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Assessing significant geomorphic changes and effectiveness of dynamic restoration in a coastal dune ecosystem

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A shift from restoring coastal dunes as stabilized landscapes toward more morphodynamic ecosystems is underway. This paper uses results from a recent case study where invasive vegetation was removed from a coastal dune complex in western Canada as a first step in a dynamic ecosystem restoration project. Spatial statistical methods, used in the natural sciences to quantify patterns of significant spatial–temporal changes, are reviewed and the local Moran's I_i spatial autocorrelation statistic is explored for detecting and assessing significant changes. Cluster maps of positive (depositional) and negative (erosional) changes were used to derive statistically significant volumetric changes within discrete geomorphic units (beach, foredune, transgressive dune) over one year following vegetation removal. All units experienced net increases in sediment budgets compared to a pre-restoration surface. The beach experienced the highest episodic erosion and volumetric change and greatest net annual sediment budget. Compared to the beach, the annual sediment budget of the foredune was 19% whereas the transgressive dune was 33%. The foredune recovered rapidly to initial erosion during restoration and subsequent natural events with consistently positive sediment volumes and attained a form similar to that pre-restoration. Aeolian deflation and sand bypassing through the foredune was greatest in the two months following vegetation removal and peak accretion in the transgressive dune resulted from depositional lobes extending from the foredune, smaller dunes migrating within the complex, and growth of a precipitation ridge along the eastern margin.

Several methodological and logistical considerations for detecting significant change in dynamic dune landscapes are discussed including sampling strategy design, data normalization and control measures, and incorporating uncertainty and inherent spatial relations within acquired datasets to ensure accuracy and comparability of results. Generally underutilized in coastal geomorphology, spatial autocorrelation methods (e.g., local Moran's I_i) are recommended over spatially uniform threshold approaches for the ability to detect local change processes and explore hypotheses on spatial–temporal dynamics.

Finally, several key geomorphic indicators, that are believed to aid in re-establishing ecological conditions and processes that favor more resilient and natural dune ecosystems, are identified for assessing the effectiveness of dynamic restoration projects including: increased aeolian activity, enlarged active sand surface area, positive sediment budgets, increased dune morphodynamics, improved geomorphic diversity, and enhanced geomorphic resilience. Although limited in temporal scope, the case study results show that the initial phase of the restoration treatment was effective in enhancing all indicators except for increasing sand surface area. Given decadal scale observations of climatic changes and longer-term eco-geomorphic trajectory toward stabilization in the region, however, it is unlikely that the geomorphic effectiveness of this restoration effort will continue without continued frequent treatment interventions.

1. Introduction

In areas with appreciable onshore sand supply, foredunes are a significant component of the coastal sediment budget as they store and cycle substantial amounts of sand in the backshore (e.g., Short and Hesp, 1982; Psuty, 1988; Hesp, 2002; Psuty, 2004). As such, coastal dunes provide an important buffer that can protect shorelines against storm surge flooding, coastal erosion, and more gradual sea-level rise (e.g., Davidson-Arnott, 2005; Houser et al., 2008; Mascarenhas and Jayakumar, 2008; Eamer and Walker, 2010). Coastal dunes are also ecologically significant as they provide critical habitat for many specialized endemic, migratory and endangered species (e.g., Wiedemann and Pickhart, 1996; Wiedemann, 1998; Grootjans et al., 2002; Hesp, 2002) and serve as an important natural resource and land use base for coastal development (e.g., Nordstrom, 1990; Riksen et al., 2006; Nordstrom, 2008).

Traditionally, coastal dune systems have been restored to a 'stabilized' state so as to halt natural geomorphic processes of erosion, sand

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drift, and dune migration. This has often involved planting non-native plants, shrubs, or trees or by physically hardening or armouring dune features. Such stabilization efforts have been implemented for a variety of purposes including forestry and agriculture (e.g., Van Der Meulen and Salman, 1996; Riksen et al., 2006), urban and recreational development (e.g., Riksen et al., 2006), groundwater storage and recharge (e.g., Arens et al., 2004; Arens and Geelen, 2006), and flood protection and wave erosion defense (e.g., Hillen and Roelse, 1995; Arens et al., 2001; Grootjans et al., 2002; Arens et al., 2004; Mascarenhas and Jayakumar, 2008). Over the last three decades, however, coastal researchers and managers have recognized that efforts of dune stabilization have resulted in the loss of landform dynamics, complexity, and resilience. In turn, this has entailed notable ecological impacts, such as declines in early successional floral species and a corresponding loss of species richness and diversity (e.g., Grootjans et al., 2002; Arens et al., 2004; Hilton et al., 2005; Nordstrom, 2008). Artificially stabilized dune systems are often resistant to all but the most extreme disturbances and, as a result, have dysfunctional geomorphic and ecological regimes that do not experience lower magnitude disturbance cycles required for maintaining natural dune ecosystem structure and function (Nordstrom, 1990, 2008).

Re-establishment of natural disturbances and related morphodynamics in dune landscapes are being incorporated increasingly into restoration projects that seek to restore lost ecosystem dynamics and services. Recent work suggests that a more dynamic landscape, wherein natural geomorphic processes are stimulated, provides a more resilient ecosystem with more favorable ecological conditions for native communities and endangered species. For instance, restoration projects are seeking to reactivate aeolian activity and dune mobility via vegetation removal by fire, herbicides, mechanical or manual pulling, or soil tillage that encourage a more dynamic landscape and associated ecosystems (e.g., van Boxel et al., 1997; Nordstrom et al., 2002; Arens et al., 2004; Rozé and Lemauviel, 2004; Van Der Meulen et al., 2004; Arens and Geelen, 2006; Nordstrom, 2008; Hilton et al., 2009; Kollmann et al., 2011). This 'dynamic' approach to restoration effectively enhances aeolian activity and dune morphodynamics to produce a more diverse landscape with more periodic erosion–stabilization cycles that, in turn, provides required environmental conditions and gradients required by natural ecological communities (Kooijman, 2004; Van Der Meulen et al., 2004; Arens and Geelen, 2006; Nordstrom, 2008). Although dynamic restoration approaches are not yet conventional, a paradigm shift from decades of dune landscape stabilization and ensuing ecological dysfunction toward more dynamic, disturbance resilient approaches appears to be underway.

