International Journal of Remote Sensing
Vol. 32, No. 1, 10 January 2011, 231–241

Technical Note

LiDAR-derived measures of hurricane- and restoration-generated beach morphodynamics in relation to sea turtle nesting behaviour

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(*Received 16 June 2008; in final form 23 April 2009*)

Coastal ecosystems provide sea turtle nesting habitat, and thus their maintenance is vital to promote conservation of the species. Before and after a very active hurricane season, airborne Light Detection and Ranging (LiDAR) was used to quantify the topographic dynamics of a critical nesting beach in east central Florida, USA, that was subjected to erosion and restoration. The surface area and volume of the beaches along a 41 km stretch, which is home to the highest concentration of loggerhead and green turtle nests in North America, differed significantly between pre- and post-hurricane and between pre-hurricane and post-restoration periods. Sea turtle nesting success (nesting emergences : total emergences) in the season after the hurricanes was correlated with various LiDAR-detected characteristics to determine how sea turtles responded to beach dynamics resulting from the storms and subsequent restoration. We found that the more the shape of the beach profile was altered from its pre-hurricane morphology, the more nesting success decreased.

1. Introduction

Beach ecosystems are highly dynamic due to regular cycles of erosion and accretion. However, during hurricanes and other severe storm events, these cycles can be interrupted, leading to increased levels of erosion (Zhang *et al.* 2005). Restoration projects, typically involving acquiring and redistributing sand, have become widespread as a means of protecting coastal developments in the face of such erosion. Over the past decade, Light Detection And Ranging (LiDAR) remote sensing has been shown to be an effective tool for assessing the dynamics of shoreline and dune morphology (Woolard and Colby 2002, Shrestha *et al.* 2005, Liu *et al.* 2007). Moreover, it has been used to develop habitat models for coastal flora (Sellars and Jolls 2007), as well as to assess hurricane-induced erosion (Zhang *et al.* 2005, Robertson *et al.* 2007) and the restoration projects that follow (Gares *et al.* 2006).

Although many coastal species are negatively impacted by storm damage (Oli *et al.* 2001, Snyder and Boss 2002), sea turtles are particularly vulnerable, as they rely on specific beaches for reproduction and exhibit high-nest-site fidelity to their natal beaches (Carr and Carr 1972). However, why particular beaches or stretches of beach are chosen over others is unknown. Sea turtle eggs are buried and incubated in the sand, thus physical attributes of the beach directly affect reproductive success

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International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2011 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160903439973

(Karavas *et al*. 2005, Foley *et al*. 2006). With hurricanes, nests can be damaged via washouts or flooding causing reproductive success to decline (Pike and Stiner 2007).

In 2004, the Florida coastline was subjected to an unusually active hurricane season with four major hurricanes hitting the peninsula within a 6 week period. Two of these storms (Hurricanes Frances and Jeanne) directly impacted the east coast, which contains important nesting beaches for two species of sea turtle: the threatened loggerhead (*Caretta caretta*) and the endangered green sea turtle (*Chelonia mydas*). This stretch of coast includes the Archie Carr National Wildlife Refuge (ACNWR), which is home to the highest concentration of nesting loggerhead turtles in the western hemisphere (Ehrhart and Raymond 1983) and the highest concentration of nesting green turtles in continental United States (Ehrhart and Raymond 1987). Due to severe erosion as a result of the 2004 storms, a large-scale beach restoration project was conducted in early 2005. The objective of this study was to use airborne LiDAR to measure beach morphology following intense hurricane activity and subsequent restoration, and to determine if the topographic dynamics affected loggerhead and green turtle nesting patterns.

2. Methods

2.1 *Study area and data collection*

The study area consisted of a 21 km stretch of coastline along a barrier island on the east coast of Florida, USA, which was divided into 42, ~0.5 km segments for monitoring purposes (figure 1). It comprised the entire ACNWR, which extends from Sebastian Inlet at the southern end to Melbourne Beach at the northern end. The entire study area is open for public recreation. Commercial and residential developments exist intermittently throughout the ACNWR.

