP	Number of Patches (none)	Yes	Yes	Yes	Yes
	PD	Patch Density (#/100 ha)	Yes		Yes	
	PSCV	Patch Size Coefficient of Variation (%)	Yes		Yes	
	PSSD	Patch Size Standard Deviation (ha)	Yes		Yes	
Shape	AWMPFD	Area Weighted Mean Patch Fractal Dimension (none)	Yes		Yes	Yes
	AWMSI	Area Weighted Mean Shape Index (none)	Yes	Yes	Yes	
	MPFD	Mean Patch Fractal Dimension (none)	Yes		Yes	
	MSI	Mean Shape Index (none)	Yes		Yes	
Core Area	CACV1	Core Area Coefficient of Variation (%)	Yes	Yes	Yes	Yes
	CACV2	Disjunct Core Area Coefficient of Variation (%)	Yes		Yes	
	CAD	Core Area Density (#/100 ha)	Yes		Yes	
	CASD1	Core Area Standard Deviation (ha)	Yes		Yes	
	CASD2	Disjunct Core Area Standard Deviation (ha)	Yes		Yes	
	CPLAND	Core Area Percent of Landscape (%)	Yes		Yes	
	LCAS	Landscape Core Area Similarity (%)			Yes	
	MCA1	Mean Area per Core (ha)	Yes		Yes	
	MCA2	Mean Core Area 2 (ha)	Yes		Yes	
	MCAI	Mean Core Area Index (%)	Yes		Yes	
	NCA	Number of Core Areas (none)	Yes		Yes	
	TCA	Total Core Area (ha)	Yes	Yes	Yes	Yes
	TCAI	Total Core Area Index (%)	Yes		Yes	
Diversity	MSIDI	Modified Simpsons Diversity Index (none)			Yes	Yes
	MSIEI	Modified Simpsons Evenness Index (none)			Yes	
	SHDI	Shannons Diversity Index (none)			Yes	
	SHEI	Shannons Evenness Index (none)			Yes	
	SIDI	Simpsons Diversity Index (none)			Yes	
	SIEI	Simpsons Evenness Index (none)			Yes	

Table 2. (*Continued.*)

Structural feature	Index (Acronym)	Full name (Unit)*	Class level Initial	Class level Final	Landscape level Initial	Landscape level Final
Configuration	IJI	Interspersion and Juxtaposition (%)	Yes	Yes	Yes	Yes

*For detailed definitions about these landscape metrics, see McGarigal and Marks (1995).

of six metrics – AWMPFD, AWMSI, MPFD, CAV2, MCAI and IJI (see table 2 for description of the metrics). Spearman's rank correlation coefficients were computed for all the remaining 25 metrics and the results are summarized in table 4. LPI, MPS and NP were selected as the first three core metrics because they are critical to quantify landscape fragmentation (McGarigal and Marks 1995). Nine metrics whose correlations with any of the first three core metrics reached at least 0.85 were considered to be redundant and were eliminated from further consideration. They were PSCV, PSSD, MSI, CASD1, CASD2, PD, TA, NCA and TCA. Then, CACV1 was selected as a critical metric representing the core area structural group (see table 2). MSIDI, a Simpson index, was selected as a core diversity metric. Five metrics which were highly correlated with MSIDI were eliminated. They were MSIEI, SHDI, SHEI, SIDI and SIEI. Six other metrics were eliminated because they were highly correlated with one or more of the metrics which were eliminated earlier. Finally, three ecologically critical metrics – AWMPFD, TCA and IJI, which were eliminated earlier, were added back to represent three structural groups (see table 2). Thus, the final list contained eight metrics: LPI, MPS, NP, AWMPFD, CACV1, TCA, MSIDI and IJI. Similar procedures were adopted at the class level with the information from tables 5 and 6 and the final list had eight metrics: LPI, PLAND, MPS, NP, AWMSI, CACV1, TCA and IJI (see table 2).

3 Results and discussion

3.1 *Landscape level*

Based on table 7 and figure 5, landscape pattern and its change can be characterized at the landscape level for different spatial observational units. The mean patch size (MPS) is a critical metric and can serve as a habitat fragmentation index (McGarigal and Marks 1995). In 1989, among all eight units, the Pensacola Bay watershed and the city buffer area had the largest and smallest MPS, respectively. The MPS of the Pensacola Bay watershed was 6.91 ha, approximately 14.01% larger than the PEDA's mean patch size which was 6.06 ha; while the MPS of the city buffer area was 4.07 ha, approximately 33% smaller. This indicates that the landscape mosaic in the city buffer area was the most fragmented, while the Pensacola Bay watershed was the least. The two other buffer areas also had smaller MPS than the PEDA's in 1989. Among the four sub-watersheds, the Pensacola Bay had the largest MPS in 1989, followed by the Blackwater River (6.20 ha), the Yellow River (6.13 ha) and the Escambia River (5.22 ha), implying that the landscape mosaic in the Escambia was the most fragmented. In 2002, the mean patch size decreased consistently in each unit when compared with 1989, implying that the landscape mosaic became more fragmented. In 2002, the Pensacola Bay watershed and the city buffer area were still the two opposite extremes in mean patch size. Among the eight units, the Pensacola Bay watershed had the highest rate of decline in mean patch size (16.32%), followed

Table 3. Results of principal component analysis (PCA) and varimax rotation of the first four components at the landscape level*.

	Component number 1	2	3	4	
	Eigenvalues and cumulative proportion of variance explained by PCA				
Eigenvalue	15.926	7.954	4.209	1.637	
Cumulative variance	51.375	77.034	90.610	95.891	
	Component pattern after varimax rotation				*Communality***
LPI	**0.887**	0.121	−0.395	0.198	1.00
TA	−0.280	0.228	**0.905**	−0.157	0.97
MPS	0.188	−0.348	0.232	**−0.878**	0.98
NP	−0.323	0.317	**0.874**	−0.107	0.98
PD	−0.073	0.277	−0.235	**0.922**	0.99
PSCV	**0.907**	0.230	−0.149	0.308	0.99
PSSD	**0.970**	0.188	−0.068	−0.069	0.98
AWMPFD	0.629	−0.249	−0.717	0.093	0.98
AWMSI	0.681	0.043	−0.335	0.584	0.92
MPFD	0.640	0.072	−0.334	0.662	0.96
MSI	**−0.787**	−0.259	0.363	−0.268	0.89
CACV1	**0.804**	0.342	0.063	0.465	0.98
CACV2	0.743	0.455	0.330	0.319	0.97
CAD	**−0.893**	0.094	0.383	−0.069	0.96
CASD1	**0.964**	0.191	−0.013	−0.094	0.97
CASD2	**0.967**	0.144	−0.099	−0.001	0.97
CPLAND	**0.960**	0.061	−0.236	−0.113	0.99
LCAS	**0.960**	0.061	−0.236	−0.113	0.99
MCA1	**0.835**	−0.077	−0.071	−0.534	0.99
MCA2	**0.933**	0.019	−0.274	−0.107	0.96
MCAI	−0.735	−0.210	0.369	−0.457	0.93
NCA	−0.345	0.251	**0.879**	−0.131	0.97
TCA	−0.134	0.216	**0.933**	−0.188	0.97
TCAI	**0.960**	0.061	−0.236	−0.113	0.99
MSIDI	0.051	**0.946**	0.207	0.151	0.96
MSIEI	0.050	**0.945**	0.209	0.153	0.96
SHDI	0.283	**0.919**	0.151	0.111	0.96
SHEI	0.281	**0.920**	0.150	0.113	0.96
SIDI	0.083	**0.944**	0.198	0.158	0.96
SIEI	0.084	**0.945**	0.194	0.158	0.96
IJI	0.148	0.598	−0.285	−0.431	0.65
				sum	29.73
	Variance explained by each component after rotation				
	13.734	6.769	5.331	3.892	

*The computation considers all spatial units at two different years. Descriptions of the metrics are given in table 2. Entries (correlation coefficients) in bold are considered to be strongly associated with one or more principal components. The metrics which were excluded for further considerations are shaded.
**Communality is the proportion of variance that each variable has in common with other variables.

by the coastline buffers (15.23%), the Yellow River watershed (14.05%), the PEDA (12.19%), the Blackwater River watershed (10.62%), the highway buffers (9.85%), the Escambia River watershed (8.10%) and the city buffers (7.37%).

