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Development of a Reproducible Method for Determining Quantity of Water and its Configuration in a Marsh Landscape

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ABSTRACT

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Coastal Louisiana is a dynamic and ever-changing landscape. From 1956 to 2010, over 3,734 km^2 of Louisiana's coastal wetlands have been lost due to a combination of natural and human-induced activities. The resulting landscape constitutes a mosaic of conditions from highly deteriorated to relatively stable with intact landmasses. Understanding how and why coastal landscapes change over time is critical to restoration and rehabilitation efforts. Historically, changes in marsh pattern (*i.e.*, size and spatial distribution of marsh landmasses and water bodies) have been distinguished using visual identification by individual researchers. Difficulties associated with this approach include subjective interpretation, uncertain reproducibility, and laborious techniques. In order to minimize these limitations, this study aims to expand existing tools and techniques via a computer-based method, which uses geospatial technologies for determining shifts in landscape patterns. Our method is based on a raster framework and uses landscape statistics to develop conditions and thresholds for a marsh classification scheme. The classification scheme incorporates land and water classified imagery and a two-part classification system: (1) ratio of water to land, and (2) configuration and connectivity of water within wetland landscapes to evaluate changes in marsh patterns. This analysis system can also be used to trace trajectories in landscape patterns through space and time. Overall, our method provides a more automated means of quantifying landscape patterns and may serve as a reliable landscape evaluation tool for future investigations of wetland ecosystem processes in the northern Gulf of Mexico.

ADDITIONAL INDEX WORDS: *Landscape characterization, fragmentation metrics, landscape pattern analysis, wetlands, coastal Louisiana, geospatial technologies.*

INTRODUCTION

For the last half-century the marshes of coastal Louisiana have experienced rapid degradation. From 1956 to 2010, over 3,734 km^2 of Louisiana's coastal wetlands have been lost due to a combination of natural and human-induced activities (Couvillion *et al.*, 2011). Areas that were vast expanses of marsh have either transitioned into highly fragmented landscapes or completely converted to open water. As marsh deterioration increased, so did the understanding of their significance and the need to link wetland landscape form to ecological processes. Landscape assessments of coastal Louisiana have evolved from simple composition analyses (Chabreck, 1972; Gagliano and van Beek, 1970) to more complex computer-aided rates of change and sequencing measurements (Barras *et al.*, 2004; Bernier, Morton, and Barras, 2006). However, to better understand the degradation processes that operate within marsh landscapes, future assessments must transcend composition and consider how feature configuration and connectivity affect landscape function and stability. Previous studies (Barras, 2008; Dozier, 1983; Environmental Work Group, 2007; Evers, 1990; Evers *et al.*, 1992; Sasser *et al.*, 1986) endeavored to classify and track marsh degradation; however, those studies used visual estimation methods that were highly subjective and labor intensive. One resolution is to develop a methodology that can adjoin a wetland classification scheme with landscape structure metrics to systematically assess historical degradation trends in wetland landscapes.

Landscape characteristics and structural components are outcomes of interactions between environmental resources, disturbance mechanisms, and time (Forman and Godron, 1981). The potential for quantifying those structural components, identifying ecologically important landscape characteristics, and assessing their linkages to ecosystem function is increased through the integration of remote sensing techniques and landscape statistics (Yang and Liu, 2005). A metric-based landscape classification system would allow for the quantification of historical trends for key landscape attributes (*e.g.,* diversity and stability), functions (*e.g.,* hydroconnectivity and fish edge utilization), and drivers (*e.g.,* hurricanes, sea-level rise,

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subsidence, and human activities) within the highly dynamic wetlands of coastal Louisiana. These indices would exceed standard form and function dynamics by providing a better understanding of the ecological consequences of those changes and supply guidance for future sustainable landscape planning (Hulshoff, 1995; Leitao and Ahern, 2002).