Beach elevation data were obtained through the National Oceanic and Atmospheric Administration Coastal Services Center (NOAA-CSC 2008) website using the LiDAR Data Retrieval Tool (LDART). LiDAR data were collected using the Compact Hydrographic Airborne Rapid Total Survey (CHARTS) system by the US Army Corps of Engineers. The data had a nominal ground spacing of 3 m and had a vertical accuracy of 15 cm root mean square error (RMSE) and a horizontal accuracy of 80 cm RMSE. Data were acquired from LiDAR missions flown in April 2004 (prior to hurricane season, hereafter referred to as pre-hurricane), November 2004 (following the end of hurricane season, denoted as post-hurricane) and February 2006 (denoted as post-restoration). Although these data do not exactly correspond with the hurricane season or the end of the initial restoration, it is thought that intervening and subsequent beach changes should, by comparison, be relatively minor. The data were downloaded at a resolution of 3×3 m into ArcGIS 9.1 (ESRI, Redlands, CA, USA) for spatial and topographic analyses.

Nesting data were collected daily during early morning surveys throughout the 2004 and 2005 nesting seasons, that is generally between May and September (Weishampel *et al.* 2006). All sea turtle tracks were identified as either nesting or non-nesting emergences. Non-nesting emergences (referred to as false crawls) occur when a female turtle emerges from the ocean but returns to the water without nesting, perhaps because she does not perceive favourable nesting conditions. Nests and false crawls were identified to species, and the number of nests and false crawls were tallied within each ~0.5 km beach segment (see Weishampel *et al.* (2003) for a detailed description).

