# Remote sensing and spatial analysis of aeolian sand dunes: A review and outlook

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ABSTRACT

For more than four decades remote sensing images have been used to document and understand the evolution of aeolian sand dunes. Early studies focused on mapping and classifying dunes. Recent advances in sensor technology and software have allowed investigators to move towards quantitative investigation of dune form evolution and pattern development. These advances have taken place alongside progress in numerical models, which are capable of simulating the multitude of dune patterns observed in nature. The potential to integrate remote sensing (RS), spatial analysis (SA), and modeling to predict the future changes of real-world dune systems is steadily becoming a reality. Here we present a comprehensive review of significant recent advances involving RS and SA. Our objective is to demonstrate the capacity of these technologies to provide new insight on three important research domains: (1) dune activity, (2) dune patterns and hierarchies, and (3) extra-terrestrial dunes. We outline how several recent advances have capitalized on the improved spatial and spectral resolution of RS data, the availability of topographic data, and new SA methods and software. We also discuss some of the key research challenges and opportunities in the application of RS and SA dune field, including: the integration of RS data with field-based measurements of vegetation cover, structure, and aeolian transport rate in order to develop predictive models of dune field activity; expanding the observational evidence of dune form evolution at temporal and spatial scales that can be used to validate and refine simulation models; the development and application of objective and reproducible SA methods for characterizing dune field pattern; and, expanding efforts to quantify three-dimensional topographic changes of dune fields in order to develop improved understanding of spatio-temporal patterns of erosion and deposition. Overall, our review indicates a progressive evolution in the way sand dunes are studied: whereas traditional field studies of airflow and sand transport can clarify event-based process–form interactions, investigators are realizing a synoptic perspective is required to address the response of dune systems to major forcings. The integration and evolution of the technologies discussed in this review are likely to form a foundation for future advances in aeolian study.

## 1. Introduction

Like many branches of the Earth sciences, aeolian geomorphology spans a wide range of spatio-temporal scales: from airborne sedimentary grains that respond to changes in fluid stress in less than 1 s to broad sand seas that organize into topographic patterns over centuries to millennia. Whereas the study of grain-scale phenomena accelerated substantially following the seminal work of R.A. Bagnold (1941), it took another three decades before the broad-scale patterns of sand dunes were resolved for many of the world's largest sand seas (Breed and Grow, 1979; Breed et al., 1979a). Beginning with images from the early 1970s, remote sensing (RS) has revealed a rich diversity of dune field patterns on Earth, Mars, Venus, and

Titan. The synoptic perspective provided by remote sensing imagery has, however, only recently stimulated a shift away from the single-dune studies popularized in the 1980s and 1990s (Livingstone et al., 2007) towards dune field-scale studies that incorporate spatial analysis (SA) of boundary conditions, dune activity, dune patterns and hierarchies, and dune–dune relations (e.g., Tsoar and Blumberg, 2002; Hugenholtz and Wolfe, 2005a; Kocurek and Ewing, 2005; Mitasova et al., 2005; Ewing et al., 2006; Bishop, 2007; Wilkins and Ford, 2007; Ewing and Kocurek, 2010a,b; Hugenholtz and Barchyn, 2010; Kocurek et al., 2010).

Early work involving RS imagery focused mainly on dune mapping and taxonomy (McKee, 1979). These foundational dune classifications have been related to controlling variables such as sand supply, vegetation cover, and wind directional variability (Fryberger and Dean, 1979; Wasson and Hyde, 1983). At roughly the same time, extensive tracts of dunes were discovered on the surface of Mars during the Mariner and Viking missions (e.g., Cutts and Smith,

