Defining Dunes: Evaluating How Dune Feature Definitions Affect Dune Interpretations from Remote Sensing

Authors: Wernette, Phillipe, Thompson, Stephanie, Eyler, Rachel, Taylor, Hannah, Taube, Caleb, et al.

Source: Journal of Coastal Research, 34(6) : 1460-1470

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/JCOASTRES-D-17-00082.1

Journal of Coastal Research | 34 | 6 | 1460–1470 | Coconut Creek, Florida | November 2018

REVIEW ARTICLES

www.cerf-jcr.org

Defining Dunes: Evaluating How Dune Feature Definitions Affect Dune Interpretations from Remote Sensing

Phillipe Wernette[†]*, **Stephanie Thompson**[‡], **Rachel Eyler**[§], **Hannah Taylor**[§], **Caleb Taube**[§], **Alex Medlin**[§], **Claire Decuir**[‡], **and Chris Houser**[†]

[†]Department of Earth and Environmental Sciences
University of Windsor
Windsor, ON N9B 3P4, Canada

[‡]Department of Geology and Geophysics
Texas A&M University
College Station, TX 77843, U.S.A.

[§]Department of Geography
Texas A&M University
College Station, TX 77843, U.S.A.

ABSTRACT

www.JCRonline.org

Wernette, P.; Thompson, S.; Eyler, R.; Taylor, H.; Taube, C.; Medlin, A.; Decuir, C., and Houser, C., 2018. Defining dunes: Evaluating how dune feature definitions affect dune interpretations from remote sensing. *Journal of Coastal Research,* 34(6), 1460–1470. Coconut Creek (Florida), ISSN 0749-0208.

Coastal resiliency is the ability of a beach–dune system to recover to a previous state after a storm, and this resiliency is affected by prestorm beach and dune morphology and storm climate (*i.e.* storm frequency and intensity). Improvements in remote sensing technology such as LIDAR and structure from motion have enabled rapid collection and production of digital elevation models used to assess storm impact and recovery. Although rapid poststorm assessment requires a consistent approach for extracting dune morphology, relatively little attention has focused on defining the different parts of a dune. The goals of this paper are to examine how the definition of a dune feature drives the methodology used to extract dunes and to synthesize a comprehensive definition of dune features. An analysis of existing approaches for extracting beach and dune morphology demonstrates that there is considerable variation in how the beach–dune transition (*i.e.* dune toe) is defined. Many definitions are recursive or include ambiguous terminology, resulting in a dune toe or crest line position dependent on user interpretation of the definition. Other definitions rely heavily on user interpretation of dune features at varying stages in the feature extraction process. Reliance on visual interpretation can result in substantially different feature locations across different interpreters. Given the impact of varying definitions on dune resiliency assessments and legal implications for dune features location, this study proposes a series of semantic models for dune features. Semantic modelling of coastal morphology is vital for consistently and accurately assessing coastal recovery and predicting future coastal assessments on the basis of a consistent set of criteria.

ADDITIONAL INDEX WORDS: *Semantic modeling, coastal monitoring, coastal management.*

INTRODUCTION

Sand dunes are highly susceptible to change in response to storms, drought, and anthropogenic impacts. Extreme storm events have the potential to dramatically alter the coastal morphology over a relatively short period of time. Hurricanes, tropical storms, nor'easters, and other extreme storms bring strong wind and waves. The changes to the coast depend on the wind and wave conditions acting over the pre-existing nearshore, beach, and dune morphology. The storm-impact model of Sallenger (2000) provides a valuable approach to modelling and predicting changes to the dune morphology, where the expected response is related to the ratio of water level run-up to dune height. However, monitoring and predicting coastal change is complicated in cases where the alongshore morphology is variable. Run-up at one location might only erode the beach and not significantly affect dune morphology; however, the same run-up would completely inundate a smaller dune. Understanding patterns of coastal resiliency and predicting future changes to beach and dune morphology are predicated on the ability to accurately and consistently measure beach and dune morphology. Beach and dune morphology is commonly extracted from digital elevation models (DEMs). Current approaches for extracting beach and dune morphology from DEMs have varying degrees of uncertainty (see Wernette, Houser, and Bishop, 2016).

Many dune systems are highly variable in their height alongshore, and, as a result, it is important that researchers and managers are able to accurately assess prestorm morphology to accurately predict changes during and after a storm. Accurately predicting future coastal response to storms is valuable for coastal scientists, resource managers, and coastal communities to more effectively manage coastal infrastructure, resources, and public safety. Monitoring and accurately predicting the impact of future storms is based on understanding how the magnitude and variability of extreme storm events has affected coastal morphology in the past. Immediate prestorm and high-spatial resolution monitoring is challenging

---

DOI: 10.2112/JCOASTRES-D-17-00082.1 received 25 April 2017; accepted in revision 28 October 2017; corrected proofs received 30 November 2017; published pre-print online 12 January 2018.

*Corresponding author: wernette@uwindsor.ca

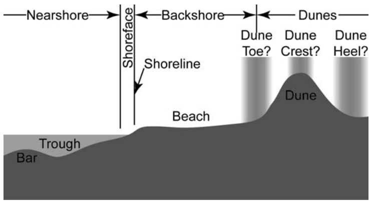

Figure 1. Terminology used in this paper to describe coastal geomorphology. The white–black–white gradients for dune toe, dune crest, and dune heel represent areas of uncertainty since current coastal literature does not agree on any single "true" location. Darker areas are more likely to be the location of a feature, lighter areas are less likely, and the gradient represents the likelihood that the location is extracted as the dune feature (on the basis of current coastal literature).

because it necessitates that the dune be measured objectively (*i.e.* without human-induced subjectivity and error) and consistently, while rapidly turning raw data into useful accurate information. A comprehensive coastal management and preservation strategy requires understanding how the coast changes, which is predicated on properly compiling and analyzing data.

Current models for predicting morphologic change utilize the simple topographic-based parameters, such as beach slope, dune height, and dune volume (Gutierrez *et al.*, 2015; Plant and Stockdon, 2012; Wilson *et al.*, 2015). However, there remains uncertainty in how to determine each of these metrics because there is no consistent method(s) or set of definitions upon which to interpret the parts of a dune. Water run-up is simulated over the beach slope and against the dune height to classify the expected change into one of four categories described in the Sallenger (2000) storm-impact model: swash, collision, overwash, or inundation. Variation in the computed beach slope and dune height can greatly affect the expected response and affect the accuracy of predicted changes. Dune height can vary greatly depending on the algorithm used to extract the landscape features (Wernette, Houser, and Bishop, 2016), which depends on the semantic definition used for the landscape features.

Dunes can be defined and divided into many different categories on the basis of their morphology and location (Hesp and Walker, 2013; Tsoar, Blumberg, and Stoler, 2004). Whereas previous studies have defined foredunes, blowouts, parabolic dunes, and transgressive dune fields on the basis of their geomorphic characteristics (Hesp, 2002; Hesp and Walker, 2013), definitions for the dune toe, dune crest, and dune heel are inconsistent and, in some cases, vague (Figure 1). Hesp (2002) defined established foredunes on the basis of "morphological complexity, height, volume, and geographical position" (p. 248, Hesp, 2002) as "shore-parallel dune ridges formed on top of the backshore by aeolian sand deposition within vegetation" (p. 246, Hesp, 2002). Although foredunes can be further differentiated on the basis of a combination of geographic location on the coast and vegetation dynamics (Hesp and Walker, 2013), neither Hesp (2002) nor Hesp and Walker (2013) defined the individual features of a dune. Perhaps the simplest feature to define is the dune crest, which has been defined as the "highest elevation of the coastal primary sand dune" (Regulation 4 VAC 20-440-10 ET SEQ, Virginia Marine Resources Commission, 1993). Although previous studies have primarily focused on defining dunes more broadly, this paper represents an evaluation of how differences in where the foredune begins (dune toe), crests (dune crest), and ends (dune heel, landward dune toe) affects the approach used to extract dune position from remote-sensing information.

