

Point pattern analysis of star dunes in Ar Rub' al Khali desert, Saudi Arabia: The application of spatial statistics to the understanding of dune field self-organization

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Abstract. The self-organization of natural landforms measured by the *R statistic* presents a perspective on the geography of star dunes and provides quantitative methods to measure the degree of self-organization. Star dunes are dunes which are most complex in their form in comparison to other dune types (crescentic, barchanoid) and are results of complex or multi-directional wind regimes, hence their complex form. This study examines the geography of star dune patterns for the Ar Rub' al Khali sand sea on the Arabian Peninsula. The nearest neighbour performs an analysis on the pattern of points and classifies the distribution as clustered, random or dispersed. The spatial statistical tools such as the nearest neighbour gives a benchmark in the measurement and understanding of distribution of natural landforms and the environmental factors that influence such behaviour.

Keywords: Ar Rub' al Khali; Aeolian; Self-organization; Spatial statistics; nearest neighbour, R statistic

1. Introduction

The employment of spatial statistics in order to define the spatial patterns of sand dunes may offer an alternative measure of changing factors such as climate and sediment supply through time. The arrangement of dunes and their patterns reveals the interaction of changes in climate, sediment supply and transport across all spatial scales (Bishop 2010). Dune size, spacing, alignment, and sediment thickness can vary spatially and also is considered as the surface expression of the factors that control the dunes dynamics and accumulation (Lancaster 1998). Dunes are created by interactions between granular material (sand) and shearing flow (the atmospheric boundary layer). The structure of these bedforms reflects the characteristics of the sediment (primarily grain size) and the surface wind (surface shear stress or friction speed and directional variability), which play a major role in determining dune morphology (Lancaster cited in Abrahams & Parsons 1995).

The use of spatial statistics in landscape pattern analysis has led to the emerging of these bedforms from a random to self-organized state within a complex geomorphic system. However, this is a relatively recent paradigm in the explanation and understanding of aeolian dune fields (Bishop 2010). Although this concept of landform analysis is abstract and growing, several recent studies have adapted spatial statistics within Geographical Information Systems (GISs). For example, Wilkins and Ford (2005) used the nearest neighbour analysis in order to identify and characterize the differences in two dimensional dune patterns within a dune field and to identify the changes in dune patterns over time for the Coral Pink Sand Dunes in southern Utah, USA. Similarly, Bishop (2007a) applied the nearest neighbour method to determine the degree of dune field self-organisation for a crescentic dune field near the southern end of Chasma Boreale, Mars. In addition, nearest neighbour analysis was

also applied to the analysis of pattern and process for monogenic volcanoes in south-eastern Australia (Bishop 2007b) and suspected volcanic cones in Mars in comparison with cone groups in Iceland (Bruno et al. 2004). The use of GISs for point representation of landforms offers accurate information about their distribution and identity in geographical space (Bishop 2007b). Bishop (2007a) also mentions that the nearest neighbour method used for point pattern analysis within a GIS can notify us about the mechanism that produced such patterns.

1.1. Study Area

Ar Rub' al Khali (or the Empty Quarter) is the world's biggest continuous sand desert, covering an area of 522,340 km² and comprising of several types of sand dunes such as Transverse, Linear and Barchans. This sand sea occupies the south-central portion of the Arabian Peninsula and is predominantly hyper-arid and influenced by the dry north-westerly Shamal winds that originate in Iraq, the Kharif winds of the south-west monsoon generated by the Inter-Tropical Convergence Zone (ITCZ) during the northern summer, and the drier, less humid winter north-easterlies from India (Bishop 2010). The Shamal winds attain wind speeds between 37-50 km/h and arrive at their peak in June, lasting until early July, (Edgell 2006). Edgell (2006) indicates that although the Kharif winds are less pervasive than the Shamal, they also play an important role in desert conditions in as much as they can extend to the southern margins of the Ar Rub' al Khali and contribute to the development of star dunes.

