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Geospatial analysis of a coastal sand dune field evolution: Jockey's Ridge, North Carolina

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Abstract

Preservation and effective management of highly dynamic coastal features located in areas under development pressures requires in-depth understanding of their evolution. Modern geospatial technologies such as lidar, real time kinematic GPS, and three-dimensional GIS provide tools for efficient acquisition of high resolution data, geospatial analysis, feature extraction, and quantification of change. These techniques were applied to the Jockey's Ridge, North Carolina, the largest active dune field on the east coast of the United States, with the goal to quantify its deflation and rapid horizontal migration. Digitized contours, photogrammetric, lidar and GPS point data were used to compute a multitemporal elevation model of the dune field capturing its evolution for the period of 1974– 2004. In addition, peak elevation data were available for 1915 and 1953. Analysis revealed possible rapid growth of the dune complex between 1915–1953, followed by a slower rate of deflation that continues today. The main dune peak grew from 20.1 m in 1915 to 41.8 m in 1953 and has since eroded to 21.9 m in 2004. Two of the smaller peaks within the dune complex have recently gained elevation, approaching the current height of the main dune. Steady annual rate of main peak elevation loss since 1953 suggests that increase in the number of visitors after the park was established in 1974 had little effect on the rate of dune deflation. Horizontal dune migration of 3–6 m/yr in southerly direction has carried the sand out of the park boundaries and threatened several houses. As a result, the south dune section was removed and the sand was placed at the northern end of the park to serve as a potential source. Sand fencing has been an effective management strategy for both slowing the dune migration and forcing growth in dune elevation. Understanding the causes of the current movements can point to potential solutions and suggest new perspectives on management of the dune as a tourist attraction and as a recreation site, while preserving its unique geomorphic character and dynamic behavior.

Keywords: DEM; Sand dunes; Migration rates; Lidar; GIS; North Carolina

1. Introduction

Highly dynamic coastal topography, characterized by rapidly moving sand dunes, fluctuating shorelines, and

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changes in land cover, represents a significant management challenge. Modern mapping technologies such as lidar and real-time kinematic GPS (RTK-GPS) offer a new approach to short-term monitoring of this dynamic environment with unprecedented spatial and temporal detail. Advanced three-dimensional Geographic Information System (GIS) provides a means for efficient integration of these new type of measurements with data from more traditional sources, such as digitized maps and photogrammetric surveys. Methods developed for topographic analysis can then be applied to the digital models of the dunes to quantify the changes in elevation surfaces. This paper presents a multitemporal, high resolution GIS analysis of the Jockey's Ridge sand dune field on North Carolina (NC) barrier islands with the aim to gain new insights into geospatial aspects of the complex coastal topography and provide valuable information for its management.

2. The Jockey's Ridge sand dune field

Jockey's Ridge, the largest active sand dune field on the east coast of the United States, is located within a 162-hectare state park on the NC Outer Banks (Fig. 1). According to previous studies (Havholm, 1996; Runyan and Dolan, 2001), this sand dune field belongs to the class of large, active, isolated coastal crescentic dunes with little vegetation called *medanos*. The dunes are asymmetrical, with gentle upwind and steep downwind sides. In a morphodynamic classification, they are transverse dunes, oriented at angles 85–125° to the dominant sand transport direction (Havholm, 1996). The dune field is complex, comprised of four distinct dunes, each exhibiting a specific morphology and behavior: east dune, leading south dune, the highest main dune, and a west dune (Fig. 2). Annual wind records document the dominance of SW winds between March and August and NE winds during fall and winter months. Based on the data collected at the U.S. Army Corps of Engineers Field Research Facility at Duck, NC, located 27 km to the north (USACE FRF, 2004), the mean wind speed for the period 1982–1999 was 6.1 m/s and the mean wind direction was 168° (SSE). For each month of the year, the 18 yr average of the mean monthly wind speed exceeded 4.5 m/s critical velocity needed to move the sand. In addition, the annual wind rose for 1982–1999

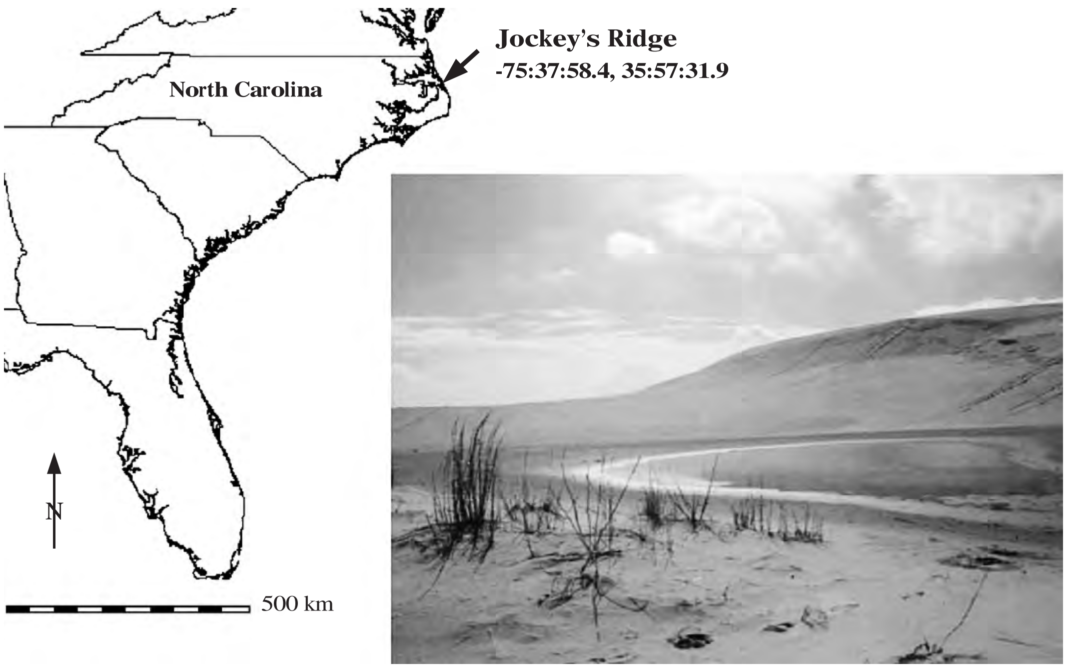


Fig. 1. Location of Jockey's Ridge dune field on the Outer Banks, the North Carolina barrier islands. Photo shows a view of the dune from the NE after rainfall in 2003.

