New spatial measures of terrain dynamics derived from time series of lidar data

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***Abstract*—We anticipate that multiyear lidar surveys, currently focused on vulnerable coastal areas, will soon become a common resource for monitoring and analysis of various aspects of regional terrain change. We propose raster based measures for mapping and quantification of discrete and continuous terrain changes by introducing novel concepts, such as core and envelope surfaces, contour evolution band, and evolution regression slope map that can provide insights into the spatial aspects of terrain dynamics and changes in structures. The methodology is applied to a section of North Carolina coast where multiyear time series of lidar data is already available. Dynamics of bare dune and beach systems, changes in structures and vegetation growth are mapped and quantified to evaluate the proposed approach.**

I. Introduction

Rapidly improving 3D remote sensing technologies, such as lidar, provide new opportunities to acquire high resolution elevation data that characterize land surface morphology and its change over large areas. Most of current lidar data processing research is focused on extraction and analysis of bare earth surface [1], identification of structures [2], and analysis of forest biomass and growth using multiple return surveys [3]. Land surface dynamics has been studied intensively in coastal regions using volume, elevation and shoreline change [4], [5], [6], [7], [8], as well as extraction and tracking of geomorphometric dune features [9].

More than ten years of coastal lidar mapping has accumulated massive time series of high resolution elevation data and new concepts and approaches are needed to move the analysis beyond elevation differences or volume change estimates. To preserve the spatial detail captured by lidar and at the same time provide useful summary information for coastal management we have proposed raster based analysis of beach-foredune system evolution from decadal series of lidar data [10]. In this paper we formalize and extend the raster based approach, introduce examples for mapping discrete and continuous terrain change, and provide results of new applications such as efficient identification of change in buildings over ten year period, mapping evolution of large, active dune system, and quantification of vegetation growth rate.

II. Methods

We define *terrain* as bare earth surface combined with structures and vegetation, usually represented by Digital Surface Model (DSM). For the purpose of this paper, we consider terrain evolution as changes in: (a) bare earth, due to natural processes such as soil erosion and sand transport, or changes caused by human intervention such as grading or beach nourishment; (b) growth or decline of vegetation; and (c) construction, modification or loss of structures (buildings, roads).

We can characterize terrain evolution over a given time period by series of raster-based DSMs $z(i,j,t_k)$ derived from lidar surveys acquired at time snapshots $t_k, k = 1,\ldots,n$. We compute a consistent time series of high resolution DSMs from diverse sets of point data using methodology that includes analysis of point cloud properties for each survey, removal of potential systematic errors, as well as simultaneous interpolation of elevation rasters and smoothing of noise using regularized spline with tension [10], [11].

Standard univariate statistics is then applied to the raster map time series on per-cell basis to identify and quantify dynamic and stable regions and extract information about change in structures and vegetation. In addition to commonly used mean elevation, standard deviation, and range we define *core surface* as the minimum elevation and *envelope surface* as the maximum elevation measured at each cell over given time period (t_1, t_n):

$$z_{core}(i,j) = \min_k z(i,j,t_k) \quad k = 1,...,n \tag{1}$$

$$z_{env}(i,j) = \max_k z(i,j,t_k) \quad k = 1,...,n \tag{2}$$

For the barrier island environment, the core surface represents boundary between stable sand volume that has not moved during the entire study period and a dynamic layer. The envelope surface represents outer boundary of the dynamic layer within which the terrain evolved during the given time period (t_1, t_n). Specific contours (elevation isolines) extracted fom the core and envelope surfaces then define a *contour evolution band* within which the given contour evolved during (t_1, t_n).

Most common application of the contour evolution band is extraction of an isoline representing shoreline (usually defined as mean high water level) and efficiently mapping shoreline evolution band, task currently performed by digitizing an envelope from time series of extracted shorelines.

Spatial pattern of time associated with the core and envelope surfaces derived as raster maps representing *time of minimum elevation* and *time of maximum elevation* can be computed as:

$$t_{max}(i,j) = t_l, \quad \text{where} \quad z(i,j,t_l) = z_{env}(i,j) \tag{3}$$

$$t_{min}(i,j) = t_p, \quad \text{where} \quad z(i,j,t_p) = z_{core}(i,j) \tag{4}$$

where values in the time maps represent the index l or p and the actual date t_l or t_p is stored as an attribute (label).

