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Spatial metrics for detecting ecosystem degradation in the ridge-slough patterned landscape

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ABSTRACT

Indicators of landscape condition should be selected based on their sensitivity to environmental changes and their capacity to provide early warning detection of those changes. We assessed the performance of a suite of spatial-pattern metrics selected to quantify the condition of the ridge-slough landscape in the Everglades (South Florida, USA). Spatial pattern metrics (n = 14) that describe landscape composition, geometry and hydrologic connectivity were enumerated from vegetation maps of twenty-five 2 × 2 km primary sampling units (PSUs) that span a gradient of hydrologic and ecological condition across the greater Everglades ecosystem. Metrics were assessed in comparison with field measurements from each PSU of landscape condition obtained from regional surveys of soil elevation, which have previously been shown to capture dramatic differences between conserved and degraded locations. Elevation-based measures of landscape condition included soil elevation bi-modality (BI_{SE}), a binary measure of landscape condition, and also the standard deviation of soil elevation (SD_{SE}), a continuous measure of condition. Metric performance was assessed based on the strength (sensitivity) and shape (leading vs. lagging) of the relationship between spatial pattern metrics and these elevation-based measures. We observed significant logistic regression slopes with BI_{SE} for only 4 metrics (slough width, ridge density, directional connectivity index – DCI, and least flow cost – LFC). More significant relationships (n = 8 metrics) were observed with SD_{SE}, with the strongest associations for slough density, mean ridge width, and the average length of straight flow, as well as for a suite of hydrologic connectivity metrics (DCI, LFC and landscape discharge competence – LDC). Leading vs. lagging performance, inferred from the curvature of the association obtained from the exponent of fitted power functions, suggest that only DCI was a leading metric of the loss of soil elevation variation; most metrics were indeterminate, though some were clearly lagging. Our findings support the contention that soil elevation changes from altered peat accretion dynamics precede changes in landscape pattern, and offer insights that will enable efficient monitoring of the ridge-slough landscape as part of the ongoing Everglades restoration effort.

1. Introduction

Characterization of spatial patterns is important for measuring and monitoring ecological processes (Turner, 1989; McIntire and Fajardo, 2009). Pattern metrics provide a quantitative tool to describe spatial heterogeneity (O'Neill et al., 1997; Turner, 2005) and enumerate landscape condition, often enabling such measurements in a cost effective way for large-ecosystem monitoring and management (Dale and Beyeler, 2001). While the proliferation of pattern metrics has been criticized as failing to link pattern and process (Gustafson, 1998; Tischendorf, 2001; Li and Wu, 2004), the broad availability of spatial pattern and image processing algorithms has impacted a wide array of environmental management efforts, ranging from biodiversity conservation (Fischer and Lindenmayer, 2007), to urban planning (Botequilha Leitão and Ahern, 2002), and understanding land use/land cover change (Riitters et al., 2002; Nagendra et al., 2004). In the context of complex large-area restoration efforts, efficiently and accurately enumerating spatial and temporal changes in condition has become a cornerstone of management decision making.

Indicators of landscape condition are useful when they are 1) sensitive to system changes (i.e., they respond to disturbance gradients), 2) specific to particular modes of change (i.e., they do not respond to other stressors, or do not vary so much that they obscure the response signal), and 3) provide early detection of incipient changes rather than manifesting only after major

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and potentially irreversible system changes have occurred. While sensitivity and specificity are widely evaluated when considering metric performance, there has only been recent attention to developing and refining early warning indicators. A rich literature in econometrics supports the plausibility of identifying leading indicators of macroeconomic conditions; variables such as interest rates, stock prices, and unemployment statistics are routinely evaluated through time to forecast future economic performance (Stock and Watson, 1989). Detecting leading indicators, namely those variables that change before the system as whole (Lahiri and Moore, 1992), requires establishing each indicators typical timing in relation to macroeconomic cycles. The same logic applies to ecological changes. An emerging literature focuses on early-indicators of catastrophic regime shifts (Rietkerk et al., 2004; Scheffer et al., 2009). Signals in time-series of key indicator variables such as increased autocorrelation and variance (Dakos et al., 2012), changing skewness (Guttal and Jayaprakash, 2008), and critical slowing (Dakos et al., 2011) indicate a system approaching a tipping point between alternative stable states. For many large-area monitoring situations replacing space for time is a necessary assumption. Spatial model simulations indicate vegetation spatial structure can signal onset of desertification in arid and semi-arid settings (Kefi et al., 2007, 2010a; Scanlon et al., 2007), and while patch based spatial indicators are still emerging (Kefi et al., 2010b) there are methodologies for inferring mechanisms from spatial snapshots (Marcos-Nikolaus et al., 2002; Mocenni et al., 2010).

Our work focuses on the ridge-slough landscape of the Everglades, at the southern tip of Florida (USA). The historical Everglades was a vast of “River of Grass” (Douglas, 2007) extending from Lake Okeechobee in the north to Florida Bay in the south. Water flowed slowly across the surface this 160 km long and 100 km wide peatland, enabling long hydroperiods that supported a mosaic of wetland types. Dominant among these in the central Everglades were the emergent sawgrass (*Cladium jamaicense*) marshes called ridges and the waterlily (*Nymphaea odorata*) and bladderwort (*Utricularia* spp.) dominated deeper water habitats called sloughs. A complex mosaic of these two patch types comprises the ridge-slough landscape, a patterned peatland that occupied much of the historical Everglades system (Davis and Ogden, 1994).