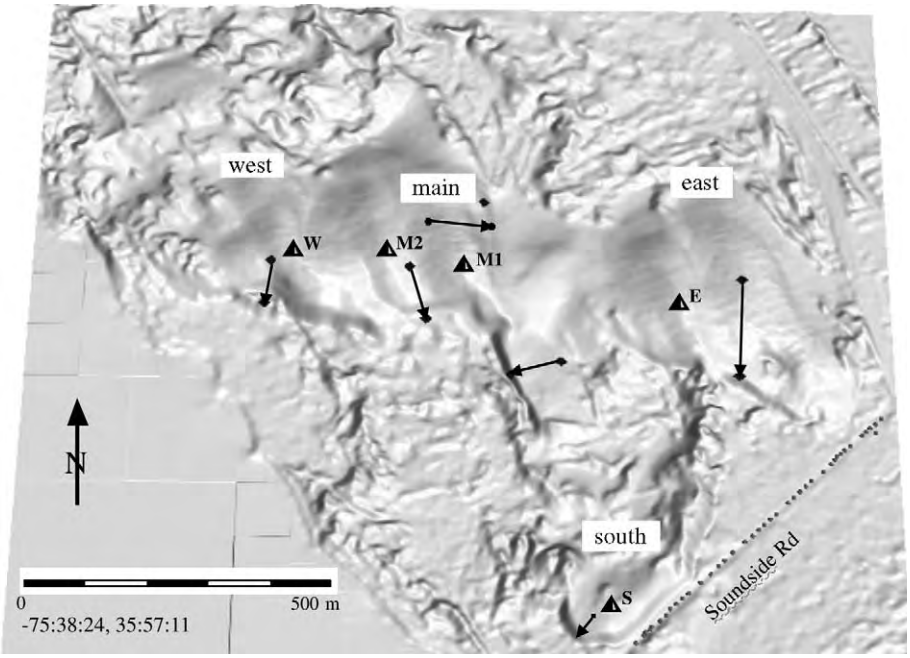


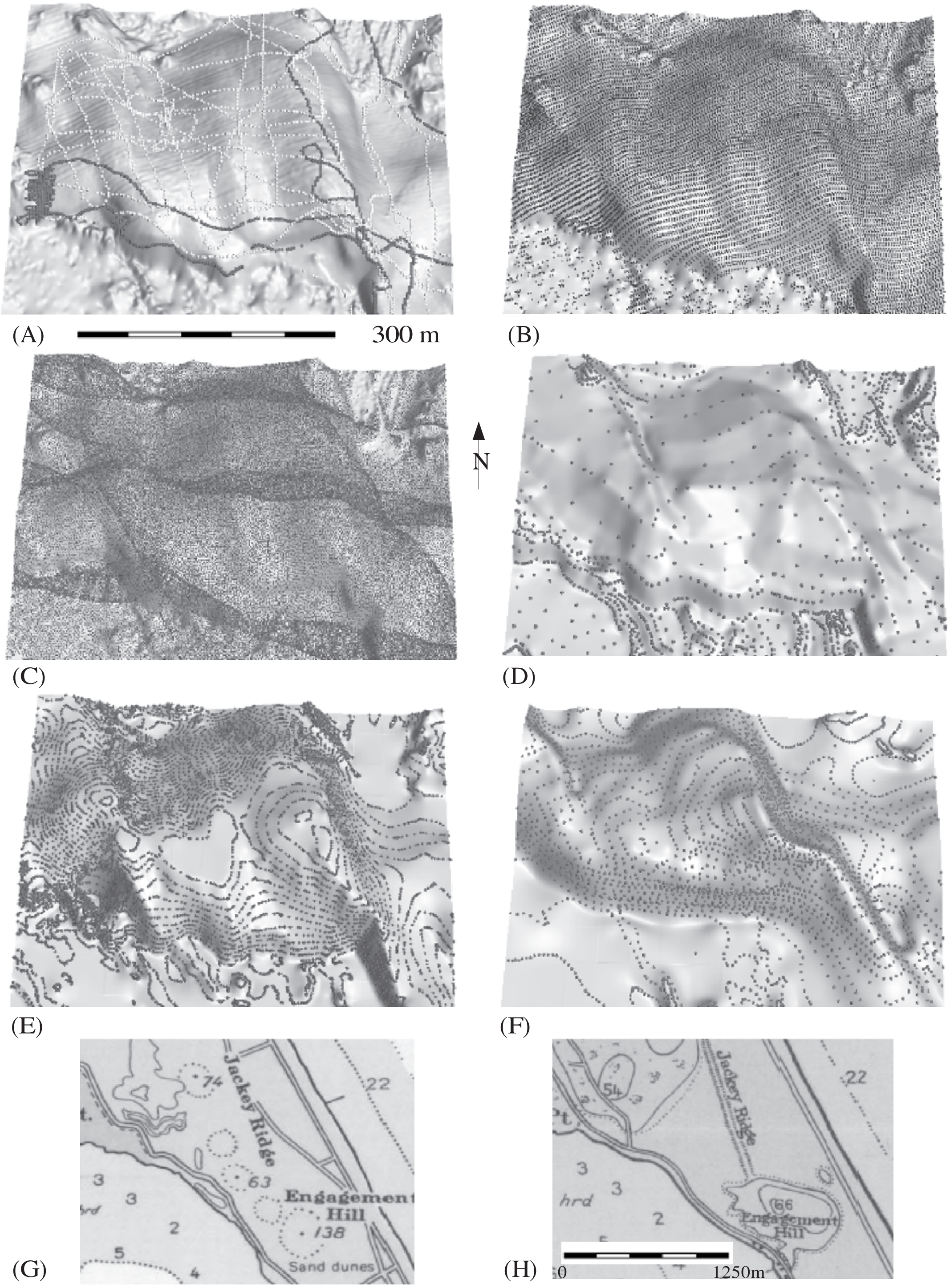
Fig. 2. Dune field elevation surface in 2001 showing location of individual dunes (main, south, east and west), their respective peaks (M1, M2, S, E, W), points on the Soundside Road used for accuracy testing, and representative profiles used for assessment of horizontal dune migration (arrows).

indicates that stronger winds (7–20 m/s) from the north and northeast are more frequent (USACE FRF, 2004), resulting in greater sand transport to the south and southwest. This conclusion is also supported by the sand transport rose for 1980–1991 (see Fig. 1 by Havholm et al., 2004).

Established in 1975, Jockey's Ridge State Park hosts around 800,000 visitors each year. When the park was planned, prevailing opinion considered the dune field relatively stable, characterized only by a slow SW movement (State of North Carolina, 1976). However, encroachment of the dunes onto the road and homes along the southern border of the park has been an ongoing problem that has required continuing management intervention. The study by Judge et al. (2000) compared the dune topography based on the 1974 and 1995 contour maps and demonstrated the long-term trend of southward migration and deflation. Evolution of the dune field over the past 50 years has been accompanied by dramatic changes in land cover in the surrounding areas, where the sand flats and small dunes have been replaced by urban development and a dense maritime forest. As a result, the available sand supply has been diminished, thus contributing to the loss of elevation of the main dune.

The major challenge for the dune management is to maintain stability of this highly dynamic feature and keep it within the park boundaries, while preserving its natural properties as a shifting, migrating dune field. In recent years, sand fencing was installed on

Fig. 3. Different spatial patterns and densities of elevation data for the main dune: (A) RTK-GPS traverses in 2002 (black) and 2004 (white); (B) Leica Geosystems aeroscan lidar 2001; (C) NASA/USGS/NOAA Airborne Topographic Mapper II lidar 1999; (D) photogrammetric mass points 1998; (E) photogrammetrically derived digital contours 1995; (F) digitized contours 1974; (G) 1961 nautical chart with elevations based on 1953 topographic map; (H) 1932 nautical chart with elevations based on 1915 topographic map. Nautical charts were obtained from the Image Archives of the Historical Map and Chart Collection, Office of Coast Survey, National Ocean Service, NOAA (http://historicals.ncd.noaa.gov/historicals/histmap.asp).


(A)
300 m
(B)
(C)
N
(D)
(E)
(F)
(G)
Jackey Ridge
74
22
63
Engagement Hill
138
Sand dunes
3
3
2
5
4
(H)
Jackey Ridge
54
22
3
3
hrd
2
66
Engagement Hill
0
1250m

the south dune to slow its migration. In December 1995, 15×10^3 m^3 of sand was removed from the park's southern boundary; and in the winter of 2003, almost 10 times more sand, 125×10^3 m^3, was removed and placed on the northwestern side of the dune field to serve as a sand source area. While some immediate problems were solved, the long-term effectiveness of this approach is not known and continued monitoring is needed to quantify the performance of individual management actions at various locations. According to the NC Division of Parks and Recreation (Ellis, 1996), understanding how the dunes function and how they have been affected by the land use change is essential if they are to be maintained as a naturally functioning system.

3. Methods

To assess the dynamic evolution of the Jockey's Ridge dune complex, a GIS database with multitemporal data layers representing topography and its properties (slope, curvature, peaks, etc.) was established. Methodology for integrating elevation data acquired by different mapping technologies was developed and topographic analysis was used to extract the characteristic features of the dunes so that their change could be measured. Land cover change was estimated based on historical maps and aerial photography.

3.1. Data acquisition

The Jockey's Ridge dune field elevation was surveyed several times over the past 100 years using a variety of mapping technologies:

2002, 2004: Real-time kinematic GPS (RTK-GPS) data were obtained by automatically sampling the surface along a survey path with a selected step (in our case 1–3 m) and 0.10 m vertical and 0.05 m horizontal accuracy. Because the movement of vehicles on the dune was restricted, performing RTK-GPS survey over the entire dune field was not feasible in the year 2002. Therefore, only linear and point features (dune crests, ridges, and peaks) that could be identified on digital elevation models (DEMs) as well as in the field were measured. Although this data did not provide information for assessment of volume change, it did permit measurement of the horizontal migration and peak elevation change. After obtaining a special permit, the 2004 survey was done using an all terrain vehicle (ATV) and, as a result, covers most of the dune, except for slip faces and vegetated areas (Fig. 3A).