In addition to MPS, seven other metrics are used to examine landscape composition or configuration for the entire mosaic at different units. Largest patch

Table 4. Spearman's rank correlation coefficient matrix for 25 metrics at the landscape level*.

	LPI	TA	MPS	NP	PD	PSCV	PSSD	MSI	CACV1	CAD	CASD1	CASD2	CPLAND	LCAS	MCA1	MCA2	NCA	TCA	TCAI	MSIDI	MSIEI	SHDI	SHEI	SIDI	SIEI
LPI	1.00																								
TA	−0.68	1.00																							
MPS	−0.16	0.33	1.00																						
NP	−0.61	**0.94**	0.12	1.00																					
PD	0.16	−0.33	**−1.00**	−0.12	1.00																				
PSCV	**0.90**	−0.53	−0.21	−0.46	0.21	1.00																			
PSSD	**0.93**	−0.52	−0.06	−0.50	0.06	**0.97**	1.00																		
MSI	**−0.87**	0.59	0.25	0.56	−0.25	**−0.91**	**−0.93**	1.00																	
CACV1	0.84	−0.46	−0.30	−0.33	0.30	**0.96**	**0.91**	−0.84	1.00																
CAD	−0.65	0.72	−0.24	0.77	0.24	−0.58	−0.61	0.54	−0.48	1.00															
CASD1	**0.91**	−0.50	−0.07	−0.48	0.07	**0.98**	**0.99**	**−0.94**	**0.92**	−0.61	1.00														
CASD2	**0.91**	−0.52	−0.14	−0.46	0.14	**0.98**	**0.98**	**−0.91**	**0.95**	−0.61	**0.98**	1.00													
CPLAND	0.74	−0.47	0.24	−0.55	−0.24	0.84	**0.86**	−0.77	0.74	−0.81	**0.87**	**0.85**	1.00												
LCAS	0.74	−0.47	0.24	−0.55	−0.24	0.84	**0.86**	−0.77	0.74	−0.81	**0.87**	**0.85**	**1.00**	1.00											
MCA1	0.41	−0.20	0.66	−0.40	−0.66	0.45	0.56	−0.39	0.29	−0.70	0.54	0.49	0.80	0.80	1.00										
MCA2	0.73	−0.55	0.26	−0.61	−0.26	0.77	0.79	−0.67	0.68	**−0.91**	0.79	0.78	**0.96**	**0.96**	0.81	1.00									
NCA	−0.66	**0.98**	0.27	**0.96**	−0.27	−0.51	−0.51	0.58	−0.41	0.77	−0.49	−0.51	−0.51	−0.51	−0.27	−0.59	1.00								
TCA	−0.45	**0.93**	0.47	**0.87**	−0.47	−0.26	−0.24	0.36	−0.21	0.49	−0.21	−0.24	−0.17	−0.17	0.06	−0.27	**0.90**	1.00							
TCAI	0.74	−0.47	0.24	−0.55	−0.24	0.84	**0.86**	−0.77	0.74	−0.81	**0.87**	**0.85**	**1.00**	**1.00**	0.80	**0.96**	−0.51	−0.17	1.00						
MSIDI	0.29	0.20	−0.43	0.36	0.43	0.43	0.34	−0.34	0.46	0.37	0.36	0.35	−0.01	−0.01	−0.26	−0.15	0.28	0.29	−0.01	1.00					
MSIEI	0.29	0.20	−0.43	0.36	0.43	0.43	0.34	−0.34	0.46	0.37	0.36	0.35	−0.01	−0.01	−0.26	−0.15	0.28	0.29	−0.01	**1.00**	1.00				
SHDI	0.36	0.08	−0.35	0.12	0.35	0.61	0.53	−0.54	0.57	0.13	0.56	0.52	0.31	0.31	0.08	0.15	0.10	0.22	0.31	**0.85**	**0.85**	1.00			
SHEI	0.36	0.08	−0.35	0.12	0.35	0.61	0.53	−0.54	0.57	0.13	0.56	0.52	0.31	0.31	0.08	0.15	0.10	0.22	0.31	**0.85**	**0.85**	**1.00**	1.00		
SIDI	0.29	0.20	−0.43	0.36	0.43	0.43	0.34	−0.34	0.46	0.37	0.36	0.35	−0.01	−0.01	−0.26	−0.15	0.28	0.29	−0.01	**1.00**	**1.00**	**0.85**	**0.85**	1.00	
SIEI	0.29	0.20	−0.43	0.36	0.43	0.43	0.34	−0.34	0.46	0.37	0.36	0.35	−0.01	−0.01	−0.26	−0.15	0.28	0.29	−0.01	**1.00**	**1.00**	**0.85**	**0.85**	**1.00**	1.00

*Only the coefficients in the lower diagonal part are presented above. The computation considers all spatial units at the two different years. Descriptions of the metrics are given in table 2.

index (LPI) quantifies the percentage of total landscape area comprised by the largest patch, which can be used to examine how landscape configuration varies. In both 1989 and 2002, there were three units whose largest patches comprised more than 14% of the landscape. These units were the Pensacola Bay watershed, the city buffer area and the coastline buffer area. The largest patch in the Blackwater River watershed comprised less than one percent of the landscape. The LPI scores were quite stable between 1989 and 2002 for each unit except the city buffer area, where a decrease of 15.36% occurred.

Number of patches (NP) can be used to quantify spatial heterogeneity of the entire landscape mosaic (McGarigal and Marks 1995). In 1989, the Yellow River

Table 5. Results of principal component analysis (PCA) and varimax rotation of the first five components at the class level*.

	Component number 1	2	3	4	5	
	Eigenvalues and cumulative proportion of variance explained by PCA					
Eigenvalue	8.994	5.433	4.587	1.594	1.278	
Cumulative Variance	35.975	57.708	76.054	82.432	87.545	
	Component pattern after varimax rotation					*Communality***
CA	0.012	0.002	0.477	**0.843**	0.078	0.94
LPI	**0.789**	0.354	0.291	−0.237	−0.048	0.89
PLAND	0.352	0.106	**0.836**	0.275	−0.184	0.94
MPS	**0.973**	−0.065	0.157	−0.023	0.022	0.98
NP	−0.088	0.478	−0.041	**0.751**	−0.247	0.86
PD	−0.139	0.616	0.142	0.236	−0.621	0.86
PSCV	0.087	**0.971**	−0.039	0.053	0.025	0.96
PSSD	**0.982**	0.043	0.094	−0.017	0.129	0.99
AWMPFD	0.076	−0.114	−0.048	**−0.798**	0.397	0.82
AWMSI	0.011	**0.895**	0.155	−0.142	−0.142	0.87
MPFD	0.078	0.517	−0.276	−0.099	−0.608	0.73
MSI	0.263	0.154	0.649	0.120	0.111	0.54
CACV1	−0.014	**0.860**	−0.286	0.189	−0.219	0.91
CACV2	0.114	**0.813**	0.125	0.116	0.337	0.82
CAD	−0.188	−0.068	**0.788**	0.447	−0.155	0.88
CASD1	**0.985**	0.008	0.059	−0.005	0.120	0.99
CASD2	**0.957**	0.048	−0.002	0.031	0.183	0.95
CPLAND	**0.752**	0.019	0.593	0.073	−0.013	0.92
MCA1	**0.981**	−0.060	0.098	−0.025	0.000	0.98
MCA2	**0.979**	−0.019	0.026	0.012	0.082	0.97
MCAI	0.250	−0.300	**0.747**	0.217	0.181	0.79
NCA	−0.129	−0.119	0.484	**0.807**	0.030	0.92
TCA	0.277	−0.015	0.473	0.739	0.237	0.90
TCAI	0.663	0.180	0.432	0.042	0.476	0.89
IJI	0.340	0.085	−0.084	−0.202	0.652	0.60
					sum	21.89
	Variance explained by each factor after rotation					
	7.908	4.357	3.883	3.690	2.048	

*The computation considers all the spatial units at the two different years. Descriptions of the metrics are given in table 2. Entries (correlation coefficients) in bold are considered to be strongly associated with one or more principal components. The metrics which were excluded for further considerations are shaded.