The purpose of this paper is to examine different ways to define dune features and how these different definitions influence the beach and dune features extracted from remote-sensing data. Previous research has examined semantic definitions of coastal dunes more generally but have not defined where the dune starts on the seaward or landward sides or where it crests. The current paper will examine the following definitions and approaches: manual delineation and interpretation (MDI) approach (Fabbri *et al.*, 2017; Lentz and Hapke, 2011), the slope-inflection point-based (SIP) approach (Stockdon *et al.*, 2007; Stockdon, Doran, and Sallenger, 2009), the least-cost path (LCP) approach (Hardin *et al.*, 2012; Mitasova *et al.*, 2011), and the relative relief (RR) approach (Wernette, Houser, and Bishop, 2016) to define the different parts of coastal dunes. Each of the definitions will be described in detail, and then applied in practice to a small portion of Padre Island National Seashore (PAIS), Texas. Differences and similarities between the different definitions will be highlighted to derive a more complete and objective definition. In addition, key advantages and disadvantages of each approach for extracting dunes will be described on the basis of the steps taken to implement the various methods. A brief comparative analysis will highlight gaps in our contemporary definitions of a dune and the four approaches for extracting dunes. This comparison will serve as the foundation for identifying future research needs. Finally, a more complete and multidisciplinary definition of a dune will be presented, which can be parameterized. Areas of future research needs will be highlighted on the basis of the comparative analysis of existing definitions and approaches.

METHODS

This paper utilizes a 1-m resolution LIDAR-derived DEM from central PAIS (Figure 2) to examine how existing definitions of dune features affect the interpreted location of the dune. Located along the Gulf of Mexico, the sampled area has a maximum elevation of ~12 m above sea level, although dune height varies significantly alongshore. The LIDAR used to generate the DEM has a reported sampling distance of approximately 1.5 m and reported global horizontal and vertical accuracies of 1.00 m and 0.15 m, respectively, although it is important to remember that the horizontal accuracy is a global measure of accuracy reported at one standard deviation. Two washover channels are present in the relatively small area, a well-defined channel in the center and another channel to the north. Both washover channels are characterized by hummocks representative of postwashover dune recovery processes. The washover channel in the central part of the DEM is more well defined and appears to contain smaller hummocks (Figure 2). This sample DEM is utilized to

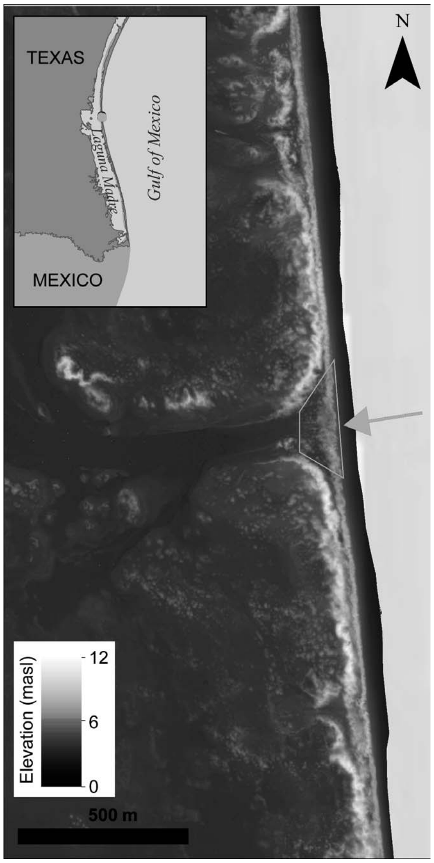

Figure 2. The influence of different semantic definitions on the extracted location of a dune is demonstrated using a small portion of Padre Island National Seashore, Texas. The large overwash channel near the center of the study area is indicated by the large horizontal arrow. Smaller arrows highlight some of the hummocks that have begun to develop in the overwash channel since it was last washed over.

demonstrate how existing methods, such as MDI, SIP, LCP, RR, and vegetation approaches, can be used to define the parts of a dune (*i.e.* dune toe, dune crest, and dune heel) and how these definitions affect the interpreted locations of different dune parts. The "Methods" section of this paper will focus on describing five commonly used approaches to extracting/interpreting the different features of a dune.

MDI Approach

The MDI approach has been widely applied to delineate and extract two-dimensional (2D) landscape features and profiles from DEMs and aerial imagery (Allen, Oertel, and Gares, 2012; Ewing, Kocurek, and Lake, 2006; Lentz and Hapke, 2011; Levin and Ben-Dor, 2004; Yao *et al.*, 2007). Lentz and Hapke (2011) describe a common approach to manually interpreting dune morphology from DEMs. They define the primary dune crest (D_{crest}) as "the maximum elevation of the seaward-most dune crest" and delineated the dune toe (D_{toe}) on the basis of "elevation and slope changes observed landward of the berm" (p. 87, Lentz and Hapke, 2011). This approach relies on the ability of a user to accurately manually digitize the location of the dune features on the basis of a variety of parameters, such as elevation, slope, and curvature. For example, the location of D_{toe} can be digitized on the basis of an abrupt change in slope from the gently sloping beach to a steeper-sloping dune face. Dune crest position can be identified as the highest elevation point closest to the shoreline. The manual digitization process can be done using a wide variety of GIS programs.

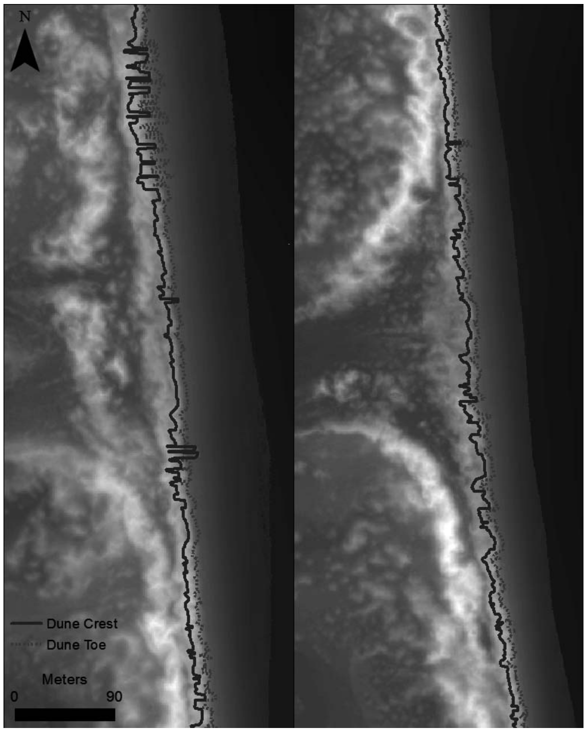

Figure 3. Dune toe and dune crest lines were extracted by person A and person B for a stable foredune (left) and in a washover channel (right). Notice the discrepancy between the feature locations based on the interpreter.

