Title:

Spatial variability in shrub vegetation across dune forms in central Saudi Arabia.

Running title:

Shrub density in central Saudi Arabia

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Abstract

In desert dune environments, vegetation may be an indicator of dune stability and rates of sediment transport. As topography and underlying controls of vegetation vary over large spatial areas variations in dune form make scaling up of field research difficult. To mitigate this, and to identify spatial variations in vegetation distributions in a Saudi Arabian sand sea, spectral information from high resolution satellite images was classified to map polygons of shrub vegetation over 360 km^2 of well-defined linear dunes, broken linear dunes and dome dune forms. When compared to topographic characteristics of the landscape extracted from a digital elevation model, vegetation densities were often highest on 10 to 20-degree slopes elevated above interdune salt deposits on dune flanks. Spatially this was confined to small areas, and density was not always related to dune form, more to the presence of groundwater which could also encourage vegetation on the tops of some dunes. Field observations identified shrubs of mainly *Calligonum* genus whose size is related to the amounts of salts, moving sediment and access to the water table that varies within and between dune forms. Shrub vegetation density is likened to surface roughness to better understand sediment movement in this environment.

1 Introduction

Vegetation distribution in desert dune systems is often related to long term dune stability (Stokes et al., 1997), short term interaction with airflows trapping and releasing sediment (Ash and Wasson, 1983; Wolfe and Nickling, 1993), and rapid changes in sediment transport rates when vegetation is removed (Bullard et al., 1997; Thomas and Leason, 2005). Understanding where and how much vegetation there is in deserts will add to our limited understanding of the interaction of vegetation on dune geomorphology in ergs (Lancaster, 2009). Information on vegetation variation at large spatial scales is limited as most research on desert vegetation is based on small scale ground sampling with plots or transects (e.g. Abbadi and El-Sheikh, 2002; El-Keblawy et al., 2015). In this research, satellite images are used to detect shrub vegetation in desert dunes at a spatial resolution and extent that is rarely studied to better understand the controls and impacts of vegetation on sediment stability and dune forms in Saudi Arabia.

Vegetation tolerates arid environments with the right adaptions and conditions that can encourage vegetation growth. Water availability is essential (Parker 1991) and this may depend on groundwater (Bruelhide et al., 2003; Hao et al., 2010; Eamus et al., 2015), ephemeral water (Olsvig-Whittaker et al., 1993; Parker 1991; Eamus et al., 2015), trapping surface run-off (Canadell et al., 1996; Hao et al., 2010), having a deep tap root or roots at different depths (Canadell et al., 1996; Hao et al., 2010) and, surviving long dry periods by limiting growth (Canadell et al., 1996; Reynolds et al., 1999). The persistence of vegetation on sand dunes is also challenged in high winds. At high wind speeds entrainment and erosion of sand prevents vegetation settling, whereas at low wind speeds vegetation will colonise and sand will accrete (Tsoar, 2005), indicating a relationship between vegetation, wind and erosion. In addition to wind and perhaps more so in the interdune regions, vegetation may favour areas with certain minerals, such as magnesium (Parker, 1991) or be inhibited by soil salinity and high acidity (Halwagy and Halwagy, 1974; Boer and Sergeant, 1998; Hao et al., 2010; El-Keblawy et al., 2015; Aly et al., 2016). Established vegetation will reinforce itself by collecting water and retaining nutrients to form resource islands, fertile patches underneath the vegetation, where nutrients collect that would otherwise lost from the system (Lugwig and Tongway, 1995; Aguiar and Sala 1999; Bochet, 2015) that assist in stabilising dunes (Tsoar, 2005; Aly et al., 2016). Conversely, the loss of vegetation reduces soil fertility and as moisture and plants recede sand becomes mobile (Schlesinger et al., 1990; Ludwig and Tongway 1995; Valentin et al., 1999). The coincidence of these factors may cause clustering of vegetation in an oasis (Gimingham, 1955) and in arid regions spatial variations of these factors may cause spatial patterning of the vegetation (Aguir and Sala 1999). Additionally, in arid environments and deserts predominant factors such as slope angle and aspect (Parker 1991, Valentin et al., 1999; Aguir and Sala 1999), salinization of groundwater and soils (Boer and Seargeant

1998; El-Keblawy et al., 2015; Aly et al., 2016), and presence of impermeable crusts (Bromley, 1977) which in sandy deserts are normally found at the base of dunes (Dunkerley, 2011) can influence vegetation distribution.

Sediment transport activity in dunes is estimated to occur when the vegetation cover falls below a threshold. There are a wide range of estimates, Wiggs et al., (1995a) settled on 14% for linear dunes in the Kalahari. The varied distribution of vegetation has also found to spatially influence surface roughness and sediment transport rates across linear dunes (Wiggs et al., 1995a, 1995b) which will then influence surface morphology (Tsoar and Møller, 1986). Current knowledge of vegetation-dune interactions has mostly been limited to small-scale field surveys designed to understand localised geomorphology and ecology (e.g. Hesp & McLachlan, 2000; El Bana et al., 2003; Li and Ravi et al., 2018; Tao et al., 2017; Al-Kewably et al., 2015) and vegetation and sand transport (e.g. Hesse et al., 2007). Practicalities mean that beyond field scale studies the impact of vegetation occurrence on spatial and temporal dune processes is less well explored, yet these are the scales that are required to parameterise models (Zhang et al., 2017) to predict dune stability and vegetation succession (Baas and Neild (2007), the tolerance of vegetation to sediment movement rates (Barchan and Hugenholtz, 2012, 2015), the interaction of vegetation during migration of different dune forms under simulated wind directions (Zhang et al., 2017), controls on patterns and biomass (Littmann and Veste, 2005) and sub-continental scale sand sea responses to climate (Thomas et al., 2005). At present there is a shortfall in wider scale empirical observations that describe the complexity of vegetation cover in desert dune systems that would benefit geomorphologists, ecologists and modellers.

Satellite mapping and spatial analysis is providing more opportunities to bridge the scales from findings of small-scale field surveys to modelling and understanding large-scale desert dune field processes (Hugenholtz et al., 2012). However, using satellite images to map and correlate environmental controls are possible where the target vegetation spectra are dominant enough to be identified within the spatial resolution of the sensor, common in some dryland environments (e.g. Aly et al., 2016; Oldeland et al., 2010; Yeteman et al., 2009; Tian et al., 2016). This leaves a major challenge in dry active dune systems where vegetation is usually sparse, offering a small spectral target that requires high spatial resolution to be detected. This is achievable with drones, with a trade off in study extent to 100s m (e.g. Quets et al., 2017), so a wider scale view with a sufficient level of detail to detect the presence of vegetation on dunes needs to be explored. To address this issue 2 by 2 m resolution World-View 2 (WV-2) images with multispectral VIS and NIR frequencies are used to discriminate a realistic target – shrub vegetation – in a sandy desert of Saudi Arabia adding to the limited information on the function of vegetation here (e.g. Hegazy et al., 1998; El-Keblawy). The aims of this research are to: identify the type, distribution, patterns and density of shrub vegetation at broad scales in a desert; if the patterns are regular or irregular in the study area; what controls the regularity or irregularity of the distribution; and does dune form or dune type relate to the different types of and distribution of shrub vegetation? Then, using the patterns and density of vegetation to estimate surface roughness, build up a picture of how the vegetation interacts with the prevailing wind intensity on the different dune forms to gain a better understanding of sediment movement in this erg.