Map algebra can then be applied to the above defined summary raster maps and to individual DSMs to efficiently extract spatial and temporal information about discrete changes in structures. Per cell univariate statistics can be used to quantify continuous elevation change such as vegetation growth or dune migration.

A. Discrete changes

Discrete terrain changes, such as construction or destruction of a building, are characterized by significant difference in elevation for a set of grid cells measured between two time snapshots t_k and t_{k+1}. To accurately identify this type of changes, adequate representation of structures is required, usually found in DSMs with resolutions 0.3-0.5m. Structures that were built or lost during the entire study period can be identified using the core and envelope surfaces, given by (1) and (2) respectively, as grid cells (i_c, j_c) that fulfill the following condition:

$$z_{env}(i_c, j_c) - z_{core}(i_c, j_c) > h_b \tag{5}$$

where h_b is the threshold relative height of the building captured by lidar. Lost structures will be located in grid cells (i_l, j_l) that fulfill the condition given by equation (5) and the following relation:

$$t_{max}(i_l, j_l) < t_{min}(i_l, j_l) \tag{6}$$

while new structures can be identified as grid cells (i_n, j_n) where:

$$t_{max}(i_n, j_n) > t_{min}(i_n, j_n) \tag{7}$$

where $t_{max}(i,j)$ and $t_{min}(i,j)$ are raster maps defined by (3) and (4). If more detailed temporal information is needed, the extracted new or lost buildings can be vectorized using the standard GIS tools and the associated centroids (i_c, j_c) can be used to perform an automated query of the entire DSM time series. Elevation differences at grid cells (i_c, j_c) computed for the individual successive time snapshots t_p and t_{p+1}, $p = 1, ..., n-1$:

$$\Delta z(i_c, j_c, t_d) = z(i_c, j_c, t_p) - z(i_c, j_c, t_{p+1})$$

can be analyzed and a time interval t_d when a new house was built can be identified using condition:

$$\Delta z(i_c, j_c, t_d) < -h_b \tag{8}$$

and when it was lost:

$$\Delta z(i_c, j_c, t_d) > h_b \tag{9}$$

Using this approach, we can also investigate whether there were any homes that were built and quickly lost within the study period or that were lost and re-built. Extracted information about the new and old buildings can be compared with county records to evaluate the results, verify permits for the new buildings and identify potential violations.

We can also extract wide range of additional information about structures and their relation to terrain evolution to support decision making and coastal management. For example, we can identify vulnerable new structures that were built on a very small core (stand on moving sand) by combining (5) and (7) with a condition:

$$z_{core}(i_n, j_n) < z_b \tag{10}$$

where z_b is minimum core elevation considered safe (e.g. based on storm surge, or sea level rise). Homes located within the shoreline evolution band (already lost or highly vulnerable) can also be easily identified.

B. Continuous evolution

Continuous terrain evolution is characterized by gradual change in elevation surface over time that can be caused, for example, by sand dune migration due to wind transport or vegetation growth. Rather than extracting locations and time where change in elevation has exceeded certain threshold, as in the case of discrete change, we quantify the continuous evolution by mapping spatial pattern and rate of elevation change over time.

Spatial distribution of linear rate of change can be estimated by computing linear regression for each grid cell (i,j) in the time series of n raster elevation maps. The result of the regression can be represented by three raster maps: (a) slope of the regression line $r_s(i,j)$; (b) offset $r_o(i,j)$; and (c) coefficient of determination $r_c(i,j)$. For active, bare, wind blown dunes both elevation growth and loss can be continuous and we can map the areas with dune erosion and dune growth as grid cells (i_e, j_e) and (i_d, j_d) respectively that fulfill the following conditions

$$r_s(i_e, j_e) < \varepsilon_e \cap r_c(i_e, j_e) > r_{cmin} \tag{11}$$

$$r_s(i_d, j_d) > \varepsilon_d \cap r_c(i_d, j_d) > r_{cmin} \tag{12}$$

where ε_e and ε_d are threshold negative and positive regression slopes indicating dune erosion and growth respectively, and r_{cmin} is a threshold value for coefficient of determination for which the relationship can be considered linear. Areas where $r_c(i,j) < r_{cmin}$ do not have clear linear trend of growth or decline and represent areas where growth has switched to decline as the dune has migrated. Similar analysis can be applied to the forest canopy surface to estimate rate of forest growth and identify areas with forest decline.