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1973; Breed et al., 1979b; Tsoar et al., 1979). It was found that, curiously, most extra-terrestrial dunes have almost identical morphology to those on Earth. Advances in computer hardware and software throughout the 1990s facilitated a shift in study to the reflectance characteristics of dune surfaces (Paisley et al., 1991; Lancaster et al., 1992; Tsoar and Karnieli, 1996; Walden and White, 1997; White et al., 1997; Blumberg, 1998; Pease et al., 1999) and innovative approaches for quantifying historical changes in dune activity (Anthonsen et al., 1996; Brown and Arbogast, 1999). In the last decade, additional progress has been made in the quantitative analysis of dune morphodynamics (Levin and Ben-Dor, 2004; Vermeesch and Drake, 2008; Bourke et al., 2009; Necsoiu et al., 2009) and dune field pattern analysis (Kocurek and Ewing, 2005; Ewing et al., 2006; Bishop, 2007; Wilkins and Ford, 2007; Mason et al., 2008; Bishop, 2010; Ewing and Kocurek, 2010a,b; Hugenholtz and Barchyn, 2010; Kocurek et al., 2010).

Recent studies have shown that improvements in the spectral and spatial resolution of RS data have substantially enhanced the ability of investigators to resolve dune features and processes, much of which were not apparent in earlier types of imagery. For instance, Wolfe and Hugenholtz (2009) used high resolution airborne Light Detection And Ranging (LiDAR) data to detect morphological signatures of barchan dunes that evolved to parabolic dunes in southwestern Saskatchewan, Canada (Fig. 1). The regional extent of these features was only apparent in the high-resolution elevation model produced from the LiDAR data. Scheidt et al. (2010) used data from the Advanced Spaceborne Thermal Emission and Reflection (ASTER) radiometer to map soil moisture dynamics and sand availability across the White Sands Dune field, New Mexico, USA. This was the first time that moisture-controlled sand availability has been quantified in detail at the scale of a dune field. Progress in quantifying dune field dynamics in three-dimensions has also enabled improved understanding of dune form evolution and morphodynamic feedbacks (Vermeesch and Drake, 2008; Reitz et al., 2010). Moreover, contemporary processes operating on the lee slopes of dunes on Mars have been revealed using free imagery from the High Resolution Imaging Science Experiment (HiRISE) (e.g., Reiss et al., 2010; Silvestro et al., 2010; Hansen et al., 2011). In all four examples the improved spectral or spatial resolution provided new insight that would be difficult, if not impossible, to obtain with any other method.

The proliferation of RS data and SA techniques in the Earth sciences has been enhanced further by the development and distribution of standardized global geospatial datasets, many of which are available to users worldwide free of charge (Table 1). This availability enables the compilation of digital atlases of sand seas, such as the Namib Sand Sea Digital Atlas (http://www.shef.ac.uk/sandsea/; Livingstone et al., 2010) or the World Digital Quaternary Atlas (http://inquadunesatlas.dri.edu). Similarly, free images and digital terrain models are available for Mars (Table 1, Fig. 2), thus accelerating research and discoveries about contemporary dune dynamics that would not be otherwise possible (e.g., Hansen et al., 2011). Areas that are relatively inaccessible can now be investigated remotely, beginning with a few clicks of a mouse button, an Internet connection, and applicable software.

While the quantitative study of aeolian dunes with RS and SA is still in its infancy, several key contributions have recently appeared in the literature that demonstrate the potential of this approach for addressing fundamental research questions about the morphometry, dynamics, and organization of dunes. To this end, this paper reviews significant advances, many of which have emerged in the literature since the mid 1990s, that indicate an important direction for contemporary dune research. By reviewing recent progress, our objective is to stimulate further advances in the application of RS and SA to the study of dune field dynamics. We focus on three key topics that serve to illustrate the emerging potential of these technologies: dune activity, dune patterns and hierarchies, and extra-terrestrial dunes. As part of this review we also highlight research gaps and opportunities. We conclude by outlining our views on the future of RS and SA in aeolian dune research.