2.1 Study Area

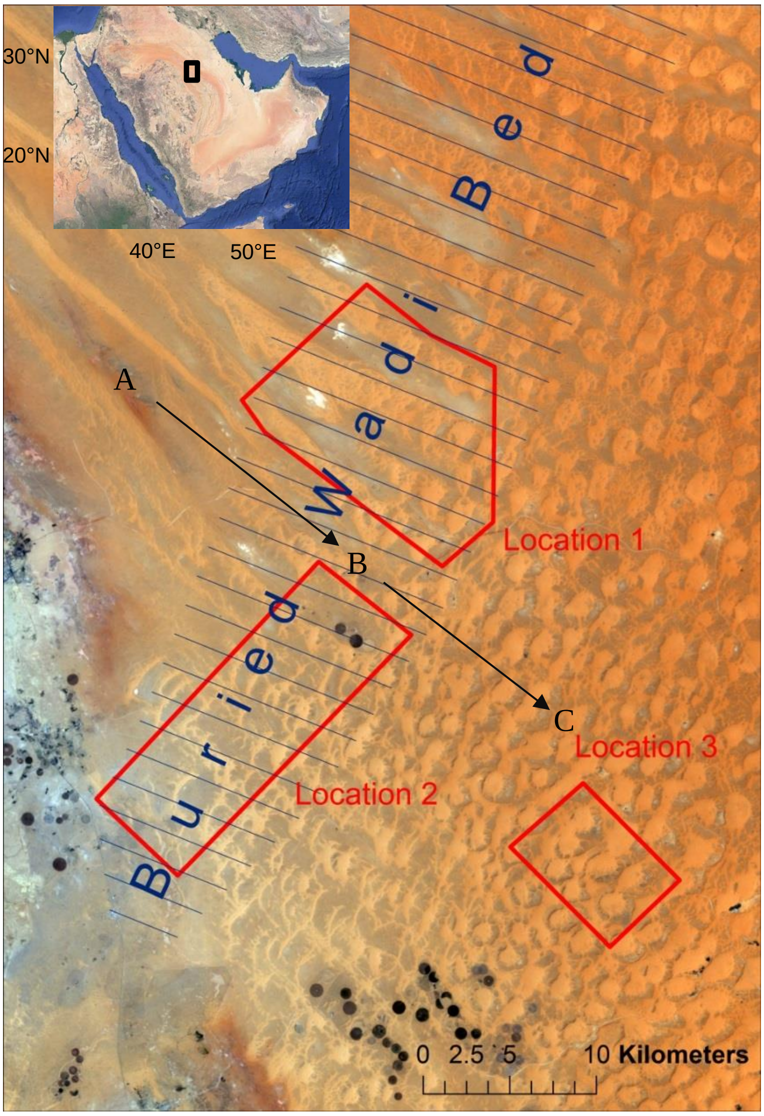

Figure 1. Study region in the Saudi Peninsula (google inset) indicating the study area (Landsat bands R3, G2, B1) showing the three locations outlined in red where detailed WorldView-2 imagery was used. Light areas are exposed rock or evaporates, orange areas are dunes surrounded by paler orange-blue interdunes. Dark areas are agriculture and urban, including circular pivot irrigation systems. The likely position of the buried Wadi Al Rimah (Al-Sulimi and Pitty1995; El-Baz; Breeze et al., 2015), yet to be accurately mapped, is hatched. Dune axis trend from north-west to south-east changing from A, linear dunes in the top left, B, through a transition zone in the centre to, C, circular domed dunes in the bottom right

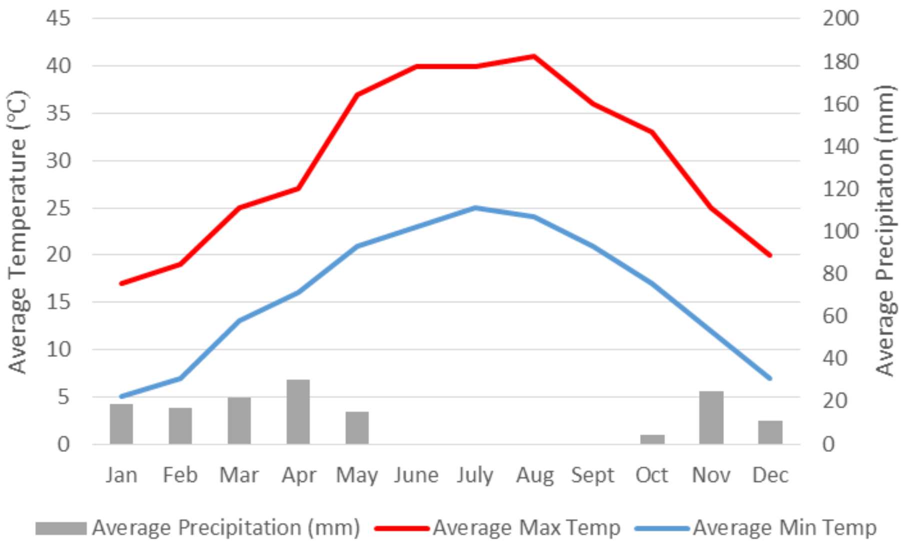

Figure 2. Precipitation and temperature of study region (Al-Dughairi, 2011).

The study region, ~ 3,260 km^2 (top left: 27˚00'00" N, 44˚12'00" E, bottom right: 26˚30'00" N, 44˚36'00" E), in the centre of Saudi Arabia (Fig. 1), is characterised by an arid landscape with an extremely fragile environment, limited nutrients and depleted soils (Abahussain *et al.* 2002; Sher *et al.* 2010). There is little rainfall, often sporadic and localised accumulating an average of 150 mm per year. Temperatures can reach up to 40˚C in the dry season (Al-Dughairi 2011) (Fig. 2). In the north-west of the study region, parallel linear sand dunes 20 to 50 m high, some of which have run for 250 km in a roughly north-west to south-east direction, comprise linear ridges of sand, 1 to 3 km wide. Between each of the linear dune ridges are 1 to 3 km wide inter-dunes, sometimes containing evaporite salt deposits. In the south-east portion of the image the dune forms are different, and the area consists of 1 to 2 km diameter dome dunes, which appear to follow the north-west to south-east trend of the linear dune forms and are surrounded narrow inter-dunes, sometimes with depths of 100m or more, and evaporite deposits in the bottom. There is a transition between these two dune forms, and this coincides roughly to the unmapped bed of the Wadi Al Rimah trending south-west to north-east across the area. The river (wadi – an Arabic term for river) has ephemeral flows into the west of the sand sea where the wadi bed takes a course under the sand sea to the north-east into Kuwait (El-Baz et al., 1996). The area is punctuated with occasional agriculture consisting of date palms, herbs and cereals (Fig. 3a). Sometimes the agriculture is supported with pivot irrigation systems supplied by pumping groundwater, forming circular vegetation patches in the landscape (Fig. 1).

(a)

(b)

Figure 3. (a) Vegetation is sparse and often shrub-like although exploitation of ground water can support small farms that may cultivate date palms. (b) A dome dune edge, showing shrubs can occur on steep slopes and on active tops of the dunes as well as close to evaporate salt deposits in inter dunes where water accumulation may occur. In the distance is the next dome dune separated by an interdune.

3.1 Methods

Three locations were selected to investigate presence and distribution of vegetation across different dune forms, elongated linear dunes, Location 1 (140 km^2), linear dunes that have a more broken pattern, Location 2 (150 km^2) and well-defined dome dunes, Location 3 (45 km^2). Location 1 and 2 are close by, and probably cross, the buried wadi, whilst Location 3 is furthest away from the buried wadi bed (Fig 1).

3.2 Image pre-processing and classification

For each of the three locations a radiometrically and geo-referenced multispectral image from the WorldView-2 (WV-2) satellite sensor (green, red, blue and NIR wavebands) with a spatial resolution of 2 m was obtained. Each image was converted to top-of-atmosphere spectral radiance (Updike & Comp, 2011) and atmospherically corrected using the Fast Line-of-sight Atmospheric Analysis of Hypercubes (FLAASH) tool in ENVI v.5.3 (Exelis, 2015), Fig 4(a). With a pixel area of 4 m^2, detection of spectra of healthy active (growing) vegetation from tree canopies, shrubs and continuous herbaceous cover, that will not be swamped in the strong spectral signal of sands, shadows and exposed geology is a realistic expectation. Thus, the classification will identify established hardy shrub vegetation that is actively growing and excludes smaller vegetation growth such as grasses and dormant non-green vegetation. The image was classified into, vegetation (shrubs), shaded dune sand, illuminated dune sand, dune sand and interdunes, and buildings and roads. For each class signature ~ 50 to 200 representative pixels was selected, and a maximum likelihood classification algorithm was applied following the findings of vegetation classifications in arid regions (Al-Ahmadi & Hames, 2009) (Fig 4(b)). After the initial classification, results and examination of spectra, to avoid confusion between vegetation, topographic shadow from dunes and small irregularities below the resolution of the sensor (possibly nebkha), vegetation training pixels were re-selected above a Normalised Differential Vegetation Index (NDVI; a spectral index used to discriminate vegetation activity, (Campbell, 1996)) threshold of 0.19. Contiguous vegetation pixels were converted to polygons (Fig. 4(c)), using ArcMap v.10.3.1 (ESRI, 2015) and mapped to show the distribution of vegetation. The centroid of each vegetation polygon (Fig 4(c)) was determined. The centroids show the Incidence of Vegetation Patches (IVP) as opposed to area, a trade-off that helps reduce over- and under-estimates of shrub vegetation canopy based on the 2 by 2 m pixel dimensions but IVP cannot measure the actual expanse of cover over a surface. Centroids additionally reduce the area bias of non-natural agricultural polygons, particularly pivot irrigation systems, field parcels, and some adjoining vegetation-shadow pixels that were difficult to eliminate in the classification. To assess the classification of shrub vegetation, the polygon size statistics were investigated, and observations from the field, combined with local knowledge and qualitative assessments of Google images, were made to identify the major types of vegetation that the classification was capable of detecting. For evidence and discrimination of vegetation related to agricultural activity, farms, pivot irrigation, field parcels and settlements were manually digitised from the unclassified WV-2 satellite images.