**Communality is the proportion of variance that each variable has in common with other variables.

Table 6. Spearman's rank correlation coefficient matrix for 18 landscape metrics at the class level*.

	CA	LPI	PLAND	MPS	NP	PSCV	PSSD	AWMPFD	AWMSI	CACV1	CACV2	CAD	CASD1	CASD2	CPLAND	MCA1	MCA2	MCAI	NCA
CA	1.00																		
LPI	0.52	1.00																	
PLAND	**0.86**	0.67	1.00																
MPS	0.57	0.58	0.62	1.00															
NP	0.78	0.18	0.57	−0.01	1.00														
PSCV	0.39	0.81	0.37	0.32	0.25	1.00													
PSSD	0.65	**0.87**	0.69	0.81	0.19	0.76	1.00												
AWMPFD	−0.75	−0.08	−0.52	−0.03	**−0.89**	−0.10	−0.11	1.00											
AWMSI	0.33	0.79	0.38	0.35	0.18	**0.88**	0.74	0.05	1.00										
CACV1	0.06	0.38	−0.03	−0.27	0.30	0.66	0.20	−0.19	0.48	1.00									
CACV2	0.54	0.82	0.48	0.46	0.33	**0.88**	0.81	−0.24	0.74	0.57	1.00								
CAD	0.78	0.45	**0.87**	0.50	0.65	0.16	0.46	−0.53	0.22	−0.17	0.33	1.00							
CASD1	0.65	**0.85**	0.68	0.81	0.19	0.74	**0.99**	−0.14	0.67	0.19	0.82	0.46	1.00						
CASD2	0.59	**0.87**	0.59	0.66	0.22	**0.85**	**0.93**	−0.17	0.74	0.37	**0.89**	0.33	**0.95**	1.00					
CPLAND	0.83	0.76	**0.93**	0.79	0.42	0.49	0.84	−0.38	0.47	−0.06	0.60	0.78	**0.85**	0.76	1.00				
MCA1	0.60	0.68	0.65	**0.98**	0.04	0.46	**0.88**	−0.06	0.44	−0.15	0.58	0.50	**0.90**	0.78	0.84	1.00			
MCA2	0.58	0.83	0.59	0.71	0.18	0.77	**0.91**	−0.14	0.67	0.25	0.77	0.33	**0.94**	**0.97**	0.78	0.83	1.00		
MCAI	0.54	0.33	0.60	**0.89**	0.05	0.02	0.56	−0.16	0.05	−0.53	0.20	0.59	0.59	0.41	0.71	0.84	0.50	1.00	
NCA	**0.91**	0.38	0.78	0.47	0.81	0.26	0.50	−0.70	0.26	−0.03	0.43	**0.90**	0.49	0.40	0.72	0.48	0.38	0.51	1.00

*Only the coefficients in the lower diagonal part are presented above. The computation considers all spatial units at the two different years. Descriptions of the metrics are given in table 2.

Table 7. Landscape metrics for different spatial units at the landscape level*.

Spatial observational unit		Year	Area	Patch		Shape	Core area		Diversity	Configuration
			LPI	MPS (ha)	NP	AWMPFD	CACV1	TCA (ha)	MSIDI	IJI
1	Pensacola estuarine drainage area	1989	2.880	6.056	150464	0.461	3892.04	304251	1.434	66.59
		2002	2.867	5.318	171333	0.364	4322.68	289370	1.613	69.72
2	Blackwater River	1989	0.873	6.204	35566	0.813	910.14	65624	1.175	62.33
		2002	0.824	5.545	39795	0.711	980.14	60923	1.349	66.07
3	Escambia River	1989	4.896	5.222	38763	0.793	2891.77	56058	1.475	65.25
		2002	4.796	4.799	42179	0.705	3092.49	57311	1.497	67.67
4	Pensacola Bay	1989	18.885	6.913	19976	1.066	5205.50	75215	1.453	73.03
		2002	18.823	5.785	23872	0.991	5990.05	70555	1.517	62.61
5	Yellow River	1989	2.139	6.134	57312	0.709	1690.47	106495	1.203	62.56
		2002	2.220	5.272	66678	0.596	1912.41	99960	1.423	67.74
6	Coastline buffers	1989	14.220	5.614	11758	1.108	3761.19	29905	1.359	80.21
		2002	14.045	4.759	13869	1.032	4225.98	28466	1.388	66.97
7	City buffers	1989	17.574	4.068	15056	1.046	5796.48	25663	1.577	74.59
		2002	14.874	3.768	16252	0.978	6362.83	23172	1.373	56.95
8	Highway buffers	1989	2.227	5.249	102876	0.505	3158.00	159490	1.540	67.99
		2002	2.214	4.733	114097	0.418	3294.19	153270	1.730	69.76

*Descriptions of the metrics are given in table 2.

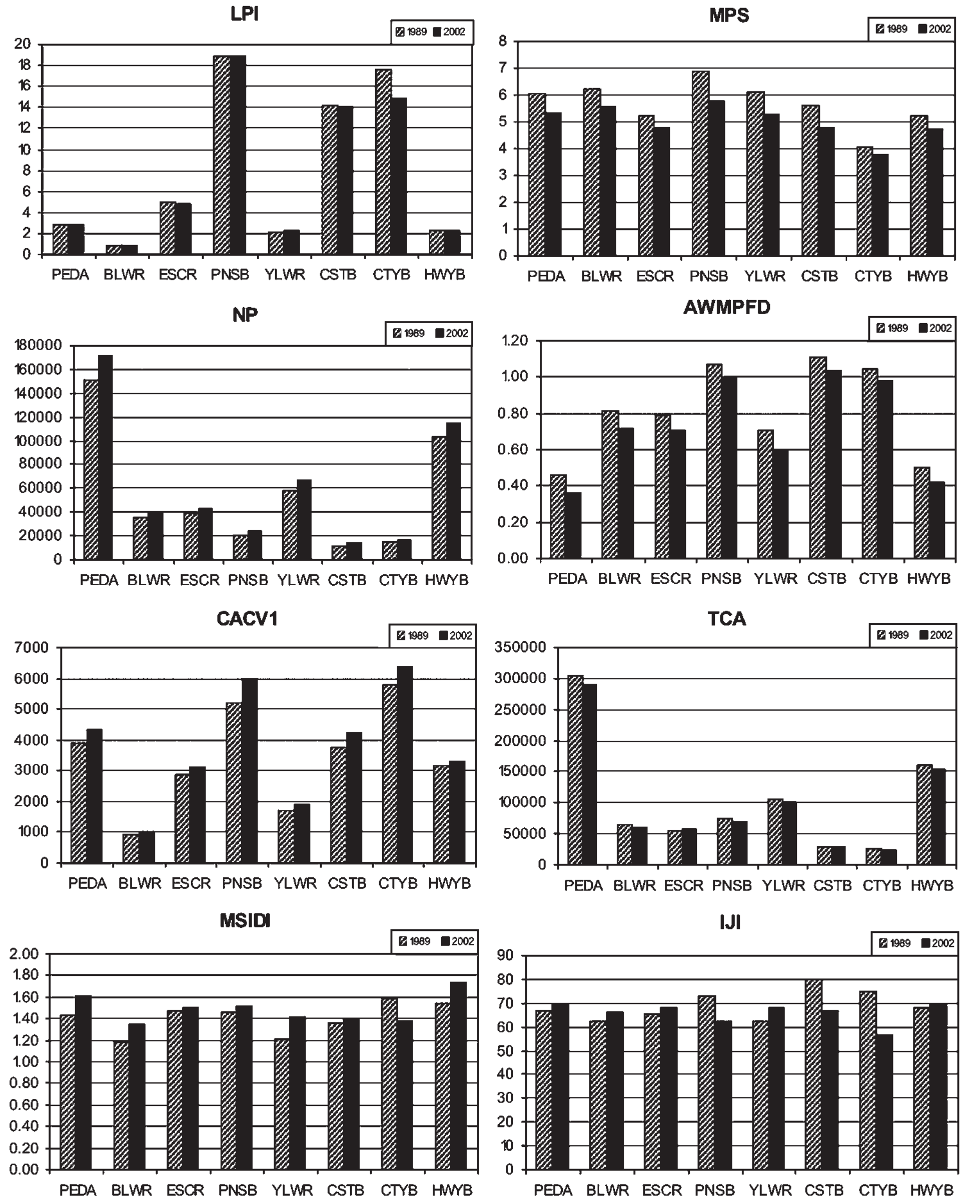

Figure 5. Change in landscape structure and pattern for different spatial observational units at the landscape level. Descriptions of the metrics and the spatial observational units are given in table 2 and figure 4, respectively.

watershed had the largest number of patches (57 312) among the four (sub)watersheds, followed by the Escambia River (38 763), the Blackwater River (35 566) and the Pensacola Bay (19 976). In 2002, the numbers of patches increased consistently for each unit, with the Pensacola Bay watershed increasing the most (19.50%). This indicates that the landscape mosaic for each unit became more heterogeneous.