Dynamic restoration projects provide distinct research opportunities to quantify and interpret resulting sediment transfers and morphodynamic responses in coastal dune ecosystems. In turn, this can provide useful insights into the effectiveness and refinement of implemented disturbances and treatment regimes. To date, much research on the restoration of dynamic coastal dunes is predominantly ecological and focuses on soil and vegetation changes (e.g., van Boxel et al., 1997; Ketner-Oostra and Sykora, 2000; Grootjans et al., 2002). Geomorphic research has concentrated primarily on measuring changes in active sand surface area or cross-shore topographic profiles with only indirect measures of aeolian activity (e.g., Nordstrom et al., 2002; Arens et al., 2004, 2005; Wondergem, 2005; Arens and Geelen, 2006; Hilton et al., 2009). This research has provided foundational knowledge of the responses of dune landscapes to dynamic restoration. Recent investigations in other areas of physical geography (e.g., Luoto and Hjort, 2006; Thompson et al., 2006; Adelsberger and Smith, 2009; Wheaton et al., 2010) and spatial ecology (e.g., Wulder et al., 2007; Nelson and Boots, 2008), however, have applied more robust spatial analysis methods to quantify, detect, and interpret significant patterns of change in landscapes that have direct relevance and utility for assessing the effectiveness of dynamic restoration treatments in coastal dune ecosystems.

In response to this opportunity, this paper reviews established spatial statistical methods that can be used to quantify and examine significant spatial–temporal volumetric and geomorphic changes within dynamic coastal dune landscapes. The utility of one particular method, local Moran's I_i, for detecting and assessing the impacts of dynamic restoration is demonstrated by a case study where invasive vegetation was removed from a foredune-transgressive dune complex. From this, various methodological and logistical considerations for detecting significant changes in dynamic dune landscapes are discussed and several key geomorphic indicators that can be used to assess the effectiveness of dynamic restoration methods are presented.

2. Quantifying and detecting significant geomorphic changes within dune landscapes

Traditional methods for examining geomorphic changes and related sediment transfers within beach-dune systems have involved interpretation of historical aerial photography (e.g., Tsoar and Blumberg, 2002; Mathew et al., 2010; Heathfield and Walker, 2011), analysis of cross-shore topographic profiles (e.g., Morton et al., 1994; Davidson-Arnott and Law, 1996; Aagaard et al., 2004), monitoring of erosion/deposition pins or quadrat plots (e.g., Gares, 1992; Davidson-Arnott and Law, 1996; Arens et al., 2004; Levin et al., 2006; Ollerhead et al., 2013), and interpretation of digital elevation models (DEMs) derived from detailed repeat topographic surveys (e.g., Gares et al., 1996; Arens, 1997; Andrews et al., 2002; Ruz and Meur-Ferec, 2004; Anthony et al., 2006, 2007) or, more recently, high resolution aerial LiDAR data (e.g., Woolard and Colby, 2002; Sallenger et al., 2003; Houser and Hamilton, 2009; Saye et al., 2005; Eamer and Walker, 2010; Houser and Mathew, 2011). Data from these methods are commonly used to generate estimates of active sand surface area and/or volumetric changes of sediment and related geomorphic responses (e.g., beach-dune erosion and rebuilding, incipient dune growth, dune migration rates). Such results are very useful for interpreting landform to landscape scale responses of beach-dune systems to natural disturbances such as wave erosion by storms, hurricanes, or climatic variability events (e.g., Allan et al., 2003; Ruz and Meur-Ferec, 2004; Anthony et al., 2006; Houser et al., 2008; Houser, 2009; Houser and Hamilton, 2009) as well as to implemented disturbances for restoration purposes (e.g., Nordstrom et al., 2002; Arens et al., 2004, 2005; Wondergem, 2005; Arens and Geelen, 2006; Hilton et al., 2009).

Robust and repeatable methods that account for uncertainty are required to distinguish between noise in acquired DEM datasets and changes that are statistically significant. DEM precision and accuracy are a function of a variety of fundamental factors, including the quality of survey point data (a function of instrument precision), sampling strategy and point density, sampling frequency and temporal consistency, surface composition (e.g., soft sand vs. stable soils), topographic complexity, and chosen interpolation methods (e.g., Wise, 1998; Wechsler, 2003; Wechsler and Kroll, 2006; Heritage et al., 2009; Wheaton et al., 2010). Furthermore, when calculating change surfaces from DEMs, error resulting from uncertainty is additive as a result of comparison of DEMs with individual uncertainties. No standard convention exists for considering and incorporating uncertainty, as evident in recent research on beach-dune morphological changes derived from DEMs (e.g., Woolard and Colby, 2002; Mitasova et al., 2005; Anthony et al., 2006; Mathew et al., 2010), which implements different methods of data acquisition (e.g., LiDAR, RTK-GPS, digital photogrammetry, laser total station surveys) and spatial interpolation models (e.g., inverse distance weighted, regularized spline with tension, kriging) each with respective uncertainties and handling of error. In some cases, data uncertainties are not specified