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Patterns and Paleoshorelines of White Sands Dune Field, New Mexico

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Patterns and Paleoshorelines of White Sands Dune Field, New Mexico

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Abstract

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by

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The University of Texas at Austin, 2011

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The dune field at White Sands, New Mexico, shows a well-defined pattern of dunes and interdune areas, as well as spatial variations in this pattern. The purpose of this research is to determine which measured pattern parameters are most consistent across the dune field and to determine the cause of depositional spatial variability. This was accomplished using an airborne LiDAR generated digital-elevation model (DEM) collected in June 2007 and covering 39 km^2 of the dune field. Properties of the dune field are defined by measurements from three dune populations: 1) 110 randomly selected dunes, 2) 247 dunes along transects oriented in the net transport direction, and 3) 171 dunes from three zones within the field where differences in pattern are visible. Measurements of eight common dune parameters show that the lowest coefficients of variation occur with dune orientation and crestline sinuosity, which largely define the field pattern. Cross-plotting of parameters shows generally poor correlations, which is thought to reflect variation around field-scale means that are comparable to other dune fields globally. Removing the dunes from the LiDAR DEM reveals a depositional substrate with breaks in slope interpreted as three paleoshorelines associated with Pleistocene Lake Otero. The paleoshorelines are antecedent boundary conditions that exert the primary control on spatial variability within the dune pattern.

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Introduction

Patterns in dune fields are thought to develop because of self-organization that occurs through dunes interacting with one another (Werner, 1995; Ewing and Kocurek, 2010a; Kocurek et al., 2010). Aeolian dunes evolve within a set of environmental variables that include wind strength and direction, sediment supply, topographic relief, areal extent, and the geometry of the sediment source (Kocurek and Lancaster, 1999; Kocurek and Ewing, 2005; Ewing and Kocurek, 2010b). These environmental variables are boundary conditions that influence the emergence and modification of dunes forming the components of a pattern (Kocurek et al., 2010). Fluctuations in dune patterns, therefore, are either the consequence of changing boundary conditions over long time scales or the natural evolution of the pattern toward a quasi-steady state. Pattern changes are evident when dunes change from one form to another (e.g., barchan dunes morphing into parabolic dunes) or when dunes change in their physical dimensions across space. Both of these types of changes are seen in a digital elevation model (DEM) created from a LiDAR survey taken in June 2007 of a portion of the dune field at White Sands National Monument, New Mexico. The DEM captures dune pattern variation in a high resolution, three-dimensional format that can be manipulated using geographic information systems (GIS) software to provide substantial detail on the dune population within the study area. With the increasing accessibility of LiDAR technology, systematic quantification of pattern components has become a viable means for addressing spatial changes observed in dune field patterns.

This study focuses on quantifying dune parameters and spatial trends at White Sands with the goals of determining parameters that best define the dune-field pattern and the cause of spatial variability within the pattern. Three different dune populations were used for these purposes: 1) a population consisting of randomly selected dunes from throughout the entire study area; 2) a population of dunes that cross a predetermined set of evenly spaced transects oriented in the net transport direction; and 3) a population of dunes within selected zones where dune height and spacing appear to depart from the general pattern. The cause of spatial variability in the pattern was investigated by exploring the hypothesis that previously identified paleoshorelines continue to exert an influence upon the present dune pattern. The position and elevations of these paleoshorelines were determined and their relationship to the dune pattern explored.

Setting

White Sands dune field is an approximately 450 km² expanse of aeolian gypsum sand dunes located within the Tularosa Basin of south-central New Mexico (Fig. 1). To the west of the dune field lies a deflationary basin known as Alkali Flat from which gypsum sand is deflated and continues to source the dunes (McKee and Moiola, 1975). The climate of the region is semiarid and Lake Lucero and other smaller playas to the west of the dune field are the only bodies of water in Tularosa Basin. During the cooler and wetter climate of the Pleistocene the Tularosa Basin hosted a large pluvial lake called Lake Otero (Herrick, 1904; Gile et al., 1981). Lake beds indicate a highstand of approximately 1218 m (Seager et al., 1987). As the lake contracted during the Holocene in association with episodes of aridity, it left behind telltale shorelines first recognized in outcrop in the White Sands area by Herrick (1904) and described in detail by Langford (2003). Along with the current Lake Lucero shoreline at 1185 m elevation, Langford mapped two higher paleoshorelines associated with ancestral Lake Otero at ~1191 (1190-1193) m and ~1201 (1199-1203) m elevation (Fig. 2). The lower and younger paleoshoreline is termed L2, the older, higher one L1. Langford mapped a third paleoshoreline at 1210 m without detailed commentary.

White Sands dune field began forming ~7000 years ago with the deflation of gypsum grains derived from evaporitic minerals that precipitated after the desiccation of Lake Otero (Langford, 2003; Kocurek et al., 2007). Currently the sand is swept northeastward by dominantly southwest winds with an average annual wind vector of N75°E (Ewing et al., 2006). Sand travels upslope a dune field substrate whose shallow gradient across the study area never exceeds 1° except in areas of sour on the western dune margin. Sand transport at White Sands dune field is strongly influenced by the presence of a shallow water table perched within the gypsum accumulation sequence beneath the active sand dunes (Kocurek et al., 2007). Stabilization by gypsum cementation and vegetation also plays a role (Schenk and Fryberger, 1988). Dune-field accumulations average 8.5 m deep in the center of the dune field (Kocurek et al., 2007). Below this wedge are the gypsum-rich clay and silt sediments of paleo-Lake Otero.

The study area is composed mainly of barchan and crescentic dunes which transition into parabolic dunes on the eastern, downwind edge (Fig. 3). Within the overall dune pattern, four zones are distinguishable by differences in dune spacing and height (Fig. 3). A zone of wide interdune spaces lies in the central study area (Zone 3 in Fig. 3). East of this area lies a zone with taller, more closely spaced dunes trending roughly north-south (Zone 4 in Fig. 3). Two narrow zones trending north-south and lying next to each other on the southern upwind margin of the dune field also have taller accumulations of more closely spaced dunes compared to the dune field pattern as a whole (Zones 1 and 2 in Fig. 3).

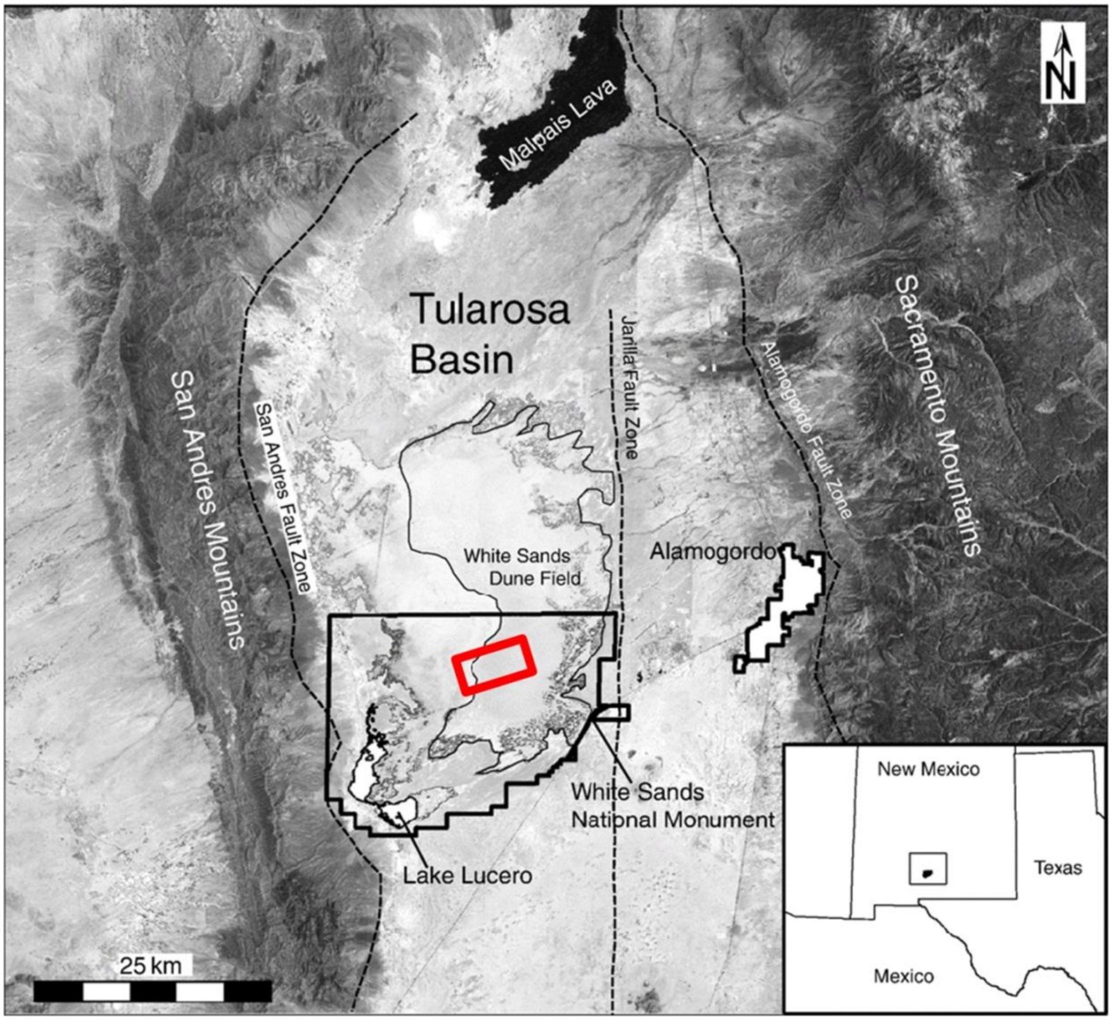


Figure 1. White Sands dune field is located within the Tularosa Basin in south-central New Mexico. The study area is located in the red box within White Sand National Monument. Modified from Kocurek et al., (2007).

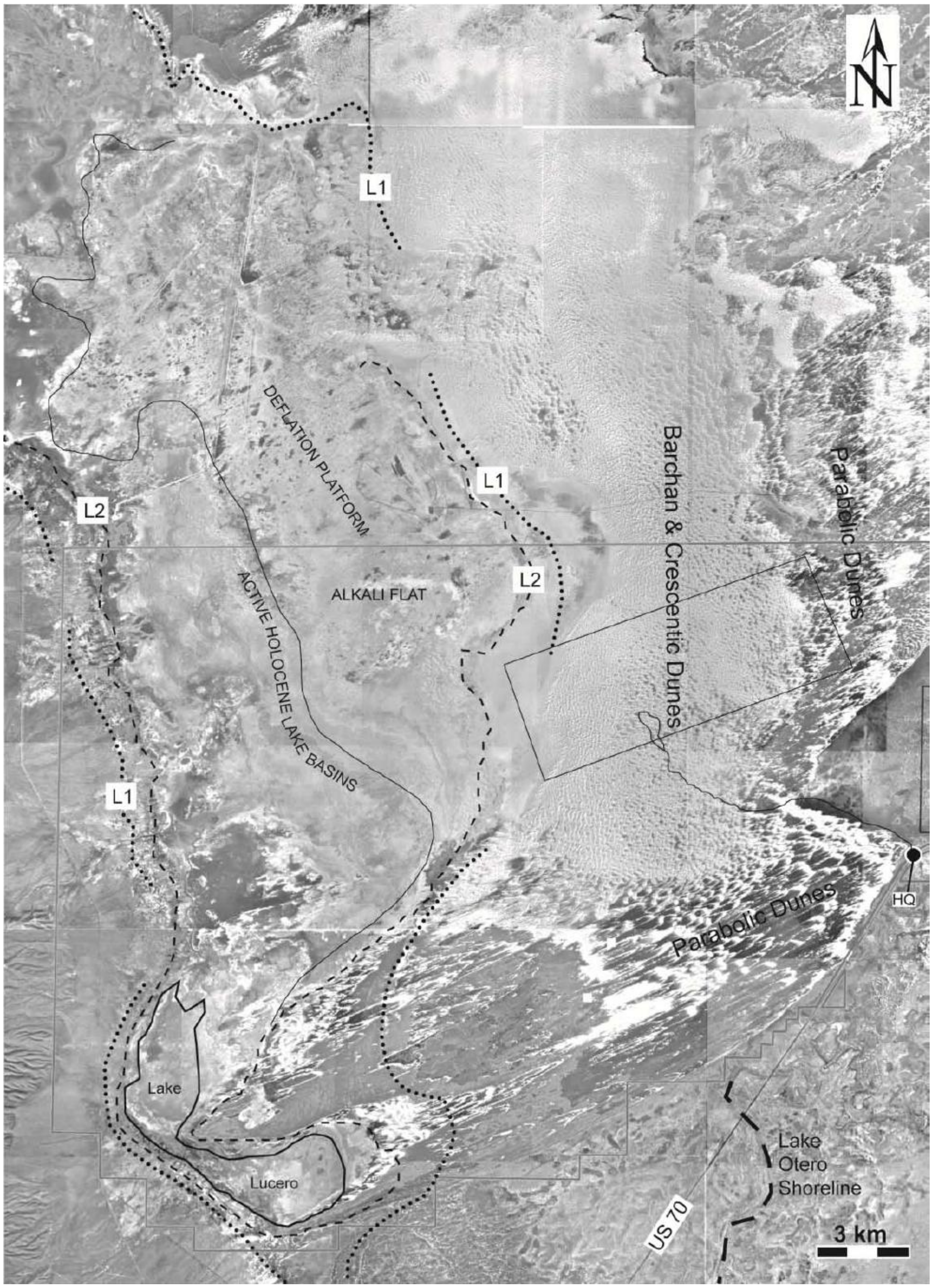


Figure 2. White Sands dune field with paleoshorelines as mapped by Langford (2003). The paleoshorelines are L1 (~1201 m), L2 (~1191 m), and one located in the southeast corner at 1210 m elevation. The main body of the dune field is composed of crescentic and barchan dunes bordered by parabolic dunes. Current deflation of the western Alkali Flat and playa lake beds continues to supply sand to the dune field. The tilted rectangle indicates the position of the LiDAR image shown in Figure 3.

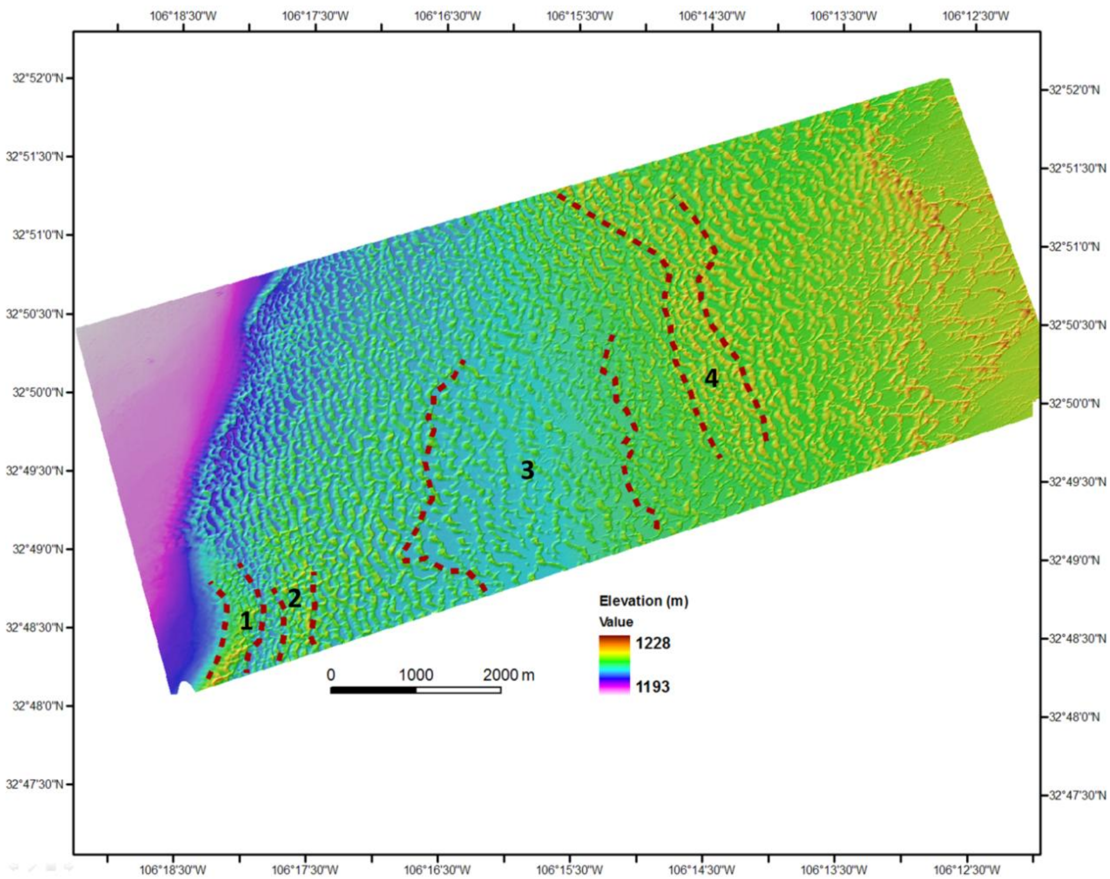


Figure 3. The study area is a 39 km² LiDAR image extending from the western dune field margin to a zone of parabolic dunes at the downwind eastern edge. Dunes are migrating northeastward up a gentle gradient. Zones of dune patterns different from the overall dune field pattern are outlined in dashed red lines. Warmer colors represent higher elevations.