The presented methodology is general and can be used with any software that supports raster data processing. Our

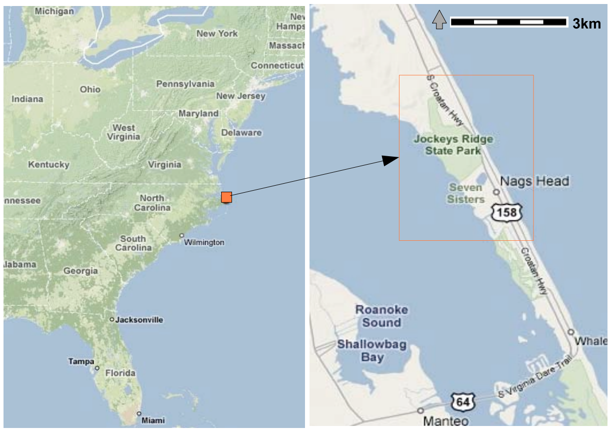

Fig. 1. Location of the study area: Nags Head, Outer banks barrier islands, North Carolina, USA

TABLE I
ELEVATION [M] AT CENTROIDS OF A LOST HOME H1A AND A NEWLY BUILT HOME H1B.

yr	1997	1998	1999	2001	2004	2005	2007	2008
H1a	10.3	10.3	10.6	10.8	**10.2**	**2.3**	2.6	3.2
H1b	3.0	3.0	2.4	2.5	**2.4**	**14.6**	14.5	14.5

implementation is based on the open source GRASS GIS [12], [13].

III. RESULTS

We have evaluated the proposed methodology using time series of elevation data available for the northern section of North Carolina barrier islands. These islands are characterized by significant shore erosion and dune migration, causing damage to homes, roads and infrastructure. Improved understanding of terrain dynamics in this region is essential for effective coastal management and sustainable development.

We present results for two sections of a barrier island in the Nags Head area (Figure 1): (a) $1.5\,km^2$ of beach-foredune system referenced here as Nags Head East; (b) $1.8\,km^2$ section west of Hwy 158 that includes a large, active dune within the Jockey's Ridge State Park.

A. Beach and structures in Nags Head East

Time series of $0.5\,m$ resolution DSMs was generated from a set of nine lidar point clouds collected during the years 1996, 1997, 1998, 1999, 2001, 2004, 2005, 2007, 2008, leading to time series with variable time step that had to be taken into account for the analysis. Different lidar technologies used in the surveys required careful data processing and integration using methodology described in [10]. Per cell statistics was then applied to the DSM series resulting in maps representing the core surface and envelope (Figure 2), time at minimum and time at maximum elevation, elevation mean and standard deviation (Figure 3). Map algebra operations and regression analysis were then used to extract more detailed information about structures, beach, and foredune evolution.