The goal of this work is to evaluate and improve methods of analyzing and classifying the configuration and fragmentation of northern Gulf of Mexico (NGOM) wetland landscapes. Reviews of relevant landscape classification and metric applications were performed to assess the regional and landscape-level (holistic versus segmented) approaches of configuration classification and landscape statistics, respectively. With the ability to account for localized landscape- and class-level composition and configuration, the fusing of an established wetland classification scheme with landscape statistics emerged as the optimal method for classifying Louisiana wetland landscape patterns. The Dozier system, a wetland classification scheme that was selected for use in this study, is a Louisiana-based scheme that uses visual interpretation to characterize landscape patterns using percentage and configuration of water within the marsh (Dozier, 1983). The Dozier system was developed by assessing historical photography and establishing a two-part classification scheme based on the amount and configuration of water features that are typical in coastal Louisiana wetland landscapes. This system was developed with the intentions of classifying, quantifying, and assessing the sequence of wetland landscape evolution. To automate the Dozier system, a segmented (grid-based) method using FRAGSTATS version 3.3 (McGarigal *et al.*, 2002) was selected for computing landscape statistics. FRAGSTATS, a spatial pattern analysis program, has the ability to rapidly compute a wide variety of landscape metrics for categorical map patterns. A FRAGSTATS grid-based approach can provide class-level metrics through roving window analyses or assessments of individual nonrelated grids (tiles), or summary landscape-level statistics, all of which can be useful for landscape classification. Combining landscape metrics into algorithms that replicate the Dozier method can assist in linking landscape form to associated ecological functions, providing a means for performing landscape reconstruction and predictions, and ultimately providing ecosystem managers with a landscape-based decision tool.

METHODS

The site selected for analysis in this study is the 800-km^2 area that buffers the Houma Navigation Canal (HNC) in southeastern Louisiana (Figure 1). The HNC site is located in the Terrebonne basin and is bordered on the north by the Gulf Intracoastal Waterway; the east by Bayou Terrebonne; the west by Minors Canal, Lake de Cade, and Bayou du Large; and extends south to the lower regions of the Bayou Sauveur and Lake Quitman U.S. Geological Survey topographic quadrangles. Selection of this site was multipurposed: (1) the area provides a broad spectrum of wetland habitats (*e.g.*, swamp forest and fresh, intermediate, brackish, and saline marshes), physical characteristics, and unique ecosystem drivers; and (2) it is consistent with previous manual marsh classification studies, allowing for comparison of results.

The fragmentation classification method (Spatial Integrity Index; SII) developed as part of this study uses land/water classified imagery and a two-level classification system. The two levels used in this system are (1) category: ratio of water to land, and (2) configuration: marsh-water density, shape, and connectivity (modified from Dozier, 1983). The category system assigns values 1–7 to represent percentages of water as follows: category 1, 0– <5 percent water within marsh; category 2, 5– <10 percent water; category 3, 10– <25 percent water; category 4, 25– <40 percent water; category 5, 40– <60 percent water; category 6, 60– <80 percent water; and category 7, ≥80 percent water. The configuration classes are designated by the density, shape, connectivity, and size (category class dependent) of water bodies within the landscape. Configuration class A includes patterns that are typically large water features with connected patches and linear edge. Configuration class B includes patterns that are typically small, disconnected patches with increased random distribution and fewer instances of connection. Configuration class C consists of patterns that contain discernible regions of both configuration classes A and B. Figure 2 illustrates example category and configuration classes developed as part of the SII system.

To account for varying degrees of degradation and to assess classification consistency through time and space, three temporal data points were selected (based on availability of qualified data) for use in this study [1958 panchromatic photography (Tobin Research Inc., 1958); 1968 panchromatic photography (U.S.