Area weighted mean patch fractal dimension (AWMPFD) is an index quantifying the complexity of patch shape, with higher scores indicating greater complexity in patch shape. Among the four (sub)watersheds, the Pensacola Bay received the highest AWMPFD scores in both years. The coastline buffer area and city buffer area received much higher scores than the PEDA. Between 1989 and 2002, the AWMPFD scores for all units decreased, indicating less complexity in patch shape. This follows the earlier findings (e.g. Lam and De Cola 1993) that the patch shape of a landscape under intensive human influence tends to be more regular.

Two metrics characterizing core area were examined. Total core area (TCA) reflects both landscape composition and configuration, and can be used to quantify habitat quality (McGarigal and Marks 1995). Among the four (sub)hydrological units, the Yellow River watershed had the largest TCA for both years. Between 1989 and 2002, the TCA for each unit shrank consistently. Patch core area coefficient of variation (CACV1) represents the relative variation in core area per patch, and conveys more useful information than TCA (Mcgarigal and Marks 1995). Among the four watersheds, the Pensacola Bay watershed showed the largest CACV1 scores in both years. In both 1989 and 2002, the city buffer area had larger CACV1 scores than the PEDA's. Between 1989 and 2002, the CACV1 scores increased consistently for all units, implying that the patch core areas became more variable.

The modified Simpson's diversity index (MSIDI) is used to measure diversity at the landscape level. For both 1989 and 2002, the MSIDI scores did not vary much across units. Between 1989 and 2002, the MSIDI scores for all units except the highway buffer area shrank.

The last index used is IJI (interspersion and juxtaposition index), which measures the extent to which patch types are interspersed. In 1989, the Pensacola Bay watershed had the highest IJI score among four (sub)hydrological units, but had the lowest score in 2002. This indicates that the landscape mosaic in Pensacola Bay watershed became less interspersed with similar adjacent patch types. Like the Pensacola Bay watershed, two buffer areas (city and coastline) also showed a decline in their IJI scores. All other units increased somewhat in IJI scores.

3.2 *Class level*

The proportion of land-use and land-cover classes for each spatial unit holds important information about the composition of landscape mosaic. How this proportion changes can help understand the driving forces behind observed changes in landscape pattern over space and time. The proportion of land-use and land cover for each unit is presented in table 8. For the entire PEDA, the largest proportion of land class in 1989 was forest land, occupying 58.01% of the total area. This shrank to 55.48% in 2002. The two urban classes occupied 10.16% of the total area in 1989 and increased to 13.65% in 2002, representing an increase of 34.35%. Both woody wetland and agricultural land shrank slightly between 1989 and 2002.

When compared to the PEDA, the three predefined buffer areas had much higher proportions of urban land in both years. The city buffer area had the largest proportion of urban land among all units, which was 37.44% and 47.54% in 1989 and 2002, respectively, representing an increase of 26.98%. At the same time, forest land and agricultural land shrank by 36.56% and 59.85%, respectively. Between 1989 and 2002, the proportion of urban land in the coastline buffer area increased by 29.30%, while forest land and agricultural land decreased by 28.75% and 37.21%, respectively. Within the highway buffer area, agricultural land declined by 32.13% between 1989 and 2002.

Among the four sub-watersheds, the Pensacola Bay had the largest proportion of urban land in both 1989 (35.94%) and 2002 (45.07%), representing an increase of 25.04%. The proportion of forest land in the Pensacola Bay was the smallest among the four watersheds in both years. Between 1989 and 2002, agricultural land declined by 45.98% in the Pensacola Bay watershed. When compared with the Pensacola Bay watershed, the other three watersheds had a higher proportion of forest land; whereas urban land, although relatively smaller in the percentage, had increased at a much higher rate. Finally, during the period 1989–2002, woody wetland declined consistently for all units, with the highest rate occurring in the city buffer area.

Further analysis at the class level focuses on eight metrics for three classes: low-density urban, evergreen forest and woody wetlands. These classes were chosen because they were quite dynamic, as can be seen from table 8. The amount of low-density urban increased substantially, while evergreen forest and woody wetlands declined consistently in each unit. Substantial change from forest and woody wetland to low-density urban may be an important change in landscape pattern that affects landscape function. Woody wetlands, although relatively small, are ecologically important for wildlife habitat, flood protection, water purification and recreation.

Table 8. Land-use and land-cover proportions for each spatial unit*.

Land use and land cover		Spatial observational units							
		PEDA	BLWR	ESCR	PNSB	YLWR	CSTB	CTYB	HWYB
LDU	1989	1.17	0.62	0.84	4.55	1.00	3.27	23.79	1.83
	2002	5.01	3.26	3.40	15.96	4.90	11.11	34.99	7.39
	Change	326.81	423.67	304.42	250.50	389.65	239.69	47.07	303.26
HDU	1989	8.99	6.38	6.74	31.39	7.58	19.70	13.65	11.04
	2002	8.64	6.23	7.08	29.11	7.15	18.59	12.55	10.27
	Change	−3.92	−2.45	5.10	−7.25	−5.59	−5.64	−8.05	−7.04
AGL	1989	15.24	12.97	25.51	3.24	15.84	1.48	4.91	18.70
	2002	15.14	13.89	26.46	1.75	14.81	0.68	4.02	18.52
	Change	−0.69	7.04	3.74	−45.98	−6.51	−54.36	−18.08	−0.94
EGF	1989	40.15	48.36	29.10	34.97	47.96	11.28	13.49	35.89
	2002	29.74	38.82	19.69	29.44	33.81	7.08	5.41	24.36
	Change	−25.93	−19.73	−32.32	−15.83	−29.50	−37.21	−59.85	−32.13
MXF	1989	18.06	21.01	24.58	7.13	17.61	5.91	8.23	16.19
	2002	25.74	27.60	31.00	5.80	30.02	5.16	8.37	23.85
	Change	42.52	31.35	26.10	−18.60	70.42	−12.67	1.69	47.36
WWL	1989	9.73	9.83	11.56	13.13	9.02	8.75	2.42	8.38
	2002	9.14	9.12	11.05	12.41	8.41	7.90	1.87	7.78
	Change	−6.08	−7.21	−4.41	−5.54	−6.76	−9.78	−22.84	−7.22
EHW	1989	0.65	0.34	0.94	2.13	0.37	3.60	0.39	0.73
	2002	0.65	0.63	0.69	2.44	0.27	4.03	0.36	0.69
	Change	0.92	81.99	−27.22	14.64	−25.91	12.05	−7.74	−5.17
BRL	1989	0.10	0.00	0.01	1.72	0.00	2.28	0.99	0.28
	2002	0.10	0.00	0.02	1.70	0.01	2.26	0.28	0.29
	Change	−0.81	−22.95	89.64	−1.25	465.82	−0.97	−72.00	2.64
WTR	1989	5.91	0.47	0.60	1.72	0.62	43.72	32.13	6.96
	2002	5.84	0.45	0.49	1.70	0.61	43.18	32.14	6.86
	Change	−1.12	−3.67	−18.47	−1.25	−1.18	−1.23	0.02	−1.46

*Descriptions of the abbreviated land-use and land-cover units and the spatial observational units are given in table 1 and figure 4, respectively.