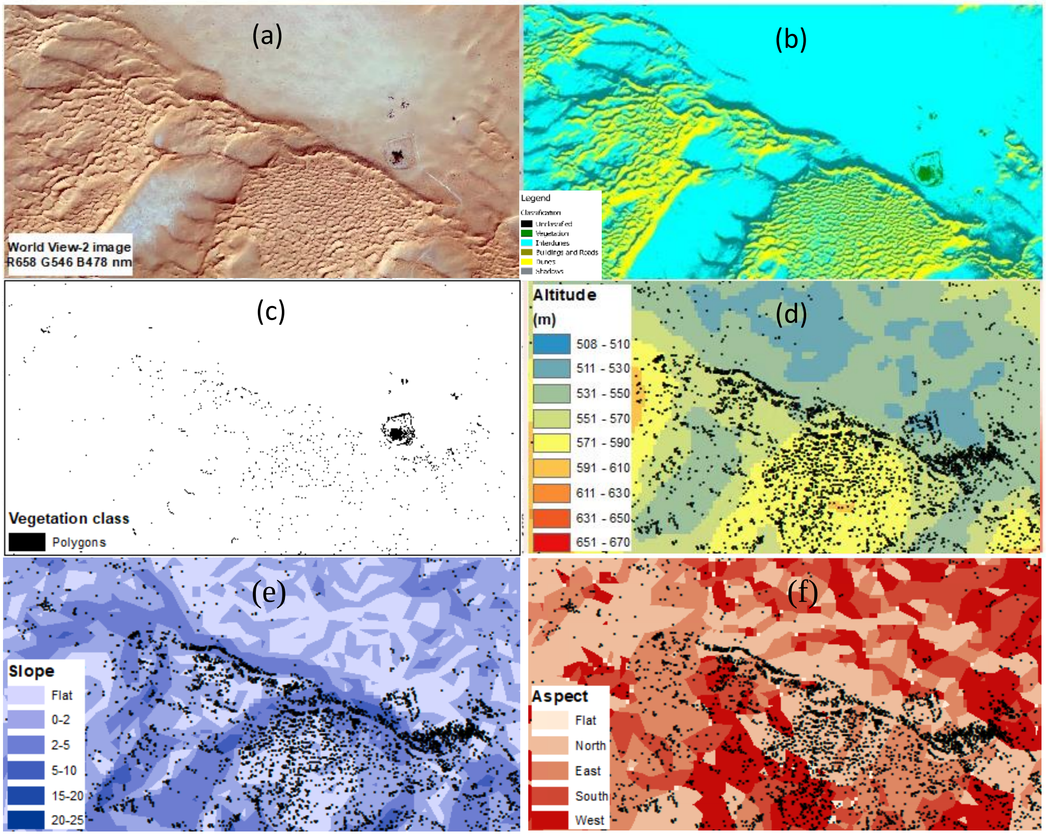

Figure 4. (a) WorldView-2 image over Location 1 showing a linear dune (lower left half) and interdune area (upper right half) with a small farm (centre right). (b) Image classification, (c) shrub vegetation polygons, (d) elevation and vegetation polygon centroids (black dots) (e) slope and vegetation polygon centroids and, (f) aspect polygons with vegetation polygon centroids.

3.3 Topographic characteristics

For topographic characteristics of elevation, slope and aspect of the Locations 1 to 3, the ASTER satellite Digital Elevation Model (DEM) with altitude at a resolution of 30m, was used. With a pixel area of ~ 900 m^2, complex micro-dune features that may influence vegetation cannot be mapped so the expectation from this data set was to map associations with the general topography. Elevation (metres above sea level), slope angle (degrees) and aspect (degrees from north) for each individual pixel were calculated from the DEM, using ArcMap. Elevation was classified into eight categories in 20m increments ranging from 510 metres to 670 metres above sea level, slope angle data were classified into five categories 0 to 2, 2 to 5, 5 to 10, 10 to 20, 20 to 25 degrees, and aspect was reclassified into 90-degree segments centred on; North (315° to 45°), East (45° to 135°), South (135° to 225°) and West (225° to 315°). As conditions in terms of water availability and wind erosion are quite different at the crests and base of dunes (Tsoar 2005; Boer & Sargeant 1998), which have similar slope angles, the analysis was further split into 'upper topography', that includes the top of the dunes and convex slopes leading into the upper dune flanks, and 'lower topography', including the lower dune flanks and the concave slopes leading into the interdunes. To do this, the DEM was detrended by subtracting the mean elevation of each Location to remove the natural gradient of the land, giving a range of values above and below zero. The de-trended DEM was then classified into 20 m interval classes and central class was used to define the topography split. For each DEM pixel (30 by 30 m) the frequency, or density, of IVP was calculated, and compared to each of the categories for elevation (Fig.4 (d)), slope (Fig.4 (e)) and aspect (Fig.4 (f)) for both the upper and lower topography to help interpret relationships of vegetation to wind intensity and direction, groundwater, soil crusts and sediment activity (movement).

4. Results

4.1 Image classification

Three classified images were produced (e.g. Figure 4(c)), and the amounts of each class are shown in Table 1. Shrub vegetation cover made up 0.9 % to 1.5%, shaded sand ranged from 3.7 % to 12 %, illuminated sand, other sand and interdunes ranging from 87.1 % to 95.3 % with negligible contributions from buildings and roads. The NDVI threshold in the class training stage reduced the potential of confusion between vegetation inside shadow as shadow as inspection showed that there were instances where vegetation was detected inside areas of dune shadow.

Table 1. Percentage of each class for each study location from the supervised image classification

Class	Location 1	Location 2	Location 3
Shrub vegetation	0.9	1.0	1.5
Shaded dune sand	12.0	3.7	10.3
Illuminated dune sand	15.2	4.6	3.6

Other sand and Interdunes	71.9	90.7	84.7
Buildings and roads	> 0.01	0.1	> 0.01

To estimate errors in the vegetation classification and, to overcome the impracticalities of a detailed ground survey over these spatial scales of 100s km^2, the vegetation polygon size statistics were used to provide an estimate of confidence in the vegetation detected (Figure 5). Depending on Location 1, 2, and 3, 80 to 90 % of polygons were 3 pixels or less corresponding to individual or small groups of shrubs. Just over 95% of polygons were below 5 to 6 pixels and field observations of vegetation blocks of $24m^2$ (e.g. approximately 6 by 4 m or 3 by 8 m) are not unreasonable. Larger blocks of vegetation can occur, but it is more likely these polygons form elongated and more complex shapes that are difficult to confirm or discard remotely as vegetation, so we consider these as uncertain. At the other extreme it is not unreasonable to consider areas over 500 m^2 (e.g. 25 by 20 m) to be associated with agriculture, as this is where most of these polygons are found and were observed in the field. These patches often correspond to uncontrolled vegetation growth around irrigated areas and are unlikely to have been confused with another class such as shadow. The percentage of polygons that fall inside this range of uncertainty contribute no more than 6% of polygons and 10% of area for each location and consider this as a measure of the degree of error in the classification. This indicates that over 90% of polygons are extremely likely to be detections of vegetation. Using the polygon centroid avoids area calculations of and provides the IVP as a metric of shrub vegetation patch incidence to estimate the shrub vegetation density.