2001: Lidar survey by the North Carolina Floodplain Mapping Program (2004) was performed using Leica Geosystems aeroscan with linear scanning pattern and about 1 point per 3-m density (Fig. 3B). Multiple returns taken from an altitude of 2300 m enabled extraction of bare ground surface points, with the published vertical accuracy in open areas of 0.20 m and horizontal accuracy of 2 m.

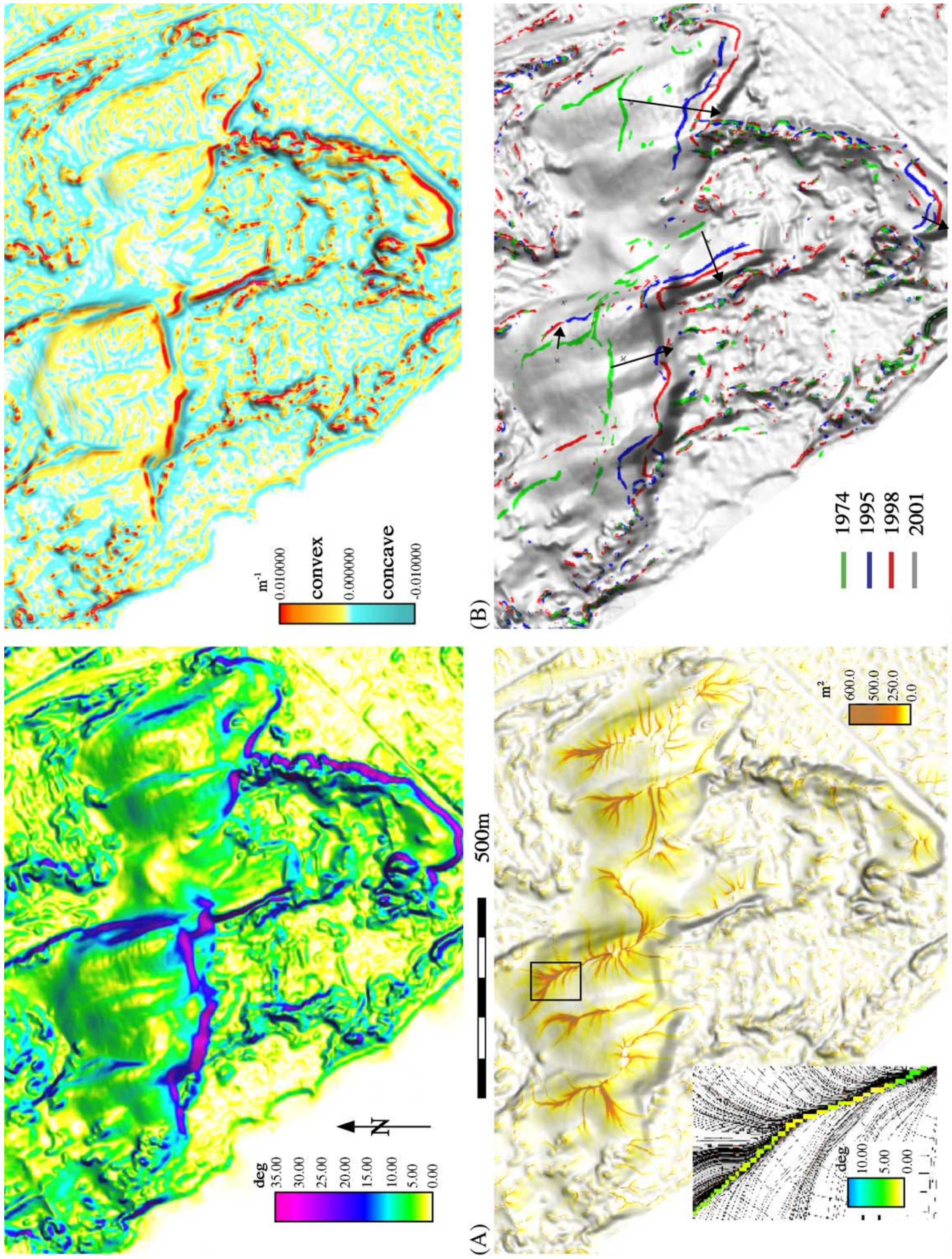
1999: Lidar survey by USGS/NASA/NOAA was done using the Airborne Topographic Mapper II (for technical details see NOAA Coastal Services Center, 2004; Stockdon et al., 2002). Terrain was sampled from an altitude of 700 m using overlapping 200–300 m swaths and elliptic scanning pattern (Fig. 3C). Elevation was measured every 1–3 m with a reported vertical accuracy of 0.15 m in bare areas and a horizontal accuracy of 0.8 m. Only the first return points were acquired, representing the terrain surface that includes the top of the vegetation and buildings.

1998: Spot elevations and breakline points (Fig. 3D) were derived from 1 : 7200-scale aerial photography. The published vertical accuracy of the data is 0.06 m for spot elevations and the horizontal accuracy is 0.30 m.

1995: Digital elevation data included contours, breaklines, and spot elevations (Fig. 3E) determined from a photogrammetric survey with a 0.76-m vertical accuracy for contours, 0.03-m accuracy for spot elevations, and a horizontal accuracy of 0.4 m.

1974: Digital 1.5-m (5-ft) contours (Fig. 3F) were acquired from a park map derived from a photo-

Fig. 4. Topographic parameters derived from the 1 m resolution 2001 DEM: (A) slope (slip faces in red/magenta); (B) profile curvature (convex crests in red); (C) uphill slope line density (ridges in brown), inset shows contours and individual slope lines merging on a ridge overlayed by grid cells with slope values used to compute the average windward ridge slope; (D) extracted crests for 1974 (green), 1995 (blue), and 1998 (red) draped over the 2001 surface showing horizontal migration of the Jockey's Ridge dune complex.


(A)
(B)
(C)
(D)
deg
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
N
500m
m⁻¹
0.010000
convex
0.000000
concave
-0.010000
m²
600.0
500.0
250.0
0.0
1974
1995
1998
2001

grammetric survey, with a 0.7-m vertical accuracy for contours, 0.15-m accuracy for spot elevations, and a horizontal accuracy of 0.4 m.

1953: USGS topographic map, Manteo, NC (Fig. 3G) included only few spot elevations representing the dune peaks and a limited set of contours (10 and 15 ft) in the Jockey's Ridge area complying with National Map Accuracy Standards for 1:24,000-scale mapping. Data were derived from 1949 aerial photography using photogrammetric techniques and 1950 plane table surveys. These data were field checked in 1953 before publishing the map. At the time of the field verification, the surveyor's report indicates that the higher elevation contours derived from the photogrammetric data could not be verified. Therefore, these contours were replaced by spot elevations and a note that this was an area of shifting sands. The inability to verify the contours after a 4-year period likely represented real change from 1949 to 1953. Unfortunately for this study, these contours were omitted in the final product.

1915: U.S. Coast and Geodetic Survey 1:40,000-scale T sheet (Fig. 3H) included peaks and a limited set of 3.3-m (10-ft) contours. The contour interval implies a vertical accuracy of ± 1.15 m (5 ft). However, the uncertainty in the elevation values is increased by the fact that elevations are referenced to feet above high water. For this paper, we have not tried to convert from this early datum to NAVD88.

In addition to the elevation data, a multitemporal series of historical charts (1879), aerial photographs (1932, 1940, 1972, 1998, 2003), and historical ground-based photographs (1900–1910) were acquired from various sources and, where possible, imported into the GIS database. These products provided insights into the spatial distribution of vegetative cover and urban development as it evolved over the past century.

Elevation data from 1974, 1995, 1998, 1999, 2001, and 2004 were geo-referenced in the State Plane coordinate system, horizontal datum NAD83, units feet (the 1974 data were converted from NAD27), vertical datum NAVD88 (1974 and 1995 data were converted from NGVD29, the difference between NAVD88 and NGVD29 in this location is -0.30 m). To use the full power of GIS for analysis and visualization, the lidar, RTK-GPS, and digitized elevation data were transformed to high resolution (1-m) grids creating a multitemporal set of the dune field models.