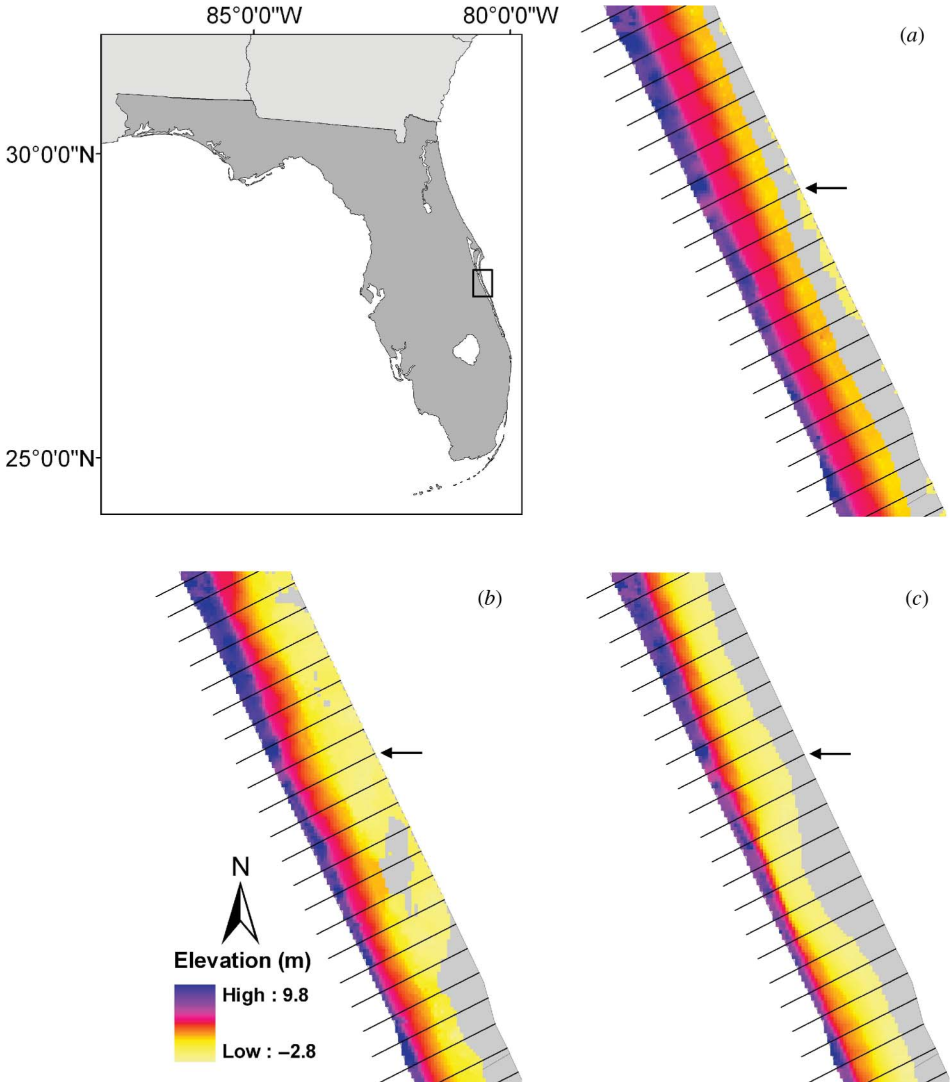

Figure 1. Map of study area and a representative ~500 m stretch of the ACNWR. LiDAR images show elevation changes from (*a*) pre-hurricane, (*b*) post-hurricane and (*c*) post-restoration. Lines show the location of the profiles, which are spaced at 25 m intervals and the black outline indicates the boundary of the St Johns River Water Management District areas classified as 'beach'. Arrows indicate the representative profile that is used as an example in figure 2.

2.2 *Data analysis*

For consistency, public land-use designations provided by the St Johns River Water Management District (SJRWMD 2008) were used to include only LiDAR for areas categorized as 'beach'. To determine the location of morphological changes, two different measures, i.e. surface area and volume, were derived for each ~0.5 km beach segment at pre-hurricane, post-hurricane and post-restoration time periods using ArcGIS 3D Analyst. Surface areas and volumes for each time period were compared using paired *t*-tests. Additionally, ArcGIS 9.1 was used to depict beach

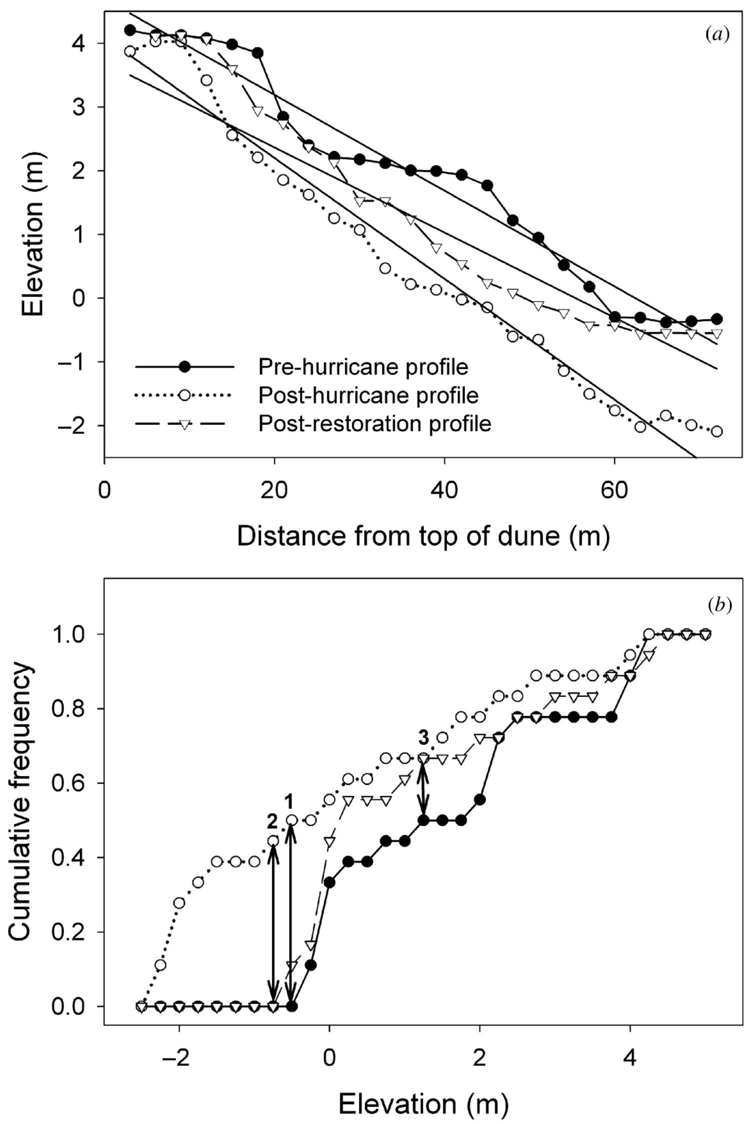

Figure 2. (*a*) An example profile shown before and after the hurricanes and after restoration. Straight lines represent the overall slope for each profile. (*b*) Using the K–S test, profiles are compared by converting them to cumulative frequency distributions. The maximum distance between the curves is noted as the D-value. Three comparisons are shown here: (1) pre- versus post-hurricane ($D = 0.50$), (2) post-hurricane versus post-restoration ($D = 0.44$) and (3) pre-hurricane versus post-restoration ($D = 0.17$).