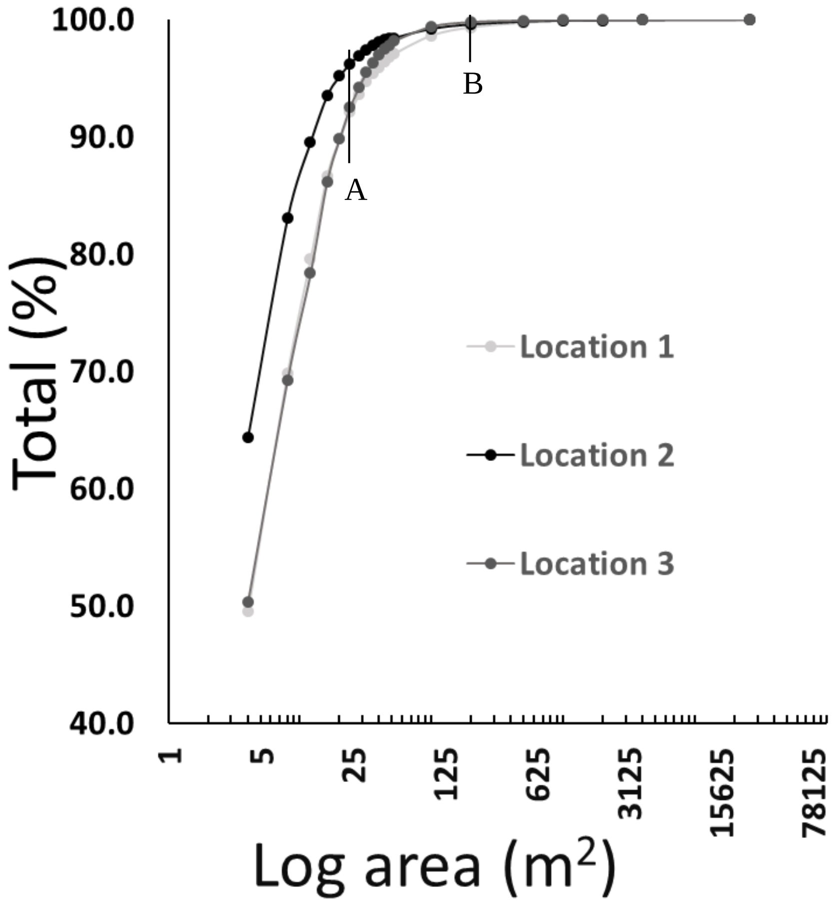

Figure 5. The percentage of vegetation polygons by area (m^2) for the three locations. Labels are a guide to the numbers of contiguous pixels making up each polygon and the x axis is logged for visualization. The least certain vegetation polygons, i.e. those that are unusually large and too small for cultivation fall between lines A and B.

4.2 Topographic relationships with IVP

The elevation range for each of the locations on the study area are 510 m to 690 m for Location 1, 510 m to 650 m for Location 2 and 550 m to 670 m for Location 3, indicating that Location 3 is slightly more elevated whilst Locations 1 and 2 have the lowest elevations over the buried wadi area (Al-Sulaimi and Pitty, 1995; El-Baz ????, Breeze et al., 2015). The density of IVP in each location for each category of elevation, slope and slope aspect along with the proportion of area, and proportion of vegetation pixels in each category are shown (Figures 6, 7, 8). For each elevation class in Location 1, the percentage area is evenly distributed at approximately 10% in each category (Figure 6 (a)). In Location 2, almost half the area is between 570 and 590 m (Figure 6 (b)) and in Location 3, 75% of the area is between 610 and 650 m. The percentage of pixels with one or more centroid count generally follows the area trends and shows the split in the proportion of vegetated and non-vegetated pixels used to calculate the average IVP. Average IVP values are similar across Location 1 elevations except for the extreme low and high elevations. In Location 2 and 3 there are contrasts in average IVP values and greater IVP variability between the upper and lower topography.

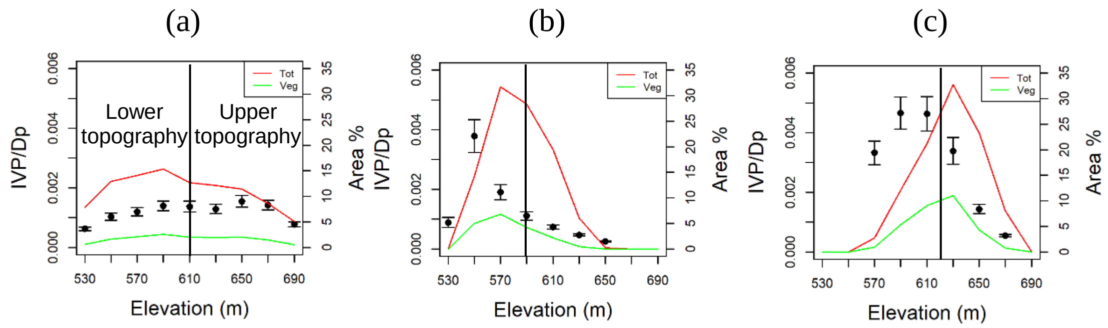

Figure 6: For each elevation category (20 m interval), percentage of the total area (Tot), area with at least one IVP count in a DEM pixel (Veg), and points with bars, the average IVP count per DEM pixel (IVP/Dp) for (a) Location 1, (b) Location 2, (c) Location 3. Error bars are variance (x10 for visualization), the vertical bar marks the boundary between the upper and lower topography.

In terms of slope angle at least 85 % of the area in each location are made up of 0 to 15-degree slopes with the remainder above 15 degrees which are the flanks of the dunes (Figure 7 (a-c)). In comparison to percentage area there are only a few percentage points differences in pixels with an IVP count above 15 degrees. IVP counts and IVP variability generally increases on the slopes greater than 10 degrees except for Location 2 where variability does not change much. When these data are split into lower and upper topography to discriminate similar slope angles found at the top and base of the dunes, particularly in Location 3, om the upper topography, IVP increases on the upper flanks, and decreases on the top of the dunes (Figure 7 (d)) and the lower topo, IVP increases on the lower flanks and increases at the base of the dunes (Figure 7 (e)), these variation are more subtle in Location 1 and not well marked in Location 2 (not illustrated).

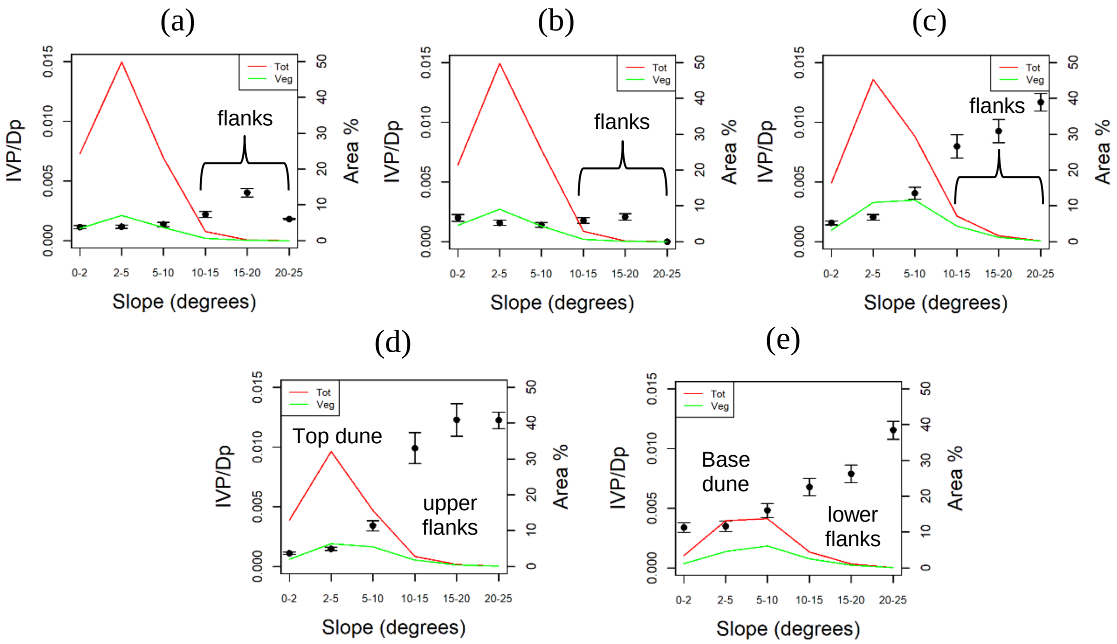

Figure 7: For each slope category, percentage of the total area (Tot), area with at least one IVP count in a DEM pixel (Veg), and points with bars, the average IVP count per DEM pixel (IVP/Dp) for, (a) Location 1, (b) Location 2, (c) Location 3 for the upper and lower dunes and Location 3 (d) upper topography and (e) lower topography. Error bars are variance (x10 for visualization).