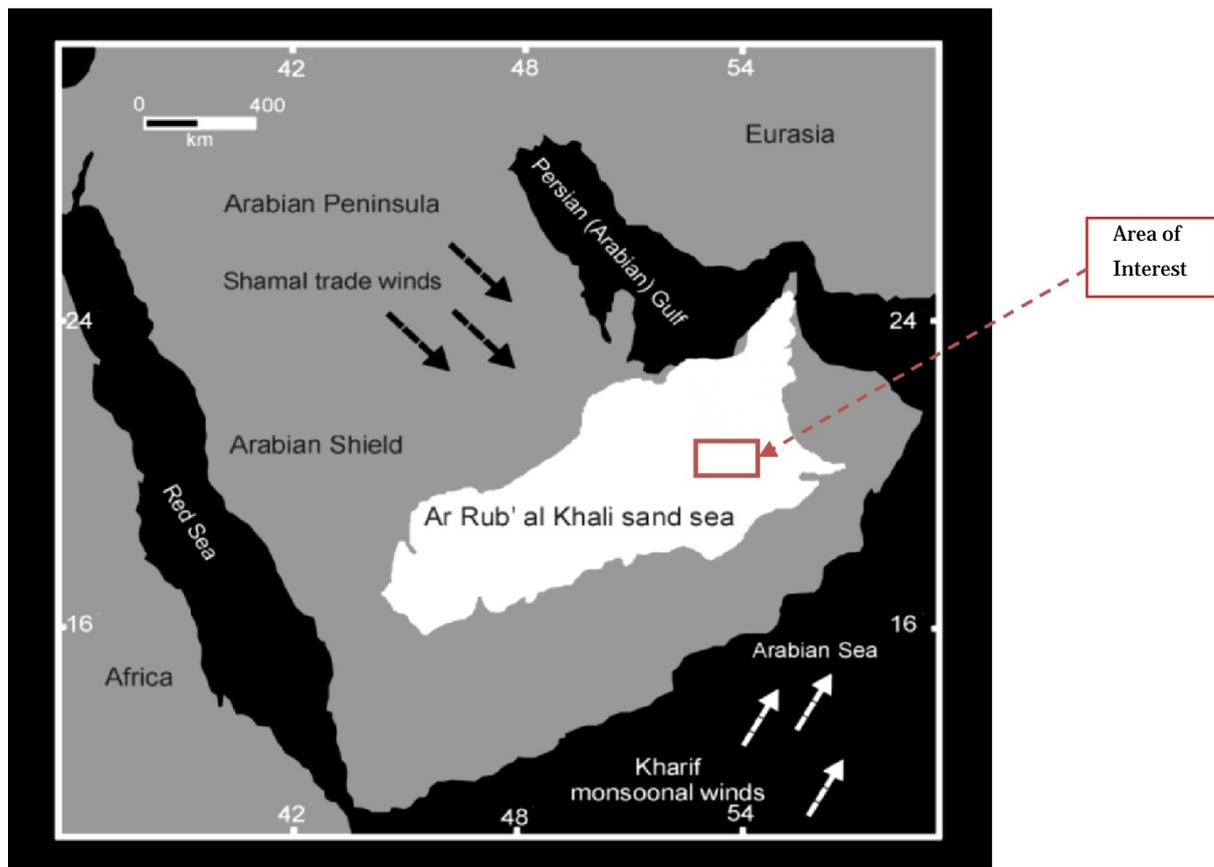


Figure 1. Approximate Area of interest (Map Adapted from Bishop 2010)

1.2. Star Dune Morphology

Star dunes are mainly located in the eastern part of Ar Rub' al Khali desert in an area of about 1,100 km², in which mostly consists of the surrounding interdune areas (Edgell 2006). These dunes can reach a height of more than 300 m and usually contains a greater volume of sand than any other dune type (Lancaster cited in Abrahams & Parsons 1995). Star dunes are characterized by "a pyramidal shape, with three or four arms radiating from a central peak and multiple avalanche faces. Each arm has a sharp sinuous crest, with avalanche faces that alternate in aspect as wind directions change. The arms may not all be equally developed and many star dunes have dominant and primary arms on a preferred orientation. The upper parts of many star dunes are very steep with slopes at angles of 15° to 300°; the lower parts consist of a broad, gently sloping (5° to 100°) plinth or apron," (Lancaster cited in Abrahams & Parsons 1995). According to Lancaster (1989), their formation is shown to be associated with multi-directional or complex wind regimes, at times where most sand transport occurs.