3.2. Spline-based spatial approximation for high resolution DEMs

The input elevation data had different point densities, spatial distributions, and accuracy (Fig. 3A–F). To extract the features needed for quantitative assessment of the dune evolution, a common, high-resolution digital representation is required. Spatial approximation by the Regularized Spline with Tension and Smoothing method (RST; Mitasova and Mitas, 1993; Mitasova et al., 1995) was used for computing the 1-m resolution grid DEMs from lidar point clouds, digitized contours, and RTK-GPS data. This method is known to produce surfaces with minimum artifacts and high accuracy, even in areas with sparse data (e.g., Mitasova et al., 1996; Hofierka et al., 2002). In our application, this was important for interpolating some of the contour data, RTK-GPS traverses, and vegetated areas with sparse points in the 2001 lidar data set. An additional advantage of the method is the capability to simultaneously compute topographic parameters (Mitasova and Hofierka, 1993), thus ensuring consistency between the DEM and the derived slope and curvature maps. The method has been implemented in open source GRASS GIS (Neteler and Mitasova, 2004) as a module called *s.surf.rst*, which was used in this project. The 1-m resolution provided sufficient detail for representation of important dune features, such as active crests and slip faces as well as some man-made features (e.g., partially buried fences), without the need for manually defined breaklines (Mitasova et al., 2004).

To assess the consistency and accuracy of the interpolated DEMs and to identify potential systematic errors or vertical datum inconsistencies, 40 points were selected along Soundside Road, a local paved road bordering the park on the south that is assumed to be a stable feature (Fig. 2). Elevation differences between the RTK-GPS elevations (with the highest accuracy among the methods used) and the interpolated DEMs were computed in the test points. The differences were then used to derive the root mean square difference (RMSD) and mean absolute difference (MAD) as measures of internal consistency for the multitemporal elevation data set. The RMSD/MAD between the RTK-GPS point data and the interpolated DEMs was between 0.02/0.06 m (1999 DEM) and 0.65/0.43 m (1998 DEM).

3.3. Topographic analysis and identification of dune features

Topographic analysis was used to extract features defining the location and geometry of individual dunes. These features– peaks, slip faces, active crests, windward side ridges, and active dune areas– are essential for measuring the dune migration and understanding its evolution. Slope and profile curvature (Fig. 4A,B), needed for extraction of slip faces and dune crests (Fig. 4D), were computed simultaneously with the interpolation of the DEMs using the first- and second-order partial derivatives of the RST function and principles of differential geometry (Mitasova and Hofierka, 1993). Previous application of this approach to lidar data demonstrated that suitable selection of the

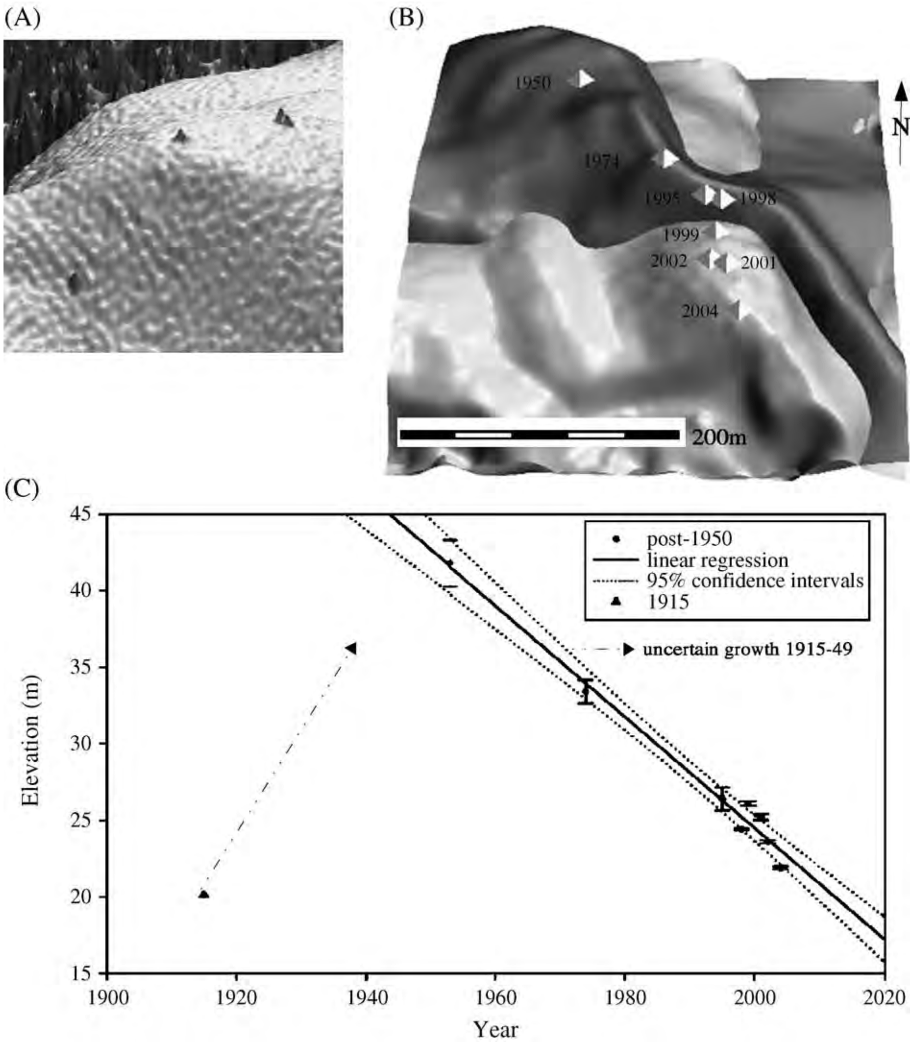


Fig. 5. Jockey's Ridge main dune peak: (A) noise or people captured near the top of the dune in 1999 lidar data; (B) peak migration 1953–2004 (1974: dark surface, 2001: light surface); (C) change in elevation 1915–2004.

RST parameters (tension and smoothing) is essential for extraction of the topographic parameters at the level of detail matching the size of the dune features (Mitasova et al., 2004).

3.3.1. Peaks

Although dune peaks can be relatively easy to identify as the points with the highest local elevation, this task was far from trivial at Jockey's Ridge and required careful analysis of data. In addition to the common issues related to the use of different vertical datums, low curvature of the dune ridge made the peaks difficult to identify in the field during the 2002 and 2004 RTK-GPS surveys. Moreover, the 1999 lidar data included points that probably captured people on the top of the dune, increasing the maximum measured elevation more than 1 m above the dune surface (Fig. 5A). These points had to be removed before determining the 1999 main peak elevation.

3.3.2. Active crests and slip faces

Based on three-dimensional visual analysis of the dune model with profile curvature draped over the elevation surface as a color map (Fig. 4B), profile curvature >0.008 m^{-1} (convexity) proved to be a good indicator of dune crests. Slopes $>30°$ (close to the angle of repose for sand) were used to identify the slip faces (Fig. 4A). For the 1999 first-return lidar data, the slopes had to be combined with land cover to exclude the steep slopes caused by vegetation and buildings.

3.3.3. Dune ridges

In general, ridges can be identified using plan (tangential) curvature; however, this approach is not very suitable for the dunes with smooth windward sides and low values of curvature. Therefore, an alternative approach based on the density of slope lines (lines in the direction of surface gradient, perpendicular to contours) generated uphill from each grid cell was used (Mitasova et al., 1996). This approach is an inverse version of the flow accumulation algorithm commonly used for extraction of streams (e.g., Tarboton, 1997), where slope lines are traced downhill from each cell and cells with slope line density (flow accumulation) exceeding a given threshold define the stream network. To extract ridges, slope lines were computed using a D-infinite (vector-grid) algorithm (Mitasova et al., 1996) to avoid artificial patterns produced by the standard D-8 methods on smooth surfaces typical for dunes. Dune ridges were then extracted as grid cells that had the number of slope lines passing through them (slope line accumulation) >600 (Fig. 4C). The average slope of the windward side of the dunes was then computed by manually defining representative windward profiles along these ridges, extracting slope values along the profiles from the slope maps using map algebra, and computing the average value for each dune (Fig. 4C insert).