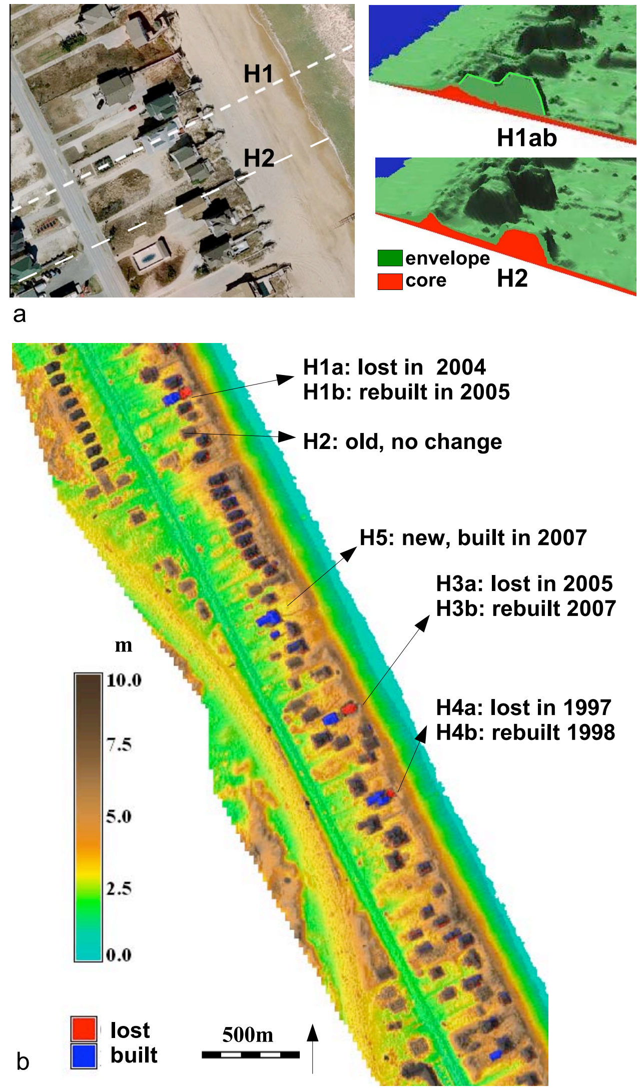

Fig. 2. Nags Head East: identification of new and lost homes using core and envelope surfaces: (a) 2007 orthophoto and core/envelope crossections for a lost and rebuilt home H1ab and a stable home H2: (b) new and lost homes draped over 2008 DSM.

The core in the Nags Head East area has mean elevation of $2.6\,m$ and total volume of close to 1 million m^3. Mean difference between the core and envelope is $1.2\,m$ and relative volume of stable core to envelope is only 65 %, indicating highly dynamic terrain in this area apparently due to natural sand redistribution and addition or removal of structures. Standard deviation map (Figure 3) shows significant temporal variability in elevation associated with foredunes (due to wind transport and dune maintenance), while the lower beach and shoreline band exhibits low standard deviation. Stable paved areas (roads and driveways) have both standard deviation and regression slope zero (Figure 3).

The map algebra operations, given by (5), allowed us to efficiently estimate locations of homes that were built or lost over the past 10 years (Figure 2). Total of 98 beachfront

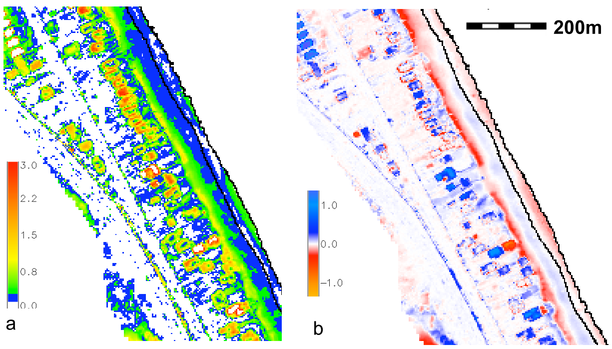

Fig. 3. Nags Head East: (a) standard deviation map; (b) linear regression slope map with shoreline evolution band (black lines).

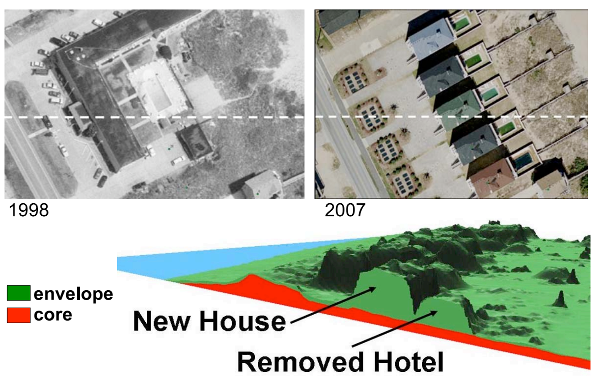

Fig. 4. Complex combination of lost and new buildings: (a) 1998 and 2007 orthophotos, (b) core and envelope surfaces

houses were identified, 82 existed the entire time, 7 were destroyed and 9 were built. Each house that was destroyed during the study period was rebuilt on the same lot, but at a different location. This observation is consistent with coastal construction setback regulations that require that newly constructed houses be located a distance of 30 times the long-term average annual erosion rate from the vegetation line as surveyed in the field. Depending on the dimensions of the lot, complex building patterns may emerge through the time series analysis of the DSMs. Preliminary comparison with aerial imagery and county records highlights the complexity of changes (Figure 4) as a destroyed single larger building (in our case a motel) can be replaced by several smaller ones, some of which overlap with the old building. Although comprehensive evaluation of the accuracy needs to be performed, the method has been quite successful even for the cases when change occurred in 90ies, when only lower resolution lidar data were available. Query at the centroids of the extracted buildings allowed us to identify the time intervals when these buildings were lost or built (Figure 2, Table I). Further refinement of the method will be needed to improve correct identification of homes that were rebuilt at the same location or had large overlap with the previous location.