One potential disadvantage of the MDI approach is that the delineated position of D_{toe} and D_{crest} may vary by the interpreter (Figure 3; Edwards, 1999; Zhang and Goodchild, 2002). This positional variability is highlighted in Figure 3, where the different color lines represent the different image interpreter. Given the intrapersonal variability in delineations, it is feasible that a single interpreter may delineate the same D_{toe} and D_{crest} features in two different locations given enough time between interpretations. Ambiguity and subjectivity in dune toe and crest position definitions can potentially introduce varying degrees of positional uncertainty into the landscape feature positions, depending on the landscape interpreter. However, if the landscape interpreter has expert knowledge of the study area, then the MDI approach may be valuable over a small area. An expert in a given area is more likely to be familiar with how the landscape has changed in the past and continues to change, and would be able to draw on this experience to identify landscape features more accurately than somebody who has less experience in that same location.

Although feature definitions used in the MDI approach are subject to user interpretation errors, this approach may be useful to inform the thresholds and metrics used in other approaches. Examining the values of many different parameters along an interpreted ridgeline can be useful to determine what an appropriate threshold might be for the many parameters in defining crest lines. For example, convergence and divergence may be useful parameters for identifying some landscape features (Wernette *et al*., 2016). Convergence is a measure of landscape closedness useful when identifying basins and troughs, whereas divergence is a measure of landscape openness useful to identify peaks and ridges. This parameter is potentially useful for highlighting and manually delineating the location of features such as D_{toe}, D_{crest}, and even dune heel (D_{heel}), although the method does not currently include any definition for D_{heel}. Since D_{heel} is analogous to the landward dune toe (see Wernette, Houser, and Bishop, 2016), it possible that a definition could be created for this feature in the MDI approach. However, the exact location of the landscape features will still ultimately depend on an individual's interpretation of the convergence/divergence map. Subjectivity in MDI definitions of dune toe and crest are not based on any definitive or consistent criteria, such as slope or other morphometric, and are still likely to introduce some user interpretation error while encapsulating expert knowledge.

SIP Approach

A semiautomated approach to extracting dune features developed by Stockdon *et al*. (2007) and Stockdon, Doran, and Sallenger (2009) defines the dune toe and dune crest on the basis of the change in slope. The dune toe is defined as the "location of maximum slope change within a region around a coarsely digitized line" (p. 5, Stockdon *et al*., 2007). Dune crest elevation is defined as "the highest-elevation peak landward of the shoreline and within a user-defined beach width," where elevation peaks are identified as "inflection points where the slope changes from positive to negative, moving seaward from the landward extent of the (shore-normal) profile" (p. 61, Stockdon, Doran, and Sallenger, 2009). Inflection points are useful for semiautomating the extraction of beach and dune features because these two features are typically defined on the basis of the change in slope caused by sediment transport and deposition. The location of D_{crest} is determined on the basis of 2D cross-shore profiles, which are extracted from three-dimensional (3D) DEMs. It is important to note that the original approaches to extracting D_{toe} and D_{crest} outlined by Stockdon *et al*. (2007) and Stockdon, Doran, and Sallenger (2009) applies a smoothing filter to the LIDAR-derived DEMs before extracting the cross-shore profiles, thereby altering the original data and potentially influencing the results.

Applying this SIP approach to a raw LIDAR DEM yielded erratic data points, where the extracted D_{toe} and D_{crest} positions varied greatly along the length of the study area (Figure 4). This variability may be due to many reasons, such as vegetation and other noise in the DEM that may be misinterpreted as landscape features. To avoid the irregularities caused by the raw DEM, the raw profile was filtered by averaging over a local neighborhood window. During the filtering process the window size was adjusted to eliminate elevation differences above or below a certain value. This smoothing window size varies depending on the user and geomorphology of the study area, and requires tacit knowledge of the study site (Stockdon, Doran, and Sallenger, 2009). For comparison against other approaches, a spatial averaging profile was run using a 3-by-3 window size, eliminating extreme elevation differences over a 9-m^2 area. Using the smoothed DEM, the SIP approach was applied again, and the resulting image displayed the location of shoreline and dune crest.

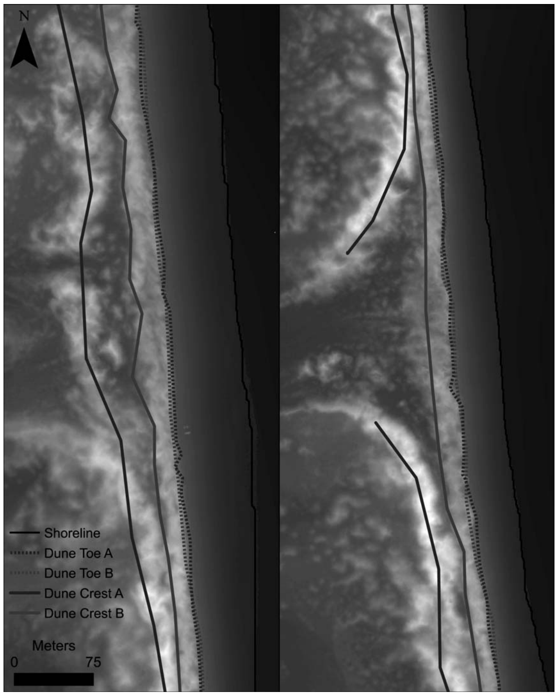

Figure 4. Dune toe (dashed line) and dune crest (solid line) were extracted on the basis of the definitions and approach outlined in Stockdon *et al*. (2007) and Stockdon, Doran, and Sallenger (2009).

The SIP approach can be semiautomated because the definition is based on an abrupt and quantifiable positive-to-negative or negative-to-positive change in slope. Therefore, a slope-change algorithm can be applied to the DEM to get a moderately accurate representation of D_{toe} and D_{crest}. However, to get a consistent set of smooth curvilinear dune features, the raw data must be smoothed before processing. Without smoothing, the amount of time spent manually editing the extracted features was significantly greater than the same process if the raw DEMs were preprocessed and smoothed. Manual editing of the points is required in both cases to ensure that the results are consistent. The SIP approach does not define D_{heel}, and is therefore unable to extract this feature. Since the back-barrier shoreline is often difficult to extract consistently in a very low-relief environment or is far away from the dune, extracting features landward of D_{crest}, such as D_{heel}, is not feasible using the SIP approach.

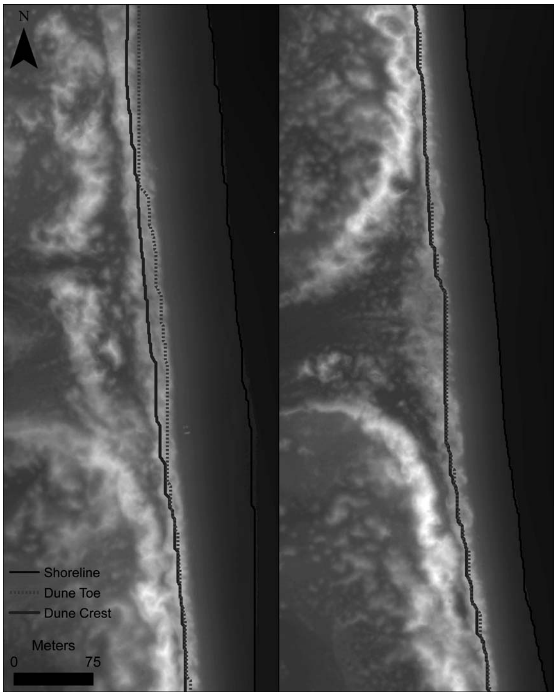

Figure 5. Sample dune toe and dune crest lines extracted from the DEM using a LCP approach where a foredune is present (left) and in a washover channel (right). There is a significant difference in the dune toe and dune crest locations when the entire DEM is used, as opposed to a DEM that has been clipped to remove the secondary dune.