## 2. Characterizing dune activity

Dune activity is typically viewed as an index of aeolian sand transport potential (e.g., Fryberger and Dean, 1979; Ash and Wasson, 1983; Lancaster, 1988a) that spans a continuum: from bare dunes characterized by uninhibited erosion and deposition (active), to entirely fixed dunes exhibiting no surface change (stabilized). Stabilized dunes are commonly covered by extensive vegetation (e.g., Ash and Wasson, 1983; Lancaster, 1988a). We recognize that the terms dune activity and dune mobility are often used synonymously, but a case can also be made to treat them more distinctly (Thomas, 1992; Lancaster, 1994). For instance, describing a dune as having high mobility, or simply being mobile, is inherently suggestive that the dune is demonstrating migratory movement. Not all types of dune, however, migrate. In terms of characteristic behavior dynamic linear dunes typically 'extend' and star dunes 'accumulate' (Thomas, 1992; Livingstone and Thomas, 1993). Mobility, therefore, might not be the most suitable term for describing dynamism across all dune types. Using the term "activity" could be less ambiguous. The redistribution of sand on dunes may lead to active morphological change, but does not necessarily imply migration. Working on the Kalahari dune field with its prevalence of linear dunes, Bullard et al. (1997) in fact preferred to discuss the dune mobility index of Lancaster (1988a) as an index of dune potential activity instead.

Monitoring dune activity, therefore, relates to observing and quantifying surface change on a dune related to the aeolian sand transport potential. The variable states of activity are associated with different sand fluxes on the individual dunes. Kocurek and Lancaster (1999) provided a robust framework for understanding dune activity through the three components of sand supply, sand availability, and wind transport capacity. Simply put, transport capacity is the potential sand transport rate of the wind; sand supply is the quantity of source material; and sand availability is the susceptibility of surface grains to be entrained by the wind. The complex interplay between these components forms an important control on the level of aeolian sand transport occurring in dunefields. However, it important to recognize that dune activity is not necessarily a direct correlate of climatic processes that regulate supply, availability and transport capacity. Lags, non-linear response, and other controls
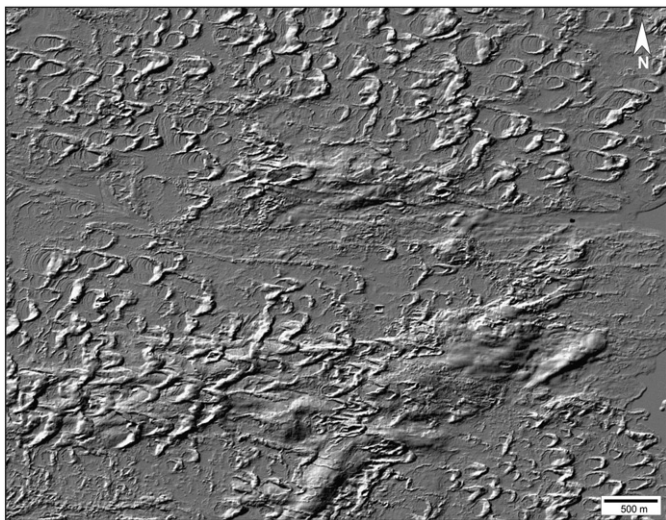


**Fig. 1.** Hillshade image showing detailed topographic features of parabolic sand dunes in the Great Sand Hills, Saskatchewan, Canada. Dominant wind direction is from west (left side of image).

**Table 1**
Examples of free or low-cost data suitable for investigating aeolian dune dynamics. URL addresses lead to online data warehouses to obtain these data.