TABLE II
EVOLUTION OF JOCKEY'S RIDGE PEAK ELEVATIONS IN [M].

Peak/Year	1950	1974	1995	1999	2001	2007	2008
Main	42	33	26	26	25	21	22
East	22	21	18	18	18	18	19
West	-	23	20	21	21	22	22

B. Jockey's Ridge state park sand dune

The second study area, located within Jockey's Ridge state park, includes large, active sand dune, that was previously analyzed using feature extraction and measurement of feature migration between 1974 and 2004 [9]. New, more recent lidar surveys provided additional data suitable for application of per cell statistics approach in this area. The time series analysis was performed using $2\,m$ resolution DSMs derived from lidar surveys acquired in 1999, 2001, 2007 and 2008 and from photogrammetric and digitized contour data available for 1974, 1995. First, core and envelope surfaces (Figure 5) were computed and a mask was created for the active dune area, defined as area above $6\,m$ elevation threshold extracted from the envelope surface. This approach ensured that the study area included all active dune locations as the dunes migrated horizontally towards South and East between 1974 and 2008. The threshold of $6\,m$ was selected to include only bare sand areas and for consistency with the previous research [9].

The crossections of the core and envelope surfaces (Figure 5) reveal large core with peak elevation of $20.8\,m$, a very high value for the coastal barrier islands environment but below the current Main peak elevation of $22\,m$ (Table II). The mean elevation of the core is only $5.4\,m$ and the stable core volume, representing sand that has not moved over the past 34 years, is 3.7 million m^3. The peak elevation of the envelope is 33.3m (Main dune peak height in 1974) with the envelope encasing more than twice as much volume (8.3 million m^3) as the core, confirming presence of a large dynamic layer. Crossections of the core and envelope (Figure 5) show massive relocation of sand along the Main and East dunes while the relatively lower, central area has been more stable over the past 34 years.

Our previous research, based on year-by-year elevation differences and tracking of peak elevation at different sections of the dune field, indicated that the dune is flattening [9]. The regression slope map (Figure 6) provided significantly more detailed quantitative information about this process by highlighting the highest rates of elevation loss on the dune ridges. Windward sides of the dunes exhibit strong linear trends in elevation loss that gradually increase towards the peaks, with the highest loss rates measured on the Main dune (Figure 6a). As the dunes migrate south and east, elevation along the south and east oriented slip faces steadily increased at even higher rates, due to deposition of sand transported from the windward side. Coefficient of determination r_c for both areas exceeded 0.7 (Figure 6b). Area with no linear trend ($r_c < 0.3$) defined the leading edges of the dunes where the trend changed from growth to loss.