3.3.4. Active dune subregion

Visual analysis of contours, generated from the DEMs at 0.3 m interval and displayed along with elevation, slope and land cover maps, was used to

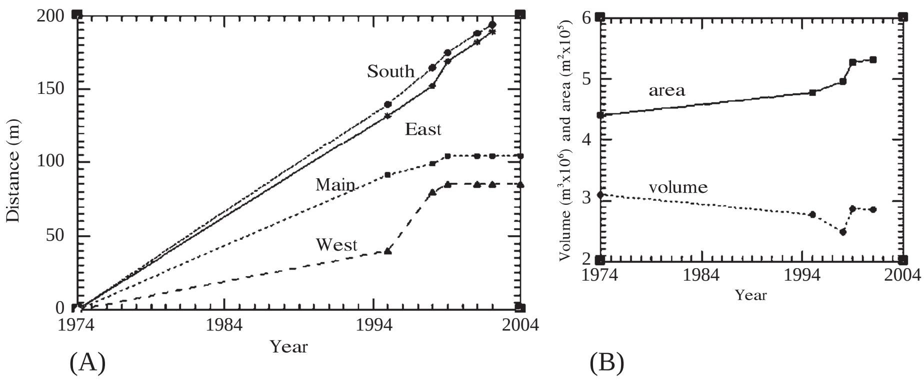


Fig. 6. Evolution of the dune field: (A) horizontal migration of individual dunes given as cumulative distance measured between the dune crests along representative profiles (see Fig. 2) and (B) dune volume and area change for the active dune subregion defined by elevation $z>6$ m.

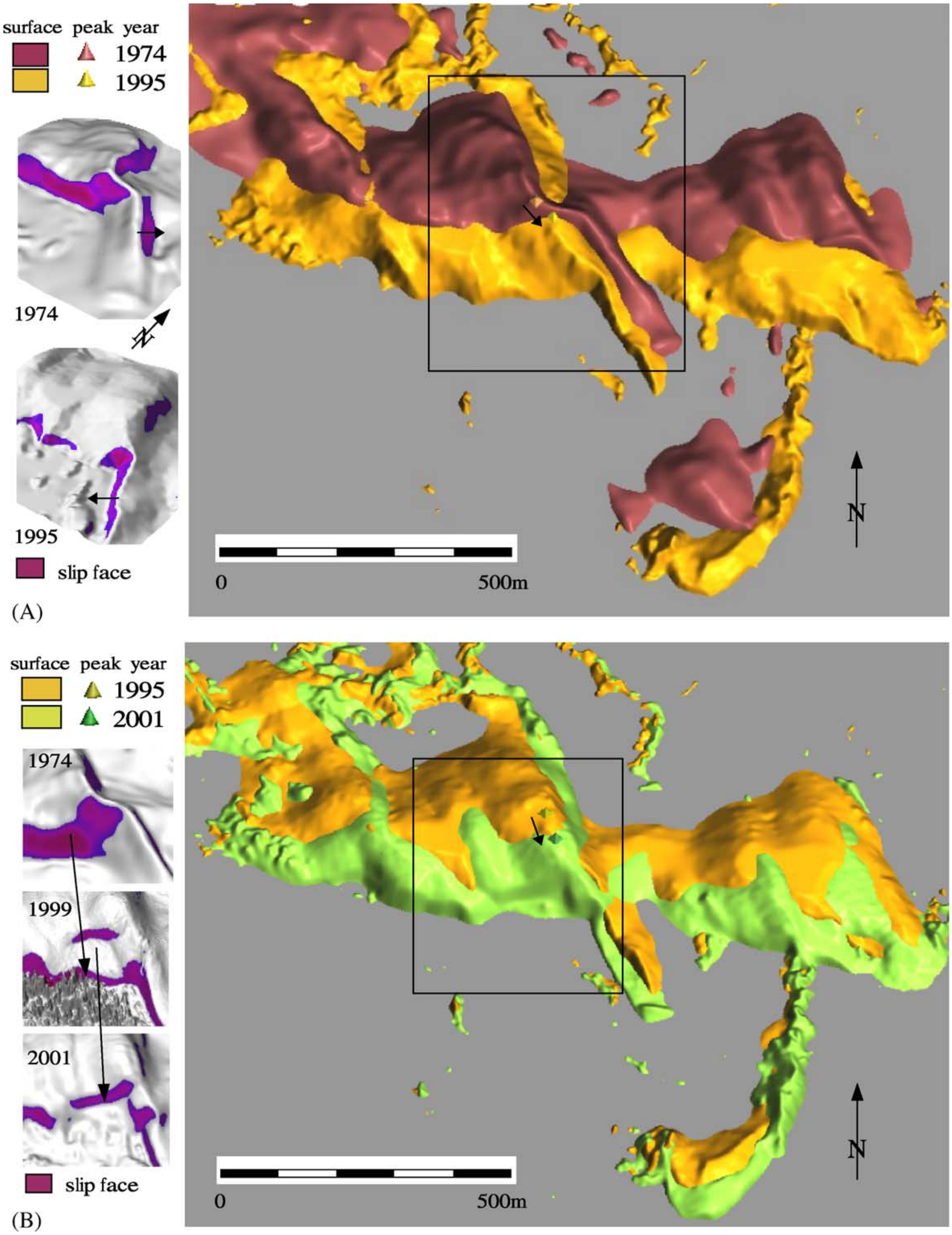


Fig. 7. Overlay of active dune surfaces (subregions without vegetation where elevation $z > 6$ m), demonstrating similar patterns of southward migration between (A) 1974– 1995 and (B) 1995– 2001. Higher of the two surfaces is visible and migration of the main peak is represented by arrow. Inserts show changes in slip faces: (A) reversal in the slip face direction from east in 1974 to west in 1995 on the lower ridge of the main dune and (B) evolution of a new slip face “inside” the main dune in 1999.

identify a threshold elevation that defines the active dune subregion. Topography below this threshold flattens and includes only small, mostly stable vegetated features. Elevation surface above the threshold has typical dune geometry and bare sand. For all DEMs (1974 – 2001) this threshold elevation was found to be 6 m. For the 1999 DEM, the elevation threshold had to be combined with land cover derived from the 1998 aerial photography to eliminate trees and buildings. Map algebra was then used to compute the active dune DEMs as surfaces with elevation $z > 6$ m.

3.3.5. Quantification of the dune change

Jockey's Ridge, as a complex dune field, has spatially and temporally variable migration, growth, and deflation rates (Fig. 6A). To quantify its evolution, an approach based on topographic analysis of elevation surfaces that involves extraction of dune features and measurement of the change in their location was used (Fisher et al., 2005). High resolution DEMs and GIS tools make such analysis feasible and effective.

To assess the dune field evolution, the multitemporal set of DEMs was first analyzed visually using three-dimensional models of overlayed surfaces and