Methods

LIDAR

Dune measurements were based on a 9 June, 2007 airborne LiDAR survey (Fig. 3). LiDAR provides a means of remotely mapping a three-dimensional surface with a high degree of accuracy. Instrumentation consists of an airplane-mounted laser that directs a laser pulse downward to the surface target with the total travel time of the reflected beam used to calculate the elevation of the surface. Equally critical to the measured travel time is a precise determination of surface location which is measured by a ground positioning system (GPS) mounted on the plane. The LiDAR survey for this study was flown by the Center for Space Research at the University of Texas at Austin using an Optech ALTM 1225 LiDAR instrument integrated with an Ashtech Z-12 dual frequency GPS receiver and a Litton LN-200 inertial measurement unit. The Optech 1225 records the first and last pulse and is integrated with a full waveform digitizer capable of recording the entire reflected pulse. The instrument was flown in a single-engine Cessna 206 Turbo Stationair. Laser pulse rate frequency was 100 KHz, or approximately 5 points per square meter, yielding over 16 million points within the survey area. Aircraft altitude was approximately 1000 m above the surface and ground speed was 60 m/s (134 mph). Georeferencing was done based on GPS stations at the Alamogordo Regional Airport and at Space Harbor on the White Sands Missile Range. Georeferenced elevation data were then used to construct a digital elevation model (DEM). The LiDAR image covers a 39 km^2 area of mostly crescentic and barchan dunes and extends in the transport direction from the edge of the dune field to a topographic high coinciding with the beginning of a zone of parabolic dunes. The image was preprocessed into a NAD83 UTM 13N geodata benchmark using ArcGIS software. Aerial photos from a 2005 White Sands Missile Range digital orthophoto quarter quadrangle (DOQQ) were layered around the LiDAR image to provide geomorphic context.

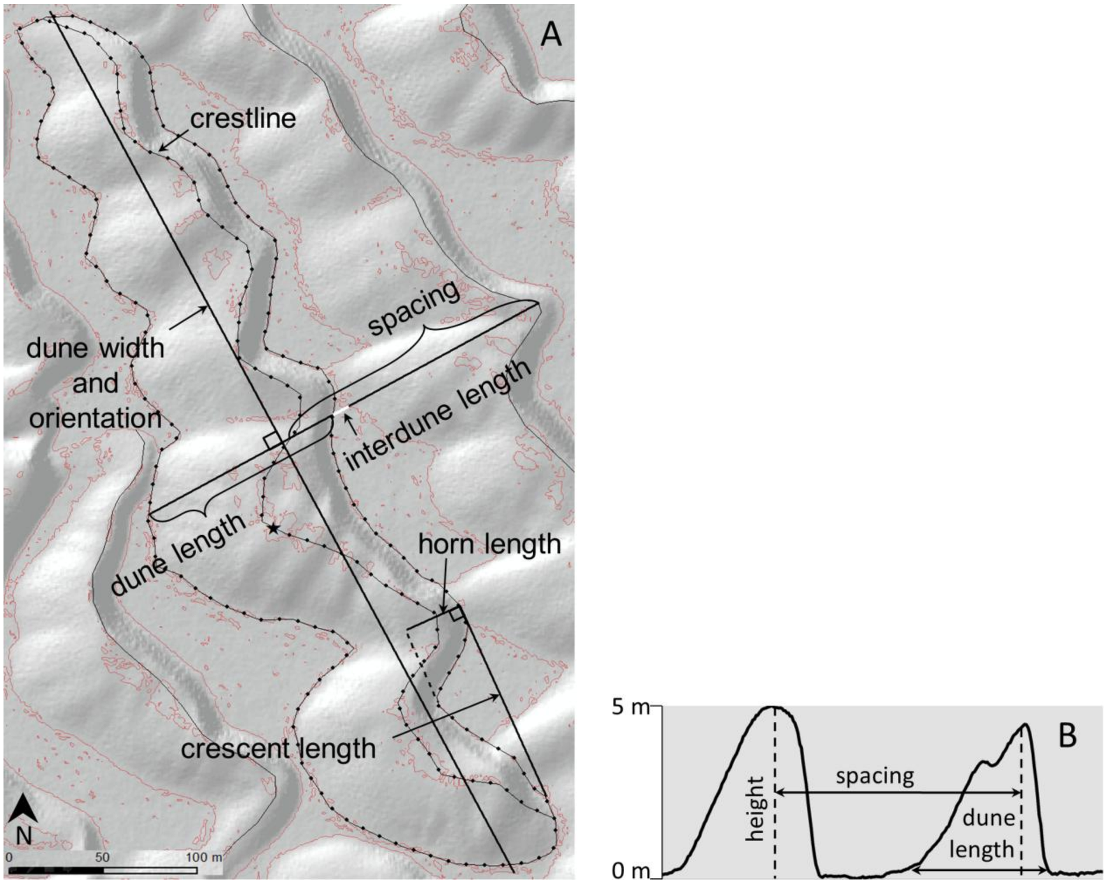
SINGLE PARAMETER PLOTS AND CROSS PLOTS

Single parameter plots were used to test the regularity of parameters within the study area and to determine how similar dunes of different populations are to one another. Plots were created by sorting parameter measurements from small to large and graphing them as frequency distributions. Basic statistics of mean, median, standard deviation and coefficient of variation (standard deviation / mean) were calculated for all measured parameters. The coefficient of variation was used as a normalizing metric to permit comparison between different datasets. Values range from 0 to 1, with lower values indicating less variation within the dataset. Dune parameters were measured only for crescentic and barchan dunes because parabolic dunes are poorly represented within the LiDAR survey. Parameter measurements for all populations were based on dune polygons isolated from the base surface as shown in Figure 4A. Eight commonly used parameters were measured to characterize the dune field: 1) maximum and average height, 2) crest-to-crest spacing with and without interdune areas, 3) crestline length, 4) dune length and width, 5) dune orientation, 6) crestline sinuosity, 7) crescent length and 8) horn length (Fig. 4A). Additionally, dune footprint surface area, total dune surface area and dune volume were collected from the three-dimensional dataset using ArcGIS. The base of individual dunes was defined by a contour line where the slope reached 2.5°, which is consistent with field observations. Dunes were traced manually in ArcGIS and parameters of footprint area, dune surface area and volume were calculated based on these dune outlines.

Cross plots indicate correlation between two parameters via goodness-of-fit (r^2) for linear regressions. R^2 measures the amount of variability that can be predicted in a parameter from its relationship to another parameter and has values ranging from 0 (no correlation) to 1 (perfect correlation). Mean values were also calculated for all cross plots. Cross plots that were examined include: 1) spacing with and without interdune areas to average and maximum dune height, 2) crestline length to average and maximum height, 3) dune length to average and maximum height, 4) dune width to average and maximum height, 5) dune volume to average and maximum height, 6) dune volume to crestline length, 7) dune volume to dune surface area, 8) dune footprint area to dune width, and 9) dune surface area to dune width.

DUNE SAMPLING POPULATIONS

Measurements were made from three different dune populations to determine which sampling method was most sensitive to spatial differences in pattern. The populations included a random sampling of 110 dunes selected by an automated algorithm, another population of 247 dunes encountered along four transects oriented in the net transport direction and separated by approximately 1 km, and a population of dunes from within the distinct zones seen in Figure 3. Figure 5 shows all dune populations selected for measurement. Dune parameters measured for the randomly selected dunes include those described in Figure 4A. For the 247 dunes of the field-scale transect dune population, only parameters of dune height, spacing and dune length were measured along the length of transect intersecting the dunes (Fig. 4B). Dunes within the four zones were measured in two ways: 1) comprehensively, as in the case of the randomly selected dunes, and 2) along net transport-oriented transects, similar to the field-scale transect dunes. In the case of zonal transects, comparable sample size between the different zones was achieved by spacing transects 125 m apart in Zones 1 and 2, and 500 m apart in Zones 3 and 4. Sample sizes in zonal transects are n = 45 for Zone 1, n = 40 for Zone 2, n = 44 for Zone 3, and n = 42 for Zone 4. Measurements were made at the intersection of transect and dune, as in the field-scale transect population, and only included parameters of dune height, spacing and dune length. For comprehensive parameter measurements within the zonal dune populations, all individual dunes were sampled in Zones 1 (n=26) and 2 (n=20). The number of dunes sampled for Zone 3 (n=44) and Zone 4 (n=42) was kept the same for both the comprehensive parameter measurements and the transect parameter measurements. Comprehensive parameter measurements, then, were gathered for randomly selected dunes and zonal dune populations, whereas transect populations (the field-scale transect dune population and zonal transect dune populations) were limited to height, spacing and dune length measurements only.



Figures 4A and 4B. Definition diagram A shows parameters measured for random and zone dune populations. Pink 2.5º contours define dune polygons from which volumes and surface areas were calculated. Average dune height is the difference between average crestline elevation and average dune base elevation, both sampled at 10 m intervals. The star shows the location of the highest dune elevation along the crestline. Maximum height is the vertical distance between the star and the average dune base elevation. Sinuosity equals crest length divided by dune width. Spacing, dune length and interdune length were measured perpendicular to dune orientation. Crescent length was measured horn to horn. Horn length is perpendicular to crescent length. Definition diagram B shows dune transect parameters measured in the transport direction.

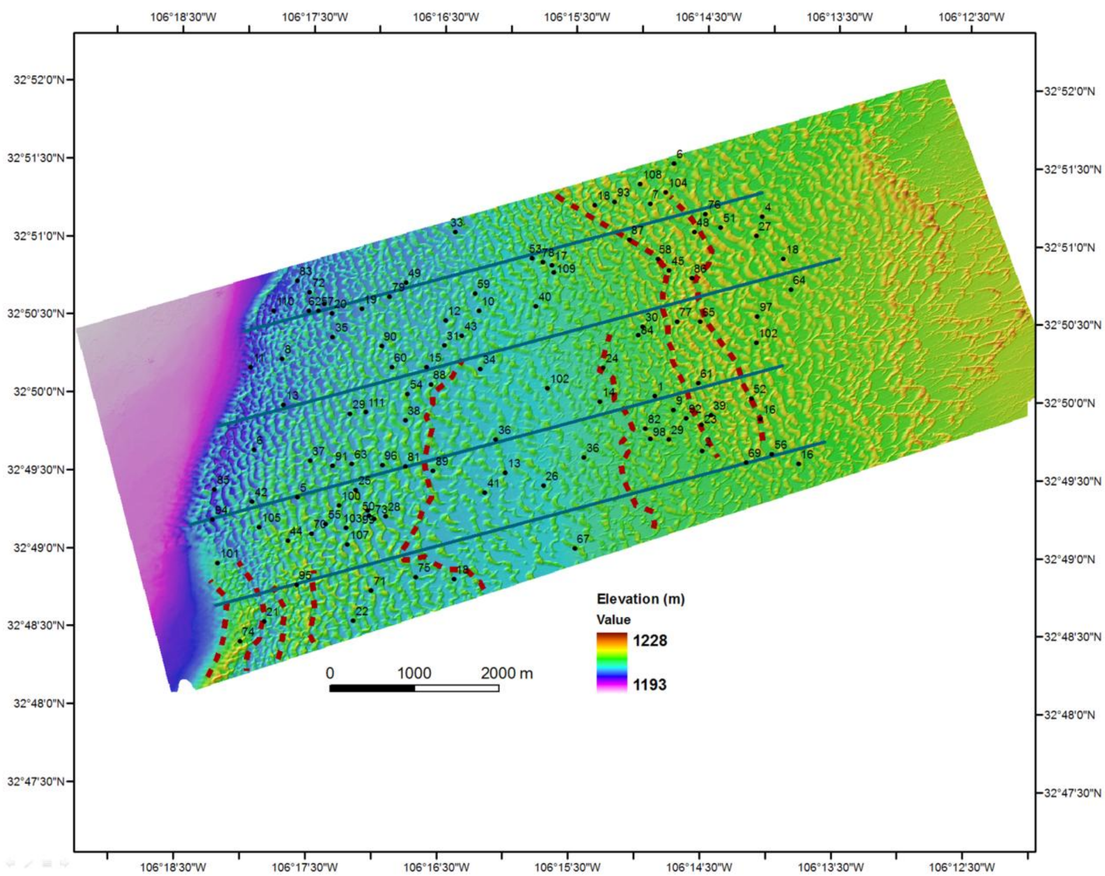


Figure 5. Three different dune populations are indicated in the crescentic/barchan portion of the dune field by 1) 110 random points, 2) four linear transects in blue, and 3) four zones selected for visually distinct dune spacing and height differences, outlined in red. Transects extend in the transport direction of N75°E.

PALEOSHORELINES

Antecedent topography can be an important boundary condition controlling spatial changes within dune systems. We hypothesized, therefore, that Lake Otero paleoshorelines buried beneath White Sands Dune Field and first recognized by Ewing et al., (2008), are influencing the distribution of dune patterns across the dune field. Visualization of the paleoshorelines beneath the dune field was accomplished by Ewing et al., (2008), who used a computer algorithm that eliminated dunes from the LiDAR image by connecting local minimum elevations along transects separated by 1 m in the cross-transport direction (Fig. 6). The positions of the paleoshorelines were refined in the present study to determine if their average elevations have any effect on dune pattern. Average elevations for each paleoshoreline were determined by statistically examining breaks in slope on thirty-four profiles of the base surface taken in the direction of net transport (N75°E). Maximum slopes on the base surface only range up to 1° in this section of the dune field, so profiles taken of the base surface were vertically exaggerated 100 times to accentuate the subtle topography (Fig. 7). At the vertically exaggerated scale, the intersection of two lines was used to define paleoshorelines at points of maximum upward convexity (rollover points) on each of the profiles (Fig. 7).

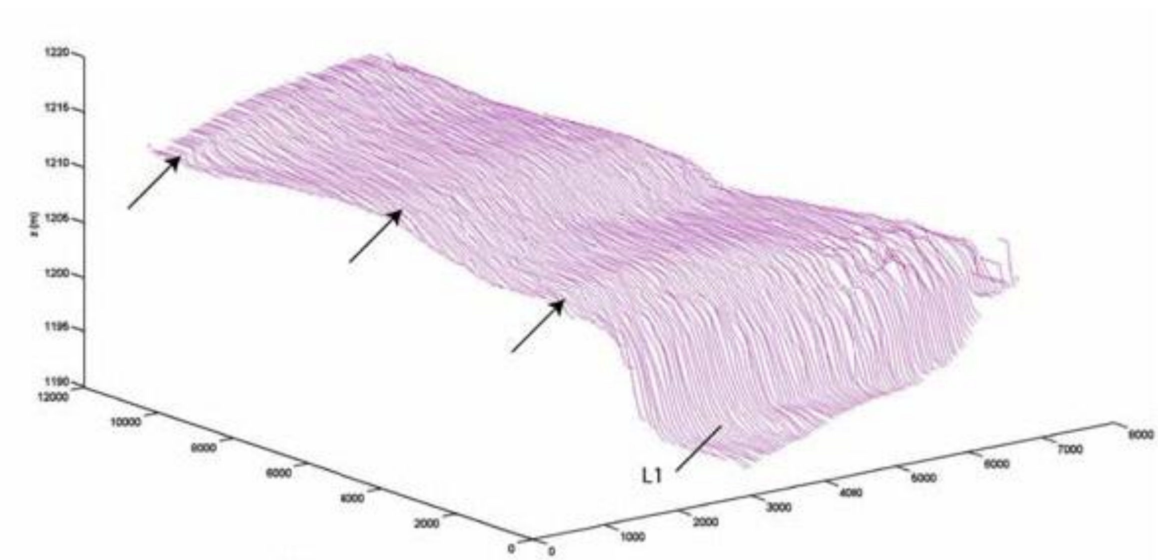


Figure 6. Stripped basal dune surface from Ewing et al., (2008), showing the location of three paleoshorelines above L1, a paleoshoreline mapped by Langford, (2003). The arrows show areas where distinct breaks in slope occur, which are interpreted as paleoshorelines of Lake Otero. Vertical exaggeration (V.E.) 1:200.

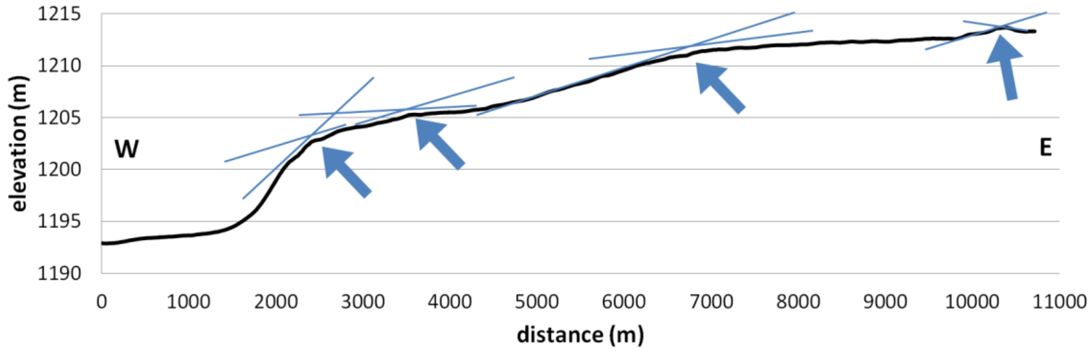


Figure 7. A single topographic profile stripped of dunes shows how paleoshorelines were defined by crossing lines at points of maximum upward convexity. V. E. 1:100.