profiles every 25 m along the entire study area for each dataset. Each profile extended 90 m inland and recorded elevation every 5 m (figure 1). Beach slope was then calculated from each profile using a best-fit line (figure 2(*a*)), and slopes were analysed using paired t-tests. Kolmogorov–Smirnov (K–S) tests were used to determine whether beach profiles changed significantly over time (Sokal and Rohlf 1981, Gotelli and Ellison 2004). This simple method has been used to detect differences in topographic properties from leaf (Mechaber *et al.* 1996) to ocean (Gille 2004) surfaces. The K–S test converts each profile to a cumulative frequency curve, then measures the greatest distance between the two curves (figure 2(*b*)). The statistic generated is a *D*-value, which is proportional to the degree of difference between the two curves. Although several methods have been offered to characterize the actual shape of a beach profile (e.g. Allen 1975, Cooper *et al.* 2000), previous studies have shown the K–S test to be useful in determining whether temporal variation exists among topographic elements (Käyhkö 2007). Beach slope and profile (*D*-values) were then averaged within each ~0.5 km segment.

Nesting success within each segment was calculated by dividing the number of nests by the total number of emergences (Brock *et al.* 2009). Because the total number of nests may be highly variable between seasons, while nesting success remains relatively constant, nesting success is a more reliable indicator of change. Each ~0.5 km segment was categorized into: 100% natural, less than 50% restoration, between 50% and 99% restoration and 100% restoration classes, based on the shoreline length that was restored in 2005. These designations were chosen due to the patchy nature of the restoration, as only areas of beach adjacent to a structure or public park were restored, rather than one continuous stretch. A pairwise analysis of variance (ANOVA) using Tukey's Honestly Significant Difference (HSD) test (Gotelli and Ellison 2004) was performed to detect any changes in nesting success from 2004 to 2005 in each category. Multiple linear regression using stepwise model selection was performed to determine if changes in beach slope, profile, volume and surface area significantly related with nesting success.

3. Results

Surface area and volume both showed a significant decline from pre- to post-hurricane. Additionally, surface area and volume were significantly different from pre-hurricane to post-restoration (figure 3). Results of the analyses of beach profiles and slopes revealed that, while some areas had significantly different profiles and/or slopes when pre-hurricane was compared to post-hurricane and post-restoration ($P < 0.05$), most areas were not significantly different. It is possible, however, that the lack of significant differences is in part a by-product of the nature of the K–S test where very different shapes could produce cumulative frequency graphs with low *D*-values.

Although there was a decrease in nesting success in loggerheads for all restoration categories and for green turtles in all but the natural area, only the areas with 50–99% and 100% restoration showed significant changes. In these two areas, loggerhead and green turtle nesting success declined significantly from 2004 to 2005 (figure 4). The stepwise selection of multiple regression models revealed that changes in beach profile, slope and volume combined to make the best model for loggerheads. This model was significantly negatively correlated with nesting success (coefficient of determination, $R^2 = 0.346$, $P < 0.001$). Within the model, both changes in profile and slope were significant ($P < 0.001$). This result led us to perform individual regressions of beach profile and slope against loggerhead nesting success. The regression of profile change versus nesting success yielded significant negative correlations for loggerhead (figure 5(*a*)) and green turtles (figure 5(*b*)).