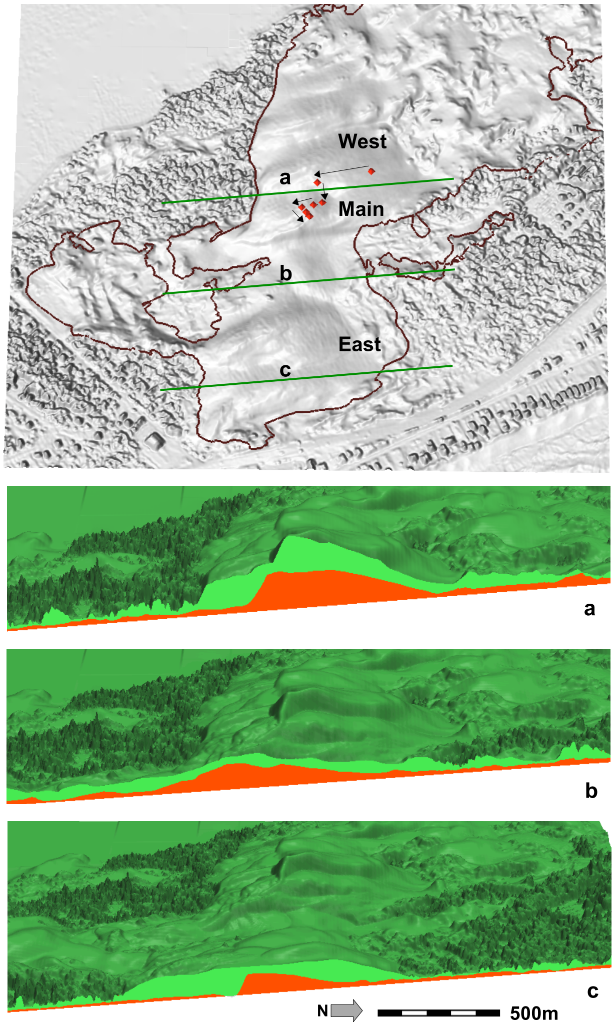

Fig. 5. Sections of Jockey's Ridge sand dunes on 2008 DSM (top); crossections showing stable core (red) and dynamic layer with envelope (green) for time period 1974-2008. Points on DSM represent locations of the Main dune peak as it migrated between 1950-2008.

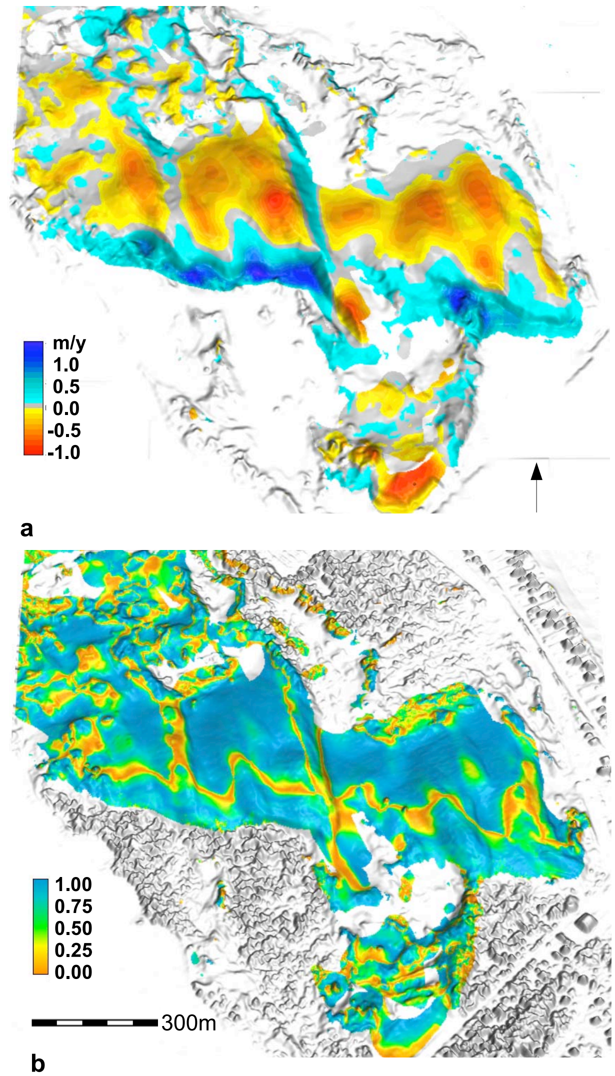

Fig. 6. Jockey's Ridge in 1995 with color maps representing spatial pattern and value of (a) linear regression slope - rate of increase or decrease in elevation, and (b) coefficient of determination.

Dramatic decrease in dune height (Table II) has been influenced by vegetation spreading and growing around the dune. The spatial pattern of vertical vegetation growth rate was mapped using per cell linear regression. The rates were diverse with fastest growing forest at $0.26\,m/y$ within the park, while the forest in neighboring areas has grown at slower rate of $0.18\,m/y$. The proposed approach provided information not only about the mean forest growth rates but also about their spatial distribution.

IV. Conclusion

We have proposed an efficient, raster based method for extracting information on discrete changes in structures and continuous terrain evolution from time series of airborne lidar surveys. Our analysis was focused on coastal applications but the methodology is general and can be applied in other environments.

Rather than analyzing each time snapshot one by one, we have proposed to first extract core and envelope surfaces and use their differences to identify changes in structures. More detailed temporal information can then be extracted, by performing automated query only at identified centroids. Future work will include assessment of spatial and temporal accuracy of this approach, especially for complex cases where the new buildings overlap with the old, destroyed ones.

The regression raster maps provide insight into spatial patterns of terrain dynamics especially for those processes that exhibit linear change in elevation over time, observed in our case, on coastal dunes.

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