For aspect (Figure 8 (a) to (c)) the proportion of area is slightly greater areas of north or west facing aspects, with no specific convergence with the percentage area of pixels with one or more IVP count. Average IVP counts between aspects do not vary much in Locations 1 or 2 but more so in Location 3 where average IVP is least on south facing slopes. Little significant variation was found between upper and lower topography except in Location 3 (Figure 8 (d) and (e)). Percentage area in the lower topography is less than the upper topography and in the upper dunes average IVP values are lowest particularly on south and east facing slopes. On the lower topography average IVP is greatest on the east and south facing slopes.

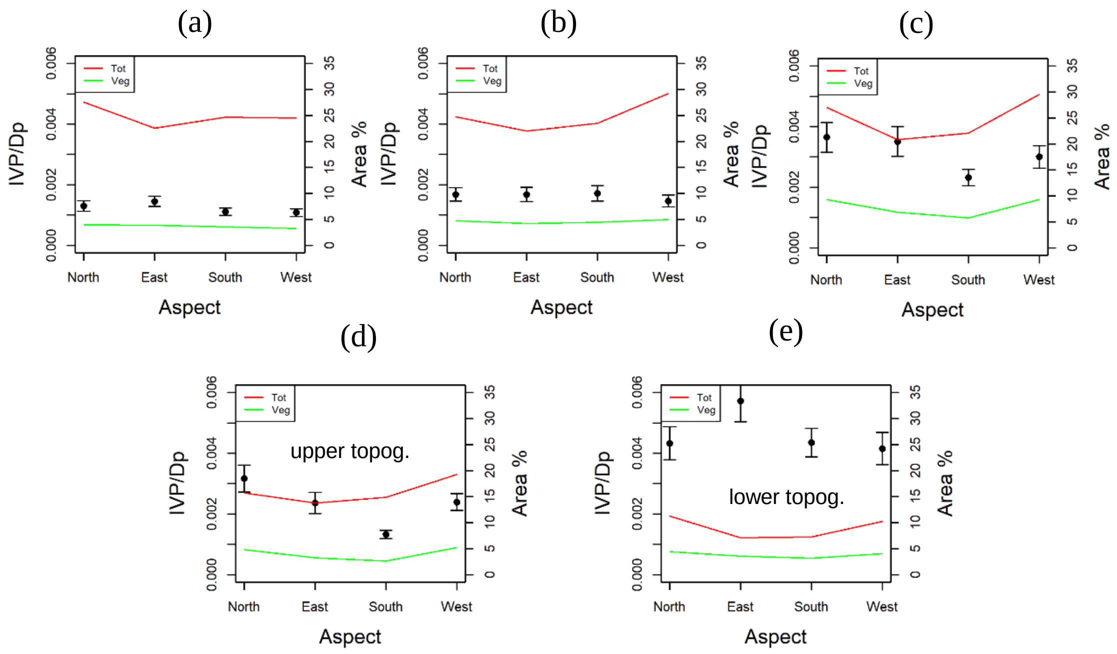

Figure 8: For each aspect category, percentage of the total area (Tot), area with at least one IVP count in a DEM pixel (Veg), and points with bars, the average IVP count per DEM pixel (IVP/Dp) for (a) Location 1, (b) Location 2, (c) Location 3 for the upper and lower dunes, and Location 3 (d) upper topography and (e) lower topography. Error bars are variance (x10 for visualization).

4.3. Spatial distribution in IVP and vegetation.

The spatial distribution of the vegetation polygons and the dominant vegetation types that were identified from the field are shown (Figures 9 (a), 10 (a), 11 (a)). Typical vegetation types that were identified as being detected in the classification were *Calligonum sp.*, *Haloxylon sp.*, *Tamarix sp.*, *Phoenix sp.*, (Date palms) and some patches of herbaceous plants including wheat cultivation. These are larger vegetation types of mainly shrubs, palms and vegetation concentrated by irrigation from farming. *Calligonum* was observed to range in height from a few 10s of centimetres to a metre in height. The IVP density shows that the distribution of this vegetation is non-uniform, scattered or in concentrated areas (Figures 9 (b), 10 (b), 11 (b)), a clear indication that as well as topography there are localised circumstances driving these vegetation distributions. In Location 1 (Figure 9 (b)) vegetation density in the upper topography areas, containing the tops of the dunes, can be extremely low and scattered whereas some areas are high density, particularly in the east where the dunes are more rounded in shape. Vegetation is found on many flanks of the linear dunes over the upper and lower topography boundary, where the slopes are steepest. In the lower area, high density vegetation clusters are found adjacent to farm areas, and clustered in isolated areas away from the farms. Vegetation density varies across the interdunes with very low counts over the evaporite deposits in the west of the location. Field observations show that *Calligonum* is predominant across the landscape (approximately 100 cm high) with smaller dwarf sizes (20 to 60 cm) on the interdunes. Around the pivot irrigation, salt tolerant *Haloxylon* sp. are common. *Tamarix* has been observed in the south west corner (Figure 9 (a)).

Vegetation in the upper topography of Location 2 is scattered and of low density, there are no concentrations of density on the top of the dunes, except for a few of the steeper slopes on the dune flanks across the lower area boundary (Figure 10 (b)). Vegetation is more abundant in the lower topography across the interdunes and there are no significant densely vegetated areas in the central part of the location. This contrasts with the vegetation around the farms in the north west and south east where there are high densities of vegetation, that are confined by the steeper dune slopes. Field observations identify a distinct change in vegetation around the farming areas where *Haloxylon*, *Tamarix* and herbaceous vegetation are observed in contrast to the central area where *Calligonum* is present, with dwarf sizes in the lower, interdune areas. (Figure 10 (a)).

In Location 3 there are marked contrasts in the vegetation distribution. In the upper topography on the tops of the dome dunes vegetation is quite scattered. Vegetation then occurs with greater frequency and density towards the steep slopes at the boundary of the upper and lower topography (Figure 11 (a)). This does not seem to be trending with a specific aspect. In the lower topography, on the steeper slopes and the interdune areas there are greater incidences of vegetation with high densities. In these areas of high density, the influence of irrigation from farms is less marked than Location 1 and 2. Of note are small arcuate and linear vegetation patterns radiating from the dunes across the interdunes (Figure 11 (b)). The tops of the dome dunes have low densities of large (100 to 150 cm high) *Calligonum* bushes whereas in the interdunes there is a mixture of low density smaller sized (30 to 50 cm) and larger (100 to 150 cm) *Calligonum* bushes, particularly in the areas where vegetation was noted to be of high density. *Tamarix* is found in enclosed depressions in the interdunes. Herbaceous