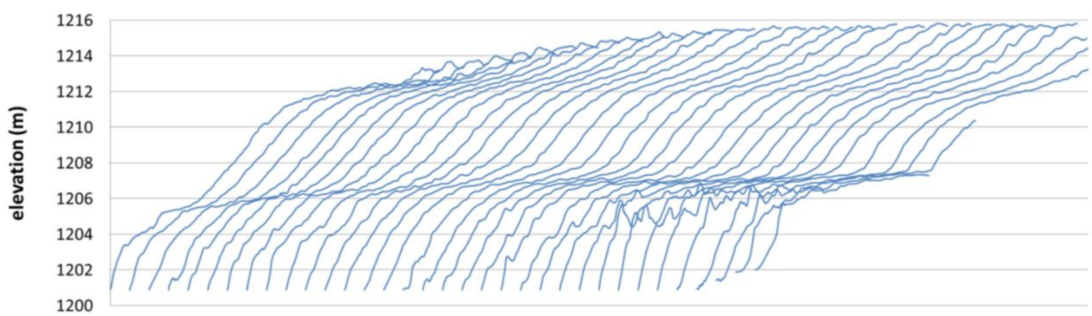


Figure 8. A sequence of 34 paleoshoreline profiles separated by 125 m and arranged north to south. V.E. 1:500.

Results

Single Parameters Plots

Statistics and data ranges of single parameters for the random dune population are given in Table 1. Statistics for height, dune spacing and dune length for transect and zone dune populations measured along net transport direction are found in Table 2. A complete compilation of parameter measurements for zone dunes is found in Tables 3-6. Within the random dune population, dunes range in average height from 2-9 m and have an average height of 4.7 m. Maximum height ranges from 3-13 m and averages 7.5 m. Dune spacing including interdune areas ranges from 51-302 m and has a mean of 134 m. Spacing without interdunes averages 97 m and ranges from 30-188 m. Dune crestline length has an average of 559 m and ranges from 81-1556 m. Dune width ranges from 80-1282 m and averages 449 m. Dune length ranges from 25-164 m and has a mean of 87 m. The average crescent length is 91 m and ranges from 21-245 m. Horn length per crescent averages 23 m and ranges from 2-10 m. Sinuosity ranges from 1.0-1.7 and averages 1.2. Dune footprint area averages 36,140 m^2, dune surface area averages 37,027 m^2, and average dune volume is 123,348 m^3. Dune orientation has a mean of 338° and ranges from 33-286°. The tightest distribution (or least amount of variation) occurs with crestline sinuosity and dune orientation, with coefficients of variation of 0.11 and 0.14, respectively. The next lowest coefficients of 0.28 and 0.26 are the respective values of average and maximum heights. Dune length similarly has a coefficient of variation of 0.27.

Along the dunes sampled by field-scale transects, height averages 4.5 m, spacing including interdune areas averages 122 m, and spacing without interdunes averages 87 m. Dunes average 86 m in length. Of these parameters, the lowest coefficient of variation (0.29) occurs with spacing without interdunes and dune length. Zone dune populations were treated like field-scale transects and like randomly selected dunes in separate analyses. The transect dune population within Zone 1 has a mean height of 3.4 m, a mean crest-to-crest spacing of 75 m, a mean of 71 m for spacing without interdune areas, and a mean dune length of 77 m. The similarity of the two spacing values indicates the dunes are very close together. The lowest coefficient of variation (0.26) occurs with spacing with and without interdunes. Zone 2 has a mean height of 6 m, a mean crest-to-crest spacing of 106 m, a mean spacing without interdune areas of 102 m, and a mean dune length of 99 m. Dune length and spacing without interdune areas have the lowest coefficient of variation (0.26). The mean height for Zone 3 dunes is 4 m and spacing with interdunes averages 162 m, whereas spacing without interdunes has a mean of 87 m. Dune length in Zone 3 averages 91 m. The lowest coefficient of variation (0. 27) occurs with dune length and spacing without interdune areas. Zone 4 has an average height of 6 m, an average crest-to-crest spacing of 129 m, an average spacing without interdune areas of 100 m, and a mean dune length of 99 m. Dune length has the lowest coefficient of variation (0.22).

Zonal dune parameters measured comprehensively according to the definition diagram in Figure 4A produce an average height of 6 m and a maximum height of 9 m in Zone 1. Average spacing of Zone 1 including interdunes is 87 m. Spacing without interdunes is 80 m. Crestline length averages 270 m while dune width has an average of 252 m. Dune length has a mean of 76 m, average crescent length is 72 m, and average horn length is 18 m. Sinuosity averages 1.1 and the mean orientation for Zone 1 is 352°. Average two- and three-dimensional surface areas are 17,592 and 17,981 m^2, respectively, and the volume averages 81,874 m^3.

Zone 2 heights are the tallest in the dune field with an average height of 7 m and an average maximum height of 11 m. The average spacing including interdunes is 103 m and 98 m without interdunes. Dune crestline length is on average 306 m and dune width averages 268 m. Crescent length has a mean value of 84 m and a mean horn length of 23 m. Average sinuosity is 1.1, as in Zone 1. Dunes have a mean orientation of 347°. The average footprint area is 22,383 m^2, the average dune surface area is 23,150 m^2, and dune volume averages 120,643 m^3.

Zone 3 falls in the middle of the study site where dunes are broadly spaced. Besides having low average and maximum height means of 4 and 7 m, respectively, spacing with interdunes increases to an average of 167 m and falls to an average of 92 m without interdunes. Crestline length has a mean of 535 m, dune width has a mean of 407 m, and dune length has a mean of 92 m. Crescent length averages 90 m and horn length has a mean of 25 m. Average sinuosity is 1.3 and dune orientation averages 326°. Average footprint area is 33,181 m^2, average dune surface area is 33,812 m^2, and average dune volume is 91,345 m^3.

Zone 4 is a ridge of more closely spaced dunes, though not as closely spaced as those in Zones 1 and 2. Average height is 5 m and maximum height averages 8 m. Average spacing is 108 m with interdunes and 86 m without interdunes. Crestline length has a mean of 549 m and dune width averages 452 m. Average dune length is 86 m. Mean crescent length is 82 m and horn length averages 21 m. Mean sinuosity is 1.2 and average dune orientation is 335°. Average footprint area, dune surface area and volume are 36,954 m^2, 37,903 m^2, and 127,991 m^3, respectively.

For all populations with comprehensively measured parameters in the manner of Figure 4A, the coefficients of variation range from 0.17-0.33 for average dune height , 0.16-0.35 for average maximum height, 0.30-0.36 for crest-to-crest spacing, and 0.25-0.36 for spacing without interdunes areas. Coefficients of variation for the four zones are lowest for orientation and sinuosity, as with the randomly selected dunes, and range from 0.08-0.16. Zones 2 and 4 have low coefficients of variation for average and maximum height, which range from 0.16-0.22. All four zones share relatively low coefficients of variation ranging between 0.20-0.39 for dune spacing, spacing without interdunes, and dune length. Average dune lengths for all dune populations have relatively low coefficients of variation ranging from 0.20-0.39.

CROSS PLOTS

Cross plots for random, field-scale and zonal transect dunes are shown in Tables 7 and 8. Cross plots calculated for comprehensive zonal dune parameters are shown in Table 9. Cross plots have overall weak correlations except in the following cases: 1) dune volume to crest length, 2) dune volume to surface area, 3) dune footprint area to dune width, and 4) dune surface area to dune width. A standard cross plot used to characterize fields of bedforms is the spacing to height ratio. These two parameters are typically related, but this trend was absent in all of the dune populations at White Sands Dune Field. However, average values range from 10-51 which is within the normal range for aeolian systems (Lancaster, 1988). The lowest values correspond to Zones 1, 2 and 4 and the highest value to Zone 3.

Table 1. Dune parameter statistics for the randomly selected dune population are measured according to the definition diagram in Fig. 4A.

Random Dune Population, n = 110	**range**	**mean**	**median**	**standard deviation**	**coefficient of variation**
average height (m)	2.1- 9.3	4.7	4.6	1.3	0.28
maximum height (m)	3.1-13.1	7.5	7.4	2.0	0.26
spacing with interdunes (m)	50.9-302.1	134.1	128.3	46.2	0.34
spacing without interdunes (m)	29.8- 187.5	96.6	93.7	30.6	0.32
crestline length (m)	80.7- 1555.6	559.0	467.1	335.1	0.60
dune width (m)	80.0- 1282.2	448.6	372.6	250.0	0.56
dune length (m)	24.6-164.3	86.7	86.9	23.7	0.27
crescent length (m)	20.6–244.9	91.4	85.2	39.7	0.43
average horn length (m)	1.9– 9.6	22.6	18.6	16.6	0.74
sinuosity	1.0–1.7	1.2	1.2	0.13	0.11
2d surface area (m^2)	2640 -107764	36140	28746	24601	0.68
3d surface area (m^2)	2713- 10136	37027	29453	25231	0.68
volume (m^3)	4900-473434	123348	90987	98874	0.80
orientation (°)	32.6-285.7	337.5	340.3	21.9	0.14

Table 2. Dune parameters for transect (A) and zone (B) dune populations measured along transport-direction surveys, as shown in in Fig. 4B.

A. Transect Dune Population n = 247	**range**	**mean**	**median**	**standard deviation**	**coefficient of variation**
height (m)	0.5- 3.1	4.5	4.2	2.0	0.44
spacing with interdunes (m)	22.3-359.6	121.9	113.1	49.5	0.41
spacing without interdunes (m)	22.3– 58.6	87.1	84.8	25.2	0.29
dune length (m)	22.1- 54.8	85.9	82.9	24.9	0.29
B. Zone Transect Dune Population	**range**	**mean**	**median**	**standard deviation**	**coefficient of variation**
Zone 1, n = 45					
height (m)	1.0– 6.5	3.4	3.2	1.5	0.45
spacing with interdunes (m)	38.6-112.4	74.8	75.8	19.1	0.26
spacing without interdunes (m)	38.6-112.4	70.8	67.9	18.3	0.26
dune length (m)	28.1-130.8	77.1	72.0	24.5	0.32
Zone 2, n = 40					
height (m)	1.8-11.2	6.4	6.6	2.4	0.37
spacing with interdunes (m)	37.4-161.0	106.0	106.0	29.0	0.27
spacing without interdunes (m)	37.4-161.0	102.2	104.9	26.3	0.26
dune length (m)	47.9-167.5	99.0	97.6	25.8	0.26
Zone 3, n = 44					
height (m)	0.9-7.7	4.3	4.4	1.7	0.41
spacing with interdunes (m)	43.6-359.6	161.5	156.0	66.7	0.41
spacing without interdunes (m)	41.3-137.6	86.9	88.8	23.4	0.27
dune length (m)	40.7-133.8	90.5	88.4	24.9	0.27
Zone 4, n = 42					
height	2.9-9.3	5.6	5.7	1.6	0.28
spacing with interdunes (m)	55.6-194.2	129.3	134.2	34.3	0.27
spacing without interdunes (m)	38.6-169.1	100.2	104.9	27.1	0.27
dune length (m)	45.0-146.1	99.3	99.4	21.8	0.22

Zone dune populations 1-4 are presented in the next four tables. Parameters are measured according to the definition diagram in Fig. 4A.

Table 3. Zone 1 dune parameters.

Zone 1 n=26	**range**	**mean**	**median**	**standard deviation**	**coefficient of variation**
average height (m)	3.1-8.8	5.5	5.2	1.8	0.33
maximum height (m)	4.7-14.1	8.6	7.6	3.0	0.35
spacing with interdunes (m)	26.3-148.0	86.8	84.5	26.1	0.30
spacing without interdunes (m)	26.3-137.5	79.6	78.7	23.3	0.29
crestline length (m)	93.5-888.9	269.6	231.0	162.4	0.60
dune width (m)	79.4-807.0	251.9	212.8	144.7	0.57
dune length (m)	31.0-157.9	76.2	71.4	29.5	0.39
crescent length (m)	19.1-144.5	71.9	64.9	31.7	0.44
average horn length (m)	1.8-56.8	17.6	14.7	12.0	0.68
sinuosity	1.0-1.3	1.1	1.1	0.1	0.08
orientation (°)	298.2-32.6	351.8	352.1	26.7	0.16
2d surface area (m^2)	4323-52445	17592	15273	10863	0.62
3d surface area (m^2)	4373-53899	17981	15722	11151	0.62
volume (m^3)	11017-352395	81874	56772	76304	0.93

Table 4. Zone 2 dune parameters.

Zone 2 n=20	**range**	**mean**	**median**	**standard deviation**	**coefficient of variation**
average height (m)	4.9-10.0	7.3	7.6	1.4	0.19
maximum height (m)	6.4-14.2	11.0	11.9	2.4	0.22
spacing with interdunes (m)	50.4-169.2	102.5	93.7	33.9	0.33
spacing without interdunes (m)	50.4-169.2	98.2	92.2	31.1	0.32
crestline length (m)	104.7-839.7	305.8	209.3	196.6	0.64
dune width (m)	123.7-714.1	267.9	204.2	159.9	0.60
dune length (m)	50.3-162.0	88.9	82.8	28.8	0.32
crescent length (m)	31.1-166.8	84.4	76.9	37.2	0.44
average horn length (m)	2.7-79.8	23.4	18.4	19.3	0.82
sinuosity	1.0-1.4	1.1	1.1	0.1	0.11
orientation (°)	310.0-11.6	347.0	347.7	13.7	0.08
2d surface area (m^2)	5369-67199	22383	15457	17749	0.79
3d surface area (m^2)	5551-69145	23150	16016	18315	0.79
volume (m^3)	22813-356883	120643	78268	102919	0.85

Table 5. Zone 3 dune parameters.

Zone 3 n=44	**range**	**mean**	**median**	**standard deviation**	**coefficient of variation**
average height (m)	1.2-5.6	3.7	3.8	1.0	0.27
maximum height (m)	2.1-9.4	6.5	6.6	1.6	0.24
spacing with interdunes (m)	47.8-321.6	167.0	161.3	59.7	0.36
spacing without interdunes (m)	27.6-200.5	91.7	87.6	32.7	0.36
crestline length (m)	58.6-1688.0	534.7	433.4	351.1	0.66
dune width (m)	56.8-1248.9	406.6	355.3	238.6	0.59
dune length (m)	36.7-166.1	92.0	85.6	30.8	0.34
crescent length (m)	23.1-225.0	89.8	87.9	39.2	0.44
average horn length (m)	1.3-82.0	25.0	21.9	17.5	0.70
sinuosity	1.0-1.7	1.3	1.3	0.2	0.13
orientation (°)	288.7-21.0	325.5	325.7	18.7	0.13
2d surface area (m^2)	1761-110300	33181	26149	23085	0.70
3d surface area (m^2)	1777-113404	33812	26835	23566	0.70
volume (m^3)	1584-358665	91345	73007	72014	0.79

Table 6. Zone 4 dune parameters.

Zone 4 n=42	**range**	**mean**	**median**	**standard deviation**	**coefficient of variation**
average height (m)	2.7-6.6	4.9	5.1	0.8	0.17
maximum height (m)	5.2-10.3	8.4	8.5	1.3	0.16
spacing with interdunes (m)	37.4-215.1	107.7	110.7	34.6	0.32
spacing without interdunes (m)	37.4-125.6	85.7	84.7	21.5	0.25
crestline length (m)	136.6-1692.1	548.6	465.1	336.3	0.61
dune width (m)	141.1-1426.1	451.5	375.7	280.2	0.62
dune length (m)	60.0-120.7	85.5	84.4	16.9	0.20
crescent length (m)	21.6-229.2	82.4	76.7	34.5	0.42
average horn length (m)	2.0-77.4	20.8	18.5	13.6	0.65
sinuosity	1.0-1.5	1.2	1.2	0.1	0.09
orientation (°)	289.8-15.9	334.8	334.4	18.2	0.12
2d surface area (m^2)	6992-137336	36954	28581	27452	0.74
3d surface area (m^2)	7192-140350	37903	29434	28119	0.74
volume (m^3)	17544-532896	127991	96534	106719	0.83

Table 7. Means and linear regressions of parameters for dunes selected at random, field-scale transects, and transects within Zones 1-4. Dune height for randomly selected dunes is the average height, whereas it is the height encountered along the transects for field-scale and zonal dunes.

Cross Plots	random n = 110		transect n = 247		zone 1 n = 45		zone 2 n = 40		zone 3 n = 44		zone 4 n = 42	
	mean	**r^2**	**mean**	**r^2**	**mean**	**r^2**	**mean**	**r^2**	**mean**	**r^2**	**mean**	**r^2**
spacing with interdunes / height	30.5	0.005	32.9	0.081	26.4	0.026	18.6	0.266	42.6	0.212	24.2	0.069
spacing without interdunes / height	21.8	0.042	24.0	0.066	25.2	0.001	18.0	0.236	24.7	0.006	19.0	0.011
dune length / height	19.3	0.135	22.6	0.227	27.0	0.112	17.2	0.280	25.0	0.157	18.7	0.117

Table 8. Means and linear regressions of additional parameters for the random dune sample.

Cross Plots	mean	r^2			mean	r^2
spacing with interdune areas / maximum height	19.0	0.002		dune width / maximum height	59.2	0.199
spacing without interdune areas / maximum height	13.6	0.027		dune volume / average height	24581	0.391
crest length / average height	121.6	0.083		dune volume / maximum height	15172	0.430
crest length / maximum height	74.0	0.149		dune volume / crest length	203.9	0.767
dune length / average height	19.3	0.135		dune volume / surface area	3.1	0.909
dune length / maximum height	12.0	0.112		dune footprint area / dune width	75.4	0.498
dune width / average height	96.7	0.133		dune surface area / dune width	77.3	0.956

Table 9. Means and linear regressions of parameters for dunes selected within Zones 1-4.