LCP Approach

Introduced by Mitasova *et al.* (2011) and extended by Hardin *et al.* (2012), one approach to extracting the shoreline, D_{toe}, and D_{crest} is by using a LCP algorithm. In this case, D_{crest} is defined as the "least cost path between two given end points of the ridge," where the LCP is based on an exponential "cost" function that is inversely related to the DEM elevation (p. 2, Mitasova *et al.*, 2011; Equation [1]). Although no specific information is provided about how to define the start and end points for the cost-path analysis, it is possible to derive these two points using an inflection point approach, similar to Stockdon *et al.* (2007) and Stockdon, Doran, and Sellenger (2009), or manual interpretation. A least-cost flow algorithm is applied to determine the lowest cost path to get from the predefined start point to the predefined end point. In this way, the algorithm determines the lowest cost path to travel from the start point to end point, where the cost of moving from one cell to the next is defined by the cost function. The resulting path is interpreted as the foredune ridge line (Figure 5), although ambiguities in defining the cost surface function, starting point, and end point may result in significantly different D_{crest} locations:

$$J = e^{-bz} \tag{1}$$

where, J, the cost of traversing a given cell, is a function of b, a "tunable parameter," and z, the elevation of the raster cell.

The LCP approach applies a similar process to extract D_{toe}, which is defined as the "location where the beach meets the foredune," or the "location where the cross shore profile deviates the most from a line connecting the dune ridge and shoreline" (p. 2, Mitasova *et al.*, 2011). An interpolated surface is first created extending from the dune ridge line to the shoreline and with a "mechanical tension" applied on the basis of adjacent elevation values (p. 2, Mitasova *et al.*, 2011). A new surface is generated by computing the difference between the original DEM and the interpolated surface to extract D_{toe}. The same inverse exponential cost function is applied to the differenced surface to extract D_{toe} between two predefined end points. Similar to D_{crest}, extracting the D_{toe} location requires a set of predefined start and end points, which can be extracted many different ways. This dune toe line is continuous from the start to end point (Figure 5), regardless of any breaches in the foredune that might be caused by storm surge. Because D_{toe} location is spatially continuous and based on maximum deviation from a line connecting the shoreline and D_{crest}, the current definition is unclear about which factor (spatial continuity or maximum deviation) is weighted more heavily when there are abrupt changes in dune toe position, such as the abrupt change when entering a dune washover channel.

Hardin *et al.* (2012) extended the LCP approach by simulating the impact of storm surge on the beach and dunes. Storm surge was simulated over LCP-extracted topographic parameters on the basis of predictions from wave forecast models. This simulated storm surge can be used to predict possible morphologic changes on the basis of the traditional storm-impact model (Sallenger, 2000). Since the LCP approach defines dune features on the basis of a quantifiable LCP between two predefined points, it can be applied via custom python scripts and open-source GIS software, such as the Geographic Resources Analysis Support System (Hardin *et al.*, 2012; Mitasova *et al.*, 2011). One challenge with the LCP approach is that features are defined solely on the basis of a LCP algorithm that is not able to distinguish between secondary dunes and foredunes in a complex coastal landscape. The LCP approach definitions require extensive preprocessing to effectively isolate foredune morphology. Additionally, the precise effects of the unclear D_{toe} and D_{crest} definitions on the storm surge impact modelling are yet unclear, as Hardin *et al.* (2012) relied solely on the LCP approach.

Vegetation Limit Approach

Vegetation plays a key role in the formation of coastal dunes by slowing wind transporting sand inland from the beach (Davidson-Arnott, 2010; Woodroffe, 2002). Vegetation slows wind velocity and reduces the transport potential below the threshold required for aeolian transport processes, thereby causing sediment to be deposited adjacent to the vegetation. Although results on the precise amount of vegetation required to influence sediment transport are mixed, dunes are more likely to form where vegetation is present. There is disagreement about the percent vegetation cover at which sand transport becomes negligible, with some studies suggesting vegetation cover as low as 30% can be effective (Buckley, 1987) and other studies suggesting it is 60% (Walker *et al.*, 2006). In a study of vegetation on South Padre Island, Texas, even a small amount of vegetation (12.5% cover) was found to be as effective as very abundant vegetation (57% cover) for preserving dune height and promoting dune growth (Judd *et al.*, 2008). Although the exact percent vegetation cover required to significantly affect aeolian sand transport remains unclear, the underlying principle remains unchanged. As a result, it is possible, although challenging, to use dune vegetation as an indicator of dune morphology. Specifically, vegetation boundaries have been used to delineate the dune toe as "the area at the foot of the dune where vegetation begins" (Levin and Ben-Dor, 2004).

One relatively simple approach for extracting vegetation from remotely sensed data is to compute the normalized-difference vegetation index (NDVI) using four-band aerial imagery to create a false-color composite. Computing NDVI from the near-infrared and red bands helps highlight and differentiate vegetation from bare earth or other materials. Since vegetation is vital to coastal dune development, it is possible that the seaward vegetation limit might be interpreted as the dune toe line (Levin and Ben-Dor, 2004). Defining dune features on the basis of vegetation extent is advantageous because it enables feature change analysis using historical aerial imagery. This process could be automated using a high-pass filter for detecting abrupt edges such as D_{toe}, although the current paper uses a simple visual interpretation approach to extract D_{toe} on the basis of the vegetation extent, as indicated by change in NDVI (Figure 6).

Although vegetation information is often directly observed or derived from aerial imagery, the same vegetation edge can also be gathered from high-resolution LIDAR data. LIDAR is an approach to generating high-resolution and highly accurate DEMs. Depending on the vegetation structure, first returns will tend to represent the vegetation elevation, whereas subsequent colocated returns will represent either the ground surface or some lower-elevation vegetation structure. In this case, it is possible to generate a DEM using only the first returns and another DEM using all subsequent returns. Subtracting the first-return DEM from the second-return DEM yields a vegetation structure map. Since extracting vegetation from LIDAR data is beyond the scope of this paper, readers interested in more information about vegetation mapping via LIDAR should refer to Hantson, Kooistra, and Slim (2012), Kempeneers *et al.* (2009), and Rango *et al.* (2000).

Although vegetation abundance has been used to define microecological communities within a dune ecosystem (Boomsa and de Vries, 1980; Ghabbour, Cancela Da Fonseca, and Mikhail, 1987; McLachlan, 1991; Stallins, 2001; Stallins and Parker, 2003) and differentiate between dune types (Hesp, 2002; Nordstrom, Lampe, and Vandemark, 2000), it is important to note that vegetation abundance may not be a representation of dune morphology in all environments. For example, dunes along South and North Padre Islands can be well developed and be absent of vegetation, whereas other dunes along the same stretch of coast can be well developed and completely covered by vegetation. Vegetation abundance can potentially serve as a valuable indicator of dune morphology (Levin and Ben-Dor, 2004), but to do so requires first-hand knowledge of the local site conditions, geomorphology, and ecology.