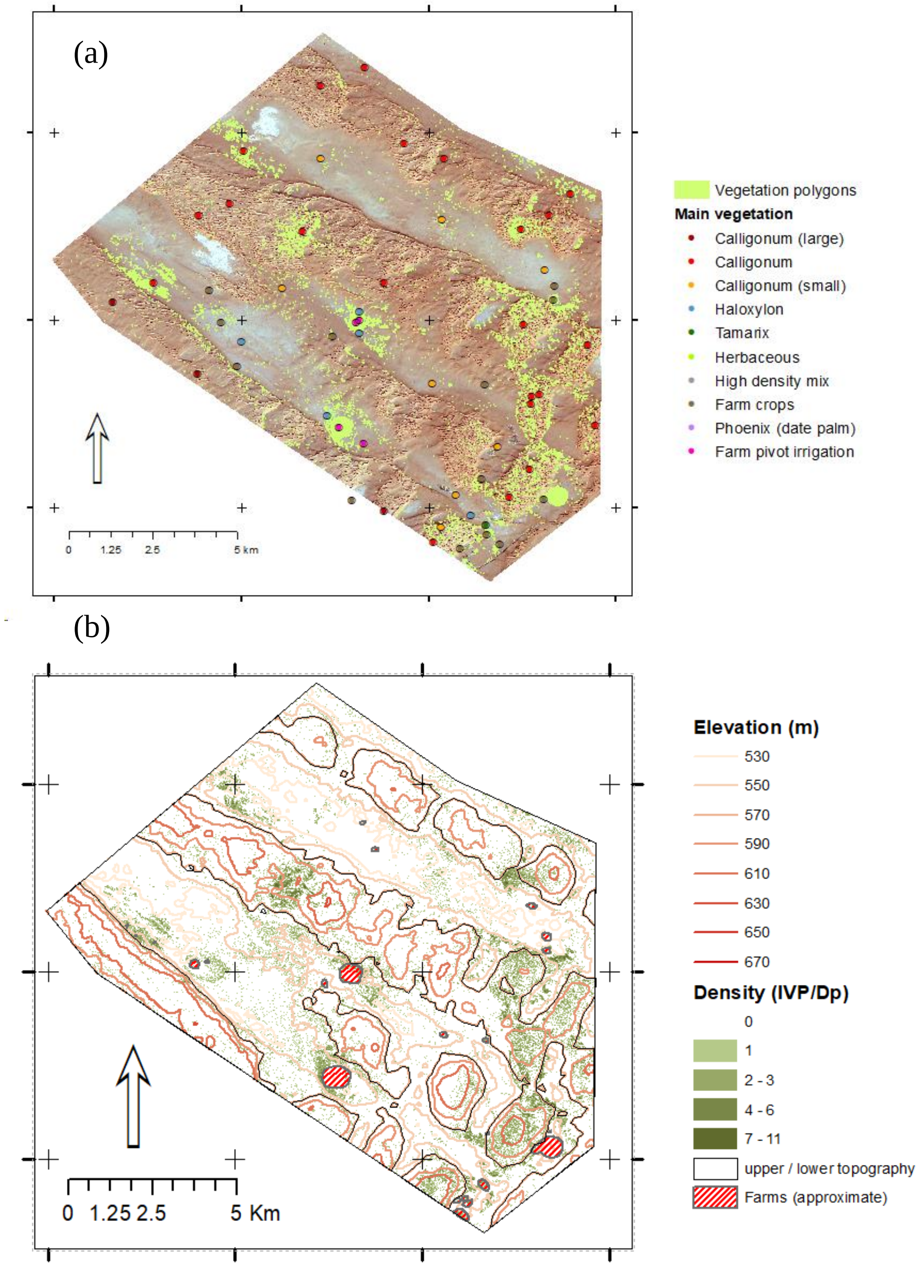

Figure 9. Location 1. (a) Distribution and coverage of the vegetation polygons and the major vegetation types observed in the field overlain on the WV-2 image. (b) Contour map showing elevation overlain with the upper and lower topography boundaries, the distribution of IVP centroid counts per 30 by 30 m DEM pixel (IVP/Dp), and the approximate locations of farming activity.

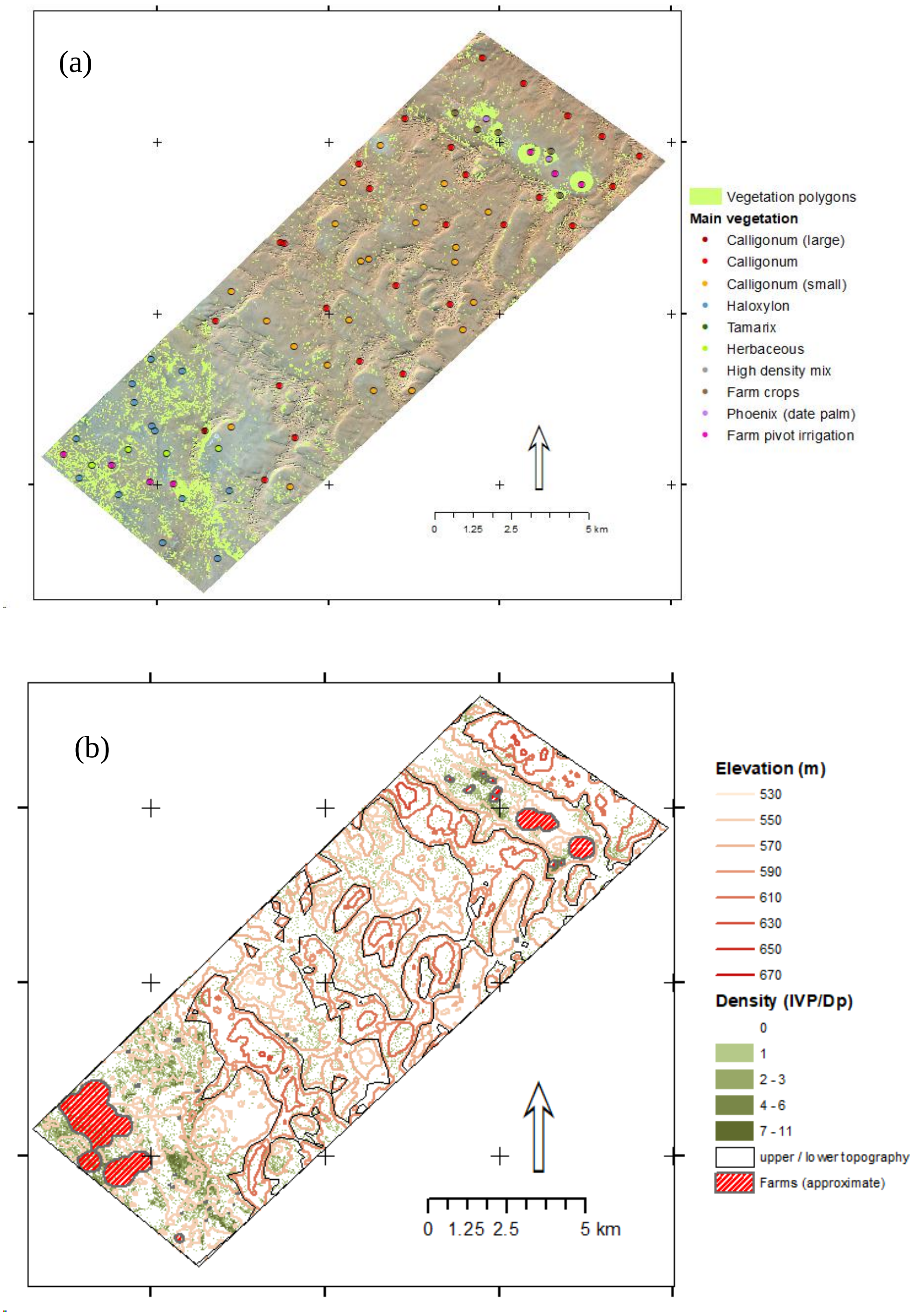

Figure 10. Location 2. – caption as Figure 9

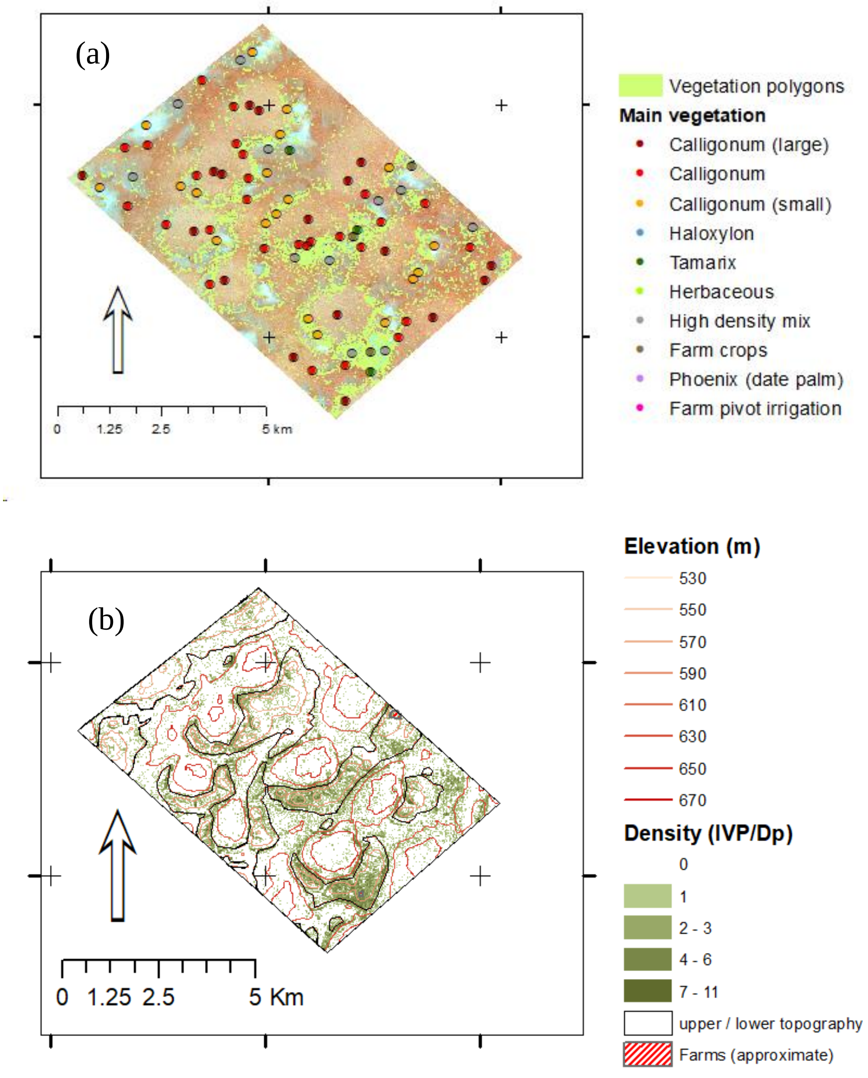

Figure 11. Location 3. – caption as Figure 9.