Zone 1 Cross Plots, n=26	**mean**	**r^2**			**mean**	**r^2**
spacing with interdune areas / maximum height	11.0	0.125		dune width / maximum height	29.6	0.327
spacing without interdune areas / maximum height	10.1	0.104		dune volume / average height	13691	0.470
crest length / average height	49.8	0.295		dune volume / maximum height	8719	0.439
crest length / maximum height	31.7	0.307		dune volume / crest length	281.7	0.877
dune length / average height	15.4	0.001		dune volume / surface area	4.1	0.898
dune length / maximum height	10.1	0.010		dune footprint area / dune width	70.1	0.872
dune width / average height	46.6	0.307		dune surface area / dune width	71.6	0.877
Zone 2 Cross Plots, n=20	**mean**	**r^2**			**mean**	**r^2**
spacing with interdune areas / maximum height	9.5	0.135		dune width / maximum height	23.5	0.398
spacing without interdune areas / maximum height	9.2	0.109		dune volume / average height	15190	0.465
crest length / average height	40.4	0.277		dune volume / maximum height	9935	0.52
crest length / maximum height	26.5	0.416		dune volume / crest length	344.9	0.910
dune length / average height	12.2	0.309		dune volume / surface area	4.8	0.983
dune length / maximum height	8.2	0.216		dune footprint area / dune width	75.0	0.964
dune width / average height	35.7	0.265		dune surface area / dune width	77.6	0.964
Zone 3 Cross Plots, n=44	**mean**	**r^2**			**mean**	**r^2**
spacing with interdune areas / maximum height	26.7	0.145		dune width / maximum height	52.6	0.187
spacing without interdune areas / maximum height	15.0	0.009		dune volume / average height	23568	0.269
crest length / average height	148.8	0.057		dune volume / maximum height	13138	0.339
crest length / maximum height	81.8	0.121		dune volume / crest length	160.5	0.810
dune length / average height	25.9	0.200		dune volume / surface area	2.6	0.939
dune length / maximum height	14.4	0.207		dune footprint area / dune width	75.9	0.964
dune width / average height	90.0	0.125		dune surface area / dune width	77.3	0.965
Zone 4 Cross Plots, n=42	**mean**	**r^2**			**mean**	**r^2**
spacing with interdune areas / maximum height	13.2	0.017		dune width / maximum height	52.6	0.198
spacing without interdune areas / maximum height	10.4	0.071		dune volume / average height	24721	0.274
crest length / average height	109.5	0.193		dune volume / maximum height	14531	0.245
crest length / maximum height	63.9	0.202		dune volume / crest length	211.1	0.935
dune length / average height	17.6	0.253		dune volume / surface area	3.2	0.988
dune length / maximum height	10.3	0.194		dune footprint area / dune width	76.7	0.974
dune width / average height	90.0	0.195		dune surface area / dune width	78.7	0.975

PALEOSHORELINES

Rollover point elevations from base surface profiles were plotted in a histogram to determine the average positions of the paleoshorelines (Fig. 9). Four distinct paleoshorelines were identified beneath the dune field with median elevations of 1203, 1205.5, 1211.5 and 1215.5 m, rounding to the closest half-meter. Erosion of the dune accumulation edge at the southern end of the dune field margin limited the number of intact paleoshoreline profiles at the 1203 m elevation to ten. This lowest paleoshoreline correlates to the L1 paleoshoreline of Langford (2003).

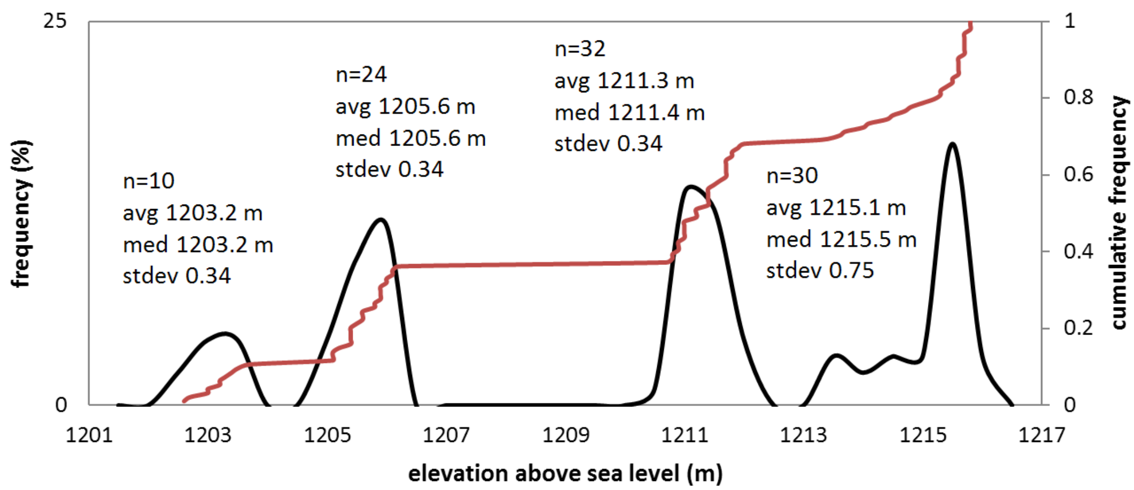


Figure 9. Histogram and cumulative frequency distribution showing the distribution of paleoshorelines across the study area. Sample sizes of profiles with discernable rollover points as well as average, median and standard deviation values are given in boxes next to their associated peaks.

Discussion

In this study, dune parameters were measured to determine which ones are most consistent across the dune field and are, therefore, best at characterizing the overall dune field. To accomplish this, three different dune sampling methods were employed to investigate differences in parameter and cross plot results. Ultimately, comparison of field-wide populations of randomly selected and field-scale transect dunes resulted in only minor differences in parameter and cross plot measurements. Populations based on transects tend to have a wider range of values for height and spacing than the randomly selected dunes and zonal populations measured in the manner of Figure 4A because of the difference in where measurements were taken. Transect parameters were measured at the point of transect intersection with the dune and sometimes include heights near dune terminations, whereas random dunes are always measured from the middle of the dune. Zonal dune populations served to highlight pattern variations within White Sands Dune Field, which was their intent.

Certain dune parameters stand out in all dune populations as being most consistent across the dune field. This is quantified via the coefficient of variation, which is lowest for the parameters of sinuosity and orientation. Average dune orientation for the 110 field-wide randomly selected dunes is 338°, and for Zones 1-4 averages 352°, 347°, 326° and 335°, respectively. This compares well to the average orientation of 345° for > 2000 dunes at White Sand Dune Field (Ewing et al., 2006). Orientation is a larger scale parameter than sinuosity and appears to be integral to the visibility of the pattern at White Sands Dune Field and probably to most of the world's dune fields. However, similar to the interplay of warp and woof in a piece of cloth, sinuosity plays a complementary role to orientation in making the dune field pattern stand out. Other parameters with relatively low coefficients of variation throughout the dune field include dune length, height and spacing with and without interdunes. These parameters, therefore, are the parameters that best characterize the dune field.

When parameters were plotted against one another, their covariation was found to be only weakly correlative except in cases where parameters are strongly linked by definition, as in the cases of dune volume to crestline length and surface area, dune footprint area to dune width, and dune surface area to dune width. Strong three-dimensional correlations like this allude to the similarity of dune shapes within the dune field. Globally, the ratio of spacing to height typically ranges from 10-50 with an average of ~25 (Lancaster, 1988). In this study, average spacing to height ratios at White Sands Dune Field range from 10-51, the lowest values corresponding to Zones 1, 2 and 4 and the highest to Zone 3. Correlations usually exist between spacing and height, but no correlation was found between the two in any of the White Sands dune populations, although the average values are within the normal range for aeolian systems. Even the zonal dune populations had low spacing to height correlations. With few exceptions, cross plot correlations are weak across the board, which indicates that parameter variations are producing a cluster of variability around a mean. In other words, at the particular scale of this study, no trend is produced in the data. To be useful, every cluster of values produced by plotting parameters against each other could be reduced to a single point for comparison with different dune fields.

The zonal dune populations were specially selected in areas of dune pattern anomaly and the statistics produced by these populations reflect how they differ from the dune pattern of White Sands Dune Field as a whole. Looking at parameters as measured in Figure 4A, dunes in Zone 1 average 6 m in height and 252 m in dune width and are closely spaced with a mean crest-to-crest spacing of 87 m not varying significantly when interdune areas are removed for a mean of 80 m. Dune length is 76 m on average. Dunes in Zone 2 are the tallest in the dune field with an average of 7 m and dune widths are comparable to Zone 1 dunes with a mean of 268 m. Spacings with and without interdunes in Zone 2 are 103 m and 98 m, respectively, indicating close dune spacing. Dune length is longer with an average of 89 m. In contrast, dunes in Zone 3 are on average longer (407 m), shorter in height (4 m) and much more widely spaced (167 m with interdunes and 92 m without interdunes) than in the previous two zones. Dune length has a mean of 92 m. Dune parameter averages for Zone 4 include a dune height of 5 m, a maximum height of 8, spacing with interdunes of 108 m and spacing without interdunes of 86 m. Dune length in Zone 4 is 86 m. When compared to overall field parameters, Zone 4 is comparable to field-wide dune populations in terms of average and maximum height and dune length, but has more closely spaced dunes. However, the dunes of the other four zones are significantly taller or shorter than the dune field as a whole and have spacings that vary significantly from the field-wide average.

What explains the presence of zones within White Sands dune field whose dune parameters are different from the dune field overall? One important boundary condition that affects sediment transport in a dune field and is known to be uniquely variable at White

Sands dune field is its antecedent topography of lake paleoshorelines. Having statistically estimated the average elevations of paleoshorelines allows us to compare their distribution across the dune field with those of the zones (Fig. 10). A single cross-section of the dune field that traverses the four zones shows that some of the tallest dunes are close to the upwind margin of the dune field. It is important to note that the measured heights of the dunes located in Zones 1 and 2 ignore sand accumulations present below the bases of the dunes that add even more elevation to the dunes there. The interdunes along these drier, more closely spaced ridges do not go down to a common base. To illustrate the contribution by these accumulations of sand to the height of the sand ridges, average interdune heights above the base surface were calculated for the different zone dune populations (Fig. 10). Higher than average interdune heights in addition to tall dunes are quantifiable measurements of the sand ridges, which are especially noticeable in Zones 1, 2 and 4. Sand accumulations in Zones 1 and 2 are not continuous in the LiDAR image but the 1205. 5 m elevation paleoshoreline associated with them can be surmised to extend northward of the LiDAR image along sand ridges visible in the dune field (Fig. 11). These sand ridges may be deduced to be associated with paleoshorelines. Interestingly, while Zones 1 and 2 are sites of sand deposition, they are part of the southern upwind margin of the study site being cut into by erosion. This is precisely the place where the 1205.5 m elevation paleoshoreline loses its integrity due to scouring at the dune field margin. Indeed, the lowest paleoshoreline at 1203 m elevation persists only fleetingly, as seen in Figures 6 and 8, appearing in the northern third of the dune margin before disappearing in the south, obscured first by a rounding out of the paleoshoreline profile and then destroyed by erosion of the southern dune accumulation edge. Any changes associated with the subtle topography of this part of the dune field are obliterated by erosion and dune trough scouring. It is possible that the process of erosion is exhuming a supply of sand that exists in this location because of a paleoshoreline and is causing the construction of Zones 1 and 2.

East of the paleoshoreline at 1205.5 m is the widely spaced, wet interdune area that characterizes Zone 3. Dunes in Zones 1, 2 and 4 have thicker, drier gypsum accumulations beneath them, and are less affected by the water table. In contrast, dunes in Zone 3 rest directly upon the damp substrate with the water table very near the surface (Kocurek et al., 2007). Dunes in this zone are characterized by greater lengths but shorter heights, with wide spacings between dunes. Zone 3 rests on the flat, broad terrace that extends from the 1205 m paleoshoreline to the next highest one east of Zone 3 at 1211.5 m elevation (Figs. 6, 7, 8 and 10), and may have originated as a bypassed lagoonal area during shoreline retreat. Langford (2003) refers to higher shorelines at 1207 m and 1210 m elevation as isolated sub-basins of Lake Otero. It is reasonable to infer that the paleoshoreline he mapped at 1210 m elevation correlates to the one placed at 1211.5 m elevation in this study. Leeward of the 1211.5 m paleoshoreline is the location of Zone 4. The highest paleoshoreline of 1215.5 m elevation occurs on the western edge of the LiDAR image where crescentic dunes transition into parabolic dunes. It is worth noting that the Lake Otero highstand is thought to have occurred around an elevation of 1218 m. Considering the roughness of measurements prior to LiDAR, it is possible that the recently estimated paleoshoreline at 1215. 5 m elevation and the one estimated by Seager et al., (1987) are one and the same.

If it is true that paleoshorelines with slopes of approximately 1° may be affecting dune-scale patterns, then the action of antecedent topography is powerful, indeed. The low relief of the antecedent topography may in part be a function of the gypsum accumulation found beneath the dune field. The paleoshorelines are expressed on a base surface that occurs on top of an 8-m thick sand accumulation built up by the migrating dune field. This means the paleoshorelines visible in profiles are not at the original elevation at which they formed during the Pleistocene, instead being translated upward as they are buried by sand. This would mean the estimated paleoshoreline elevations are not pinpointing original elevations but only translations thereof. How paleoshorelines are translated through a several meter thick gypsum sand accumulation built up by the migrating dune field, how this affects or confounds attempts at reconstructing Pleistocene shorelines of the area, how paleoshorelines continue to affect dune patterns, and whether sand is being transported from the paleoshoreline break to provide material that builds up ridges of sand, as suggested at Zones 1 and 2, are some questions raised by these observations.

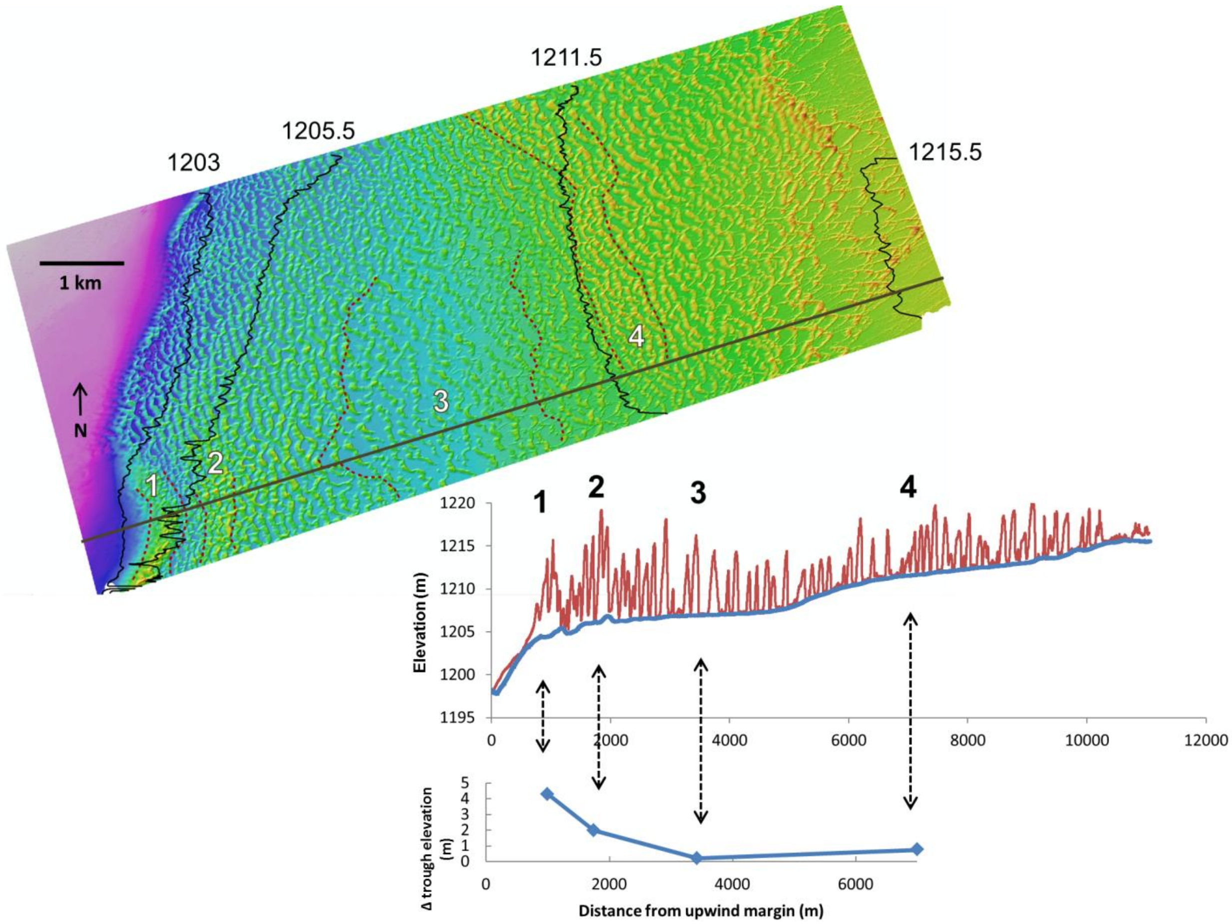


Figure 10. LiDAR study area with Zones 1-4 within dashed red lines and average paleoshoreline positions in black. Paleoshoreline elevations in meters are positioned around the image close to their respective base elevation contours. The transect across the LiDAR image is seen in profile on the middle plot with dunes outlined in red on top of a blue base profile. Zones 1-4 are labeled above the profile. Average interdune elevations are plotted on the bottom graph in blue and arrows link them to the four zones. The wide interdune spacings of Zone 3 lie between paleoshorelines, whereas the other sandier zones lie leeward of the paleoshorelines. Dunes close to paleoshorelines have greater accumulations of sand as indicated by greater interdune heights above the base surface.