The MPS increased substantially in each unit during the period 1989–2002 (table 9 and figure 6). Among the eight units, the city buffer area had the largest mean low-density urban patch size (MPS) in both years. At the same time, both the number of low-density urban patches (NP) and class proportion (PLAND) increased in each unit. This represents a process of pervasive suburbanization by which numerous residential urban clusters emerged and agglomerated to form larger masses in each unit. The largest patch index (LPI) scores were quite small for each unit except the city buffer area. The shape of low-density urban patches was fairly regular, as indicated by relatively low AWMSI (Area-Weighted Mean Shape Index) scores in each unit except the city buffer area. Here the AWMSI was quite large in 1989 but shrank substantially in 2002. In both years, the total low-density urban core area (TCA) was quite small for each unit except the city buffer area, where large, well-developed residential areas existed. The city buffer area also had the largest core area coefficients of variation (CACV1) among all units in both years. The IJI scores of low-density urban patches were greater than 40 in each unit for both years. The IJI scores showed little change between 1989 and 2002 except for the Pensacola Bay watershed, the city buffer area and the coastline buffer area, where residential urban patches became less interspersed with similar adjacent patch types.

Between 1989 and 2002, the mean evergreen forest patch size (MPS) for the PEDA declined, indicating that the evergreen forest landscape became more fragmented (table 9 and figure 7). Among the four watersheds, the Escambia River had the smallest mean evergreen forest patch size in both years. The MPS of evergreen forest patches was relatively large in the Blackwater River and Yellow River watersheds in 1989, but declined substantially in 2002. In both years, the MPS of evergreen forest patches was relatively small for the coastline buffer and city buffer areas. The Pensacola Bay watershed was the only unit where the MPS of evergreen forest patches increased between 1989 and 2002, indicating that many small patches were removed as a result of intensified suburbanization. Between 1989 and 2002, the number of evergreen forest patches (NP) increased in the PEDA and the watersheds of Blackwater River and Yellow River, but declined in other units. The largest evergreen forest patch index (LPI) shrank in each unit. The evergreen forest patch shape tended to be less complex in each unit, as indicated by the decrease in AWMSI (Area-Weighted Mean Shape Index) scores between 1989 and 2002. Among all units, the city buffers and the coastline buffers had the smallest total evergreen forest core area (TCA) but their core area coefficients of variation (CACV1) score was the largest in both years. The TCA scores declined substantially in each unit during the period of 1989 and 2002. The evergreen forest patches were fairly well interspersed in both years.

The Escambia River watershed had the largest mean woody wetland patch size (MPS) in both years (table 9 and figure 8). Between 1989 and 2002, the MPS shrank in each unit except the Pensacola Bay watershed and the coastline buffer area where many small-size woody wetland patches were removed due to Pensacola's increased suburbanization. The number of woody wetland patches (NP) declined in each unit except the Blackwater River watershed, where a small increase occurred. Among all units, the Escambia River watershed had the largest scores for largest woody wetland patch index (LPI) in both years, while the city buffer area had the smallest scores. During the period 1989–2002, the AWMSI (Area-Weighted Mean Shape Index) scores decreased in each unit except the coastline buffer area where a small increase occurred. The city buffer area had the smallest total woody wetland core

Table 9. Landscape metrics for different spatial units at the class level*.

	Spatial observation unit															
	PEDA		BLWR		ESCR		PNSB		YLWR		CSTB		CTYB		HWYB	
Year	1989	2002	1989	2002	1989	2002	1989	2002	1989	2002	1989	2002	1989	2002	1989	2002
Low Density Urban																
LPI	0.011	0.016	0.009	0.057	0.009	0.048	0.032	0.086	0.028	0.033	0.063	0.102	17.574	12.559	0.018	0.027
PLAND (%)	1.18	5.02	0.62	3.27	0.84	3.41	2.97	10.41	1.00	4.90	3.27	11.11	23.79	34.99	1.83	7.39
MPS (ha)	0.816	2.085	0.723	2.403	0.790	1.616	0.713	1.734	1.043	2.620	0.647	1.434	2.482	2.725	0.808	2.071
NP	13122	21920	1902	2998	2158	4266	5757	8293	3375	6576	3337	5115	5871	7864	12241	19257
AWMSI	1.089	1.515	1.529	2.143	1.587	1.972	1.489	1.840	1.621	2.034	1.596	1.879	25.925	18.469	1.133	1.616
CACV1	3090.9	988.2	2700.0	710.2	1766.7	1113.3	2600.0	1121.9	1697.4	791.9	3100.0	1323.1	7655.3	6951.5	2933.3	1042.5
TCA (ha)	293	1671	3	263	6	127	15	263	265	978	5	64	4202	2919	291	1414
IJI	55.70	55.53	56.49	57.67	59.87	59.51	48.74	42.64	57.53	59.66	50.59	42.45	81.67	70.59	52.44	51.28
Evergreen Forest																
LPI	0.170	0.140	0.478	0.364	0.319	0.273	0.617	0.395	0.440	0.363	0.716	0.484	0.840	0.388	0.211	0.168
PLAND (%)	40.15	29.74	48.36	38.82	29.13	19.71	22.82	19.21	47.96	33.81	11.28	7.09	13.49	5.42	35.89	24.36
MPS (ha)	11.741	7.910	14.797	10.564	6.749	4.652	8.035	8.598	14.525	8.046	3.064	2.797	2.670	2.330	8.522	5.833
NP	31157	34255	7212	8109	8737	8578	3922	3085	11607	14773	2431	1672	3093	1423	22744	22552
AWMSI	2.617	2.034	2.771	2.542	2.763	2.200	2.498	2.308	3.185	2.361	2.393	2.363	2.908	2.311	2.632	2.051
CACV1	639.6	699.4	481.9	545.6	709.4	720.0	798.7	597.2	618.5	753.5	1377.7	1196.7	1319.4	1131.9	711.1	770.3
TCA (ha)	124178	79461	38572	27886	13597	6657	12239	9862	59240	34728	1058	611	1179	299	55704	30692
IJI	71.18	71.56	69.32	69.14	66.21	64.01	71.07	70.30	70.72	71.55	76.55	77.24	82.08	70.15	71.86	72.43
Mixed Forest																
LPI	0.269	0.221	0.846	0.824	0.526	0.820	0.171	0.098	0.696	0.572	0.187	0.140	0.427	0.284	0.166	0.207
PLAND (%)	18.06	25.74	21.01	27.60	24.61	31.03	4.65	3.79	17.62	30.02	5.91	5.16	8.23	8.37	16.19	23.85
MPS (ha)	8.342	10.361	8.389	8.306	9.621	11.184	3.247	2.953	8.641	13.093	2.997	3.008	3.492	4.641	6.792	8.832
NP	19727	22635	5526	7331	5178	5617	1979	1771	7166	8060	1302	1133	1444	1105	12869	14585
AWMSI	2.610	2.846	2.904	2.749	2.787	3.191	1.924	1.848	3.017	3.463	1.934	1.884	2.069	2.161	2.030	2.458
CACV1	978.1	822.6	1004.6	1001.9	718.8	731.8	722.4	825.7	1061.9	717.5	675.1	558.1	797.0	624.2	749.5	703.9
TCA (ha)	43530	67732	12946	15912	12977	17327	778	503	16716	33891	412	293	577	766	19676	34077
IJI	58.67	66.72	56.22	62.66	59.73	67.30	71.54	73.23	54.68	66.07	74.55	77.94	72.18	71.35	61.82	69.66

Table 9. (*Continued.*)