5. Discussion

Mapping of shrub vegetation density from high resolution satellite images on the different dune forms of, elongated linear dunes, Location 1, broken linear dunes, Location 2, and dome dunes, location 3, has broadened the understanding of shrub vegetation distribution and interactions of vegetation with sediment movement across a desert dune environment in central Saudi Arabia. The aggregate statistics and mapping of IVP (Incidence of Vegetation Patches) underscored some characteristic topographic variations controlling vegetation presence and coupled with mapping of shrub vegetation density and identification of shrub types has shown that there are spatial variations in conditions and controls that encourage or inhibit vegetation. These controls influence vegetation surface roughness to better understand how to model geomorphic processes in the area to build a synopsis of vegetation controls on sediment movement.

In Location 1, across the linear dunes a similar average shrub density across all altitudes on the upper and lower topography does not emphasise any major elevation related differences in vegetation control, except for the extreme highest elevations (670 to 690 m), that are most exposed in terms of wind intensity and distance from the water table, and the extreme lowest elevations (510 to 530 m) which are occupied with evaporite deposits (Figure 6 (a)). Wind intensity does not make any major differential impact on vegetation densities between these wide dunes and interdunes (530 to 670 m) and on average a large part of this location is made up of shallow slopes with low vegetation densities. The densest shrub vegetation congregates on the steep slopes between 10 and 20 degrees that make up a small percentage area (Figure 7 (a)) and this area is a place where vegetation is thriving from groundwater and escaping the inhibiting factors of soil crusts and evaporites, wide exposed interdunes, and gusty tops of the dunes. North and east facing slopes enhance vegetation density as they are generally high angle slopes, but the extreme steep slopes (20 degrees and above) with low vegetation density have loose moving sediment that will smother shrub vegetation growth. Between the linear dunes, in the interdunes, the vegetation is mainly small *Calligonum* bushes where very low densities relate to depressions that contain evaporite deposits and greater densities relate to slightly higher relief caused by the accumulation of sands and clays that have drifted off the linear dunes (Figure 9 (a)). Although the vegetation can extract the groundwater, these stunted *Calligonum* bushes are trying to survive with the high salt content of the interdunes, the sand and clay drifts which are likely to contain less salts encourage larger growth forms. In the interdunes salt tolerant *Haloxylon* bushes take advantage of the extra water seepage from farms and congregate around the irrigated areas, whereas the presence of *Tamarix* shows that the water table is accessible in some interdune areas. The perennial *Calligonum* bushes that exist in high-density areas in the dunes, mainly in the east of Location 1, indicate that the water table is accessible in the elevated dune areas, away from salt concentrations and this is in the vicinity of the buried wadi bed. There are also outlying areas of high shrub vegetation density providing evidence the water table is accessible in other areas.

The broken linear dunes in Location 2 have the highest shrub vegetation densities at the lower elevations (less than 570 m) which make up a majority of this area (Figure 6 (b)). Vegetation densities decrease with altitude (630 to 650 m) as sediment transport is more active on these broken dunes that have all round exposure to prevailing winds. There is no favoured slope angle, even though the proportion of area for each slope category is almost identical to Location 1 (Figure 7 (b)). Two factors are at play, farming results in many more patches of vegetation on the lower flatter slopes and there is a lack of concentrated vegetation patches on steeper slopes. The intensity of farming causes a distinct split in shrub vegetation density and type due to the exploitation of groundwater for cultivation in the interdunes (Figure 10 (a)). This has caused a proliferation of *Haloxylon* that can survive in interdune areas with relatively higher salt content utilising the irrigation seepage from the date palms and farm crops. Away from the irrigated areas in the interdunes, small *Calligonum* persists in low densities, by surviving off groundwater in the same way as Location 1, and on the dunes where sediment is unstable, it is difficult for shrubs to establish and few *Calligonum* survive.

There is a distinct contrast in shrub vegetation density with elevation in the dome dunes of Location 3. The density is greatest in the lower elevations 550 to 630 m and much lower above 630 m because the wind intensity is stronger at higher elevations, where colonisation and establishment of vegetation is much more difficult, in comparison to the lower to middle elevations that are quite sheltered (Figure 6 (c)). In terms of percentages there are greater areas of slopes above 10 degrees than Location 1 and 2, and these dune flanks have much greater average vegetation densities than Location 1 and 2. The differences in densities on similar slope angles between the upper and lower flanks and dune base and dune top are distinct (Figure 7(d) (e)). This is because the tops of the dunes are exposed to intensities of winds that cause sediment to move, and the wind intensity is reduced on the upper flanks, so vegetation can more readily establish lower down. The reduction in vegetation density on the lower flanks is a balance between reaching the water table and the inhibiting concentrations of salts from the evaporites in the interdunes. The tops of the dunes support large isolated *Calligonum* shrubs which are of low density because of the constant movement of sand makes it difficult for new bushes to establish (Figure 10 (a)). Towards the rims of the domes on onto the tops of the steep slopes *Calligonum* bushes become smaller but much denser where the wind has less intensity, and sediment is more stable. There are some spatial variations in bush size around the dome dune flanks which suggest complex local influences between, salts, wind intensity and water availability. Moving down the flanks of these dunes *Calligonum* colonise the sides of sand spurs (e.g. Figure 3 (b)), similar to those found on star dunes, that protrude into the interdunes and sometimes cross to an adjacent dome.

These features do not contain high amounts of evaporite salts and are formed slowly by multiple changing wind patterns with limited sediment movement that allow establishment of shrubs. Around and slightly higher in elevation than the evaporites, where vegetation can use the water table and tolerate salts, vegetation is dense and more likely to be small *Calligornum*. Irrigation around farms in the interdunes causes mixed high-density vegetation, and the presence of *Tamarix* indicates that there is a water table close to the surface.

Overall in these three locations, the balance in exposure to wind intensity, positions relative to soil, evaporite salts and accessibility to a water table are major factors influencing the vegetation. Not unreasonable suggestions, as in the upper topography of dunes Tsoar (2005) and Lancaster (2009) describe a reduction in vegetation where sediment is more likely to be moving because of the impact of wind intensity increasing across the tops of dunes at higher and more exposed elevations. This was found on the tops of the dome dunes and in the broken linear dunes which are raised above the interdunes but was not always the case on the linear dunes where vegetation densities could be high. In the lower topography Tsoar (2005) also found that vegetation in interdunes is found elevated above soil crusts but positioned upslope and close enough to reach the water table much in the same way we find around the dome dunes. In the linear dune areas, Location 1 and 2, shrubs can exist in evaporite depressions, albeit as a dwarfed form. It was also found that bigger shrubs were found on sand drifts in some interdunes, reflecting the observation of Tsoar and Møller (1986) that vegetation will more readily colonise on sands rather than fine soils in arid locations. In this area, Bradley et al., (2018) identified increases of and variations in amounts of evaporite and carbonate minerals in the interdunes when compared to the dunes, and these differences influence the type and size variations of the shrub vegetation found across the interdunes. Dunkerley (2011) found that vegetation can be coincident with agricultural activity because irrigation distributes groundwater and nutrients, and this was found around farms in the three study locations, clearly a consequence of pivot irrigation and small farm activities. Even around unused pivot irrigation the results and observations from the field find that vegetation, such as *Haloxylon* and an herbaceous cover, can grow in areas of previous agricultural disturbance, which Dunkerley (2011) also found can be a consequence of soil crusts being broken up by previous ploughing. Our findings do not fully agree with some processes simulated by the dune modelling community. It was found that steep slopes could support vegetation, areas that modellers might consider as slip faces where vegetation cannot grow faster than the toppling of sediment (Barchan and Hugenholtz, 2015). As vegetation presence in these locations is assisted by the water table, consideration of the relationship of water tables to support vegetation on steep slopes could be an area to advance in dune models.