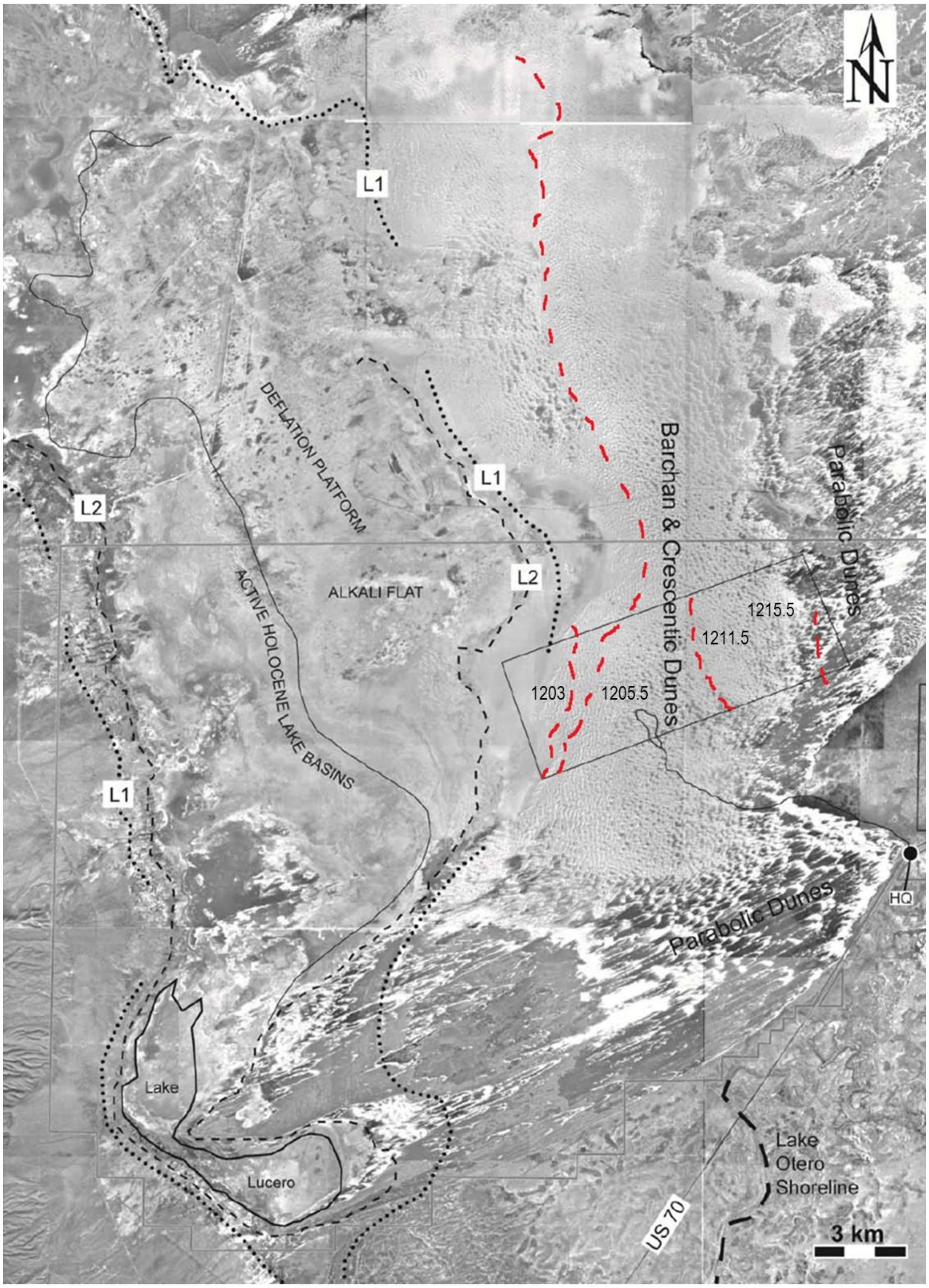


Figure 11. Dashed red lines show the position of paleoshorelines at 1205.5 and 1211 m elevation within the rectangle denoting the LiDAR study site. The 1205.5 paleoshoreline is extrapolated northward along a band of closely spaced dunes.

Conclusions

1) Dune sampling methods of randomly selected dunes versus field-scale transect dunes showed only minor differences in single parameter measurements. A significant degree of variability exists in most single parameters except for orientation and sinuosity.

2) In all dune populations, orientation and sinuosity are the parameters with the lowest coefficients of variation and, therefore, are the most consistent parameters across the dune field. Because orientation is a larger scale parameter than sinuosity, it gives rise to the overall pattern of the dune field, although sinuosity is a complementary contributor.

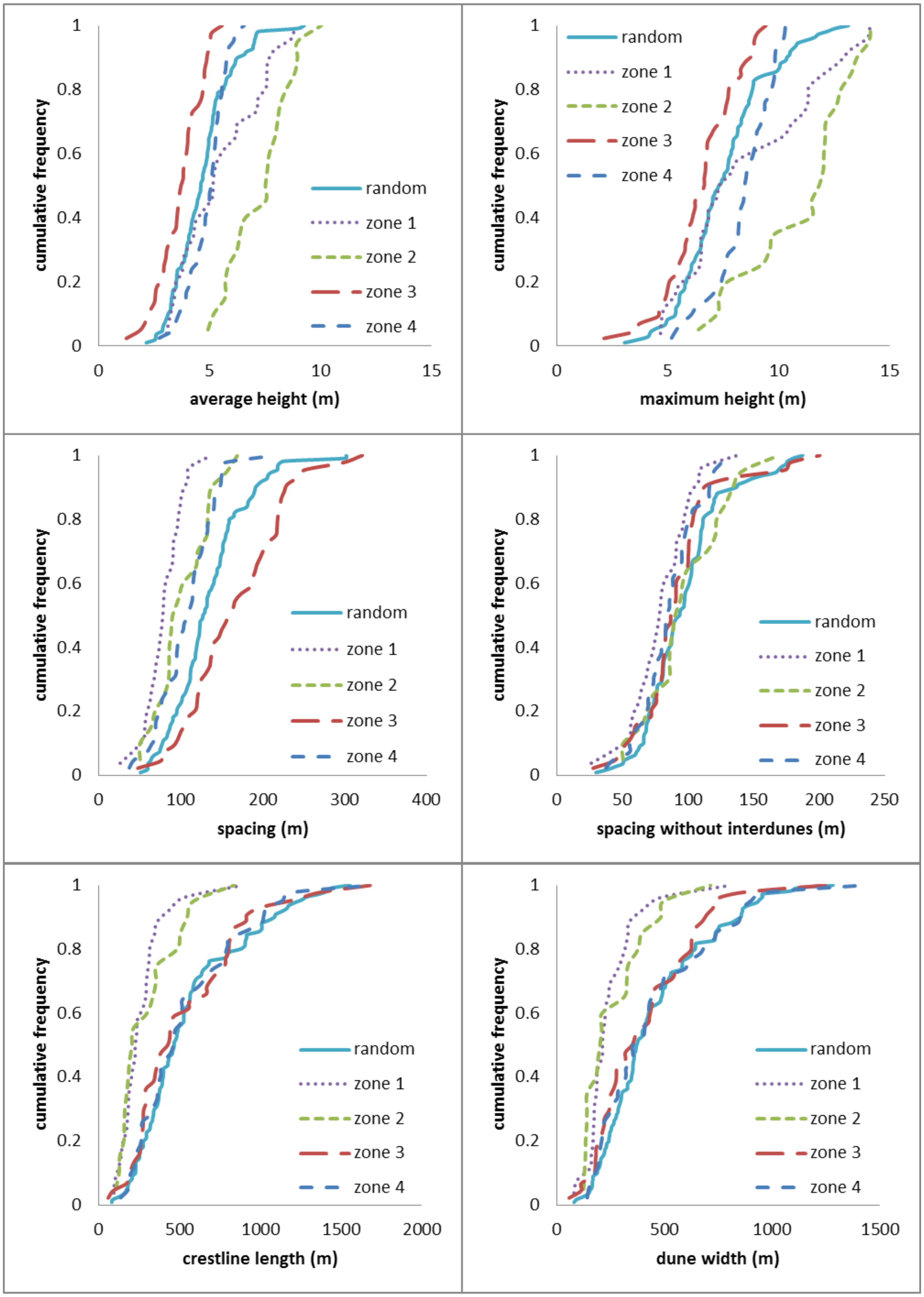
3) Covariations of single parameters as determined by goodness-of-fit linear regressions of cross plots have remarkably low correlations except in the cases of dune volume to crestline length and surface area, dune footprint area to dune width, and dune surface area to dune width. Weak overall cross plot correlations indicate that cross plots produce a cluster of variability around a mean. The reduction of the cluster of variability to a single, average point representing White Sands dune field as a whole would allow comparison with other world dune fields treated in the same fashion.

4) Dunes sampled within visually distinct zones illustrate spatial differences that occur within the overall pattern of the dune field. Dunes in Zones 1, 2 and 4 are more closely spaced, taller and shorter in dune width than those in Zone 3. Zones 1, 2 and 4 are located leeward of paleoshorelines, whereas Zone 3 is an area of flat, lake-terrace topography whose base surface intersects with the capillary fringe zone of the shallow water table.

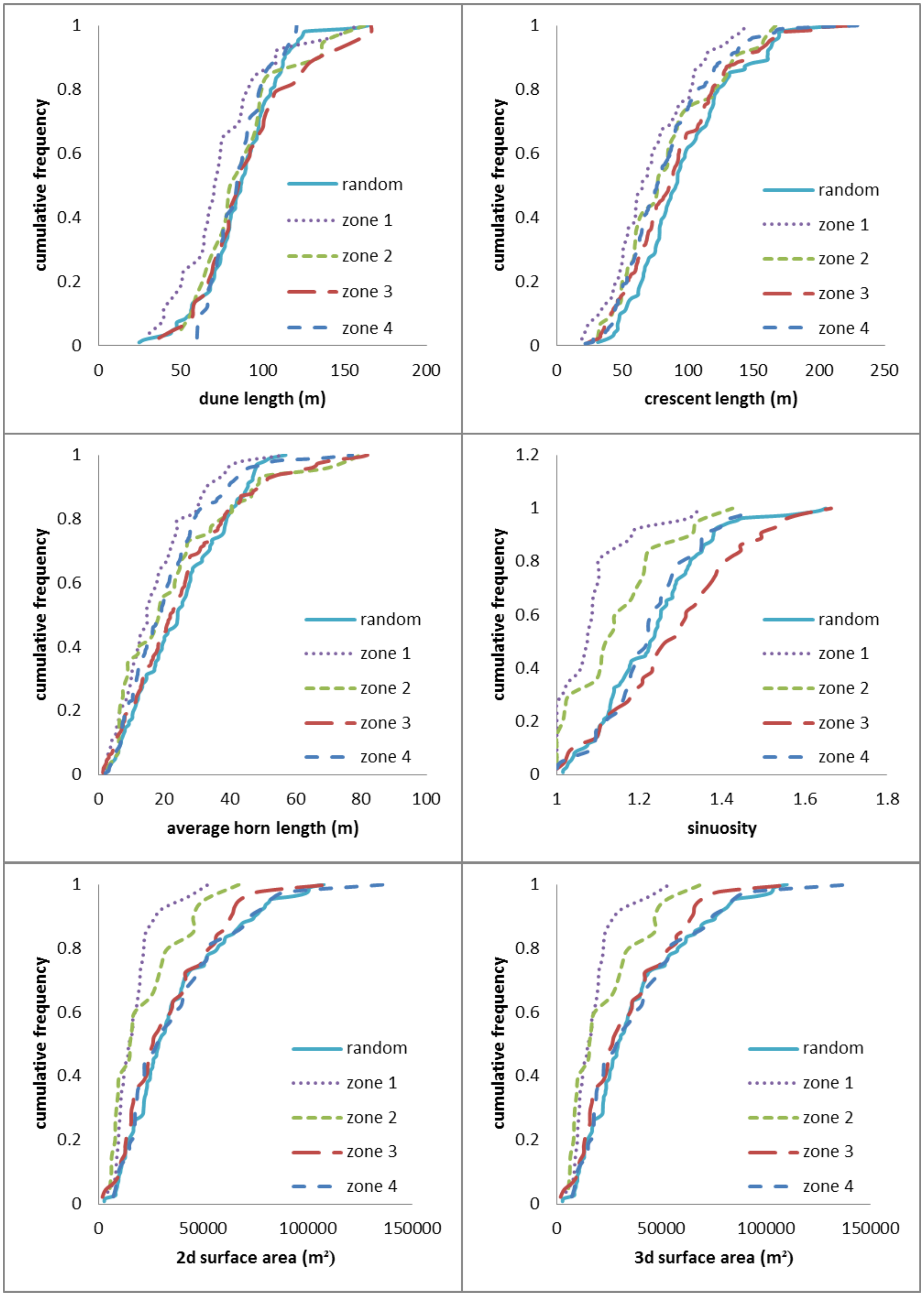
5) Zones of different dune spacings and heights appear to be influenced by antecedent topography in the form of paleoshorelines recently discovered beneath the White Sands dune field study area. Refinement of paleoshoreline positions beneath the dune field gives median elevations of 1203 m, 1205.5 m, 1211.5 m and 1215.5 m.

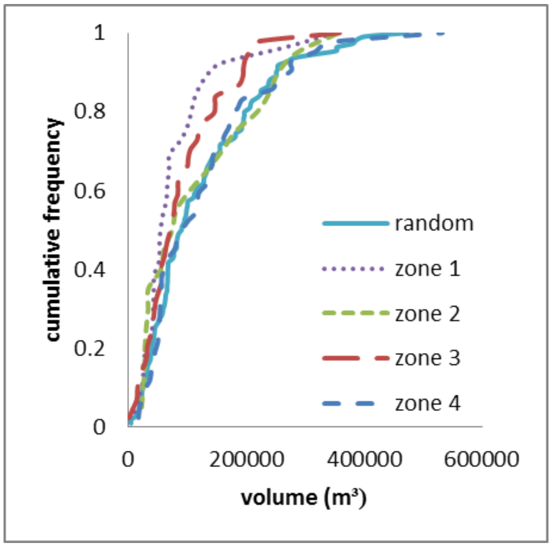
Appendix 1

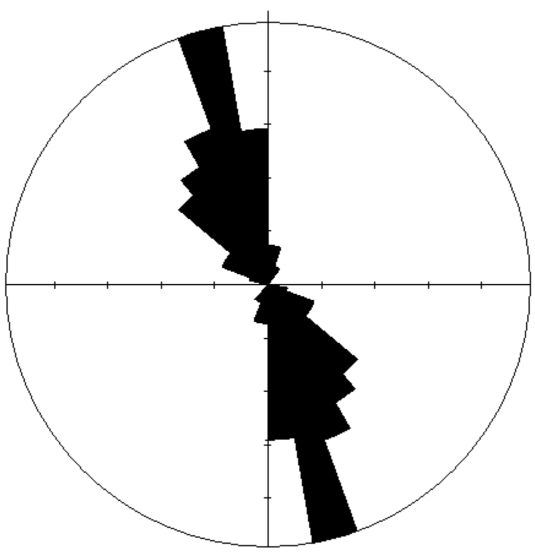
Cumulative frequency plots of single parameters for randomly selected and zonal dune populations measured according to the definition diagram in Figure 4A are shown below. The parameters include average height, maximum height, spacing with interdunes, spacing without interdunes, crestline length, dune width, dune length, crescent length, average horn length, sinuosity, 2d surface area, 3d surface area, and volume. Dune orientations are presented in the form of rose diagrams.