4. Discussion and conclusions

Hurricanes and beach restoration projects can significantly alter the physical characteristics of the beach to which marine turtles are sensitive. Several studies have quantified

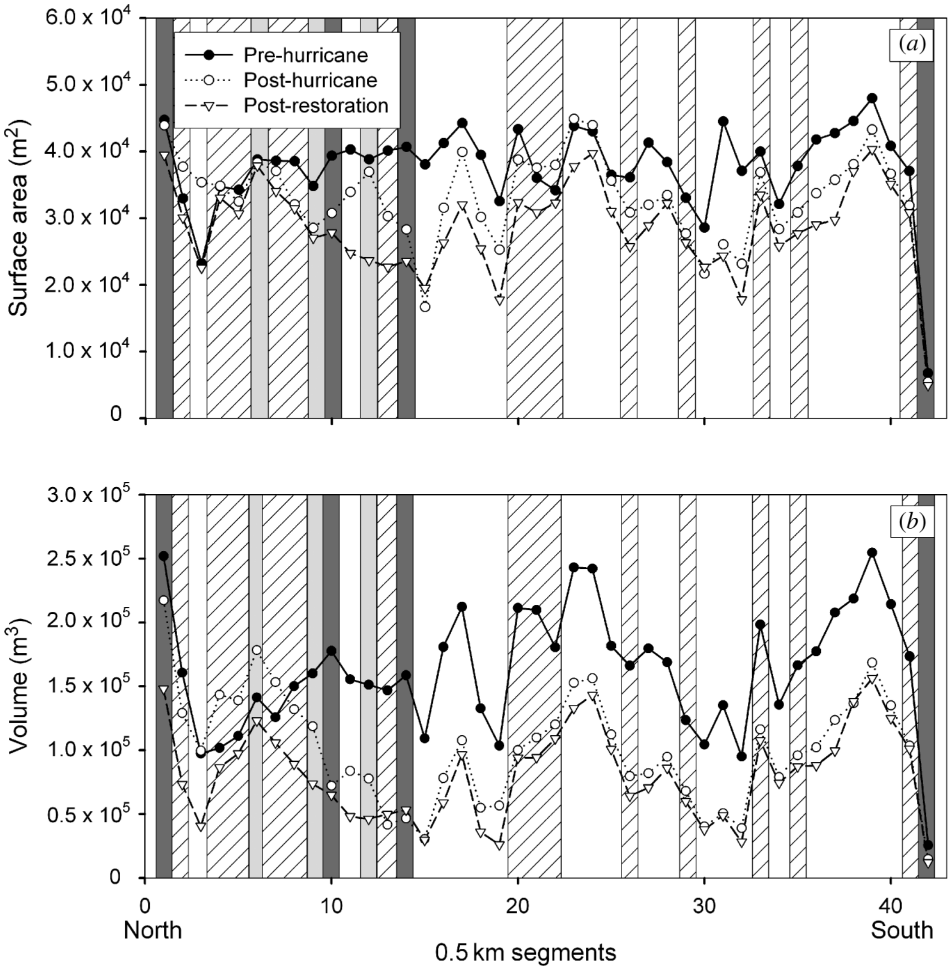

Figure 3. (*a*) Surface area and (*b*) total sand volume of each ~0.5 km beach segment along the 21 km study area before and after the hurricanes and after restoration. Dark grey areas are 100% natural, light grey areas are <50% restored, striped areas are 50–99% restored and white areas are 100% restored. Post-hurricane and post-restoration surface area and volume measurements were both significantly different from pre-hurricane measurements ($P < 0.001$ in each case).

impacts that beach restoration has on sea turtle nesting, and most indicate that a decline in nesting for one season after restoration is quite normal (Rumbold *et al.* 2001). These studies, however, did not attempt to determine what factors lead to this decline. Although Brock *et al.* (2009) found that previous restoration throughout the ACNWR in 2002 yielded significant decreases in nesting success, the decline in nesting success seen in 2005 was the most severe on record (unpublished data collected since 1989). It appears that of the variables tested here, the shape of the beach profile is a key factor contributing to sea turtle nesting success. We conclude that nesting by the two major marine turtle species in the ACNWR is sensitive to changes in beach profile shape, as demonstrated by the negative correlation between the magnitude of profile change and nesting success. Previous studies have shown that marine turtles prefer steeply sloped dunes preceded by a gradually sloped foredune (Hays *et al.* 1995). Our results are consistent with this