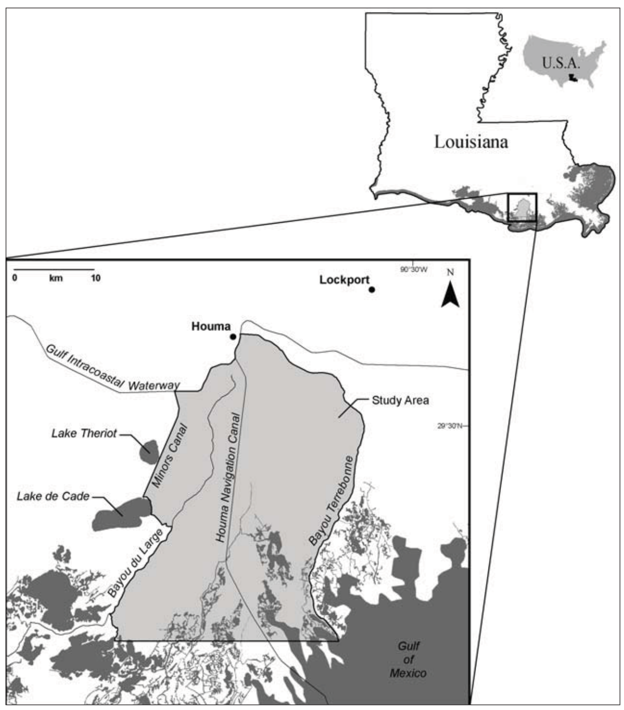

Figure 1. The Houma Navigation Canal study area in southeastern Louisiana. The study area, located along the Gulf of Mexico within the Terrebonne basin, contains extensive acreage of swamp forest and fresh, intermediate, brackish, and saline marshes that range from highly stable to highly degraded.

Army Corps of Engineers, 1968); and the 1998 digital color infrared orthophotos (Louisiana Oil Spill Coordinator's Office, 2009)]. Photo preprocessing (mosaic, subset, and resample to 1 m) and land/water classification analysis (Folse *et al.*, 2008) were performed on all three geospatial datasets using ERDAS Imagine® version 8.6 software (Leica Geosystems, 2002). This land/water classification process was used to designate image pixels as "land", "water", or "other" classes based on individual pixel signature. These classes were delineated based on vegetation and flooding regimes developed by Cowardin *et al.* (1979). All vegetation, such as marsh, burned marsh, scrub/shrub, forested wetlands, emergent vegetation, and circular vegetation within water bodies were classified as "land". Open water, floating aquatics, nonvegetated mudflats, and structures (*e.g.*, oil and gas facilities and boat docks) positioned over water were classified as "water." Since the primary objective of this study was to classify and track marsh fragmentation and erosion patterns (not direct changes due to anthropogenic activities),

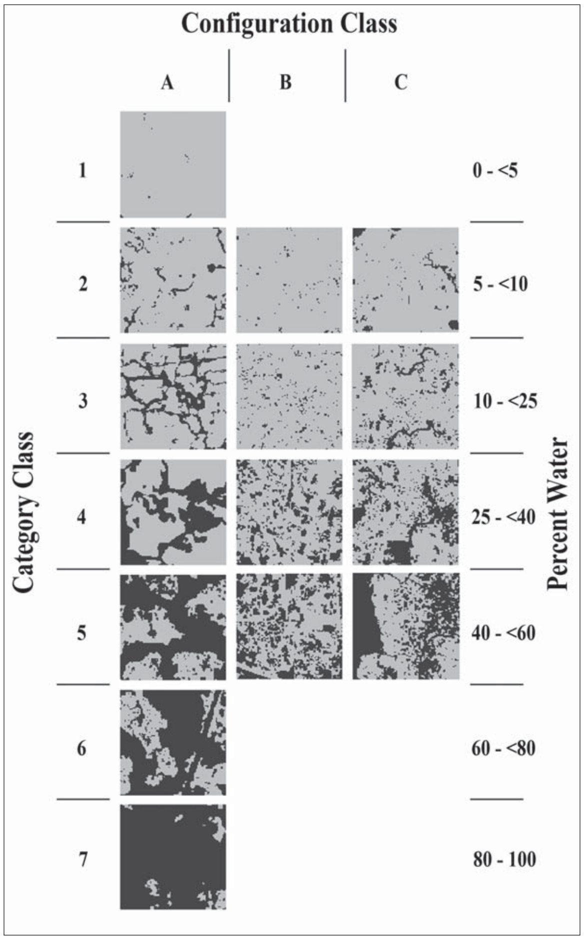

Figure 2. Examples of the Spatial Integrity Index classification scheme (modified from Dozier, 1983). Category classes, numbers 1–7, represent percentages of water (black) within the landscape (gray), and configuration classes, letters A, B, and C, are subclasses that represent the density, shape, and connectivity of water bodies in the marsh.