2. Methodology

2.1. Data Sources and Software

ArcGIS 9.3™ GIS (geographical information system) was utilized to digitize some 3020 points representing star dunes. This was performed using the on-screen (heads-up) digitizing method from a 3-s (90 m) SRTM (Shuttle Radar Topography Mission) DEM projected to WGS 84 UTM Zone 40N for the Ar Rub' al Khali sand sea. In order to support the discrimination of their complex form, orthorectified Landsat Thematic Mapper imagery (14.25 m spatial resolution) was overlaid over the DEM, providing more accuracy and precision in locational referencing of the data points used for pattern analysis. For each dune, the highest point was digitized with the assistance of the color contrast of the DEM in which higher elevation was set to be more distinguishable in color than lower elevation. In some cases, the highest elevation of the dune is very similar covering 3 pixels or more and gave difficulties to visually identify the dune's peak. However, the identifier tool in ArcGIS 9.3™ was utilized extensively in order to confirm the highest point of the dune. The Landsat TM was overlaid every time there was uncertainty in the morphology of the dunes. Dune data in this study is exclusive to stellate-like dunes taking into account the reliability of classification and geographical analysis.

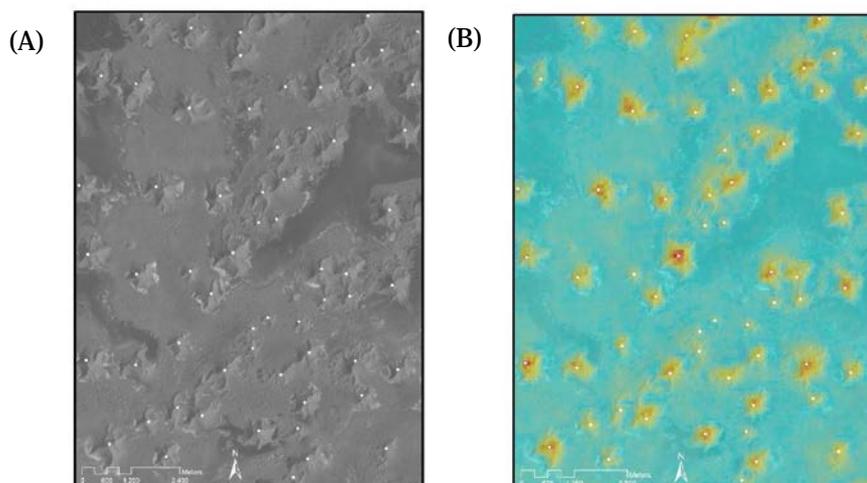


Figure 2. (A) Landsat Imagery showing star dune morphologies (B) Digital Elevation Model showing star dune elevation.