| Data | Description | Period | Spatial resolution | Spectral bands |
|---|---|---|---|---|
| Corona[a] | Earth observation photographs | 1960–1972 | 2–7.5 m | Panchromatic |
| Landsat[a,b] | Earth observation imagery | 1972–present | 15–120 m | up to 8 bands |
| MODIS — Moderate Resolution Imaging Spectroradiometer[a,b] | Earth observation imagery | 1999–present | 250–1000 m | 36 bands |
| ASTER — Advanced Spaceborne Thermal Emission and Reflection Radiometer [a,b] | Earth observation imagery | 1999–present | 15–90 m | 14 bands |
| HiRISE — High Resolution Imaging Science Experiment[c] | Mars observation imagery | 2006–present | 0.3 m | 3 bands |
| MOC — Mars Orbiter Camera[c] | Mars observation imagery | 1996–2006 | 1.4 m | Greyscale |
| MRO CTX — Mars Reconnaissance Orbiter Context Camera[c] | Mars observation imagery | 2005–present | 6 m | Greyscale |
| SRTM — Shuttle Radar Topography Mission[b] | Earth elevation data | | 90 m | |
| ASTER GDEM — ASTER Global Digital Elevation Model[a,b] | Earth elevation data | | 30 m | |
| HiRISE DTM — HiRISE Digital Terrain Model[d] | Mars elevation data | | 1–2 m | |

[a] http://earthexplorer.usgs.gov (last accessed 27 October 2011).
[b] https://wist.echo.nasa.gov/~wist/api/imswelcome/ (last accessed 27 October 2011).
[c] http://pds-imaging.jpl.nasa.gov/portal/ (last accessed 27 October 2011).
[d] http://hirise.lpl.arizona.edu/dtm/ (last accessed 27 October 2011).

also play important roles, which can offset the response of dune fields to major forcings (e.g., Hugenholtz and Wolfe, 2005a,b; Tsoar, 2005).

A key inhibitor of sand availability (and a control on dune activity) is the presence of vegetation or crusts (Ash and Wasson, 1983; Buckley, 1987). Field studies have demonstrated that the presence of vegetation effectively reduces aeolian sand transport, and vice versa (Ash and Wasson, 1983; Buckley, 1987; Wolfe and Nickling, 1993; Brown, 1997; Lancaster and Baas, 1998; Levin et al., 2008; Okin, 2008). The complex interplay and feedbacks between vegetation growth and sand transport drives the dune system towards one of the two end-member states: active or stabilized. Thus, a biogeomorphic approach is central to the study of dune activity; investigators must consider both biologic and geomorphic processes (Hugenholtz and Wolfe, 2005b).

RS and SA have provided a valuable suite of techniques for quantifying and monitoring changes in dune activity. Variations of dune activity over time can yield insight into the morphodynamic trajectory of the dune system as it responds to forcings such as climate change. To this end, some have suggested that dune activity is a "geo-indicator" of environmental change (Berger and Iams, 1996). Understanding dune activity is also of vital importance for inhabitants of semi-arid dune environments worldwide, as well as for ecosystems that co-evolve with these dynamic templates.

Efforts to quantify dune activity with RS and SA have focused on three related proxy measures: (1) sand availability, (2) dune form movement, and (3) topographic changes. Techniques for quantifying sediment availability examine the planimetric surface cover of vegetation or crust as a proxy for potential sediment transport. Techniques for measuring dune form movement discretize the position of a dune in successive images to quantify horizontal displacement. Methods for examining topographic changes use digital elevation data to explore changes in the surface of the dune (to infer sediment transport). We review advances in each and discuss upcoming challenges.

### 2.1. Measuring sand availability

In semi-arid environments, sand availability is commonly limited by surface vegetation and/or crusting. Techniques and data used to measure the spatial extent and distributions of both have undergone considerable recent evolution. Although the newest high-resolution and/or multi-spectral images are attractive from a detail perspective, the dynamics of sand availability typically change on a scale where multi-temporal studies involving long baselines and older spatial datasets, such as historical maps and analog aerial photographs, continue to be important. For many investigations, insight into the dynamics of sand availability is as important as the quantification of the present state.