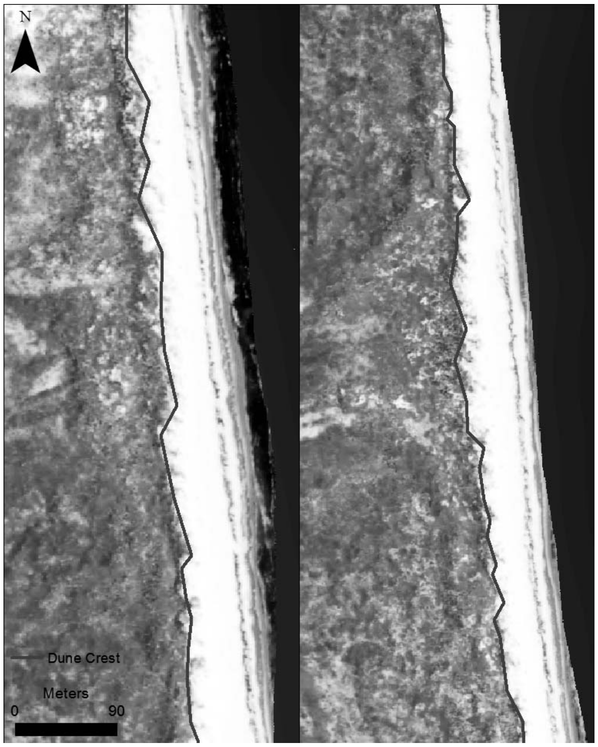

Figure 6. Dune crest can be manually delineated on the basis of the vegetation line, as indicated here by the contrast between the vegetation (high NDVI) and white exposed sand (low NDVI).

RR Approach

Dune features may also be defined on the basis of adjacency and topographic position relative to the computational scale (*i.e.* relative relief). Specifically, Wernette, Houser, and Bishop (2016) defines D_{toe} as the "first location landward of the shoreline where the average relative relief crosses 0.2″ (p. 6). D_{crest} was defined and extracted as "the location landward of the dune toe where relative relief values cross 0.8″ (p. 6, Wernette, Houser, and Bishop, 2016). D_{heel} is described as a topographic low, similar to D_{toe}, that is "landward of the dune crest" where the relative relief crosses 0.4 because "elevations landward of the dune crest are more variable" and the "slightly higher relative relief threshold… accounts for the greater variability in elevation along the lee side of the dune" (p. 6, Wernette, Houser, and Bishop, 2016). On the basis of these semantic definitions, D_{toe}, D_{crest}, and D_{heel} can be extracted on the basis of changes in the relative topographic position (*i.e.* relative relief) as you move inland from the shoreline. The RR approach is a useful approach to extracting these coastal dune features, as highlighted in Figure 7, which can be automated, although the method still requires the user to define some input parameters. Defining the user thresholds represents a source of ambiguity that can potentially affect the consistency of feature locations extracted across multiple studies.

Figure 7. Relative relief defines dune features on the basis of their relative topographic position. Dune toe, crest, and heel are all defined and can be quantifiably extracted, although the cross-shore position of a feature may vary in the alongshore direction.

The RR approach computes the elevation of the center pixel as a function of the elevation range within a given window size. The difference between the minimum elevation and the center pixel elevation is divided by the total range in elevation throughout the window. Relative relief values range from 0 to 1, with 0 being the absolute lowest elevation within the computational window and 1 being the absolute highest peak within the computational window. Errors and topographic anomalies present in the DEM are mitigated by averaging RR values across multiple scales, thereby reducing the impact of anomalies at any single scale. The window dimensions are dependent on the scale of the features being studied and the desired output resolution. Since D_{toe}, D_{crest}, and D_{heel} are all extracted by comparing the average relative relief to a user-defined threshold, the user should have tacit knowledge of scale-dependent features throughout the study area to appropriately apply the RR approach. Large computational windows are more appropriate for extracting features from larger landforms, whereas smaller window sizes will capture finer-scale features. The computational window size and thresholds used to extract dune morphology represent subjectivity in the definitions of dune features using the RR approach.

RESULTS

The definition used in the MDI approach is the vaguest, owing to substantial variation in feature location from one interpreter to another, since the location of a landform feature is entirely dependent on the ability of an individual to read and extract the dune from the DEM or derived product. This interpretation will likely vary from person to person, depending on each user's perception of the DEM, tacit knowledge of the study area, and overall understanding of coastal geomorphology. The subjectivity and potential bias may result in the same feature being delineated in two very different locations. Inconsistencies between multiple interpretations can lead to inaccurate analysis of a dune feature in a given area because the feature is not measured on the basis of the same criteria. Wernette, Houser, and Bishop (2016) noted that the MDI approach is very time intensive and is not scalable for large-scale mapping of coastal morphology, an issue stemming from the definition of dune features solely based on a user's ability to interpret the data. Despite the potential drawbacks of the MDI approach and given a trained expert with first-hand knowledge of the area, this method may be valuable for mapping small areas, assuming a single person was interpreting the features at the same scale and in a relatively short period of time. It would not be possible to automate this method since dune features are defined on the basis of the manual interpretation of the dune features, which can vary significantly between different users. To automate the MDI approach would require changing the definition of the dune toe, crest, and heel to be more quantitative and less subjective, resulting in a new method.

Slope-inflection point (Stockdon, Doran, and Sallenger, 2009; Stockdon *et al.*, 2007) defines dune features on the basis of a quantifiable change in slope gradient. In this way, the SIP approach is more objective and can be semiautomated, making it more time efficient than the MDI approach. Although not explicitly included in the dune features definitions, it should be noted that the practical application of the SIP approach requires data preprocessing, followed by manual adjustment and correction. Since LIDAR-derived DEMs can be noisy compared with coarser-resolution DEMs, the authors of the SIP approach applied a smoothing filter to the raw DEM before extracting the inflection point. Results of the current case study and Wernette, Houser, and Bishop (2016) demonstrate that the extracted dune features are more consistently located when using a smoothed DEM over a raw DEM. Although the SIP definitions are more consistent with our conceptual understanding of dune features and can be automated, they do not completely define how features are extracted. This method lacks the ability to display the D_{heel}, resulting in the need for another method to determine the locations of this feature.

The RR approach is the only tested method that defines and can extract D_{toe}, D_{crest}, and D_{heel}. This approach does not have the same subjectivity caused by manual interpretation, but is subject to user definition of the computational window size and feature thresholds. Extracting all three features means that this approach is useful for assessing dune volume and changes to this volume. As noted by Wernette, Houser, and Bishop (2016), one advantage of the RR approach is that it makes use of information across multiple spatial computational scales and can be automated over large portions of the coast. The importance of automating feature extraction is that coastal managers are better able to monitor coastal geomorphology in near real time, a stated goal of the U.S. Geological Survey.