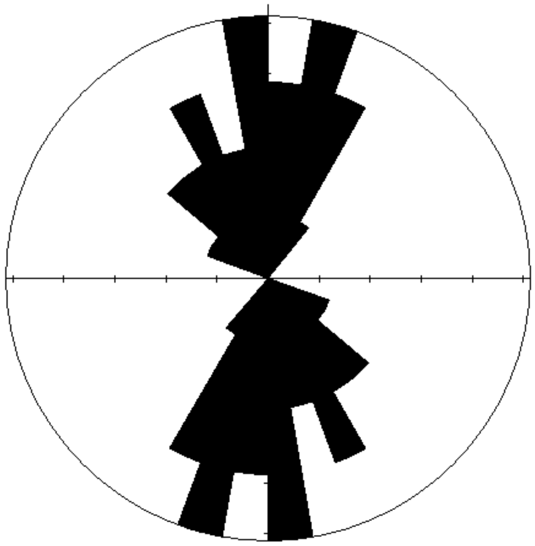
cumulative frequency
average height (m)
maximum height (m)
spacing (m)
spacing without interdunes (m)
crestline length (m)
dune width (m)
random
zone 1
zone 2
zone 3
zone 4


cumulative frequency
dune length (m)
crescent length (m)
average horn length (m)
sinuosity
2d surface area (m²)
3d surface area (m²)
random
zone 1
zone 2
zone 3
zone 4

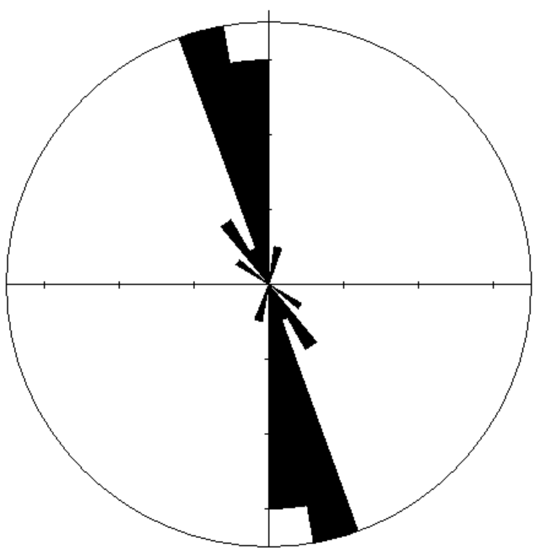




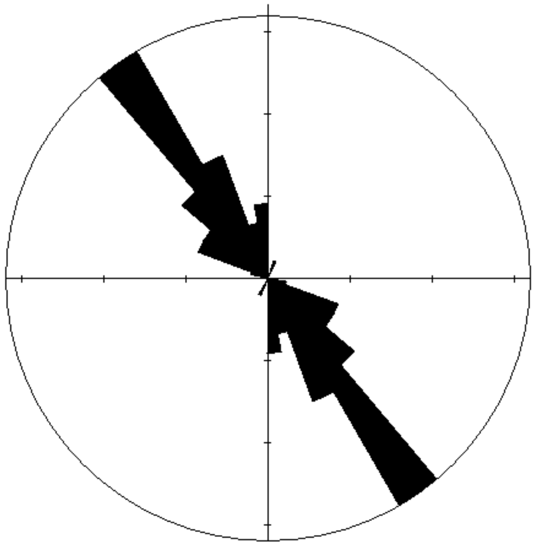
Randomly selected dunes, n=110, mean dune orientation = 338°



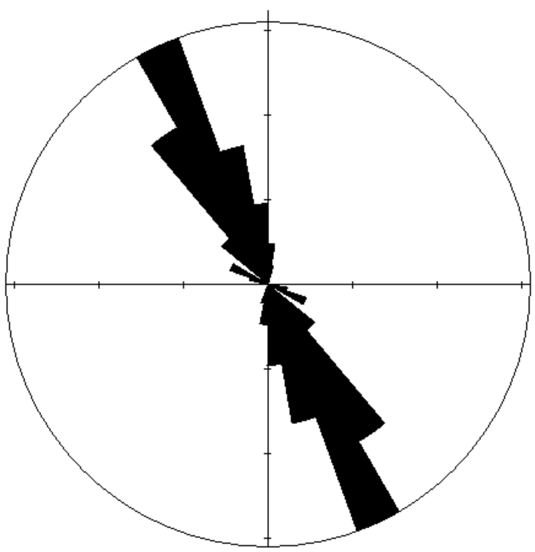
Zone 1, n=26, resultant dune orientation = 353°



Zone 2, n=20, mean dune orientation = 347°



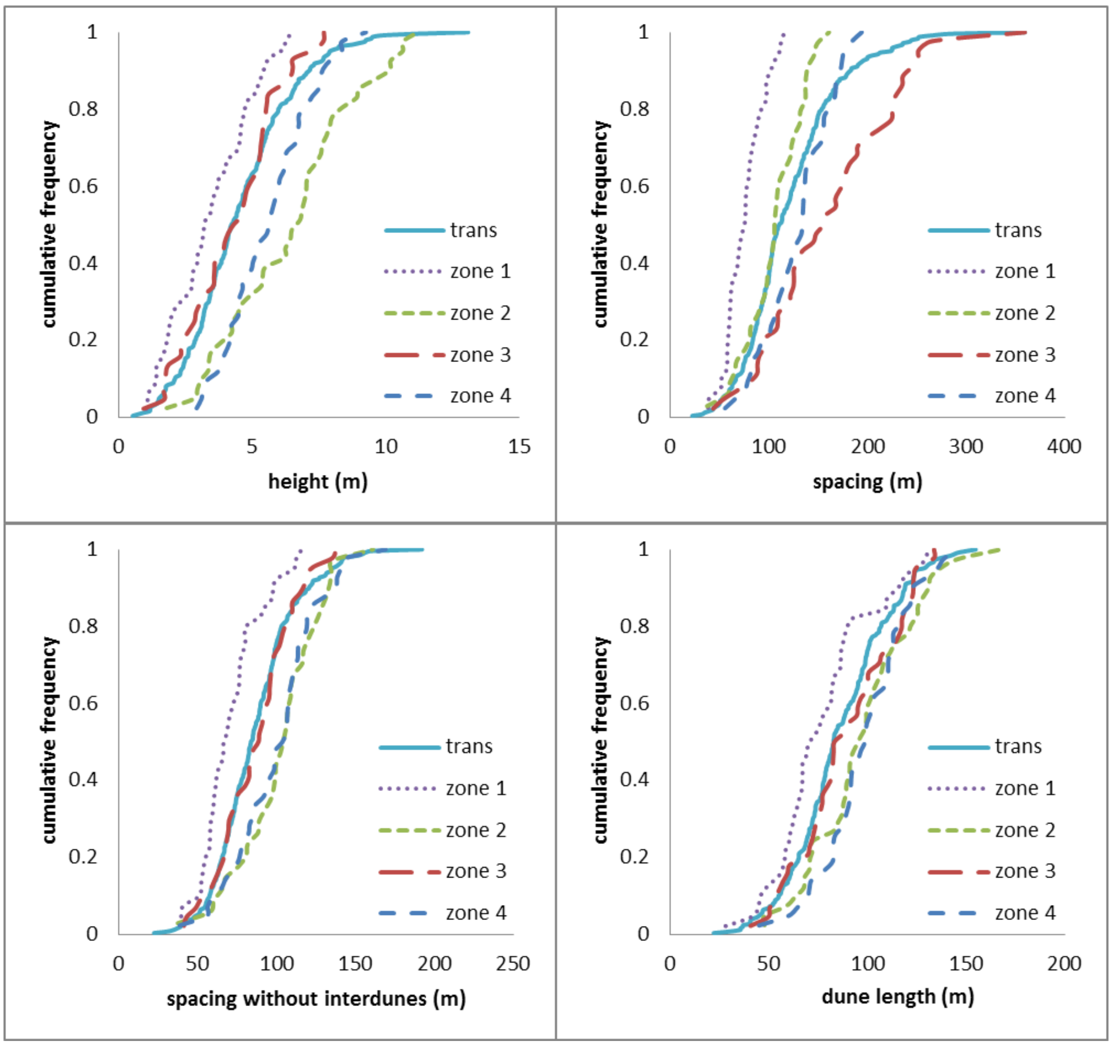
Zone 3, n=44, mean dune orientation = 325°



Zone 4, n=42, mean dune orientation = 335°

Appendix 2

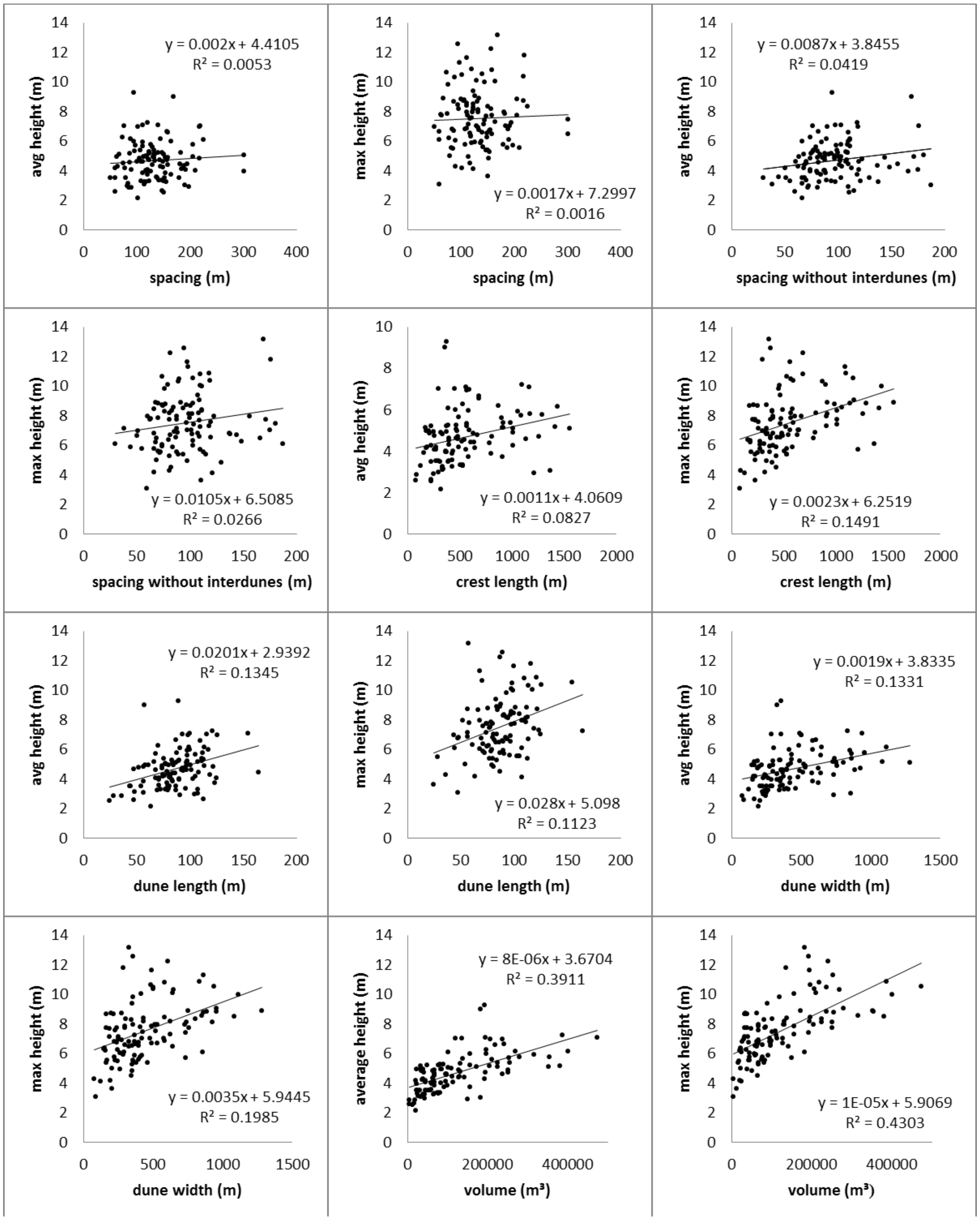
Cumulative frequency plots of single parameters for field-scale transect and zonal dune populations measured according to the definition diagram in Figure 4B. The parameters include height, spacing, spacing without interdune areas, and dune length.

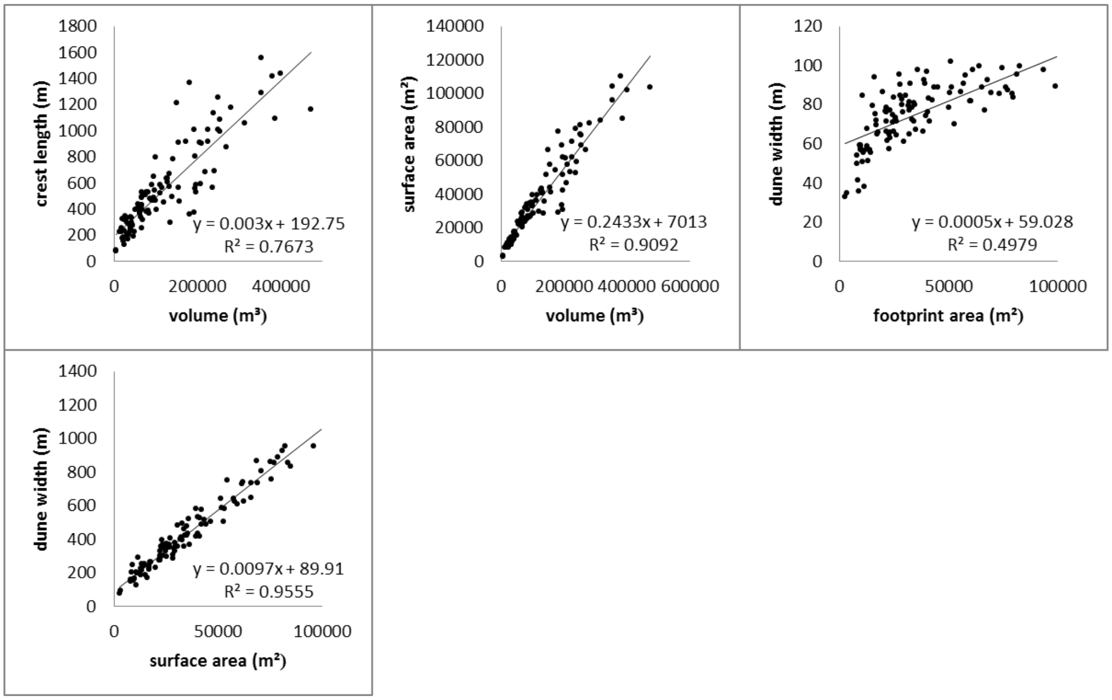


Appendix 3

Sixteen parameter cross plots of field-scale randomly selected dune populations are presented. These include:

spacing with interdunes / average height
spacing with interdunes / maximum height
spacing without interdunes / average height
spacing without interdunes / maximum height
dune length / average height
dune length / maximum height
crestline length / average height
crestline length / maximum height
dune width / average height
dune width / maximum height
dune volume / average height
dune volume / maximum height
dune volume / crestline length
dune volume / 3d surface area
footprint surface area / dune width
3d surface area / dune width

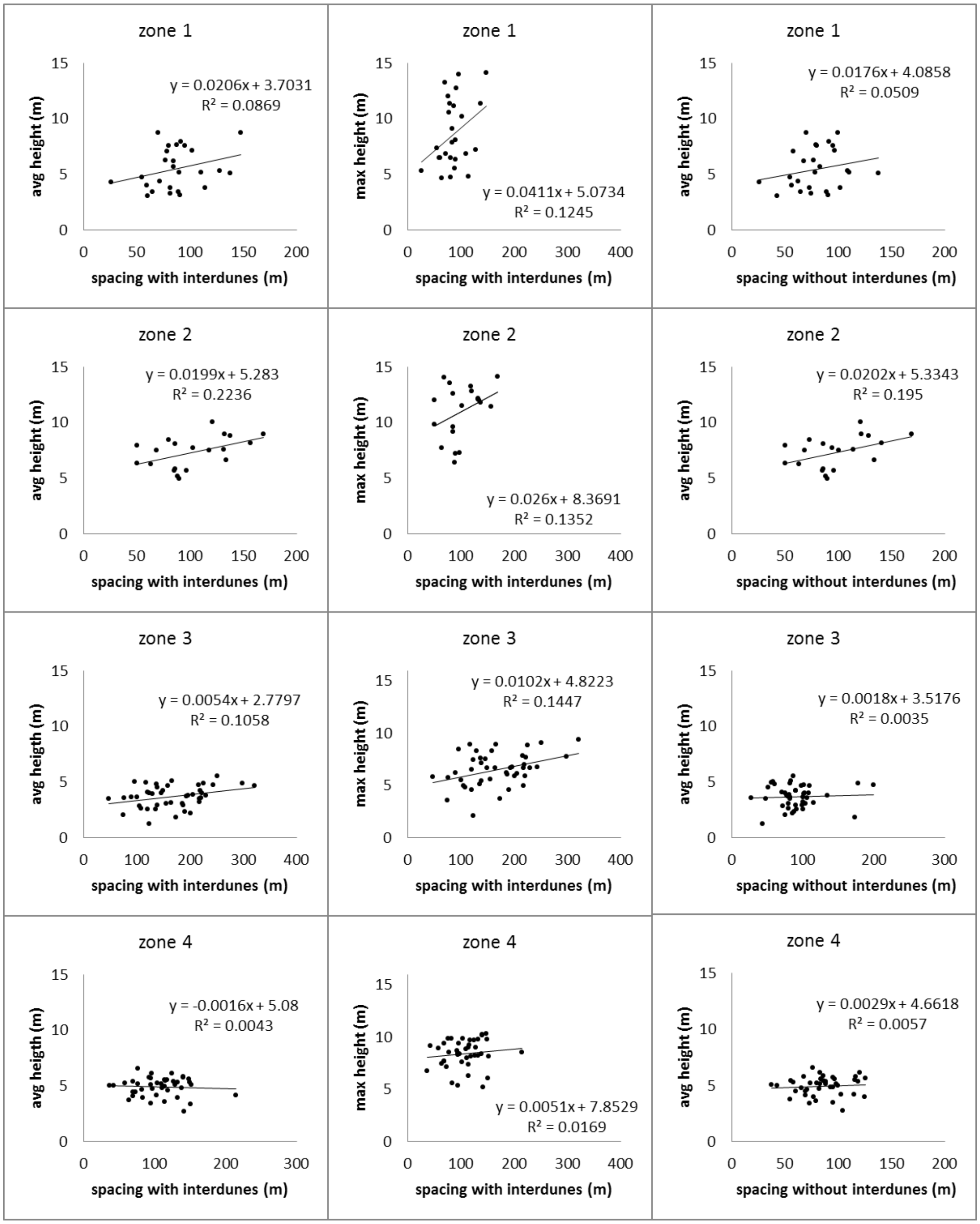

y = 0.002x + 4.4105
R² = 0.0053
avg height (m)
spacing (m)
y = 0.0017x + 7.2997
R² = 0.0016
max height (m)
spacing (m)
y = 0.0087x + 3.8455
R² = 0.0419
avg height (m)
spacing without interdunes (m)
y = 0.0105x + 6.5085
R² = 0.0266
max height (m)
spacing without interdunes (m)
y = 0.0011x + 4.0609
R² = 0.0827
avg height (m)
crest length (m)
y = 0.0023x + 6.2519
R² = 0.1491
max height (m)
crest length (m)
y = 0.0201x + 2.9392
R² = 0.1345
avg height (m)
dune length (m)
y = 0.028x + 5.098
R² = 0.1123
max height (m)
dune length (m)
y = 0.0019x + 3.8335
R² = 0.1331
avg height (m)
dune width (m)
y = 0.0035x + 5.9445
R² = 0.1985
max height (m)
dune width (m)
y = 8E-06x + 3.6704
R² = 0.3911
average height (m)
volume (m³)
y = 1E-05x + 5.9069
R² = 0.4303
max height (m)
volume (m³)