the "other" category, which consists of channelized canals and other nonwater and nonmarsh features (*e.g.*, fastlands, forested, agricultural, and developed lands), was excluded from all SII statistical and classification analyses.

A fundamental challenge to landscape analysis is identifying how the scale (grain size and extent) of observation influences the description of landscape patterns (Levin, 1992). Grain refers to the minimum spatial resolution of the data, and the extent describes the areal breadth of an analysis (Milne, 1991). Though there is no established method for selecting an appropriate spatial scale, recent studies show that the effects of grain size are more predictable than those of changing extent (Obeysekera and Rutchey, 1997; Wu *et al.*, 2002). Since the memory requirement is especially constraining in the FRAGSTATS moving window analysis, a method that segments each input raster feature into a series of tiles was selected. The initial phase of the SII system development consisted of determining the appropriate extent of each tile required for maximally classifying project area landscape patterns. Ideally, each individual tile should contain a landscape with only one SII class (based on criteria established by Dozier (1983)). To expedite the preparation of raster datasets and the extraction of tiles, a geoprocessing routine was developed using ArcGIS® version 9.1 with Visual Basic for Applications (VBA) software (Environmental Systems Research Institute, 2005). The three land/water images (1958, 1968, and 1998) were subset to 1 km^2 (100 hectares), 1/8 km^2 (12.5 hectares), 1/16 km^2 (6.25 hectares), 1/64 km^2 (1.56 hectares), and 1/256 km^2 (0.39 hectares) tiles, and classifications were performed on a randomly selected subset of tiles to determine scale appropriateness. The category classes were assigned based on FRAGSTATS computed percentage of water, and the configuration classes were manually classified using the Dozier technique. At 1 km^2, 1/8 km^2, and 1/16 km^2, tiles regularly contained three or more SII classes. Conversely, the 1/256 km^2 tiles consisted of landscapes that were too small to definitively classify using the Dozier system. The 1/64 km^2 tiles most consistently satisfied the one SII class per tile criteria, and contained a landscape extent that most closely resembles those described by Dozier (1983).

Metric selection for landscape analysis is critical since the application of those metrics can be ecosystem and species specific (Davidson, 1998). For instance, single-factor measures may be useful for evaluating landscape fragmentation, however, the effect and measure of fragmentation can be dependent on species characteristics such as range and mobility (Davidson, 1998). Similarly, selection of metrics for multimeasure assessments can be difficult since landscape metrics can be ecosystem specific and highly correlated (McGarigal and Marks, 1994). Though little value is derived from the interpretation of metrics that are highly or perfectly correlated, especially those that are inherently redundant, landscape structures that are statistically correlated (empirically redundant) can be meaningful (McGarigal and Marks, 1994). However, since the objective of this study was to successfully replicate an established classification system using patch analysis software, the issue of correlation was not considered.

The FRAGSTATS integrated batch function was used for rapid processing and computation of class-level metrics for all HNC area tiles. Tiles were sorted by adjusted water percentages (excluding the "other", or nonmarsh class) and assigned to

Table 1. *Description of metrics selected as part of the Spatial Integrity Index fragmentation and classification system, based on McGarigal and Marks (1994).*