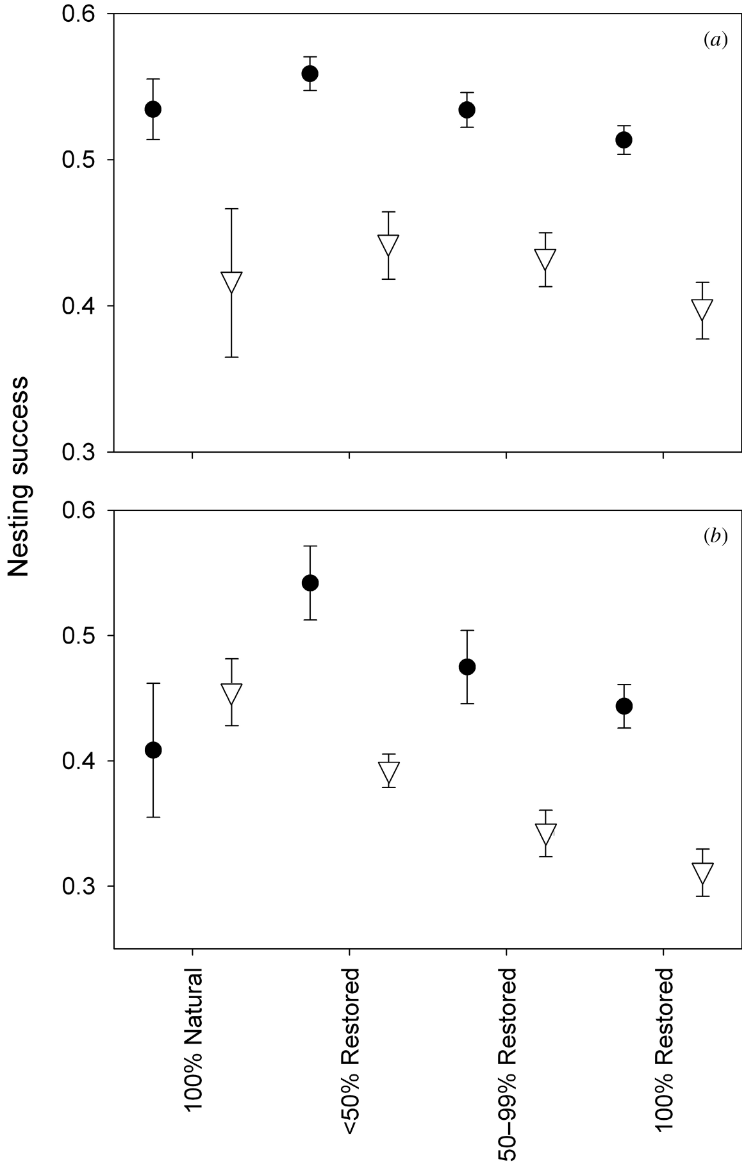

Figure 4. Mean and standard error of (*a*) loggerhead and (*b*) green turtle nesting success for pre-hurricane (black circles) and post-restoration (white triangles) in each of the four restoration categories. For both species, areas having 50 – 99% and 100% restoration had significantly lower nesting success in 2005 than in 2004 ($P = 0.002$ and $P < 0.001$, respectively, for loggerheads and $P = 0.002$ and $P < 0.001$, respectively, for green turtles).

observation as the change in profile shape, rather than a single slope measure across the entire width of the beach, was the best predictor of nesting success. Future studies will apply methods to more precisely characterize the shapes of these profiles in order to determine which morphologies are most conducive to sea turtle nesting success.

Although the *D*-values used to represent the change in profile shape do not take change in slope into account (i.e. spatial patterns of erosion or accretion), they are an