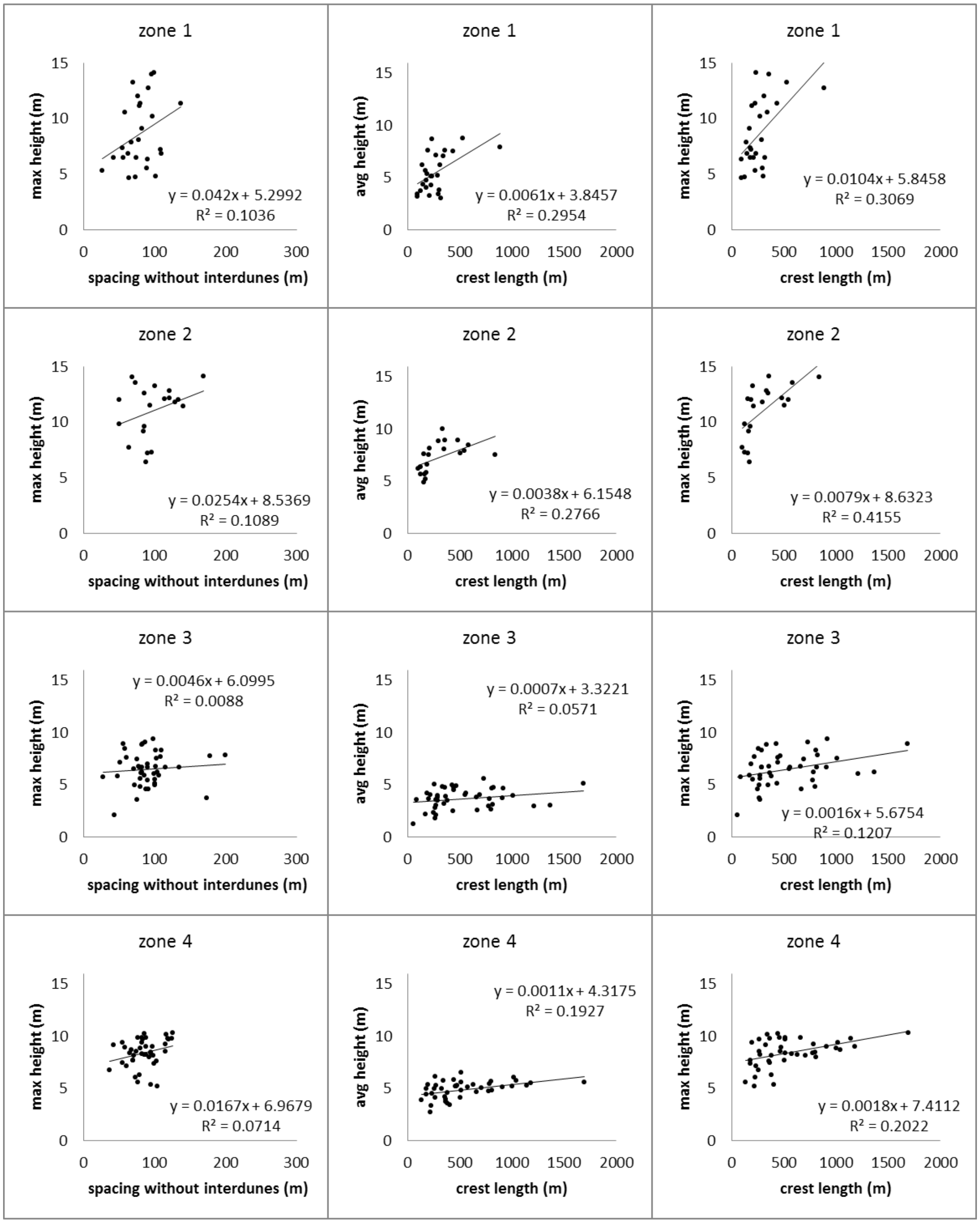

crest length (m)
volume (m³)
y = 0.003x + 192.75
R² = 0.7673
surface area (m²)
volume (m³)
y = 0.2433x + 7013
R² = 0.9092
dune width (m)
footprint area (m²)
y = 0.0005x + 59.028
R² = 0.4979
dune width (m)
surface area (m²)
y = 0.0097x + 89.91
R² = 0.9555

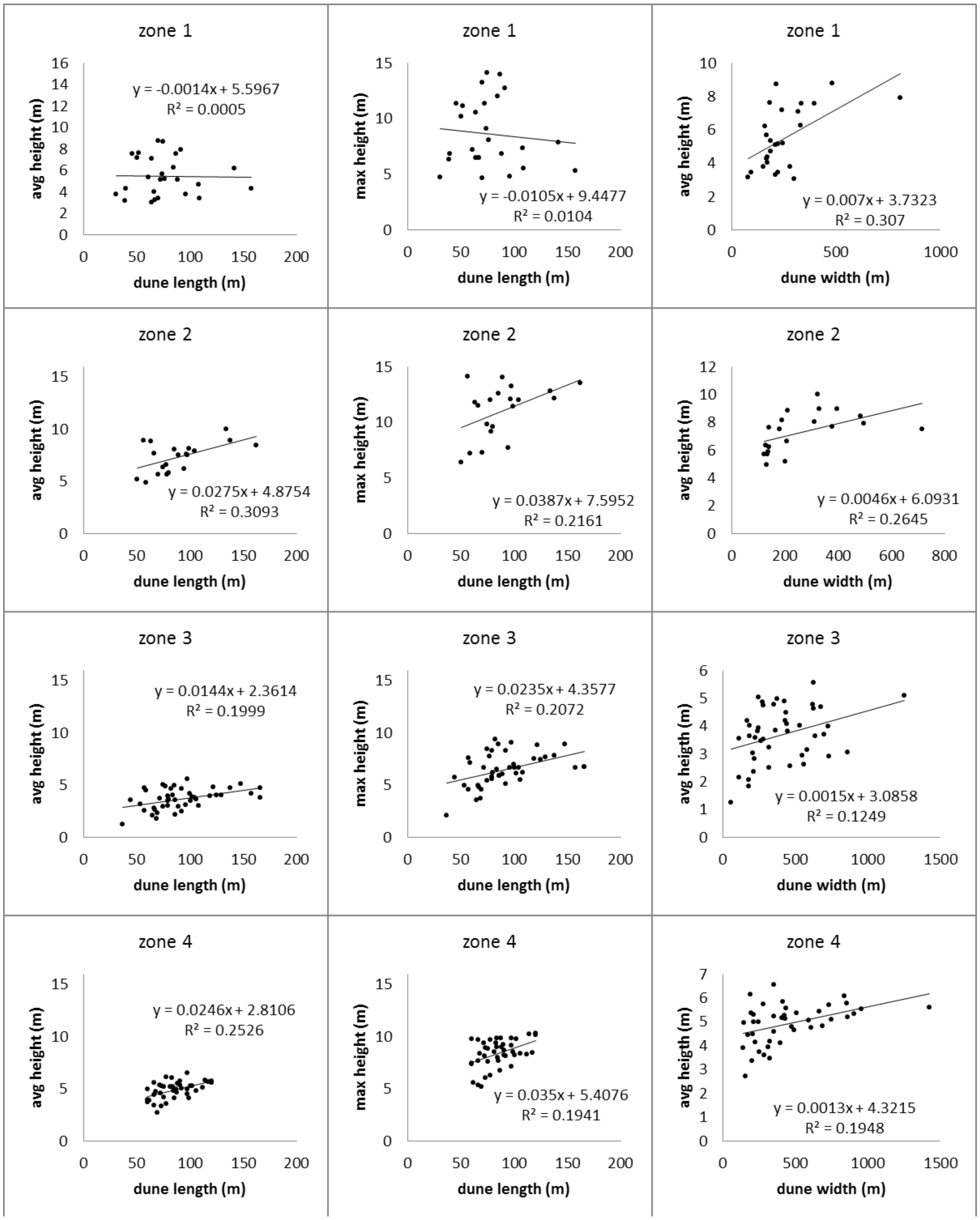
Appendix 4

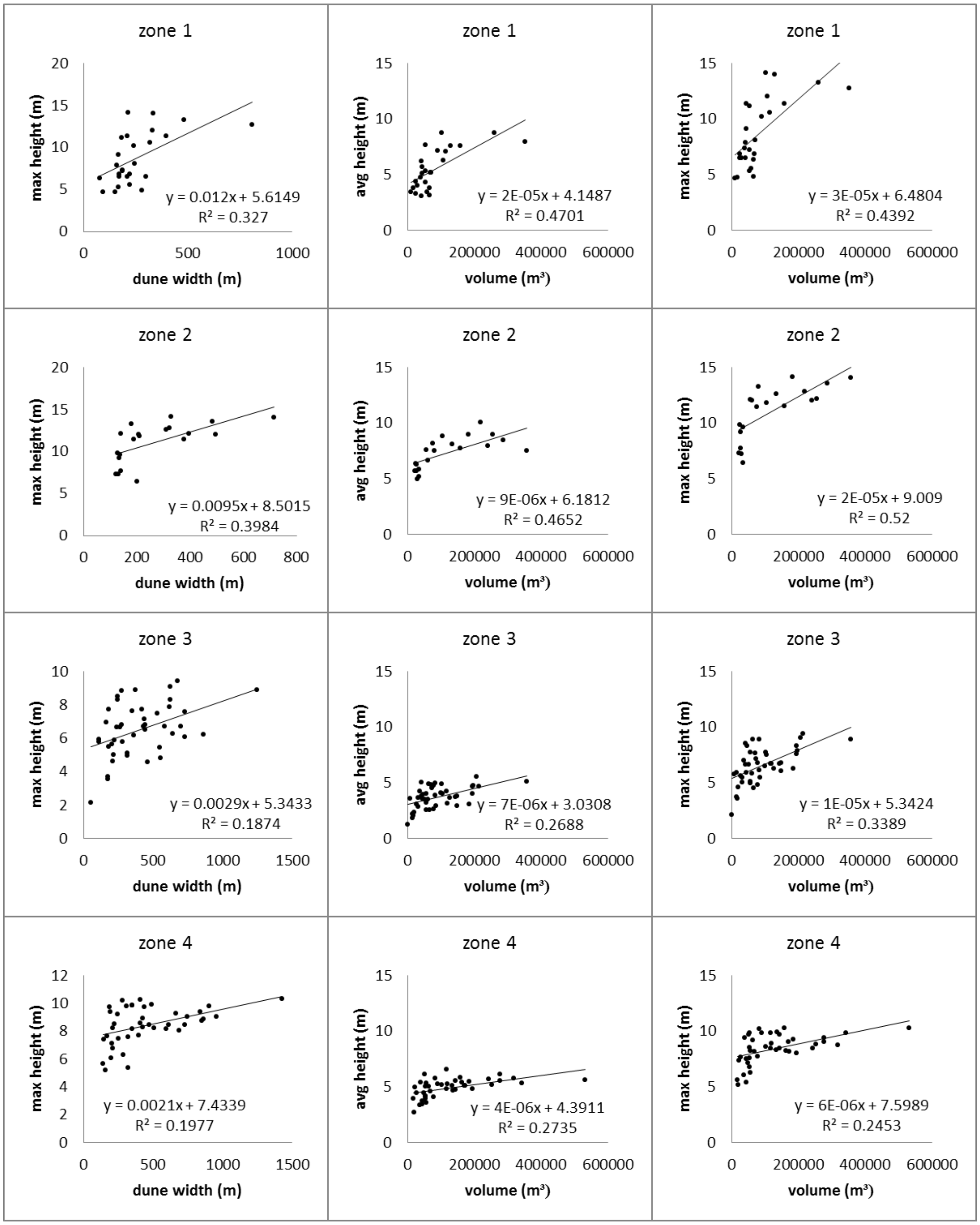
Sixteen parameter cross plots of comprehensively measured zonal dune populations follow below. These include:

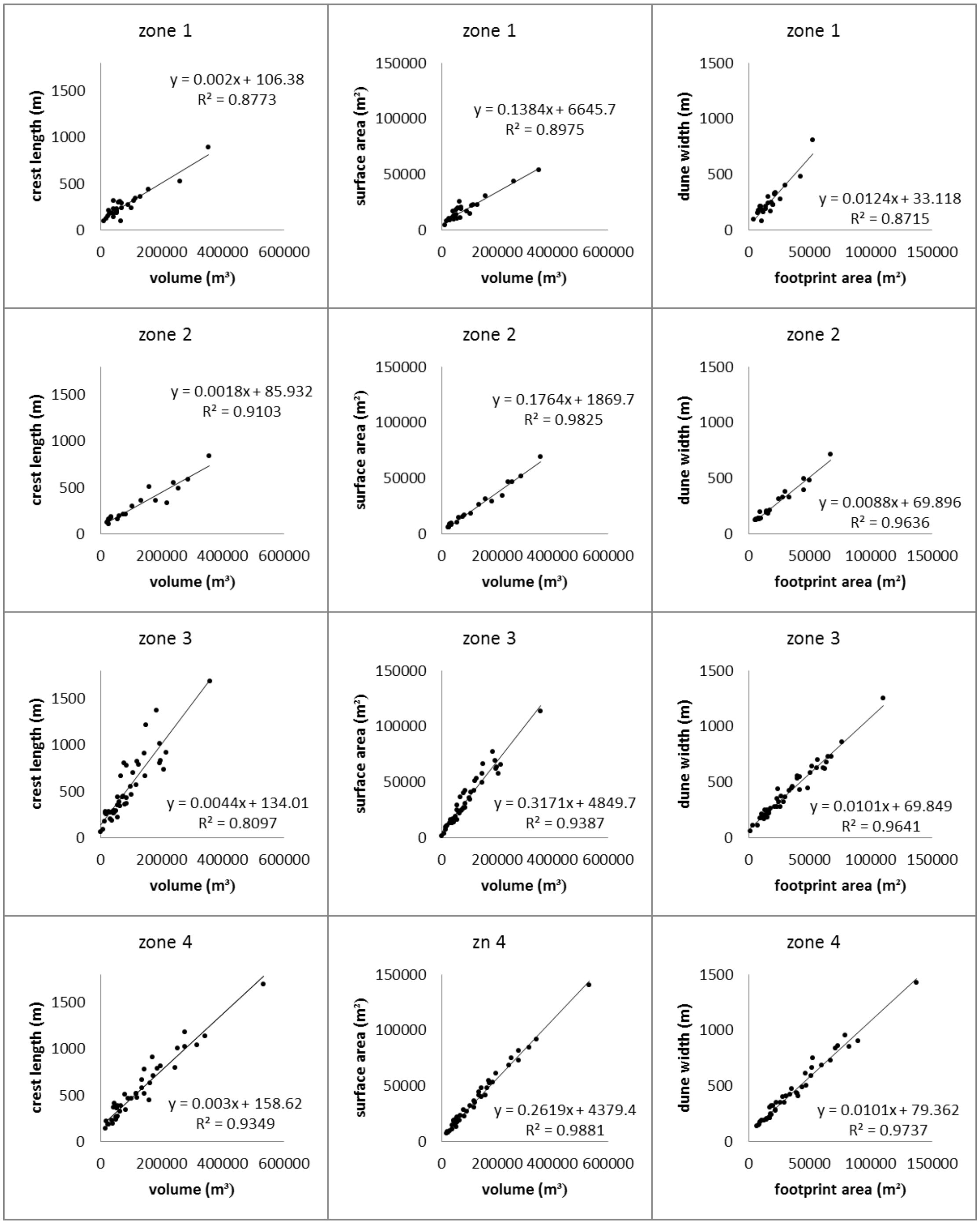
spacing with interdunes / average height
spacing with interdunes / maximum height
spacing without interdunes / average height
spacing without interdunes / maximum height
dune length / average height
dune length / maximum height
crestline length / average height
crestline length / maximum height
dune width / average height
dune width / maximum height
dune volume / average height
dune volume / maximum height
dune volume / crestline length
dune volume / 3d surface area
footprint surface area / dune width
3d surface area / dune width