Metric	Description
Clumpiness index	Frequency with which different classes appear side by side in the landscape
Landscape shape index	Class perimeter length divided by minimum length of perimeter needed for a maximally aggregated class
Largest patch index	Percentage of total landscape area composing the largest patch
Number of patches	Number of patches of the corresponding class
Patch cohesion index	Spatial connectedness of the corresponding patches
Patch density	Number of patches of the corresponding class divided by total landscape area
Percentage of landscape	Percentage of landscape composed of the corresponding class

corresponding category classes. Randomly selected samples of each category class were then assigned to configuration classes based on preliminary visual assessments of water patterns. Forty-six class-level metrics (and their pair-wise combinations) were evaluated to identify those with significantly different means (based on summary statistics for each category and configuration class combination) that could therefore provide adequate metric value thresholds for assigning each tile to the appropriate SII class. Of those assessed, seven compositional and configurational metrics emerged as responsive controls (*e.g.,* metric values for preliminarily classified 2A, 2B, and 2C classes were significantly different) of class designation within the SII classification process (Table 1). The remaining metrics provided no significant difference within category class values and were therefore removed from consideration. The seven metrics consist of clumpiness index, landscape shape index, largest patch index, ratio of number of patches to clumpiness index, patch cohesion index, adjusted patch density, and percentage of landscape. The ratio of number of patches to clumpiness index is a metric combination that provides a quasi density-by-shape value that proved useful for separating those A and C configuration classes with metric values in close proximity to the class threshold.

Since the Dozier classification system is based on the percentage, shape, distribution, and connectivity of water within the natural landscapes of coastal Louisiana, the objective of this phase was to correlate landscape metrics to those physical characteristics, and to use those relationships to establish classification criteria and thresholds. While the criteria of this system were primarily derived from the Dozier class descriptions, the metric thresholds were initially established using the average metric values for all manually classified tiles (Table 2). Iterative comparisons of metric values from matching computer- and manually-generated classifications were then used to perform classification criteria and metric threshold adjustments. These threshold values act as breakpoints by which the metric values for each tile are tested, and are subsequently used to assign tiles to corresponding category and configuration classes. Tiles with metric values in close proximity to threshold values are the most

Table 2. *Spatial Integrity Index system class count and metric means.*

Spatial Integrity Index	Count	Percentage of Landscape	Number of Patches	Patch Density	Largest Patch Index	Landscape Shape Index	Clumpiness Index	Patch Cohesion Index	Number of Patches/ Clumpiness
1	6,327	1.9	6.8	4.6	1.3	3.0	0.82	83.6	9.8
2A	4,257	7.4	7.9	5.2	5.3	3.6	0.91	95.8	9.1
2B	519	6.6	45.7	32.2	1.0	7.6	0.76	85.5	63.8
2C	552	7.4	52.6	34.0	2.6	8.4	0.75	89.3	71.3
3A	12,087	16.9	9.6	6.3	12.7	3.8	0.93	97.6	10.7
3B	543	12.9	55.5	41.8	1.9	8.7	0.78	89.1	74.8
3C	1,773	16.6	60.5	39.1	6.8	9.1	0.80	93.5	77.0
4A	11,253	32.2	10.5	6.9	26.3	3.7	0.94	98.7	11.6
4B	99	29.6	19.6	40.2	3.6	4.9	0.88	93.8	24.4
4C	1,281	30.6	51.7	33.4	15.3	9.2	0.83	96.5	63.5
5A	12,483	49.8	7.8	5.1	44.9	3.1	0.95	99.4	8.4
5B	90	48.2	5.4	27.2	6.2	3.0	0.92	96.3	6.4
5C	2,037	46.6	29.6	19.2	33.0	6.4	0.88	98.4	34.3
6	13,260	69.7	5.9	4.0	65.4	2.6	0.95	99.7	6.4
7	34,722	96.1	1.6	3.5	93.9	1.3	0.97	99.9	1.6

Table 3. *Spatial Integrity Index criteria equation class- and metric-specific conditional thresholds.*