Although the RR approach defines D_{toe}, D_{crest}, and D_{heel} on the basis of quantifiable relationships between user-defined

Table 1. *Summary table presenting the advantages and disadvantages of the MDI, SIP, LCP, vegetation, and RR approaches to interpreting dune features.*

Approach	Advantages	Challenges/Disadvantages
MDI	Utilizes expert knowledge Adaptable to a variety of data sources (*e.g.,* aerial imagery, DEMs) Possible to interpret dune toe, crest, and heel	Time-intensive for large geographies Interpreted feature locations are subjective and may vary among interpreters and over time
SIP	Smoothed DEM captures general trends in dune toe and crest	Requires subjective preprocessing (DEM smoothing) to interpret a smooth continuous line Manual quality assessment/quality control requires manually moving points Unable to interpret dune heel location
LCP	Results in continuous, smoothly varying dune features	Requires subjective preprocessing (DEM clipping) to avoid extracting taller secondary dunes Unclear about how start and end points are determined Unclear about what "cost" function is most appropriate for a given location Unable to interpret dune heel location
Vegetation	Useful with historical aerial and satellite imagery	Seasonal variation in vegetation abundance may introduce bias Annual variation in vegetation may occur because of weather and climate variability Not all geographies have vegetation and can be associated with the different parts of a dune
RR	Does not require a feature to be continuous alongshore Possible to interpret dune toe, crest, and heel	Computational window sizes are static across the geography Thresholds require user input (introduce subjectivity)

relative relief thresholds and average relative relief, the approach does not explicitly define appropriate computational window sizes. The initial computational window size is subjective and may vary depending on the user and specific location being analyzed. As demonstrated by Wernette, Houser, and Bishop (2016) and emphasized in our analysis (Figure 7), the RR computational scale affects the performance of the automated feature extraction. These thresholds and computational window sizes represent disadvantages of this approach because they require an appropriate user-defined threshold, which introduces subjectivity and increases the potential for error and inconsistency. Ambiguity in computational window sizes and thresholds are set up by the feature definitions in the RR approach. Furthermore, the thresholds are static over the entire study area, suggesting that the geomorphology does not significantly vary or have a global trend. Although this may or may not be an appropriate constraint, it is likely that the geomorphology does vary across the area, which means the threshold should vary similarly across the area.

The vegetation approach is consistent with our conceptual understanding of how a dune forms and evolves and does not require any user-defined threshold or computational window size. In addition, using vegetation extent as an indicator of dune position is valuable for historical change studies limited to aerial imagery. If the NDVI can be computed, it may also be possible to semiautomate this approach by applying a high-pass filter to detect the vegetation edge. If the vegetation edge is manually delineated, then using vegetation as a morphologic indicator is still subject to human errors because of subjectivity of the interpreter. No approach has yet defined any of the parts of a dune on the basis of vegetation abundance or presence/absence. Given the important role that vegetation plays in dune development, it follows that dune morphology could partially be defined using vegetation abundance (Levin and Ben-Dor, 2004). The challenges of using vegetation to map beach and dune morphology has potentially important legal implications as well. The Texas General Land Office (GLO) is charged with managing Texas state lands, helping with recovery from natural disasters, and managing the Texas coast. In profile view, a "beach," as defined by the Texas GLO, "extends from the mean low tide line to the line of natural vegetation along the shoreline" (Texas General Land Office, 2017). Vegetation abundance is used by the State of Texas to delineate the transition from the back beach to the foredune ridge. Using vegetation as a key indicator of beach–dune morphology can be problematic during extended droughts, significant storm erosion, or anthropogenic landscape modification (*e.g.,* vegetation planting or driving on the beach), which may modify the extent of vegetation across the landscape.

Further complicating vegetation abundance as an indicator of dune position, it is important to recognize that the vegetation abundance and vegetation edge position are partially dependent on the time of year and climatic conditions. This seasonality may be more significant in some locations than others depending on factors such as the species present, disturbance regime, and overall climate trends. During peak leaf-on times of the year, the vegetation abundance is more likely to appear significantly greater than the same area during winter months or nongrowing seasons. The lower vegetation abundance will also affect the perceived vegetation extent line and may even blur this boundary. The diversity and specific species present at a given location may also affect the perceived vegetation boundary, which, in turn, would affect the extracted dune toe position. Unfortunately, it is often very difficult, if not impossible, to locate any historical species abundance information for a study area.

DISCUSSION

Definitions of beach and dune features vary significantly throughout the literature and drive various advantages and disadvantages of each approach (Table 1). Although some of the definitions are measurable and can be parameterized, others are vague or use circular logic. In this paper, circular logic is used to refer to a part of a dune that has been defined using the term, or similar term, itself. For example, defining a dune toe as the location where the beach meets the dune is one use of circular logic in defining the parts of a dune because the term dune toe represents a transitionary boundary we are trying to locate. This is analogous to defining the boundary between the beach and the dune as the boundary between the beach and the dune. One significant issue with circular definitions is that they are not quantifiable or measurable.

Although the MDI-approach definition of D_{toe} is not circular, it is vague and relies on the analyst to determine what change in elevation and slope is significant to represent the beach–dune transition. It remains unclear what a "significant" change in elevation and slope is, and, as a result, the MDI approach cannot be objectively parameterized. The SIP, LCP, and RR approaches define D_{crest} in ways that can be parameterized; however, each approach defines the parts of a dune with varying degrees of ambiguity, in terms or circular logic. The SIP and LCP require different DEM preprocessing steps, which can significantly affect the location of the derived dune features. Applying the SIP approach requires smoothing/denoising of the raw DEM to reduce the amount of time required to manually correct the feature locations. The LCP definitions require the analyst to define the start and end points for the LCP algorithm, and also requires that the DEM is clipped to remove dunes beyond the foredune ridge. Both of these processes are vague, can vary significantly from site to site, and can influence the location of the extracted dune features. Although the RR approach does not require DEM preprocessing, it does require the analyst to define an appropriate threshold and computational window size. The thresholds and computational window size are likely to change from site to site and require expert knowledge of the site, which can vary between analysts.

The most significant issue with many definitions is the use of circular logic. The MDI approach includes the term "dune crest" in the definition of dune crest. As a result, the objectivity of the MDI approach is significantly reduced and the location of the dune crest may vary significantly among different persons' interpreting the D_{crest} location. The SIP and RR approaches do not contain circular logic in how the dune features are defined, but the LCP definition of D_{toe} is moderately problematic. Since D_{toe} is the edge of the foredune, stating that D_{toe} is the location where the foredune begins is recursive and not quantifiable. The LCP approach does, however, include an additional quantifiable definition that is predicated on accurately extracting the shoreline and dune crest positions.

Assessing volumetric resiliency of dunes alongshore requires accurately and consistently extracting the landward toe of the dune, D_{heel}. The only approach that explicitly defines D_{heel} is the RR approach. This approach defines the trailing edge of the dune on the basis of a low relative relief that is adjacent to D_{crest}. Similar to the LCP definition of D_{toe}, the RR definition and criteria for D_{heel} is predicated on the notion that D_{crest} can be accurately extracted. Since none of the other approaches defines the trailing edge of the dune, they are limited in their application to comprehensively assess 3D dune resiliency.

This paper demonstrates that there is no clear and consistent definition of the D_{toe}, D_{crest}, and D_{heel} features in existing approaches to extracting dune morphology from DEMs. This inconsistency and ambiguity has important implications for coastal management, where the method used to assess coastal resiliency will directly affect resource managers' predictions of future coastal response to extreme storm events in the context of sea-level rise. For example, since the MDI, SIP, and LCP approaches are all highly susceptible to user-interpretation errors, coastal geomorphic studies using each of them should be aware of how the definition and approach are biased. Without a comprehensive understanding of how one method compares with the others, it is difficult to inform which approach is most valuable for the analysis. Although others have attempted to define foredunes generally (Hesp, 2002; Hesp and Walker, 2013), the current paper represents an attempt to define where the foredune begins (D_{toe}), crests (D_{crest}), and ends (D_{heel}). The following semantic models were developed for D_{toe}, D_{crest}, and D_{heel} on the basis of definitions and approaches examined in this paper and similar studies (Ewing, McDonald, and Hayes, 2015; Hesp, 2002, 2013; Hesp and Walker, 2013; Mitasova *et al.*, 2010; Mitasova, Overton, and Hardin, 2005).