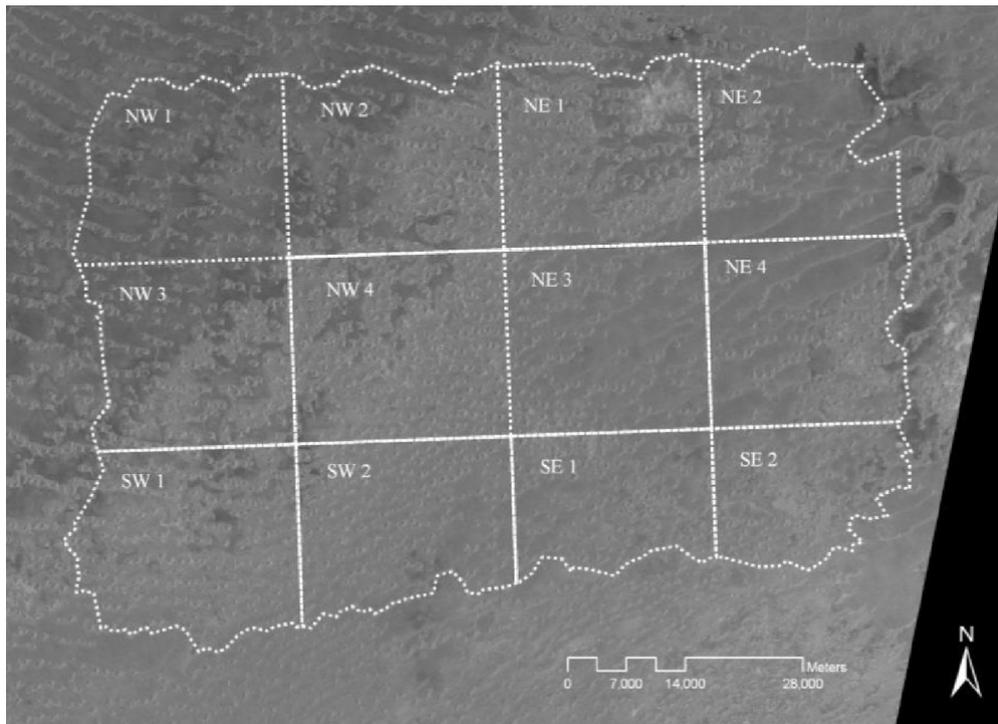


Figure 3. Landsat Imagery representing the total study area and regions of Interest.

Subsequent to the digitization process, the spatial analyst tool in ArcGIS 9.3™ was used to extract elevation for all the points representing the star dunes. Nearest neighbor analysis was performed using the extensions ArcGIS Spatial Statistical Tools and XTools Pro. Prior to the application of the nearest neighbor, the data points for the area of interest were enclosed by a convex hull achieving the minimum possible area that containing all the points and limiting the effect of Modifies Areal unit problem (MAUP). O’Sullivan and Unwin (2003) define MAUP as a problem pursuant to the aggregation of data and the alteration of boundaries within study areas. Adding that distance-based measures of landform spacing, which are components of MAUP; can be affected by boundary or edge effects. Therefore the use of convex hulls is to limit such effects. Bishop (2007b) describes a convex hull analogically “as an elastic band stretched open to contain all data points; and when released, it will assume the shape and define an area representative of all enclosed points”. The nearest neighbor was applied for the area of interest. The area was then further subdivided into 12 regions of Interest (ROIs) based on approximate equal distances acting as the boundary. A convex hull was constructed for each ROI and the nearest neighbor was applied for 6 of the ROIs that are located on the western region of the study area. The reason the nearest neighbor was run for 6 western ROIs is to avoid the natural geographic voids that are present on the eastern region of the study area and to avoid the effect of MAUP.

2.2. Synopsis of Statistical Calculations

Introduced by Clark and Evans (1954) , “The nearest neighbor analysis uses the distance between each point and its closets neighboring point in a layer in determining if the point pattern is random, regular, or clustered”, (Chang, 2008). The nearest neighbor statistic, also known as the *R statistic* or the *R scale*; is the ratio of the observed average distance between nearest neighbors of a point distribution (r_0) and the expected average nearest neighbor distance (r_e) (Wong & Lee, 2005). If the *R statistic* is less than 1, then the point pattern is more

clustered than random. However, if it is greater than 1, then the point pattern is more dispersed than random (Chang, 2008). A standard error (SE) of difference between the observed and expected average distance nearest neighbor statistic can also be measured. This statistics helps indicate how probable the difference between the observed and the expected pattern is to occur by chance. According to Bishop (2010), if the difference is relatively small compared to the standard error, this difference is regarded as not statistically significant, while a large difference relative to the standard error indicates the difference is statistically significant. In order to evaluate the significance of the difference between an observed and random distribution, a standardized Z score is utilised. If $Z_R > 1.96$ or < -1.96 it can be expressed that the difference is statistically significant at $\alpha < 0.05$. Alternatively, if $-1.96 < Z_R < 1.96$ the pattern is not statistically different from a random pattern, regardless of visual appearance (Bishop, 2010).