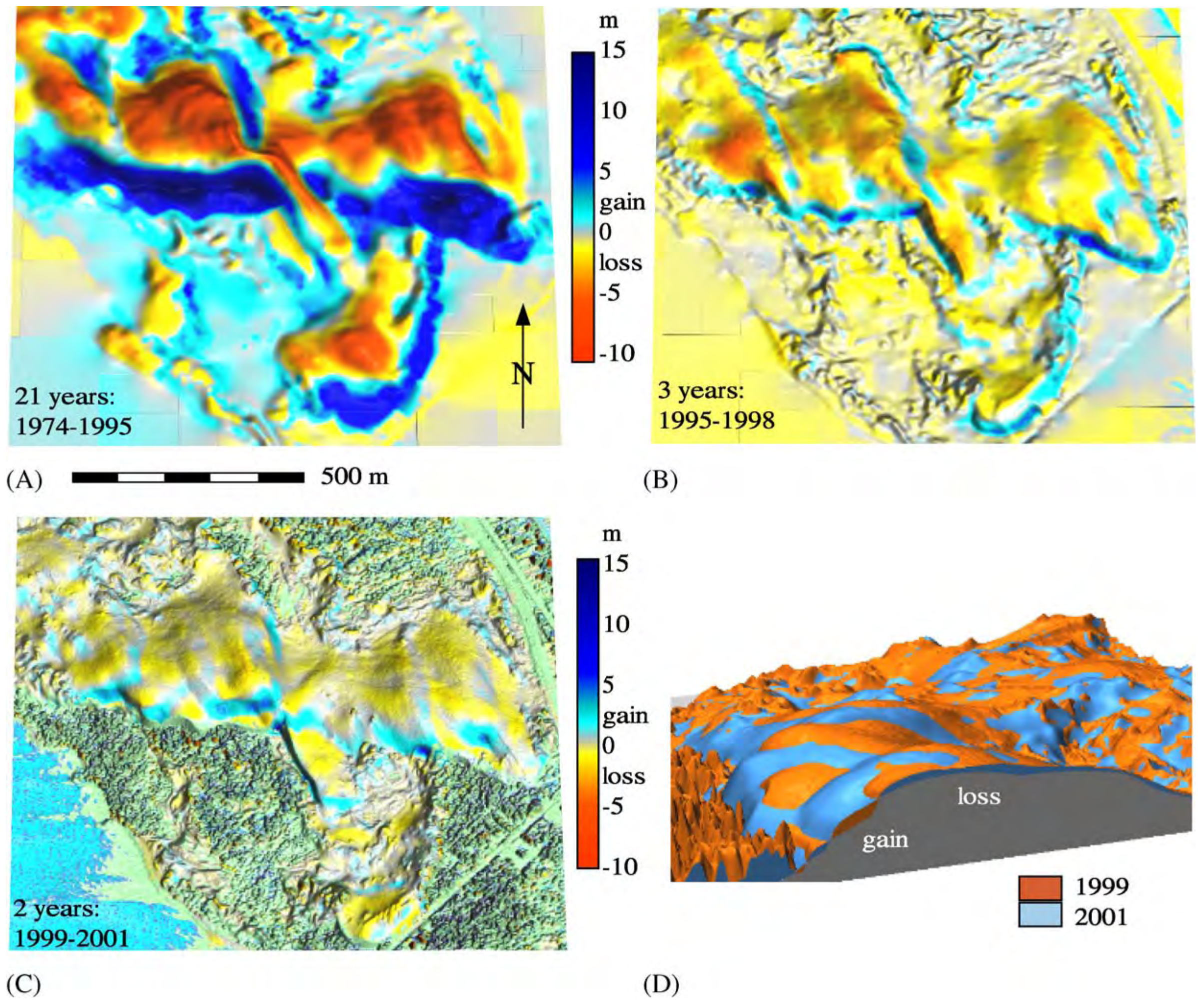


Fig. 8. Long-term and short-term elevation differences revealing continuing sand loss on the northern, windward side of the dunes and gain mostly on the southern side of the dunes along the slip faces: (A) 1974–1995; (B) 1995–1998; (C) 1999–2001; and (D) cross-section of the main dune showing dune flattening between 1999 and 2001 (profile is colored by the bottom surface).

interactive cutting planes (Fig. 7 and 8D; Neteler and Mitasova, 2004). Map algebra, spatial query, and related standard GIS tools were then used to compute the maps and summary values for the following measures quantifying the dune change:

(i) change in the elevation and location of the dune peaks,
(ii) horizontal migration of the dune field,
(iii) spatial pattern of elevation change,
(iv) evolution of active dune volume and area, and
(v) change in the windward ridge slope.

Exact measurement of the horizontal dune migration was challenging because of the complex, changing morphology of the dune field. Representative profiles were defined perpendicular to the slip faces in the locations where the crests could be clearly identified for each DEM in the multitemporal data set (Fig. 2). These profiles were used to trace the movement of individual dunes within this field and to identify potential differences in the migration rates. The horizontal migration of a dune was measured as a distance between the two consecutive locations of the active dune crest along these profiles. To quantify the rate of lateral dune migration, the shortest distance between two consecutive locations of windward side ridges, as defined by slope line densities (Fig. 4C), was measured. Change in the shape and size of crests and ridges contributed to uncertainty in the measurements; therefore, each distance was measured six times and an average value was computed. The standard deviations of these averages did not exceed 3 m.

4. Results

Visual comparison of high resolution elevation surfaces representing the dune in 1974, 1995, 1998, 1999, 2001, and 2004 confirms the prevailing southern migration of the entire dune field (Fig. 7) accompanied by dune deflation. Apparently, the overall direction of dune migration to the SW is not dictated by the long-term mean wind orientation (winds from the SE). Rather, as shown by the sand transport rose presented by Havholm et al. (2004), the higher frequency of stronger winds from NE (see also USACE FRF, 2004) lead to the prevailing SW direction of the potential sand transport. In addition, short-term changes may show up in any particular survey if the morphology captured was strongly influenced by a recent storm. Two of the data sets, 1998 and 1999, were post-storm surveys. The June 1998 flight captured the impact of a late season northeaster that occurred in early May. In addition, the 1999 lidar flight was planned as a response to Hurricane Dennis. Hurricane Dennis moved north along the NC coast on 31 August 1999, remained until 2 September, lost strength to tropical storm status, and then came ashore on 5 September. The lidar flight was conducted less than a week later on 9–10 September. Data from the USACE FRF (2004) showed that the maximum onshore winds were 24 m/s from the NE on 31 August. Following this peak, the wind speed averaged about 15 m/s from the NW to NE through 4 September and then rotated and resumed the dominant direction (SE). While it was the intent of this study to capture long-term changes, the measurements do, however, record topographic modifications resulting from essentially instantaneous short-term events. Analysis of specific dune features, described in the following sections, provides more detailed information about dune evolution while also revealing the underlying complexity of its behavior.

4.1. Morphology

Visual analysis of the three-dimensional dune models and spatial patterns of crests and slip faces revealed a complex dynamic morphology within the dune field (Figs. 4, 7 and 8). While several features point to the prevailing crescentic transverse dunes, a detailed analysis shows additional types of dunes evolving over time. The leading tip of the east dune has evolved into a low, fast-moving parabolic dune. The main dune has a complex, dynamic morphology, including a high ridge, with a distinct south-oriented slip face and an extended low ridge with a west-oriented slip face. This slip face has flipped its direction from east to west between 1974 and 1995 (Fig. 7A insert), leading to change in the direction of its migration. The high section of the main dune often develops an east-facing slip face (Fig. 4A). The leading south dune was an egg-shaped mound in 1975 that was transformed into a parabolic dune (Fig. 7A). The west dune has evolved into a characteristic crescentic dune shape with curved slip faces.

4.2. Peak change

The dune peak evolution was tracked using historical maps dating from 1915 when the first topographic mapping that included measurement of dune elevation was performed. According to this survey, the maximum elevation in the area was 20.1 m (66 ft, Fig. 3H), which is less than the current elevation of 21.9 m (71.8 ft) and less than one-half of the Jockey's Ridge maximum elevation, recorded on the 1953 topographic map as 42.1 m (138 ft, Fig. 3G). The 1915 and 1953 maps indicate that the main dune was growing rapidly at a rate of about 0.6 m/yr between 1915 and 1953. Sometime after 1953, the main dune peak (M1 in Fig. 2 and Table 1) started to lose elevation (Fig. 5C) at an average rate of 0.36 m/yr. The peak on the lower, western ridge of the main dune (M2 in Fig. 2 and Table 1) was 23.5m high in 1974, and after losing elevation between 1974 and 1998, this peak started to grow again and is now almost as high as the main peak (21.8m). East dune peak (E in Fig. 2 and Table 1), was losing elevation at a rate 0.12 m/yr between 1953 and 1998, but its elevation increased 2.3 m between 1998 and 2004 at an annual rate of 0.38 m/yr. Elevation of the west dune peak (W), held steady at around 20 m.

The horizontal main peak migration followed the southeast direction between 1953 and 1995, with an eastward turn between 1995 and 1998, then continuing in south-southeast direction in the following years, with the exception of 2001–2002 time interval, when the main peak moved westward (Fig. 5B). The main peak migrated 225 m over the 50 year period. The rapid southward translation of the main peak between 1998 and 1999, and again between 2002 and 2004, was likely influenced by hurricane winds (Dennis in 1999 and Isabel in 2003).

Table 1
Evolution of the dune peaks' elevation[a]: the highest main dune peak M1, peak on the west ridge of main dune M2 (see Fig. 2), east dune peak E and west dune peak W

Peak elevation	1915	1950	1974	1995	1998	1999	2001	2002	2004
M1	20.1	41.8	33.4	26.4	24.4	26.1	25.2	23.6	21.9
M2	n/a	n/a	23.5	19.9	19.9	21.1	21.5	n/a	21.8
E	n/a	22.5	20.9	17.7	16.6	17.8	17.9	n/a	18.9
W	n/a	n/a	n/a	20	20.5	20.3	20.6	n/a	19.5

[a] Elevation is referenced to NAVD88 (with the exception of the 1915 data, referenced to high water level). 1998 survey was done after long lasting storm.