D_{toe}. Landward of the shoreline, marked by an increase in slope moving landward from the shoreline (*i.e.* a significant local maximum in profile concavity). This feature is a topographic low in context of the dune and a topographic high in context of the beach. Unless the stoss side of the dune is completely vegetated or the beach is vegetated, the dune toe is not likely marked by a distinct vegetation edge.

D_{crest}. A local relative topographic maximum (*i.e.* topographic high within the predefined computational window size) landward of the shoreline and dune toe, marked by a significant decrease in slope gradient (*i.e.* local maximum in profile convexity) and is often associated with a change in slope azimuth. The change in slope gradient can either be from a positive slope gradient to no slope or from a positive slope gradient to a negative slope gradient. When the stoss slope is active (unvegetated) and the lee slope is vegetated, the dune crest may be marked by a vegetation line.

D_{heel}. Landward of the shoreline, the dune heel is the trailing toe of the foredune and a local relative topographic low following the relative topographic high marking D_{crest}. D_{heel} is often marked as a significant decrease in slope gradient on the lee side of a dune. With respect to a line approximately shore-normal to the overall coastal orientation, the change in profile curvature can either be from a negative slope gradient to no slope or from a negative slope gradient to a positive slope gradient (*i.e.* change in slope azimuth). When the lee slope is active (unvegetated) and the dune is migrating over a vegetated surface, the dune heel may be marked by a vegetation boundary.

The proposed definitions are attempts to eliminate ambiguity and circular logic from existing definitions while consistent with our conceptual understanding of beach and dune morphology. In each of the definitions, a dune can be generally defined as an accumulation of sediment that has been transported from the beach and vertically accreted. Although implementing these definitions completely may require somewhat complex computations, these definitions include multiple parameters and variables that can be computed automatically. These definitions are not completely comprehensive, but represent a first attempt at defining where the foredune begins, peaks, and ends, which is integral to developing more comprehensive dune extraction approaches.

Given the need for accurately monitoring and predicting coastal morphologic change at many levels of stakeholder and governmental organizations, there appear to be three primary research needs when defining dune toe, crest, and heel. The proposed research needs are as follows: (1) approaches to extracting landscape features need to have more objectivity, and limit the amount of human error introduced into the analysis; (2) to efficiently apply the extraction over small and large areas, there is a need for more automated approaches for extracting landforms from many different data sources; (3) feature extraction approaches should be scalable from personal computers to high-performance servers to ensure that the approach can be applied by a diverse array of organizations and stakeholders.

All of the approaches examined in this review have definitions that are ambiguous and are subject to varying degrees of human error, although the specific type of error is driven by the definition of the dune feature. The MDI and SIP approaches are especially prone to human-introduced error because both approaches rely exclusively on manual interpretation of the feature location. The LCP approach is also subject to human error on the basis of the arbitrary cost function applied to connect the user-interpreted start and end points. Although the RR approach definitions are easily automated, this approach is subject to human error because the user is required to specify a single starting scale of analysis for the entire DEM. The thresholds used to extract the dune features must be user specified, and it is possible that a user might set incorrect thresholds. Human-induced error is present in all of the current methods for extracting beach and dune features from remotely sensed data. This error has the potential to significantly alter the location of the extracted features. Future research focus should be on mitigating the effects of human error on the location of beach and dune features. Mitigating this error would enable coastal managers to more effectively assess the response and recovery of the beach and dunes to extreme storms by minimizing human biases.

New approaches to extracting beach and dune morphology from remotely sensed data should also be scalable. Manual delineation is not feasible over large areas because it is so time intensive. The SIP approach is semiautomated and can be applied over small and large areas; however, the SIP approach requires extensive manual adjustment to accurately represent the beach and dune features. Relative relief is the most automated approach to extracting coastal morphology. Vegetation abundance and edge detection require either manual interpretation and digitization or high-pass filtering and manual quality assessment. The RR approach can be applied over small and large areas, but can be further improved by allowing the computational window size and feature thresholds to vary across the study area. There is a general need for more automated approaches that are scalable over small and large areas. Improving the automation and scalability of extracting features will enable coastal managers to rapidly assess storm impacts at a multitude of scales and more efficiently manage coastal resources.

In addition, there is a need for automated feature extraction approaches that are scalable to a range of computing requirements. To accurately assess coastal morphologic change and the impact it has on humans, it is important that coastal managers have the ability to implement the analysis at the local, regional, state, and federal levels. Local analyses are more likely to include shorter stretches of the coast and be limited to traditional personal computers. On the other hand, state and federal agencies and organizations should be able to implement the same analysis over larger stretches of the coast because they would have greater computing resources (*i.e.* server cloud computing and artificial neural networks). Whereas the MDI and SIP approaches are feasible over small areas, they are not feasible over larger areas because they are time intensive and not cost effective. The LCP and RR are moderately scalable, although it requires DEM smoothing, a process that can be very time consuming for large areas. The RR approach is also moderately scalable, but does not make use of a varying window size or threshold, both likely to vary depending on the scale of a particular study. Designing scalable approaches ensures that coastal change can be accurately monitored and predicted by stakeholder organizations and state and federal agencies.

CONCLUSIONS

This paper demonstrates that definitions used by each of the examined approaches for extracting beach and dune morphology use circular logic or are not well defined quantitatively. Although possible to implement each one, there are unique challenges associated with each approach that are driven by these ambiguities (Table 1). For example, with the LCP approach, the definition and approach used to extract the dune crest line does not adequately describe how to determine the start and end points or how to appropriately set the tunable parameter, b, in the cost function. Given the ambiguities in existing definitions for D_{toe}, D_{crest}, and D_{heel}, there is a need for updated definitions that provide coastal researchers and managers with a consistent and objective means to monitor coastal geomorphology. The definitions proposed in this paper are based on a combination of existing definitions and provide guidance on how to consistently interpret beach–dune morphology from remotely sensed data. Developing updated definitions is the first step toward improving consistency and objectivity among coastal studies; however, future approaches should focus on three primary areas: (1) decreasing subjectivity (and increasing objectivity) in feature extraction, (2) developing automated approaches that can be applied to a wide variety of data sources, and (3) developing approaches that are scalable from personal computers to high-performance computing clusters. Meeting these three research needs will increase consistency among coastal research and management by decreasing confusion about how beach–dune morphology is interpreted.

LITERATURE CITED

Allen, T.R.; Oertel, G.F., and Gares, P.A., 2012. Mapping coastal morphodynamics with geospatial techniques, Cape Henry, Virginia, U.S.A. *Geomorphology*, 137(1), 138–149.

Boomsa, J.J. and de Vries, A., 1980. Ant species distribution in a sandy coastal plain. *Ecological Entomology*, 5, 189–204.

Buckley, R., 1987. The effect of sparse vegetation on the transport of dune sand by wind. *Nature*, 325, 426–428.

Davidson-Arnott, R., 2010. *Introduction to Coastal Processes and Geomorphology*. Cambridge, United Kingdom: Cambridge University Press.

Edwards, G., 1999. Towards a theory of vector error characterization and propagation. *In:* Lowell, K. and Jaton, A. (eds.), *Spatial Accuracy Assessment: Land Information Uncertainty in Natural Resources*. Ann Arbor, Michigan: Ann Arbor Press, pp. 183–188.