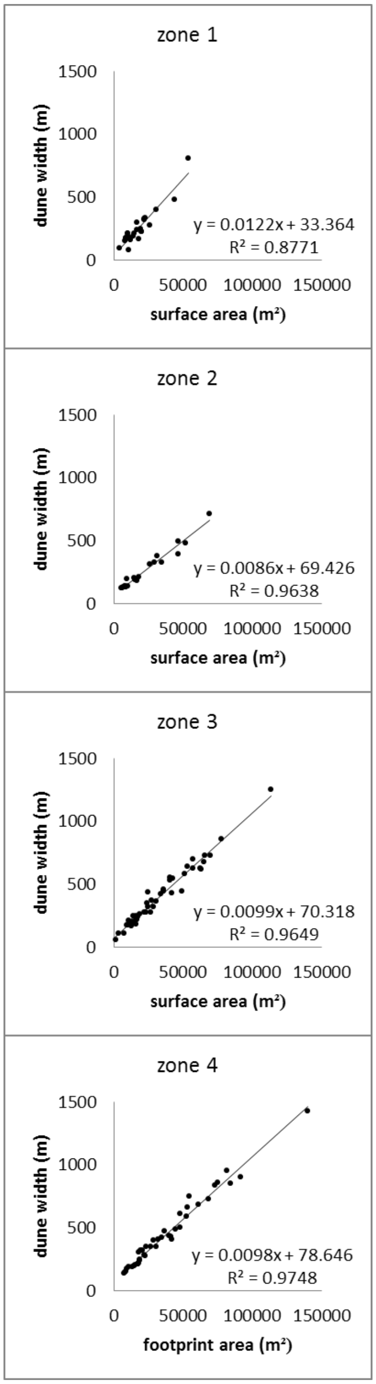

zone 1
avg height (m)
y = 0.0206x + 3.7031
R² = 0.0869
spacing with interdunes (m)
zone 1
max height (m)
y = 0.0411x + 5.0734
R² = 0.1245
spacing with interdunes (m)
zone 1
avg height (m)
y = 0.0176x + 4.0858
R² = 0.0509
spacing without interdunes (m)
zone 2
avg height (m)
y = 0.0199x + 5.283
R² = 0.2236
spacing with interdunes (m)
zone 2
max height (m)
y = 0.026x + 8.3691
R² = 0.1352
spacing with interdunes (m)
zone 2
avg height (m)
y = 0.0202x + 5.3343
R² = 0.195
spacing without interdunes (m)
zone 3
avg heigth (m)
y = 0.0054x + 2.7797
R² = 0.1058
spacing with interdunes (m)
zone 3
max height (m)
y = 0.0102x + 4.8223
R² = 0.1447
spacing with interdunes (m)
zone 3
avg heigth (m)
y = 0.0018x + 3.5176
R² = 0.0035
spacing without interdunes (m)
zone 4
avg heigth (m)
y = -0.0016x + 5.08
R² = 0.0043
spacing with interdunes (m)
zone 4
max height (m)
y = 0.0051x + 7.8529
R² = 0.0169
spacing with interdunes (m)
zone 4
avg heigth (m)
y = 0.0029x + 4.6618
R² = 0.0057
spacing without interdunes (m)


zone 1
max height (m)
spacing without interdunes (m)
y = 0.042x + 5.2992
R² = 0.1036
zone 1
avg height (m)
crest length (m)
y = 0.0061x + 3.8457
R² = 0.2954
zone 1
max height (m)
crest length (m)
y = 0.0104x + 5.8458
R² = 0.3069
zone 2
max height (m)
spacing without interdunes (m)
y = 0.0254x + 8.5369
R² = 0.1089
zone 2
avg height (m)
crest length (m)
y = 0.0038x + 6.1548
R² = 0.2766
zone 2
max height (m)
crest length (m)
y = 0.0079x + 8.6323
R² = 0.4155
zone 3
max height (m)
spacing without interdunes (m)
y = 0.0046x + 6.0995
R² = 0.0088
zone 3
avg height (m)
crest length (m)
y = 0.0007x + 3.3221
R² = 0.0571
zone 3
max height (m)
crest length (m)
y = 0.0016x + 5.6754
R² = 0.1207
zone 4
max height (m)
spacing without interdunes (m)
y = 0.0167x + 6.9679
R² = 0.0714
zone 4
avg height (m)
crest length (m)
y = 0.0011x + 4.3175
R² = 0.1927
zone 4
max height (m)
crest length (m)
y = 0.0018x + 7.4112
R² = 0.2022


zone 1
y = -0.0014x + 5.5967
R² = 0.0005
avg height (m)
dune length (m)
zone 1
y = -0.0105x + 9.4477
R² = 0.0104
max height (m)
dune length (m)
zone 1
y = 0.007x + 3.7323
R² = 0.307
avg height (m)
dune width (m)
zone 2
y = 0.0275x + 4.8754
R² = 0.3093
avg height (m)
dune length (m)
zone 2
y = 0.0387x + 7.5952
R² = 0.2161
max height (m)
dune length (m)
zone 2
y = 0.0046x + 6.0931
R² = 0.2645
avg height (m)
dune width (m)
zone 3
y = 0.0144x + 2.3614
R² = 0.1999
avg height (m)
dune length (m)
zone 3
y = 0.0235x + 4.3577
R² = 0.2072
max height (m)
dune length (m)
zone 3
y = 0.0015x + 3.0858
R² = 0.1249
avg height (m)
dune width (m)
zone 4
y = 0.0246x + 2.8106
R² = 0.2526
avg height (m)
dune length (m)
zone 4
y = 0.035x + 5.4076
R² = 0.1941
max height (m)
dune length (m)
zone 4
y = 0.0013x + 4.3215
R² = 0.1948
avg heigth (m)
dune width (m)


zone 1
max height (m)
dune width (m)
y = 0.012x + 5.6149
R² = 0.327
zone 1
avg height (m)
volume (m³)
y = 2E-05x + 4.1487
R² = 0.4701
zone 1
max height (m)
volume (m³)
y = 3E-05x + 6.4804
R² = 0.4392
zone 2
max height (m)
dune width (m)
y = 0.0095x + 8.5015
R² = 0.3984
zone 2
avg height (m)
volume (m³)
y = 9E-06x + 6.1812
R² = 0.4652
zone 2
max height (m)
volume (m³)
y = 2E-05x + 9.009
R² = 0.52
zone 3
max height (m)
dune width (m)
y = 0.0029x + 5.3433
R² = 0.1874
zone 3
avg height (m)
volume (m³)
y = 7E-06x + 3.0308
R² = 0.2688
zone 3
max height (m)
volume (m³)
y = 1E-05x + 5.3424
R² = 0.3389
zone 4
max height (m)
dune width (m)
y = 0.0021x + 7.4339
R² = 0.1977
zone 4
avg height (m)
volume (m³)
y = 4E-06x + 4.3911
R² = 0.2735
zone 4
max height (m)
volume (m³)
y = 6E-06x + 7.5989
R² = 0.2453

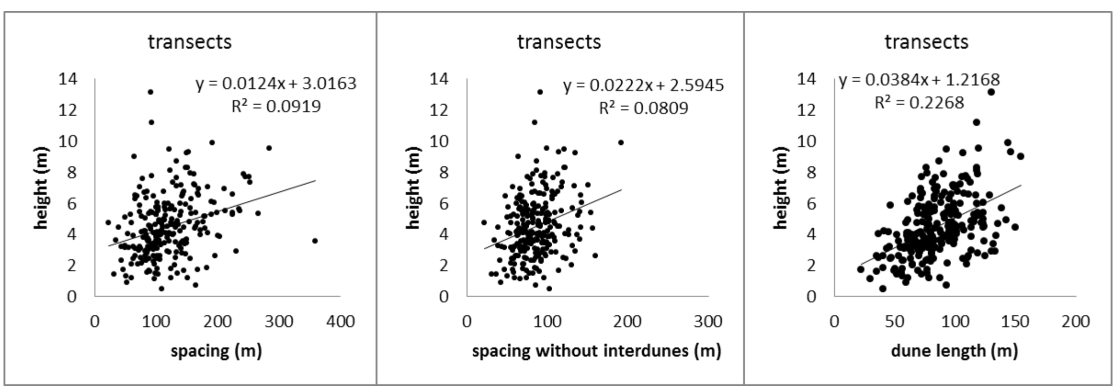

zone 1
crest length (m)
volume (m³)
y = 0.002x + 106.38
R² = 0.8773
zone 1
surface area (m²)
volume (m³)
y = 0.1384x + 6645.7
R² = 0.8975
zone 1
dune width (m)
footprint area (m²)
y = 0.0124x + 33.118
R² = 0.8715
zone 2
crest length (m)
volume (m³)
y = 0.0018x + 85.932
R² = 0.9103
zone 2
surface area (m²)
volume (m³)
y = 0.1764x + 1869.7
R² = 0.9825
zone 2
dune width (m)
footprint area (m²)
y = 0.0088x + 69.896
R² = 0.9636
zone 3
crest length (m)
volume (m³)
y = 0.0044x + 134.01
R² = 0.8097
zone 3
surface area (m²)
volume (m³)
y = 0.3171x + 4849.7
R² = 0.9387
zone 3
dune width (m)
footprint area (m²)
y = 0.0101x + 69.849
R² = 0.9641
zone 4
crest length (m)
volume (m³)
y = 0.003x + 158.62
R² = 0.9349
zn 4
surface area (m²)
volume (m³)
y = 0.2619x + 4379.4
R² = 0.9881
zone 4
dune width (m)
footprint area (m²)
y = 0.0101x + 79.362
R² = 0.9737

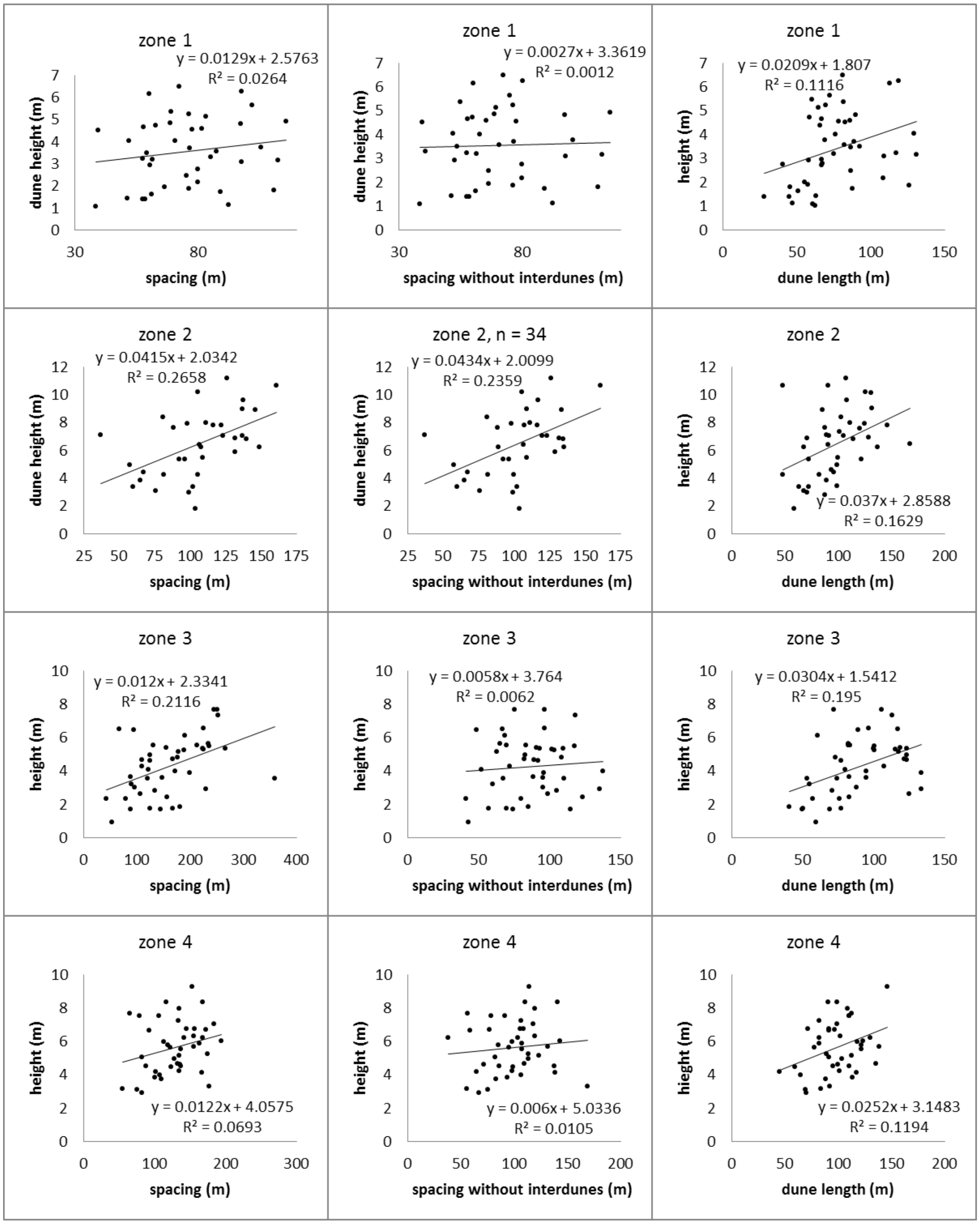

zone 1
dune width (m)
surface area (m²)
y = 0.0122x + 33.364
R² = 0.8771
zone 2
dune width (m)
surface area (m²)
y = 0.0086x + 69.426
R² = 0.9638
zone 3
dune width (m)
surface area (m²)
y = 0.0099x + 70.318
R² = 0.9649
zone 4
dune width (m)
footprint area (m²)
y = 0.0098x + 78.646
R² = 0.9748

Appendix 5

Cross plots for the field-scale transect dune population (abbreviated “transects”) and the transect zonal dune populations 1–4 are shown and include the following:

spacing / height
spacing without interdunes / height
dune length / height




zone 1
y = 0.0129x + 2.5763
R² = 0.0264
dune height (m)
spacing (m)
zone 1
y = 0.0027x + 3.3619
R² = 0.0012
dune height (m)
spacing without interdunes (m)
zone 1
y = 0.0209x + 1.807
R² = 0.1116
height (m)
dune length (m)
zone 2
y = 0.0415x + 2.0342
R² = 0.2658
dune height (m)
spacing (m)
zone 2, n = 34
y = 0.0434x + 2.0099
R² = 0.2359
dune height (m)
spacing without interdunes (m)
zone 2
y = 0.037x + 2.8588
R² = 0.1629
height (m)
dune length (m)
zone 3
y = 0.012x + 2.3341
R² = 0.2116
height (m)
spacing (m)
zone 3
y = 0.0058x + 3.764
R² = 0.0062
height (m)
spacing without interdunes (m)
zone 3
y = 0.0304x + 1.5412
R² = 0.195
hieght (m)
dune length (m)
zone 4
y = 0.0122x + 4.0575
R² = 0.0693
height (m)
spacing (m)
zone 4
y = 0.006x + 5.0336
R² = 0.0105
height (m)
spacing without interdunes (m)
zone 4
y = 0.0252x + 3.1483
R² = 0.1194
hieght (m)
dune length (m)

References

Ewing, R.C. and Kocurek, G., 2010. Aeolian dune-field pattern boundary conditions. Geomorphology 114, 175-187.

Ewing, R.C. and Kocurek, G., 2010. Aeolian dune interactions and dune-field pattern formation: White Sands Dune Field, New Mexico. Sedimentology 57, 1199-1219.

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

Ewing, R.C., Kocurek, G., Peyret, A.P.B., and Mohrig, D., 2008. Three-dimensional characterization and morphological dynamics of gypsum sand dunes at White Sands National Monument using airborne LiDAR, Planetary dunes workshop: A record of climate change. <http://www.lpi.usra.edu/meetings/dunes2008/pdf/7031>.

Gile, L.H., Hawley, J.W. and Grossman R.B., 1981. Soils and geomorphology in the basin and range area of southern New Mexico – Guidebook to the desert project: New Mexico Bureau of Mines and Mineral Resources, Memoir 39, 19-21.

Herrick, C.L.1904. Lake Otero, an ancient salt lake in southeastern New Mexico. The American Geologist 34, p. 174-189.

Kocurek, G., Carr, M., Ewing, R.C., Havholm, K.G., Nagar, Y.C., and Singhvi, A.K., 2007. White Sands Dune Field, New Mexico: Age, dune dynamics and recent accumulation, Sedimentary Geology 197, 313-331.

Kocurek, G. and Ewing, R.C., 2005. Aeolian dune field self-organization – implications for the formation of simple versus complex dune-field patterns. Geomorphology 72, 94–110.

Kocurek, G, Ewing, R.C., and Mohrig, D., 2010. How do bedform patterns arise? New views on the role of bedform interactions within a set of boundary conditions, Earth Surface Processes and Landforms 35, 51-63.

Kocurek, G. and Lancaster, N., 1999. Aeolian system sediment state: theory and Mojave Desert Kelso dune field example. Sedimentology 46, 505-515.

Lancaster, N., 1995. Geomorphology of desert dunes. Routledge, London and New York, 290 p.

Langford, R.P., 2003. The Holocene history of the White Sands Dune Field and influences on eolian deflation and playa lakes. Quaternary International 104, 31–39.

McKee, E.D. and Moiola, R.J., 1975. Geometry and growth of the White Sands Dune Field, New Mexico. U.S. Geological Survey Journal Research 3 (1), 59-66.

Schenk and Fryberger, 1988. Early diagenesis of eolian dune and interdune sands at White Sands, New Mexico. Sedimentary Geology 55, 109-120.

Seager, W.R., Hawley, J.W., Kottlowski, F.E., Kelley, S.A., 1987. Geology of the east half of Las Cruces and northeast El Paso 1° X 2° sheets, New Mexico, New Mexico Bureau of Mines and Mineral Resources, Socorro.

Werner, B.T., 1995. Eolian dunes: computer simulations and attractor interpretation. Geology 23, 1107– 1110.