Among the most striking features of ridge-slough landscape pattern is that the densely vegetated ridge patches, which occupy high elevation sites, are elongated along the axis of historical flow (SCT, 2003) within a mosaic of more sparsely vegetated, and deeper, sloughs. Despite a high density of ridges, the anisotropy of the patches enables north-south flow connectivity between deeper water sloughs (Larsen et al., 2012; Yuan et al., 2015) which is critical for dispersal and habitat utilization by a wide variety of aquatic fauna (Trexler et al., 2000). This patterning, which has been described as both regular (i.e., with a characteristic wavelength of ca. 150 m; SCT, 2003; Watts et al., 2010; Nungesser, 2011) and fractal (i.e., lacking a characteristic wavelength; Casey et al., 2016), is sensitive to hydrologic modification (SCT, 2003; Watts et al., 2010), which has been a key feature of human habitation of the South Florida system. Nearly 2000 km of levees and canals, construction of which began early in the 20th century for flood control and water supply, has dramatically altered the landscape, compartmentalizing the landscape into Water Conservation Areas (WCAs 1, 2 and 3) to the north of Everglades National Park (ENP) (Fig. 1), and, crucially, interrupting natural sheet flow connectivity (Larsen et al., 2011). Loss of the ridge-slough patterning is an important measure of landscape degradation and restoration, and has made pattern genesis mechanisms the focus of considerable research (Ross et al., 2006; Larsen and Harvey, 2010; Cheng et al., 2011; Lago et al., 2010; Acharya et al., 2015).

Metrics have been explored to describe ridge-slough patterning and provide insights about landscape condition (SCT, 2003; Wu et al., 2006; Nungesser, 2011; Yuan et al., 2015). We seek to refine them to discern those that are sensitive and specific to ecosystem change, and provide early-warning indications. Several studies strongly indicate that pattern geometry changes where hydrology has been altered (Wu et al., 2006; Nungesser, 2011). A suite of pattern metrics proposed by Wu et al. (2006) were intuitively linked to ridge-slough pattern condition. These metrics focused on patch geometry, including mean ridge width and length, straight flow distances, and landscape metrics like lacunarity that measure patch coherence. However, absent an independent measure of landscape condition against which to compare the metrics, Wu et al. (2006) were forced to simply ordinate the sites and match metric performance to large but qualitative landscape gradients established by expert judgment (SCT, 2003).

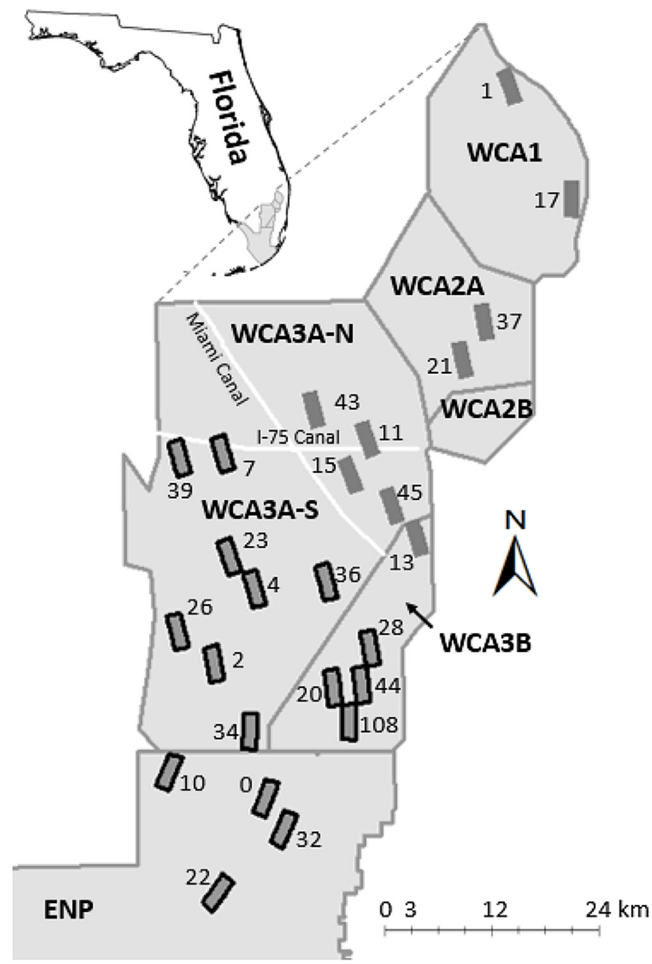

Fig. 1. The Greater Everglades study site in the extreme southern tip of Florida (USA) is monitored using a network of 2 × 4 km primary sampling units (PSUs). We selected 25 PSUs for our global analysis (grey blocks) based on historical ridge-slough conditions; we selected a subset of sites south of the Miami Canal (grey blocks with black outline) where the patterned landscape remains sufficiently intact to apply pattern metrics. Water conservation areas (WCA) are labeled along with Everglades National Park (ENP).

Field-based measures of ridge-slough condition are logistically complex in this remote and inaccessible landscape. However, significant progress towards developing these indicators has been made. Specifically, patterns of soil elevation variation have emerged as diagnostic of overall condition (Watts et al., 2010), and consistent with the theory underlying the divergence in elevations between ridges and sloughs (Larsen et al., 2007). Specifically, in the best conserved regions of the ridge-slough landscape, soil elevations are distinctly bi-modal and exhibit large variance, whereas