	Spatial observation unit															
	PEDA		BLWR		ESCR		PNSB		YLWR		CSTB		CTYB		HWYB	
Year	1989	2002	1989	2002	1989	2002	1989	2002	1989	2002	1989	2002	1989	2002	1989	2002
Woody Wetland																
LPI	1.088	1.066	0.465	0.582	4.896	4.796	2.125	2.200	2.139	2.220	2.014	2.109	0.170	0.155	0.858	0.791
PLAND (%)	9.73	9.14	9.83	9.12	11.58	11.07	8.57	8.10	9.02	8.41	8.75	7.90	2.42	1.87	8.38	7.78
MPS (ha)	13.695	13.469	12.105	11.042	20.963	20.800	14.415	16.344	11.455	11.297	9.395	10.488	4.038	3.403	10.254	10.067
NP	6476	6184	1792	1823	1118	1077	821	684	2768	2617	615	497	367	336	4415	4172
AWMSI	5.082	4.745	4.246	4.048	7.079	6.138	4.522	4.270	4.707	4.636	3.047	3.397	2.011	1.987	3.742	3.320
CACV1	2344.9	2358.8	766.5	926.2	2111.6	2091.9	1272.4	1245.6	2497.9	2511.1	1170.7	1111.1	769.0	755.0	1979.9	1721.0
TCA (ha)	35355	35966	4407	4412	12593	13035	5834	5973	12472	12512	2396	2267	195	149	15561	15836
IJI	67.05	67.97	56.57	58.09	78.78	77.00	75.45	75.40	61.07	62.13	86.44	87.47	78.34	73.41	71.26	72.24

*Descriptions of the metrics and the spatial observational units are given in table 2 and figure 4, respectively.

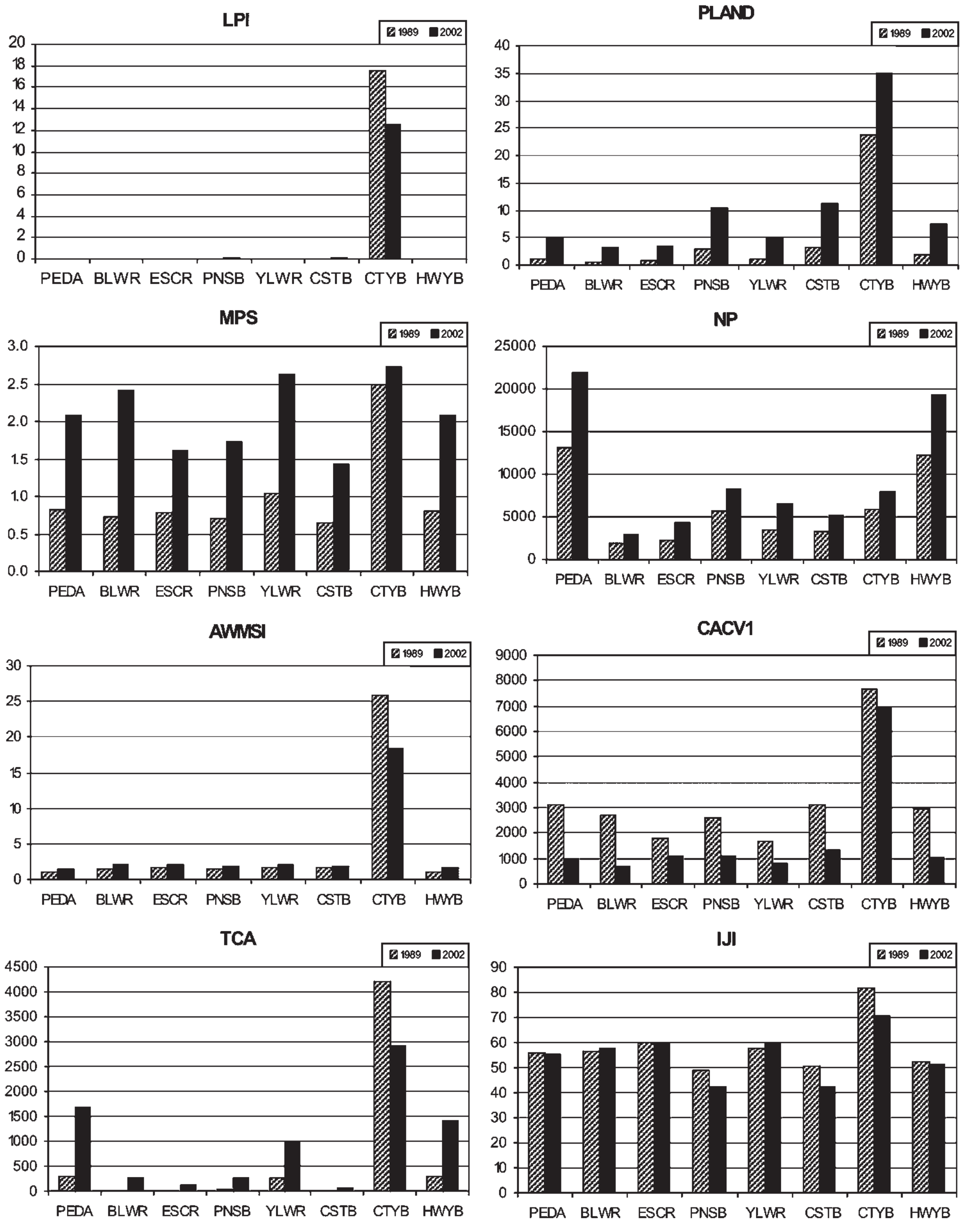

Figure 6. Change in landscape structure and pattern of the low-density urban land class for different spatial observational units. Descriptions of the metrics and the spatial observational units are given in table 2 and figure 4, respectively.

area (TCA). The Escambia River watershed had the largest total woody wetland core area among all the four watersheds in both years. The Yellow River watershed has the largest woody wetland core area coefficient of variation (CACV1) among all units in both years. Based on the IJI scores, woody wetland patches were fairly well interspersed in both years.