3. Results

The nearest neighbor statistic characterizes the distribution of star dunes for the Ar Rub" al Khali sand sea as dispersed. This indicates that the degree of pattern is significantly uniform or regular. The average R statistic for the 6 ROIs is of 1.26 which indicates a low nearest neighbor score of a dispersed pattern. Although the results incorporate a high average Z score for the 6 ROIs of 8.95 concluding that the difference between the observed and the random pattern is statistically significant, some questions are raised whether the star dune distribution is random as the R statistic (1.26) is very close to a random distribution ($R=1$). For this purpose, the statistics of a study conducted by Bishop (2010) that utilizes the same concept of this study to measure the degree of self-organization of Megabarchanoid dunes for the Ar Rub" al Khali sand sea are used for comparison.

In his study, Bishop (2010) derives the nearest neighbor statistic for some 5100 points representing megabarchanoid dunes. Furthermore, Bishop (2010) divided the area of interest into ROIs and derived the R statistic for each ROI attaining an average of 1.4 indicating a dispersed pattern in dune distribution. Comparatively, both results show dispersed distribution of points, however; the R statistic for megabrchanoid dunes are significantly higher than that of star dunes, raising questions to whether star dunes can be referred as self-organizing landforms.

ROIs	n	Area km ²	r_o (km)	r_e (km)	NN _R statistic	Z _R	Pattern
NW 1	168	435921	1.06	0.80	1.32	7.96	Dispersed
NW 2	230	455299	0.90	0.70	1.28	8.2	Dispersed
NW 3	238	451951	0.90	0.69	1.31	9.22	Dispersed
NW 4	360	502315	0.77	0.59	1.3	10.85	Dispersed
SW 1	316	479705	0.74	0.62	1.21	7.08	Dispersed
SW 2	342	441011	0.73	0.57	1.29	10.35	Dispersed
Total Area of Interest	3020	5893888	804.88	698.5	1.15	16.01	Dispersed

Table 1. Point Pattern summary table of the distribution of the R statistic for the nearest neighbor.

4. Discussion

The results indicate that the dune pattern is dispersed, in other words not random. However, the degree of non-randomness is low. In contrast, the study conducted by Bishop (2010) for the megabarchanoid dunes north-east of this study's area of interest show a higher degree of non-randomness. Therefore, it can be argued that the pattern in which star dunes form is more chaotic than those of megabarchanoid form. The complex or multi-directional wind regimes (a combination of the Shamal and Kharif winds) that play a major role in the formation of star dunes may also play an important role in their distribution. Such complex wind regimes may provide evidence that star dunes are more likely to be of random and chaotic distribution. Additionally, the low average *R statistic* of 1.26 have raised questions whether star dune can be categorized as self-organizing landforms. Although such results indicate a dispersed pattern, Bishop's (2010) results were taken into account along with the recognition that star dunes are more complex in their form and their geomorphology.

5. Summary and Conclusions

Spatial statistics (nearest neighbor analysis in specific) presented a quantitative understanding of star dunes for the Ar Rub' al Khali sand sea. The *R statistic* has provided an understanding for the distribution and development of these complex landforms and can be treated as a benchmark for point pattern analysis interpretation and understanding. In summary, the findings show that the self-organization for star dune morphology is one of dispersion. The *R statistic* for the total area of interest is of 1.15 and the maximum *R statistic* for the local extent (ROIs) is of 1.32. Sand dunes are self-organizing; however, low values of the *R statistic* have implied that star dunes have a very low level of self-organization and also close to random distribution. It can be argued that aeolian processes that influence the form of star dunes play an important role, not just in their formation but also in their distribution. Complex wind regime that results in these dunes of complex morphology can be the explanation of their low level of self-organization and chaotic distribution. In general, the *R statistic* measures the degree of self-organization in dune fields and can help identify environmental influences such as aeolian processes and their effects on the morphology of the dunes. Furthermore, spatial statistics can be used for pattern analysis of natural phenomena and comparative studies with other dune fields.

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