Spatial Integrity Index	Percentage of Landscape	Number of Patches	Patch Density	Largest Patch Index	Landscape Shape Index	Clumpiness Index	Patch Cohesion Index	Number of Patches/ Clumpiness
1	0 - < 5	-	-	-	-	-	-	-
2A	5 - < 10	< 41	< 30.0	≥ 200	< 8.4	> 0.75	> 88.8	< 55.0
2B	5 - < 10	-	-	≤ 200	-	< 84.00	> 0.0	-
2C	5 - < 10	-	-	> 200	-	> 0.10	> 50.0	-
3A	10 - < 25	< 46	< 40.7	≥ 400	< 9.0	> 0.77	> 93.0	< 60.0
3B	10 - < 25	-	-	≤ 400	-	< 84.00	> 0.0	-
3C	10 - < 25	-	-	> 400	-	> 0.10	> 50.0	-
4A	25 - < 40	< 81	< 53.5	≥ 875	< 9.1	> 0.79	> 96.5	< 102.0
4B	25 - < 40	-	-	≤ 875	-	< 84.00	> 0.0	-
4C	25 - < 40	-	-	> 875	-	> 0.10	> 50.0	-
5A	40 - < 60	< 45	< 53.5	≥ 2,000	< 8.2	≥ 0.84	> 98.5	< 53.0
5B	40 - < 60	-	-	≤ 2,000	-	< 84.00	> 0.0	-
5C	40 - < 60	-	-	> 2,000	-	> 0.10	> 50.0	-
6	60 - < 80	-	-	-	-	-	-	-
7	80 - 100	-	-	-	-	-	-	-

difficult to classify. Therefore, the final arrangements of metric thresholds were refined using tiles with metric values within ±5% of each manually classified threshold value. The resulting SII classification criteria equation consisted of sequential conditional assessments that test the metric values of each tile against the threshold value of the corresponding category class. Once the category classes are assigned, the tiles are then tested against the A configuration criteria of corresponding categories (*e.g.,* a tile must satisfy the following conditional assessment to receive 2A classification: Percentage of landscape = 5– < 0, and Largest Patch > = 200, and Cohesion > 88.84, and Clumpy > 0.755, and Patch density < 30, and Number of patch/Clumpy < 55.25, and Landscape shape index < 8.35; Table 3). Tiles not satisfying all A criteria were then subjected to simpler tests of water patch size, aggregation, and connectivity values (necessary to differentiate class B from class C landscapes), and assigned the appropriate configuration class.

In an effort to automate the data computation and SII classification process, scripting and batch routines were developed based on class- and metric-specific conditional thresholds (Table 3).

RESULTS AND DISCUSSION

The 800-km^2 HNC study area provided a diverse array of marsh composition, configuration, and conditions. Three study area land/water images were subset into 156,000 unique tiles, of which approximately 100,000 contained marsh landscapes and were used in the development of the SII classification system. Due to the complex nature of project area landscape patterns, the average values from select compositional and configurational metrics were used as preliminary thresholds within the SII classification criteria equation. Development of the criteria equation, along with class-level threshold refinements, consisted of iterative comparisons between computer-based classifications and the manually derived segmented landscapes. The final SII criteria equation consists of sequential and mutually exclusive conditional assessments that evaluate select landscape metric values against established thresholds and assigns segmented landscapes (tiles) to appropriate category and configuration classes (based on a modified Dozier classification scheme).

The SII system was developed in an effort to increase reproducibility, but primarily to reduce the subjectivity inherent to the manual Dozier classification process. As part of a previous study, Sasser and Evers (1995) employed the Dozier method to classify a portion of the HNC study area landscape. Comparisons of the SII category assignments (as part of this study) to manually derived holistic assignments (Sasser and Evers, 1995) show that only 52% of the landscapes classified by Evers received the correct category classification. Of those incorrectly classified landscapes, 86% received category designations that were one class removed from their correct assignment. These incorrectly assigned landscapes are a result of the subjective nature of manually classifying percentage of water. Conversely, an assessment of SII classified tile shows that 100, 92, 91, 90, 88, 100, and 100 percent of respective SII classes 1–7 received the same category and configuration classifications as those that were manually classified as part of this study (manual classifications were performed on configuration classes only).