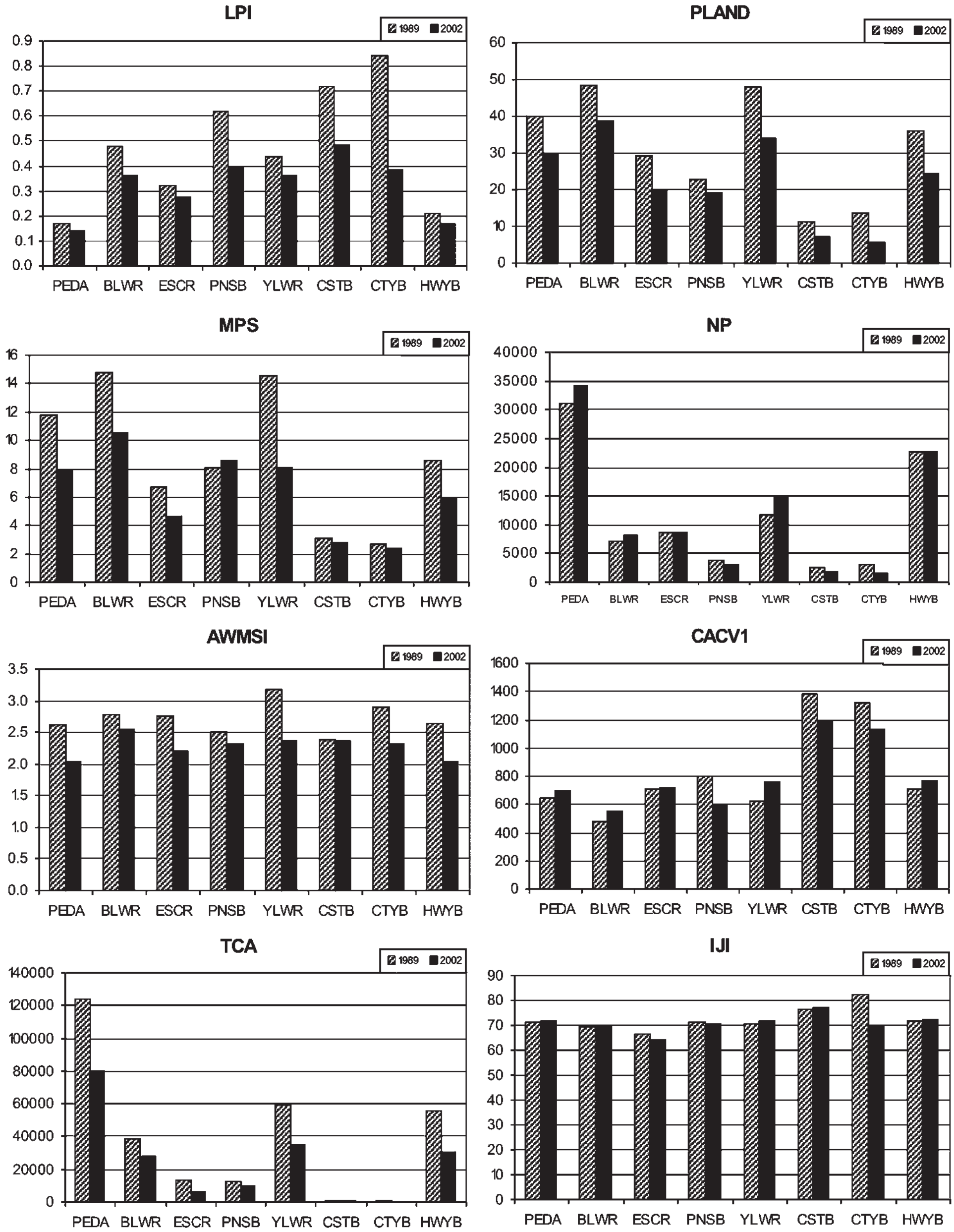

Figure 7. Change in landscape structure and pattern of the evergreen forest class for different spatial observational units. Descriptions of the metrics and the spatial observational units are given in table 2 and figure 4, respectively.

4. Conclusions

Accelerated population growth and intensified human economic activities threaten estuarine ecosystem health. Therefore, there is an urgent need to find efficient ways to manage and plan these highly sensitive environments. A quantitative assessment of landscape pattern and its change by using landscape metrics can help identify some of the most important aspects of environmental changes, which are caused by complex interactions between social and biophysical processes. Remote sensing allows a retrospective, synoptic viewing of large regions, thus providing useful data sources for computing landscape metrics that support landscape monitoring and assessment.

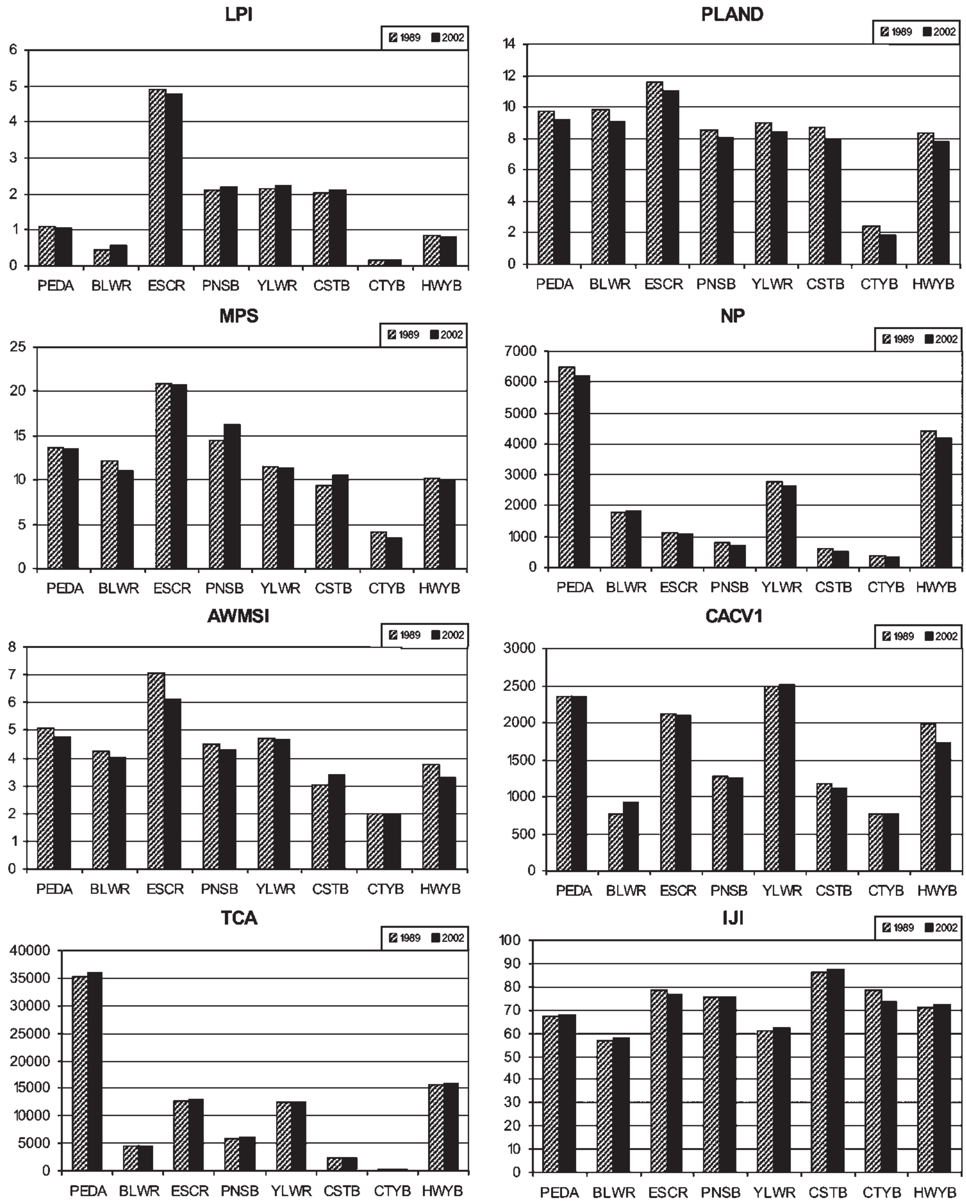

Figure 8. Change in landscape structure and pattern of the woody wetland class for different spatial observational units. Descriptions of the metrics and the spatial observational units are given in table 2 and figure 4, respectively.

By examining the Pensacola estuarine drainage area, this study demonstrates the usefulness of remote sensing, landscape metrics and multivariate statistical analysis for quantifying landscape pattern and its change. The methods identified here are based on an understanding of landscape features, the nature of landscape metrics and information extraction and reduction techniques. Two land-use and land-cover maps were produced through hierarchical classification and spatial reclassification from remotely sensed imagery. The maps were then used as the primary data for computing landscape metrics that quantify ecologically important landscape characteristics. The spatial observational units used were related to either a hydrological unit or a predefined buffer zone so that the variation of landscape pattern can be characterized. This should help understand the driving forces behind observed changes over space and time. A large set of landscape metrics were computed for different spatial units at the landscape and class levels. Landscape ecology principles, principal component analysis and Spearman's rank correlation analysis were applied to help identify a small group of core metrics that capture the major properties of a landscape. With the use of these core metrics, landscape pattern and its change were quantified for different spatial units at the landscape and class levels.

This study provides a regional case study, focusing on the Pensacola estuarine drainage area, one of few exemplary large-scale river-driven estuarine systems across the northern Gulf of Mexico. The results reveal that the overall landscape mosaics became more heterogeneous and the classes of patches tended to be more fragmented likely due to Pensacola's fast urban and economic growth during the past decade. It was found that landscape pattern and its change varied greatly across different spatial units. Landscape fragmentation is more intensive in the Pensacola Bay watershed, along the coastlines and around the city centres, where urbanization and human economic activities are more concentrated. These findings should be useful not only to those who study estuarine watershed dynamics but also to those who must manage and provide services in this highly sensitive ecosystem. Coastal managers in the PEDA should target highly fragmented areas where restoration, management or changes in policies are needed to slow, stop or reverse declining environmental trends. Given that many estuaries face the growing problems caused by excess nutrients flowing from upstream watersheds, the landscape pattern characterization technical framework developed in the current study focusing on Pensacola Bay can be easily applicable to other estuarine drainage basins. These methods can improve understanding of socio-ecological dynamics of landscape, thus facilitating a sophisticated approach to estuarine environmental conservation and protection.