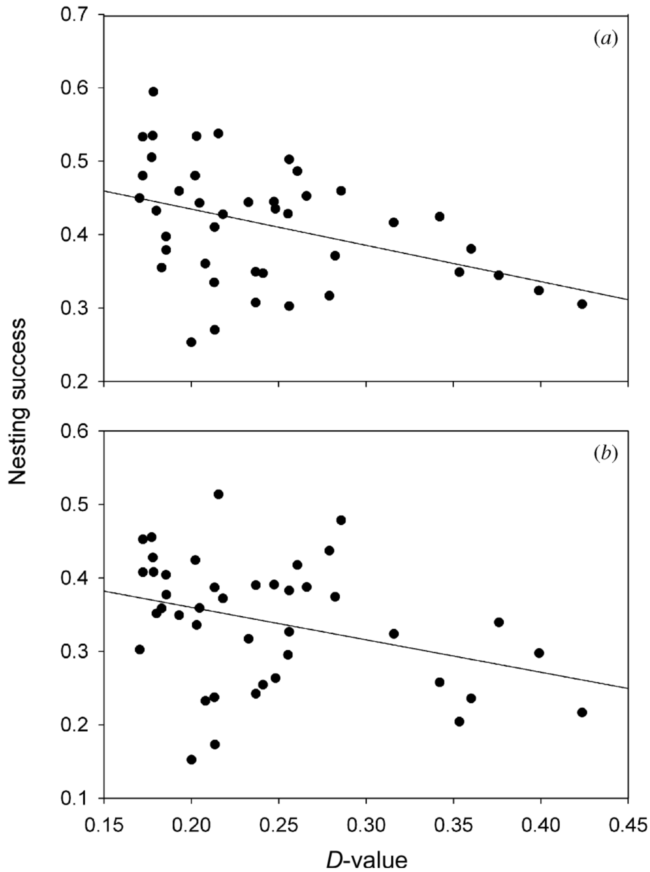

Figure 5. Regression of *D*-values versus nesting success for (*a*) loggerhead and (*b*) green turtles. High *D*-values represent large differences between the pre-hurricane and post-restoration beach profiles. Loggerheads ($R^2 = 0.16$, $P < 0.01$) and green turtles ($R^2 = 0.12$, $P = 0.03$) showed a significant negative correlation, implying that as the difference between profiles increased from one year to the next, nesting success declined.

indicator of overall change in beach morphology. Thus, it may be necessary for coastal engineers to attempt to reproduce profile shapes when restoring eroded beaches. Despite the lack of correlation between surface area or volume and nesting success, we believe these are important variables to be tested as changes in either factor can contribute differently to the overall topography. It is important to recognize that purely topographic variables were analysed here, but a host of other biotic and abiotic factors (sand grain size, moisture content, dune vegetation, lighting, etc.) also contribute to sea turtle nesting patterns and behaviour (Karavas *et al.* 2005). Often in restored areas characteristics of the new sand, such as sand-grain size, differ from those of the existing sand and, although not measured in this study, these differences are likely to contribute to changes in nesting success. While the relatively low amount of variance explained by the profile shape may be partially attributable to these differences, there is nonetheless a significant relationship between beach profile and nesting success.

While the application of this methodology to sea turtle nesting is still being explored, we believe it to be an accurate technique for analysing coastal habitat.

Though misregistration of the altimetry data will affect topographic measures (e.g. Van Neil *et al.* 2008), the displacement will generally be less than the alongshore scale of pattern of these beaches. Such horizontal inaccuracies will cause misalignments among datasets for the different time periods; however, the consistency with which these errors occur often allows them to cancel out, especially when calculating overall measurements such as volume and surface area (Sallenger *et al.* 2003). Furthermore, by averaging the slopes and *D*-values from the cumulative profiles within each beach segment, the impact of misregistration was reduced.

The use of LiDAR to map coastal systems offers an efficient way to evaluate sea turtle nesting habitat and changes in habitat, as it allows for broad surveys of the shoreline. Because of their threatened status, it is imperative that these habitats remain in optimal condition in order to facilitate the high levels of nesting success. In the face of global climate change, sea-level rise and more intense hurricane seasons, coastal management agencies will be faced with the daunting task of maintaining an extremely vulnerable ecosystem. It is important to note that regional differences in beach topography need to be considered when restoring nesting habitat, and the use of a general template for all beaches should be avoided. The ability to quickly and accurately assess changes in beach morphology through LiDAR analyses will allow for the development of targeted, site-specific restoration projects, thus expediting the management process while maintaining dune morphologies that promote high nesting success.

Acknowledgements

Thanks to NOAA, the SJRWMD, the Joint Airborne LiDAR Bathymetry Center of Expertise of the US Army Corps of Engineers and the University of Central Florida Marine Turtle Research Group, directed by L.M. Ehrhart, for the use of their data, to L. McCauley for ArcGIS support and to K.M. Borrowman, D.A. Bagley, J.M. Fletcher and S. Ceriani for additional guidance.

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