4.3. Horizontal migration

The dune field exhibits a complex pattern of horizontal migration. Quantitative assessment of migration rates for different dune sections is summarized in Fig. 6A and the spatial pattern of change is reflected in the overlayed three-dimensional models (Fig. 7) and the maps of elevation change (Fig. 8). Between 1974 and 2004, the prevailing movement of slip faces was in the S/SW direction at average annual rates of 2.8 m/yr for the west dune and 6.3 m/yr for the fastest moving east dune. As expected, the lower east and south dunes moved faster than the higher main dune (Figs. 6A and 7A), reaching the rates of migration over 10 m/yr for the 1998– 1999 time interval. Southward movement of the main dune practically stopped in 1999, when a new slip face developed 60 m inside this dune during the recovery from the 1998 storm (Fig. 7B insert). Horizontal migration of the west dune also has slowed significantly since 1998.

The migration of the south dune was accompanied by a transformation from an egg-shaped mound into a parabolic dune with a well-defined slip face observed in the 1995 data. The sand that reached the Soundside road was trucked away several times in the 1990s, so only the westward movement within the park boundary was measured. Between 1995 and 2001, this dune moved rapidly at more then 10 m/yr to the SW and started to bury a home adjacent to the southern park boundary. In 2003, the south dune was completely removed (Fig. 10A), and the sand was placed in the northern section of the park.

Analysis of the movement of the windward side ridges (perpendicular to the active crests and slip faces) revealed eastern, lateral migration of the main dune (Figs. 7 and 8), while the two east dune ridges migrated only in the southern direction with no signs of lateral migration. The angle between the windward side ridges and dune crests, measured clockwise from the ridge line, was relatively stable for the main and west dunes, ranging between 110 – 120°. For the east dune, this angle changed gradually from 100° in 1974 to 130° in 2001.

4.4. Elevation change

Differences in elevation surfaces quantify the spatial pattern of elevation loss and gain (Fig. 8). For most time intervals examined, the dune had a very consistent pattern of elevation change reflecting the typical transverse dune movement with sand losses on the windward side and gains on the leeward side (Figs. 7 and 8). Elevation on the windward side ridges never increased, except for a very short period between 1998 and 1999. Only the concave valleys on the windward side are occasionally filled with

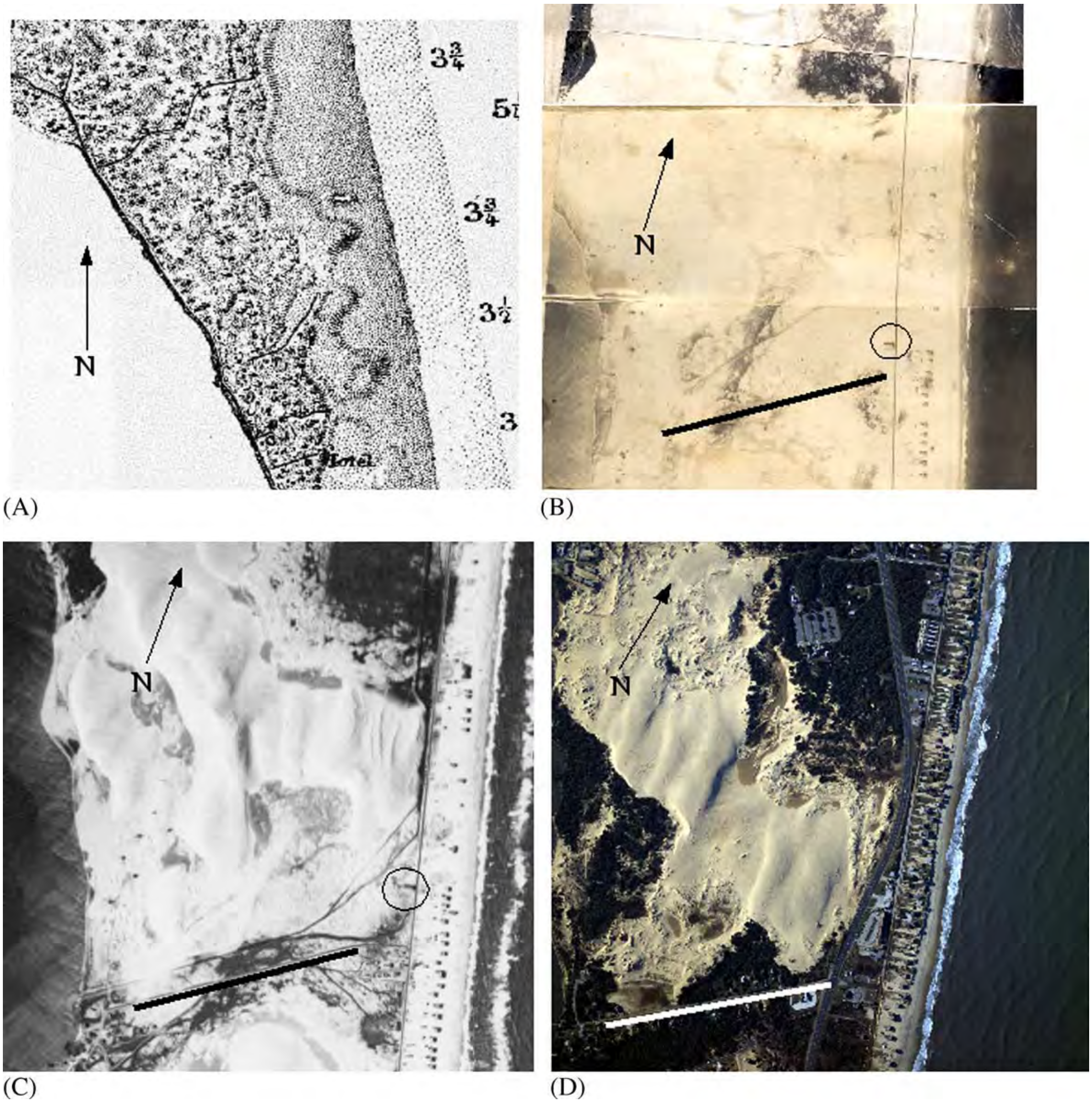


Fig. 9. Evolution of land cover: (A) 1879 nautical chart with portion of the study area covered by vegetation; (B) 1932 air photography (USACE FRF, 2004) showing no vegetation; (C) 1940 air photography with a small patch of low vegetation in a NE wet area; (D) 2003 air photography (post-hurricane Isabel) with the dune complex surrounded by dense vegetation.

sand, increasing their elevation, as observed after Hurricane Isabel. Most of the eroded sand is deposited in front of the dunes on slip faces, leading to an increase in elevation in these areas at rates higher than 1 m/yr. Except for the tip of the south dune, sand relocation has been confined to the park boundaries. Gains in elevation over 1 m/yr were observed along stabilization fences (Fig. 10B) proving their effectiveness in capturing sand; however, at the time of this study, the sand deposition rates were not sufficient to stop the south and east dune migration.

4.5. Volume, area, and slope change

The evolution of volume and area for the sandy regions of the active dune field, defined by elevation >6 m, is represented by Fig. 6B. Except for a decrease in 1998, with subsequent recovery in 1999, the volume held steady over the entire study period, despite a significant loss of the main peak's elevation. At the same time, the area of sand dune above 6 m steadily increased, confirming the flattening and spread of the dune field. The slope of the windward side of the main dune decreased from an average of 5.0° in 1974 to 3.2° in 1995, then held steady until the year 2004 when it dropped to 2.5°, most likely reflecting the impact of Hurricane Isabel.