Acknowledgements

This research has been supported by a grant from the US Environmental Protection Agency's Science to Achieve Results (STAR) Estuarine and Great Lakes (EaGLe) Program through funding to the CEER-GOM, US EPA Agreement R829458. Although the research described in this article has been funded wholly or in part by the United States Environmental Protection Agency, it has not been subjected to the Agency's required peer and policy review and therefore does not necessarily reflect the views of the Agency and no official endorsement should be inferred. The authors wish to thank several anonymous reviewers for their critical comments that greatly improve the earlier version of the manuscript.

References

ANDERSON, J.R., HARDY, E.E., ROACH, J.T. and WITMER, R.E., 1976, *A Land Use and Land Cover Classification System for Use with Remote Sensor Data* (Sioux Falls, S.D., USA: USGS Professional Paper 964).

BASNYAT, P., TEETER, L.D., FLYNN, K.M. and LOCKABY, B.G., 1999, Relationships between landscape characteristics and nonpoint source pollution inputs to coastal estuaries. *Environmental Management*, **23**, pp. 539–549.

BOWEN, J.L. and VALIELA, I., 2001, The ecological effects of urbanization of coastal watersheds: historical increases in nitrogen loads and eutrophication of Waquoit Bay estuaries. *Canadian Journal of Fisheries and Aquatic Sciences*, **58**, pp. 1489–1500.

CAIN, D., RIITTERS, K. and ORVIS, K., 1997, A multi-scale analysis of landscape statistics. *Landscape Ecology*, **12**, pp. 199–212.

DOJIRIA, M., YAMAGUCHI, M., WEISBERG, S.B. and LEE, H.J., 2003, Changing anthropogenic influence on the Santa Monica Bay watershed. *Marine Environmental Research*, **56**, pp. 1–14.

EPA, 1999, *The Ecological Condition of Estuaries in the Gulf of Mexico* (EPA 620-R-98-004).

ESRI, 2003, *ESRI Data & Maps 2002*. Available online at: http://www.esri.com/data/datacd02.html (accessed 20 December 2004).

FINKL, C.W. and CHARLIER, R.H., 2003, Sustainability of subtropical coastal zones in southeastern Florida: Challenges for urbanized coastal environments threatened by development, pollution, water supply, and storm hazards. *Journal of Coastal Research*, **19**, pp. 934–943.

FORMAN, R.R.T., 1995, *Land Mosaic: The Ecology of Landscapes and Regions,* 2nd edn (England: Cambridge University Press).

FULLER, D.O., 2001, Forest fragmentation in Loudoun County, Virginia, USA evaluated with multitemporal Landsat imagery. *Landscape Ecology*, **16**, pp. 627–642.

GERGEL, S.E., TURNER, M.G., MILLER, J.R., MELACK, J.M. and STANLEY, E.H., 2002, Landscape indicators of human impacts to riverine systems. *Aquatic Sciences*, **64**, pp. 118–128.

GRIFFITH, J.A., MARTINKO, E.A. and PRICE, K.P., 2000, Landscape structure analysis of Kansas at three scales. *Landscape and Urban Planning*, **52**, pp. 45–61.

GUSTAFSON, E.J., 1998, Quantifying landscape spatial pattern: What is the state of the art? *Ecosystems*, **1**, pp. 143–156.

HERZOG, F. and LAUSCH, A., 2001, Supplementing land-use statistics with landscape metrics: Some methodological considerations. *Environmental Monitoring and Assessment*, **72**, pp. 37–50.

HERZOG, F., LAUSCH, A., MULLER, E., THULKE, H.H., STEINHARDT, U. and LEHMANN, S., 2001, Landscape metrics for assessment of landscape destruction and rehabilitation. *Environmental Management*, **27**, pp. 91–107.

HOBBIE, J.E. (Ed.), 2000, *Estuarine Science: A Synthetic Approach to Research and Practice* (Washington DC: Island Press).

HUNSAKER, C., O'NEILL, R., JACKSON, B., TIMMINS, S., LEVINE, D. and NORTON, D., 1994, Sampling to characterize landscape pattern. *Landscape Ecology*, **9**, pp. 207–226.

LAM, N.S.-N. and DE COLA, L. (Eds), 1993, *Fractals in Geography* (NJ: Prentice Hall).

LEITAO, A.B. and AHERN, J., 2002, Applying landscape ecological concepts and metrics in sustainable landscape planning. *Landscape and Urban Planning*, **59**, pp. 65–93.

LI, X., LU, L., CHENG, G. and XIAO, H., 2001, Quantifying landscape structure of the Heihe River Basin, north-west China using FRAGSTATS. *Journal of Arid Environments*, **48**, pp. 521–535.

LIU, Y.B., NISHIYAMA, S. and KUSAKA, T., 2003, Examining landscape dynamics at a watershed scale using landsat TM imagery for detection of wintering hooded crane decline in Yashiro, Japan. *Environmental Management*, **31**, pp. 365–376.

MARSH, O.T., 1966, *Geology of Escambia and Santa Rosa Counties, Western Florida Panhandle* (Florida Geological Survey Bulletin 46).

McGarigal, K., 2002, Landscape Pattern Metrics. In *Encyclopedia of Environmentrics*, A.H. El-Shaarawi and W.W. Piegorsch (Eds), **2**, pp. 1135–1142 (England: Wiley & Sons).

McGarigal, K. and Marks, B.J., 1995, *FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure* (USDA Forest Service Technical Report PNW-GTR-351).

NFWMD, 1997, *The Pensacola Bay System Surface Water Improvement and Management Plan* (Program Development Series 97–2).

Niemi, G., Wardrop, D., Brooks, R., Anderson, S., Brady, V., Paerl, H., Rakocinski, C., Brouwer, M., Levinson, B. and McDonald, M., 2004, Rationale for a new generation of ecological indicators for coastal waters. *Environmental Health Perspectives*, **112**, pp. 979–986.

NOAA, 1999, ORCA's Coastal Assessment Framework (CAF). Available online at: http://spo.nos.noaa.gov/projects/caf/caf.html (accessed 10 December 2004).

Patil, G.P., Brooks, R.P., Myers, W.L., Rapport, D.J. and Taillie, C., 2001, Ecosystem health and its measurement at landscape scale: Toward the next generation of quantitative assessments. *Ecosystem Health*, **7**, pp. 307–316.

Ramsey, F.L. and Schafer, D.W., 1997, *The Statistical Sleuth: A Course in Methods of Data Analysis* (Belmont: Wadsworth Publishing Company).

Ravan, S.A. and Roy, P.S., 1997, Satellite remote sensing for ecological analysis of forested landscape. *Plant Ecology*, **131**, pp. 129–141.

Riitters, K.H., O'Neill, R.V., Hunsaker, C.T., Wickham, J.D., Yankee, D.H., Timmins, S.P., Jones, K.B. and Jackson, B.L., 1995, A factor analysis of landscape pattern and structure metrics. *Landscape Ecology*, **10**, pp. 23–39.

Turner, M.G., 1989, Landscape ecology: the effect of pattern and process. *Annual Review of Ecology and Systematics*, **20**, pp. 171–197.

Turner, M.G., 1990, Spatial and temporal analysis of landscape patterns. *Landscape Ecology*, **4**, pp. 21–30.

Turner, M.G., Gardner, R.H. and O'Neill, R.V., 2001, *Landscape Ecology in Theory and Practice* (New York: Springer-Verlag).

USGS, 2004, *1:250,000-scale Hydrologic Units of the United States.* Available online at: http://water.usgs.gov/GIS/metadata/usgswrd/XML/huc250k.xml (accessed 20 December 2004).

Walford, N., 1995, *Geographical Data Analysis* (England: Wiley & Sons).

Yang, X. and Liu, Z., 2005, Using satellite imagery and GIS for land-use and land-cover change mapping in estuarine watershed. *International Journal of Remote Sensing,* 00, pp. 00–01? (this volume).

Yang, X. and Lo, C.P., 2002, Using a time series of normalized satellite imagery to detect land use and land cover change in the Atlanta, Georgia metropolitan area. *International Journal of Remote Sensing*, **23**, pp. 1775–1798.

Zhang, D., Wallin, D.O. and Hao, Z., 1997, Rates and patterns of landscape change between 1972 and 1988 in the Changbai Mountain area of China and North Korea. *Landscape Ecology*, **12**, pp. 241–254.