Figure 3 illustrates the final SII classified images for the

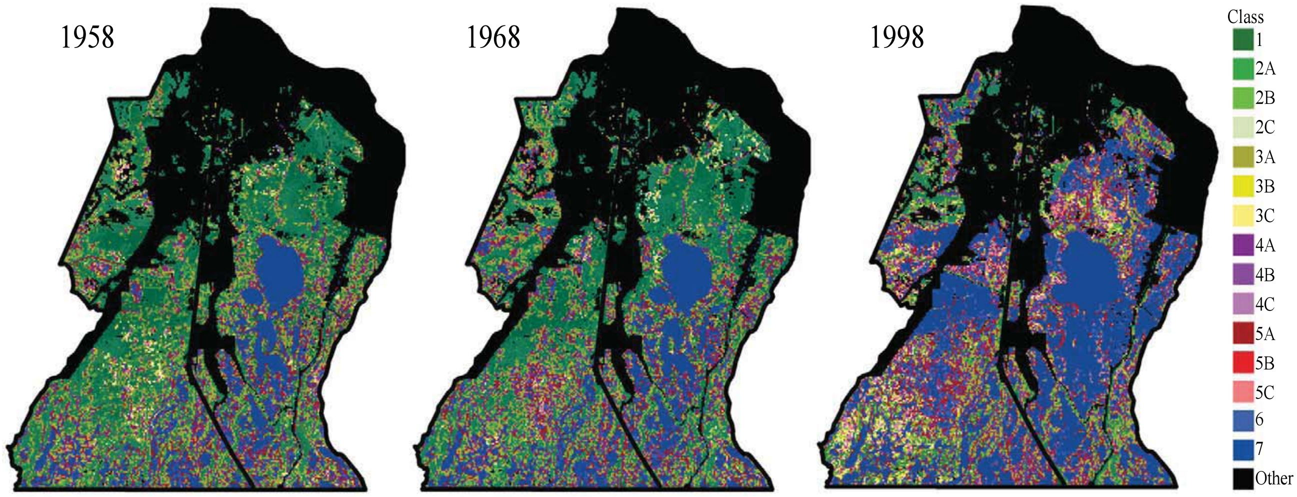

Figure 3. Final Spatial Integrity Index (SII) classifying marsh fragmentation and configuration for 1958, 1968, and 1998 landscapes in the Houma Navigation Canal project area, coastal Louisiana.

HNC study area. This figure demonstrates the SII classification systems ability to systematically categorize the type and change in degradation across a wide range of marsh landscapes. Coastwide application of this system could serve as the basis for predicting landscape change, performing landscape reconstruction, identifying or prioritizing areas of greatest need, and scaling to include indices of connectivity, landscape stability, and ecological function (*e.g.,* habitat switching, land building, and edge utilization by fish). These measures assist in the quantification of the attributes, functions, and drivers that are fundamental to coastal wetland ecosystem processes.

One specific application currently under development is the use of the SII system to track changes in marsh density, shape, and connectivity through space and time (Figure 4A). This study is being used to test a variety of spatial metrics and incorporate them into a spatially-explicit model to assess historical trends, support projections of "future with" and "future without" alternative landscape configuration patterns, and identify restoration alternatives that promote the greatest landscape stability and ecological sustainability. Another ongoing study includes the assessment and linkage of percent land and landscape configurations to the length of marsh edge for fisheries utilization (Browder, Bartley, and Davis, 1985; Figure 4B). The SII system is also being considered for use in automating key Wetland Value Assessment (WVA) models (Environmental Work Group, 2007; Figure 4C). By automating the quantification of the following Habitat Suitability Index variables: (1) emergent vegetation, (2) aquatic vegetation, (3) marsh edge and interspersion, and (4) open water areas less than 0.5 m deep, the SII system would increase reproducibility, and reduce the subjectivity and time intensive nature of the WVA process. The final example of the SII system's utility is the identification and mapping of extensively degraded areas (hotspots), or landscapes that are transitioning from less to more degraded configurations (Figure 4D). Assessments of the four hotspots located within the HNC study area have allowed for the identification of ecosystem drivers and impacts, which are critical for resource management. This system may be instrumental for future assessments and quantification of wetland degradation sequencing. To date, the sequence of degradation (configuration change) has been difficult to ascertain due to the dynamic and site specific nature of landscapes and land change drivers.