Understanding what underlying factors control the vegetation provides evidence to reconstruct the evolution of this landscape. Aeolian processes are actively moving and mixing sediment in this area (Bradley et al., 2018) and key to understanding this sediment movement is how the wind intensity from the northerly Shamal winds is likely to interact with the vegetation. The maps of vegetation density (Figures 9 (b), 10 (b), 11 (b)) show variations within, across and between different dune forms. This variation of vegetation was also found by Wiggs et al., (1995a), on linear dunes which was found to effect sediment transport activity, surface roughness (z_0), and the wind velocity profile. (Wiggs et al., 1995b). Using the maps (Figures 9 (b), 10 (b), 11 (b)), denser vegetation is likely to have higher z_0 values than dispersed vegetation and the vegetation density contrasts can be are a proxy for potential rates of sediment activity, that can infer dune maintenance, migration and dune stability. Wiggs et al., (1995b) found the roughness element concentration, λ (the ratio of the plant silhouette area and plant spacing (Raupach et al., 1980)) to be proportional to z_0. As the vegetation density estimates on the maps are a coarse analogy to λ we can establish a relationship of shrub vegetation density to proportional variations in $z_{0.}$ However, since there are huge contrasts in dune and interdune dimensions between the three locations topography will also have a bearing on wind intensity and must also be considered. Considering the landscape, in Location 1, active sediment movement occurs along the sandy linear dunes (Figure 9 (b)) where there is least vegetation and low z_0. This south-easterly sediment movement is then held up in the east of Location 1 where due to the presence of groundwater along a likely axis of the buried section of the Wadi Al-Rimah (Al-Sulaimi and Pitty 1995) vegetation is denser and increases z_0. In Location 2 (Figure 10(b)) the dunes are in a linear arrangement and from the east to west become more low lying and isolated with greater interdune expanses and a limited upwind sediment supply from the north west. On the dunes, the low-density shrub vegetation has a low z_0 and will allow active sediment movement across the location, which prevents vegetation from stabilising. In these circumstances it seems that applying sediment deposition rates movement to peak deposition tolerance of vegetation (Barchan and Hugenholtz, 2012) is applicable. In contrast to the dunes with generally more vegetation in the interdunes, albeit smaller forms of *Calligonum* due to the increased salts in the interdunes, z_0 is greater, reducing sediment movement and encouraging establishment of vegetation in greater densities than on the dunes. Around the farming areas the artificial distribution of water encourages and supports vegetation with artificially raised z_0 potentially filtering and trapping sediment from the local system. In the dome dunes (Figure 11(b)) z_0 varies appreciably more, increasing from the top of the dunes downwards as vegetation density increases. Reduction in wind intensity is evidenced by the sand spurs, also covered in vegetation that will increase z_0. The positioning of the spurs indicates weak multidirectional winds, due to topographic sheltering in the narrow interdunes. Sediment transport activity is low and dense vegetation develops along the spurs as well as on the dome dune sides. This process increases z_0 and reduces the amount of sediment movement. On the tops of the dome dunes z_0 is low as vegetation has difficulty trying to colonise where the water table is more difficult to reach and higher wind intensities can perpetuate sand movement in multi-directions.

Using high resolution satellite images to detect sparse vegetation in a desert sand sea has provided an overview of vegetation patterns and sediment movement beyond spatial scales that are usually limited to features or landscapes of a few 100s of metres (e.g. Quets et al., 2017). This is a step up from using medium resolution imagery that relies on the presence of heavy vegetation cover to produce meaningful results (e.g. Yeteman et al., 2009). At this resolution (2 by 2 m) it was difficult to identify small low biomass, such as grassy vegetation and dormant woody vegetation. During the classification development these areas were found to be spectrally more like shadow or sand classes making it difficult to separate these occurrences of vegetation because of the spectral dominance of the surrounding sands and the shadow of the feature that the vegetation creates (e.g. nebkhas). The vegetation that was detected is of bush or shrub proportions, or clusters of more permanent vegetation, identified from the field as *Calligonum sp*, *Haloxylon sp* and *Tamarix sp*. These are typical genera of vegetation in deserts in the Arabian Peninsula being found on dunes, interdunes, sand sheets and alluvium (El-Kewably et al., 2015; Fryberger et al., 1983). Their large size and persistence as perennials in the landscape will reflect evidence of longer term dune stability that are appropriate to compare vegetation cover between and within different dune types across large areas. Where large vegetation patches were detected, it was found this related to plantations of *Phoenix* (data palms) or a continuous cover of ephemeral herbaceous vegetation often due to the nursing of crops around sedentary agriculture.

It is possible that a temporal sequence of images will reveal additional patterns when different vegetation types become photosynthetically active in response to variations in temperature and precipitation (Figure 2), which may also expand the water table. In desert and arid systems different species are active at different parts of the calendar and will react to abiotic factors such as light and temperature (El-Keblawy et al., 2017), aspect determined micro-climate (Aguillar and Sala 1999; Måren et al., 2015), or requiring larger quantities of water to survive (Halwagy & Halwagy 1974; Parker 1991; Boer & Sargeant 1998; Couteron 2001). These combined factors may result in some species existing on specific landforms (El-Keblawy et al., 2015) or controlling morphology and microclimate at micro-scales (Hesp & McLachlan, 2000). Quets *et al*., (2017) showed the complex spatiotemporal dynamics of vegetation across a small area over three years using a series of drone images, however, many of these plants were small targets and probably impossible to resolve below the WV-2 spatial resolution. Supposing some of these phenological changes could be detected, temporal imagery may provide some clues to the impacts of seasonal agricultural activity on vegetation, particularly nomadic grazing. Relationships of vegetation change with rapid movements on slip faces that are integral parts of modelling (Barchan and Hugenholtz, 2012) were not possible as the resolution of the DEM excludes the detection and mapping of many smaller topographic features. For example, where we found vegetation to inhabit the steepest slopes, it is possible that there are a series of flat ledges that do not appear on the DEM, providing shelter and stability for vegetation. These resolution issues were also noted by Bullard *et al.* (2011). If this detail can be resolved with high resolution DEM data, then high resolution vegetation and sediment transport studies can be made.

Overall this research is a demonstration of a step in broad scale landscape analysis of desert dune vegetation. This information is valuable in that it is filling a gap in information on processes that drive long term environmental change in this area (McLaren et al., 2009). The findings indicate that there is spatial complexity to the vegetation density and empirical observations like this can also help modellers better understand how to force models to reactivate and stabilise dunes (Hugenhholtz et al., 2012). Along with topographic controls it was also found that sedentary agriculture influences the density, type and cover of vegetation, which may need to be considered in some sand transport models. Wider impacts of this research can help guide management of vegetation in desert systems with respect to ecosystem services (Ludwig & Tongway 1995; Boer & Sargeant 1998; Aguiar & Sala 1999; Aly *et al.* 2016; Eamus *et al.* 2015) where agriculture remains a major source of income. Understanding the controls on vegetation in this region is also crucial as groundwater exploitation (El-Keblawy & Ksiksi 2005; Konikow & Kendy 2005) may threaten the existence of natural vegetation and its influence on the landscape (Aly *et al.* 2016).

6. Conclusion

At this spatial scale and resolution, the detection of shrub vegetation distribution was a realistic expectation and it was possible to relate shrub vegetation distributions to specific topographic controls. However, the ability of vegetation to colonise these spaces varies. This may be due to the dimensions of dune and interdune topography affecting wind intensity, favourable areas to reach the water table, spatial variations in the water table, and the abundance of salts in interdunes that degrade the conditions for vegetation survival. Whilst we have improved the knowledge and understanding of the presence of vegetation in a sand sea in central Saudi Arabia, this research illustrates the complexity of distributions of shrub vegetation that dune modellers require to force their models.

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