4.6. Observed land cover change

Although the study focused on the evolution of topography, the historical maps and aerial photographs were examined for clues about the land cover changes that could help explain some of the observed elevation change. The nautical chart from 1879 (NOAA Office of Coast Survey, 2004) shows a significant portion of the current park area covered by Nags Head forest (Fig. 9A). The 1915 topographic map (Fig. 3H) indicates a much smaller spatial extent of the forest, with the area of the current dune field practically bare. The 1932 (USACE FRF, 2004) and 1940 aerial photos (Fig. 9B,C) show the area without any significant vegetation, although grass had started to emerge in the wet area to the NE. The spatial extent of vegetation rapidly increased in the 1950s, followed by urban development in the 1960s. The increase in vegetation cover is considered to be from the stabilization of the barrier islands by the artificial dune built in the 1930s (Birkemeier et al., 1984). Aerial photography taken in 2003 shows the dune field completely surrounded by dense vegetation and urban development (Fig. 9D).

5. Discussion

Analysis of the three-dimensional, multitemporal Jockey's Ridge digital elevation model revealed a complex morphology of the dune field, with different types of dunes that evolve and change over time. Clearly, to preserve this active dune complex, individual dune features must be allowed to undergo their natural change. A review of the documented historical changes in the dune field helps provide perspective to fully appreciate the evolutionary stage that Jockey's Ridge seems to be in today.

One of the more unexpected results from this investigation is that the maximum elevation in the Jockey's Ridge dune field in 1915 was approximately what it is today. The highest peak documented in the 1915 T-sheet was 20.1 m (66 ft) above high water on a feature known at the time as Engagement Hill (Fig. 3H). Just to the north is a feature called "Jackey Ridge," presumably the origin of the present name of Jockey's Ridge. Unfortunately, no elevations are indicated along this ridge. The change in the topography between 1915 and 1949 (1953 USGS topographic map, Fig. 3G) is most surprising, indicating a considerable increase in height to 42 m (138 ft) NGVD29 in this 34-year time interval. Since that time, the main peak elevation has declined, suggesting that the impressively high, active dune field (considered to be the largest one on the Atlantic coast) existed as a relatively short-term feature. The relevant question, therefore, may well change from "What is causing the decline in the main peak elevation?" to that of "What conditions were in place to cause the tremendous growth in height?"

Collier Cobb, a University of North Carolina geologist, described the dramatic changes on the barrier islands in a 1906 National Geographic article as follows (Cobb, 1906): "The strong winds pile the sands into great barchans or medanos, crescentic sand dunes known locally as whaleheads which are moving steadily southward ... the origin of the sand forming the big dunes in this Nags Head area was released from an area that was deforested." The large sand dunes during this time period might have been a result of land management decisions in the late 1800s (i.e., excessive logging) that introduced instability to the landscape in the form of a hard-to-control, fast growing, and migrating dune field. The official 1915 surveyors descriptive report characterized the area as undulating, covered with sand dunes that drift amongst the woods, killing the timber as they move slowly along (Ferguson, 1915).

The results of recent ground penetrating radar surveys revealed that this was not the first time that forests were overtaken by dunes in this area (Havholm et al., 2004). Two layers of soil were observed within the dune that indicate the presence of forested landscape around A.D. 1000 that was overtaken by sand dunes by A.D. 1260. The area became stable and again covered by vegetation by 1700, but sand had started to intrude into the forests by 1810. Lack of elevation data prior 1915 and for the period between 1915 and 1949 make it impossible to accurately describe the rapid growth of Jockey's Ridge. However, the detailed surveyor's descriptive report associated with the 1953 USGS topographic map (Garber, 1953) characterized the area as very unstable with steep ridges and high peaks. Adjacent to highway 158 were low-lying areas with standing water during the wet seasons, while just west of these low-lying areas the "ground becomes higher and sand is bare and shifting." Furthermore, the report notes that "the great sand dunes are moving westward and will eventually cover this wooded area" (i.e., the Nags Head Woods).

In contrast to this prediction, between 1950 and 1974, the sand dunes moved SE toward Soundside Road. Runyan and Dolan (2001) argued that the sand forming the modern dune field (the vicinity of Engagement Hill) probably came from a "deflation" area immediately NE of the dune field on the ocean side of Nags Head Woods. If this is the case, then the sand source that was feeding the dune growth has become depleted and bare sand has been replaced by urban development and vegetation, triggering the dune deflation that continues today. The favorable conditions (i.e., the extensive supply of sand from a northeastern source) leading to dune growth and migration were disrupted by land management decisions beginning in the 1930s (i.e., the building of a protective dune along the shore) and increasing in the 1960s (urban development) causing significant reduction in sand supply resulting in the changes we associate with the dune field today.

The shape of the individual dunes apparently plays an important role in its migration. Transverse crescentic dunes form when there is an abundant supply of sand and a constant wind direction, a situation that was characteristic for the Nags Head area during the first half of the 1900s. As the sand supply is reduced, transformation of the dunes into parabolic shape begins to take place, a process that has been documented for numerous locations (Havholm et al., 2004), including the False Cape dunes in Virginia (Hennigar, 1977). The east dune started to show the properties of a sand-starved dune with a parabolic shape, but the stabilization fences, installed to slow down its migration towards the Soundside Road, are probably contributing to its recent growth in elevation. The main and west dunes still receive sufficient amount of sand to preserve their crescentic shape, although at lower elevation.

The analysis provides little evidence that the dune evolution was significantly influenced by the large number of state park visitors moving freely across the dune field. The main dune was already losing elevation at the rate of 0.3 m/year between 1953 and 1974 (before the park was established), and this long-term average rate did not increase over the next 20 yr (1974–1995), indicating that the increased number of visitors from establishment of the park did not accelerate dune deflation. The increase in the deflation rate to 0.5 m/year over the last decade can be explained by further reduction in sand sources from expanding vegetation within the park and in its immediate neighborhood.

The attempts to reduce the deflation rate of the main dune by storing the sand removed from the southern dune on the windward side of the dune field (Fig. 10A,B) do not seem to be effective. Although this management strategy addresses the processes involved in dune migration and available sources of sand, the deposited sand may be stored too far north of the main dune to be effective. In addition, vegetation and rough topography between the dune and the storage area disrupts the flow of sand. Depositing the relocated sand in the depression immediately north of the main dune and controlling the vegetation in this area may be a more effective approach. Supporting the growth of slip faces may be helpful for reducing the rate of migration as demonstrated on the main dune where a formation of a new slip face 60 m

(A) (B) (C)

Fig. 10. Dune management: (A) location of recent management actions; (B) removal of south dune; (C) stabilization fences enhanced by discarded Christmas trees.

back from the edge of the dune effectively stopped its southern movement (Fig. 7B insert). The additional slip face that is forming perpendicular to the south arm of the main dune along the installed fences (Fig. 10A, C) has the potential to cut off possible sand supply to the remnants of the south dune and prevent its recovery and problematic migration outside the park boundaries. Numerical modeling would be effective for optimizing the stabilization and re-nourishment measures and for analyzing their performance under different conditions.

6. Conclusions

The quantitative assessment of dune evolution presented here was made possible through the use of state-of-the-art mapping technologies and GIS analysis of multitemporal elevation data. The open source GIS environment provided flexible and accurate tools needed for integration of diverse elevation data and a comprehensive quantification of topographic change.

This study provides a new insight into the evolution of the Jockey's Ridge dune field, indicating that the rapid growth of the main dune during the first half of the twentieth century was followed by a deflation accompanied by steady southward migration. Significant main peak elevation changes demonstrate that rapid dune growth and relatively high elevation (over 40 m) was a short-term phenomenon. Detailed spatial analysis located areas of current dune stability, as well as areas and direction of active dune translation that have required land management intervention. It appears that the land cover change played a crucial role in the evolution of Jockey's Ridge, first by triggering rapid growth after the vegetation was removed or died out, then by contributing to deflation of the dune field by reducing sand supply from increased vegetation and urban development. The recent acceleration of the dune deflation is bringing the main dune close to the elevation of sand dunes typical for this area at the turn of the century. The latest data show a considerable reduction of the main dune migration rate, although its deflation continues. The complexity of dune field evolution requires further monitoring of elevation and vegetation changes to avoid unexpected consequences of natural or human impacts that could trigger fast migration similar, to that observed for the south dune. Numerical modeling may be applied in future studies to explore various management alternatives that would permit preservation of this landscape feature for future generations. The task to fully understand this dynamic landscape and to implement management strategies that will preserve the ever changing "giant peaks and ridges" that have fascinated observers throughout this century continues. The recognition of these features prompted the State to acquire the property that is now designated as Jockey's Ridge State Park. The current challenge is to contain this unique landform and yet not destroy it.

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