CONCLUSIONS

The methodology described in this study provides a more automated means of quantifying landscape patterns. The SII system produced results that mimicked those developed by Dozier *et al.* (1983) by quantifying the composition and configuration of water within user-specified tiles and categorizing them based on select landscape metrics. Though the SII classification provides many advantages over other systems, it is not without limitations. These limitations include the inability to account for patch type adjacency, the time intensive nature of the required land/water analysis, and the overall scale specificity of the technique. However, through modification and further evaluation of the SII classification methodology, solutions for many of these limitations are possible.

Current and future work includes assessing method applicability with various data sets and at various scales (grain size and extent), as well as direct and indirect linkages to ecological processes. Valid comparison to reference wetlands is difficult, but correlations between spatial metrics and ecosystem services may be developed over time, provided the appropriate field data collection and analyses are conducted. With changes to coastal landscapes expected to increase with climate change and specifically sea-level rise (IPCC, 2007), the need for a more automated wetland landscape quantification and classification system is critical for detailed evaluations and predictions of impacts on NGOM functional processes. This method was

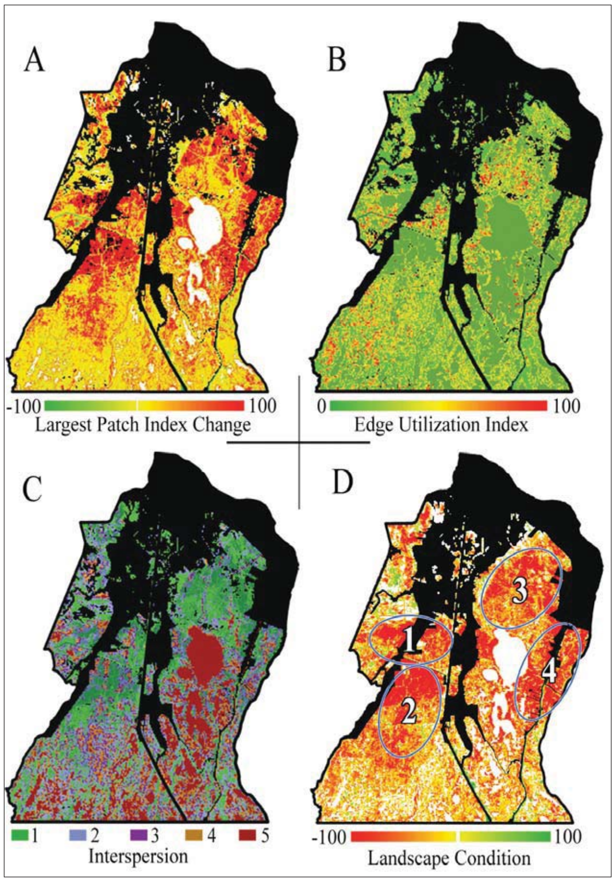

Figure 4. Example applications of the SII system within the Houma Navigation Canal project area, coastal Louisiana: (A) Illustration depicting the change in percentage of a single landscape metric (Largest Patch Index) to track the change in surface characteristics (from 1958–1998); (B) Ranking of SII classes according to edge density to establish an Edge Utilization Index (1958–1968); (C) Utilization of the SII system to classify Louisiana Wetland Value Assessment Interspersion classes (1958–1968); (D) Change assessment of SII classes for the identification and mapping of extensively degraded areas ("hotspots"), or landscapes that are transitioning from less to more degraded configurations (1958–1998). The black areas represent nonwetland landscapes ("other" class) and were excluded from all statistics and assessments.

developed to increase the accuracy and control, and reduce the time-intensive nature of classifying wetland structure and stability. Long term, the SII system provides reliable landscape evaluation capabilities and should evolve into a tool fo hindcasting and forecasting ecological processes.

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