Ewing, R.C.; Kocurek, G., and Lake, L.W., 2006. Pattern analysis of dune-field parameters. *Earth Surface Processes and Landforms*, 31(9), 1176–1191.

Ewing, R.C.; McDonald, G.D., and Hayes, A.G., 2015. Multi-spatial analysis of aeolian dune-field patterns. *Geomorphology*, 240, 44–53.

Fabbri, S.; Giambastiani, B.M.S.; Sistilli, F.; Scarelli, F., and Gabbianelli, G., 2017. Geomorphological analysis and classification of foredune ridges based on Terrestrial Laser Scanning (TLS) technology. *Geomorphology*, 295, 436–451.

Ghabbour, S.I.; Cancela Da Fonseca, J.P., and Mikhail, W.Z.A., 1987. Seasonal differentiation of soil mesofauna in a littoral dune of the Egyptian Mediterranean coast. *Biology and Fertility of Soils*, 3, 75–80.

Gutierrez, B.T.; Plant, N.G.; Thieler, E.R., and Turecek, A., 2015. Using a Bayesian network to predict barrier island geomorphologic characteristics. *Journal of Geophysical Research: Earth Surface*, 120, 2452–2475.

Hantson, W.; Kooistra, L., and Slim, P.A., 2012. Mapping invasive woody species in coastal dunes in the Netherlands: A remote sensing approach using LIDAR and high-resolution aerial photographs. *Applied Vegetation Science*, 15, 536–547.

Hardin, E; Kurum, M.O.; Mitasova, H., and Overton, M.F., 2012. Least cost path extraction of topographic features for storm impact scale mapping. *Journal of Coastal Research*, 28(3), 970–978.

Hesp, P., 2002. Foredunes and blowouts: Initiation, geomorphology and dynamics. *Geomorphology*, 48(1–3), 245–268.

Hesp, P., 2013. Conceptual models of the evolution of transgressive dune field systems. *Geomorphology*, 199, 138–149.

Hesp, P.A. and Walker, I.J., 2013. 11.17 Coastal dunes. *In:* Shroder, J.F. (ed.), *Treatise on Geomorphology*. London: Elsevier, pp. 328–355.

Judd, F.W.; Summy, K.R.; Lonard, R.I., and Mazariegos, R., 2008. Dune and vegetation stability at South Padre Island, Texas, United States of America. *Journal of Coastal Research*, 24(4), 992–998.

Kempeneers, P.; Deronde, B.; Provoost, S., and Houthuys, R., 2009. Synergy of airborne digital camera and Lidar data to map coastal dune vegetation. *In:* Brock, J.C. and Purkis, S.J. (eds.), Coastal Applications of Airborne Lidar. *Journal of Coastal Research*, Special Issue No. 53, pp. 73–82.

Lentz, E.E. and Hapke, C.J., 2011. Geologic framework influences on the geomorphology of an anthropogenically modified barrier island: Assessment of dune/beach changes at Fire Island, New York. *Geomorphology*, 126(1–2), 82–96.

Levin, N. and Ben-Dor, E., 2004. Monitoring sand dune stabilization along the coastal dunes of Ashdod-Nizanim, Israel, 1945–1999. *Journal of Arid Environments*, 58(3), 335–355.

McLachlan, A., 1991. Ecology of coastal dune fauna. *Journal of Arid Environments*, 21, 229–243.

Mitasova, H.; Hardin, E.; Overton, M.F., and Kurum, M.O., 2010. Geospatial analysis of vulnerable beach–foredune systems from decadal time series of lidar data. *Journal of Coastal Conservation*, 14(3), 161–172.

Mitasova, H.; Hardin, E.; Starek, M.J.; Harmon, R.S., and Overton, M.F., 2011. Landscape dynamics from LiDAR data time series. *Proceedings of Geomorphometry 2011* (Redlands, California), 1–4.

Mitasova, H.; Overton, M., and Harmon, R.S., 2005. Geospatial analysis of a coastal sand dune field evolution: Jockey's Ridge, North Carolina. *Geomorphology*, 72(1–4), 204–221.

Nordstrom, K.F.; Lampe, R., and Vandemark, L.M., 2000. Reestablishing naturally functioning dunes on developed coasts. *Environmental Management*, 25(1), 37–51.

Plant, N.G. and Stockdon, H.F., 2012. Probabilistic prediction of barrier-island response to hurricanes. *Journal of Geophysical Research: Earth Surface*, 117(F3), 17.

Rango, A.; Chopping, M.; Ritchie, J.; Havstad, K.; Kustas, W., and Schmugge, T., 2000. Morphological characteristics of shrub coppice dunes in desert grasslands of southern New Mexico derived from scanning LiDAR. *Remote Sensing of Environment*, 74, 26–44.

Sallenger, A.H., 2000. Storm impact scale for barrier islands. *Journal of Coastal Research*, 16(3), 890–895.

Stallins, J.A., 2001. Soil and vegetation patterns in barrier island dune environments. *Physical Geography*, 22(1), 79–98.

Stallins, J.A. and Parker, A.J., 2003. The influence of complex systems interactions on barrier island dune vegetation pattern and process. *Annals of the Association of American Geographers*, 93(1), 13–29.

Stockdon, H.F.; Doran, K.S., and Sallenger, A.H., 2009. Extraction of LiDAR based dune crest elevations for use in examining the vulnerability of beaches to inundation during hurricanes. *Journal of Coastal Research*, 25(6), 59–65.

Stockdon, H.F.; Sallenger, A.H.; Holman, R.A., and Howd, P.A., 2007. A simple model for the spatially-variable coastal response to hurricanes. *Marine Geology*, 238(1–4), 1–20.

Texas General Land Office, 2017. *Dune Protection and Improvement Manual for the Texas Gulf Coast*. Austin: Texas General Land Office.

Tsoar, H.; Blumberg, D.G., and Stoler, Y., 2004. Elongation and migration of sand dunes. *Geomorphology*, 57(3–4), 293–302.

Virginia Marine Resources Commission, 1993. Coastal Primary Sand Dune/Reaches Guidelines: Barrier Island Policy. http://www.mrc.virginia.gov/regulations/fr440.shtm.

Walker, I.J.; Hesp, P.A.; Davidson-Arnott, R.G.D., and Ollerhead, J., 2006. Topographic steering of alongshore airflow over a vegetated foredune: Greenwich Dunes, Prince Edward Island, Canada. *Journal of Coastal Research*, 22(5), 1278–1291.

Wernette, P.; Houser, C., and Bishop, M.P., 2016. An automated approach for extracting Barrier Island morphology from digital elevation models. *Geomorphology*, 262, 1–7.

Wilson, K.E.; Adams, P.N.; Hapke, C.J.; Lentz, E.E., and Brenner, O., 2015. Application of Bayesian networks to hindcast barrier island morphodynamics. *Coastal Engineering*, 102, 30–43.

Woodroffe, C.D., 2002. *Coasts: Form, Process, and Evolution*. Cambridge, United Kingdom: Cambridge University Press.

Yao, Z.Y.; Wang, T.; Han, Z.W.; Zhang, W.M., and Zhao, A.G., 2007. Migration of sand dunes on the northern Alxa Plateau, Inner Mongolia, China. *Journal of Arid Environments*, 70(1), 80–93.

Zhang, J. and Goodchild, M.F., 2002. Uncertainty in continuous variables. *In:* Zhang, J. and Goodchild, M.F. (eds.), *Uncertainty in Geographical Information*. Research Monographs in Geographical Information Systems. London: Taylor and Francis, pp. 93–130.