#### 2.1.1. Extending temporal baselines

One of the most significant barriers to progress in aeolian geomorphology has been the relatively short temporal baseline of dune activity observations and measurements. Short baselines generally provide an incomplete picture of the morphodynamic response of dunes to changes in sand availability. However, many countries maintain extensive archives of aerial photographs and historical maps that provide opportunities to develop a more complete understanding of
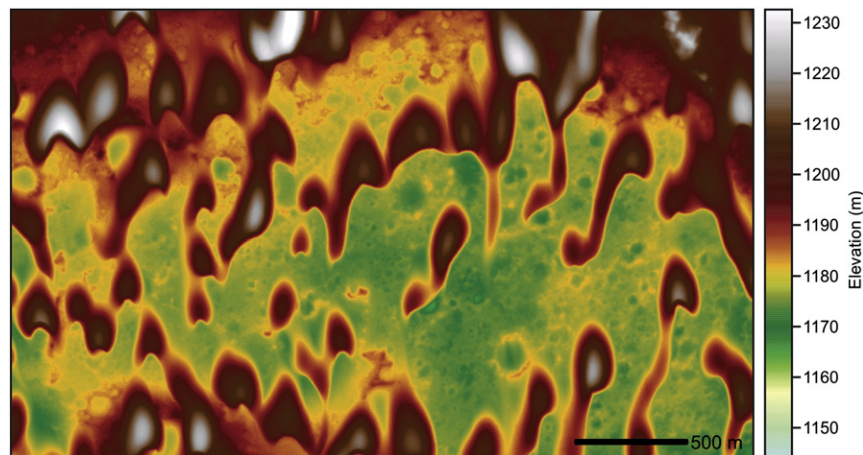


**Fig. 2.** Digital elevation model showing dunes in the Herschel Crater, Mars (DTEC_002860_1650_003572_1650_U01). These data are courtesy of the HiRISE team, Department of Planetary Sciences, University of Arizona. Data are available for electronic download at http://hirise.lpl.arizona.edu/dtm/dtm.php?ID=PSP_ 002860_1650 (last accessed 17 Dec 2010).

the dynamics and effects of sand availability. While much of this spatial data is accessible only in hardcopy format, the proliferation of image analysis and Geographic Information System (GIS) software in the early-to-mid 1990s increased the objectivity and quantitative rigor of measurements made with these data. By scanning the hardcopy photographs or negatives and digitally rectifying the internal (e.g., camera coordinates) and external (e.g., ground coordinates) image parameters, it became possible to create planimetrically true images suitable for spatial measurements. A similar process was accomplished by using large format scanners to convert historical maps into digital datasets. Several studies applied these datasets to quantify changes in vegetation cover and thereby extend the temporal baseline to as far back as the 1800s (e.g., Anthonsen et al., 1996; Levin, 2006). The study by Anthonsen et al. (1996) is particularly noteworthy because by converting a series of hardcopy topographic maps (1887–1977) and aerial photograph (1945–1992) into digital data, they were able to quantify changes in vegetation cover, the volume of erosion and deposition across the dune complex, dune migration, and morphological evolution. Anthonsen et al.'s (1996) study is exemplary as it demonstrates how various types of archival geospatial data can be integrated to resolve long-term changes in dune activity state.

### 2.1.2. Discriminating dune vegetation, soil crust and open sand

The proliferation of image analysis software in the early-to-mid 1990s increased the objectivity and quantitative rigor of measurements made with aerial photographs. This emerging geospatial framework, coupled with a move away from reductionist attempts to understand dune field dynamics, enhanced the shift away from the single-dune studies popular in the 1980s and 1990s (cf. Livingstone et al., 2007) to more synoptic-scale investigations of dune fields involving both RS and SA. In the context of dune activity, one of the earliest accomplishments was the adaptation of existing image analysis techniques to discriminate vegetation and crusts, so as to deduce the degree of sand availability.

Several forms of imagery have been used to discriminate vegetation cover on dunes and quantify its changes over time. For some dune fields, archival black and white aerial photographs have been used to great advantage, providing long temporal baselines and reasonably high spatial resolution (e.g., Gaylord and Stetler, 1994; Tsoar and Blumberg, 2002; Hugenholtz and Wolfe, 2005a; Marín et al., 2005; Levin, 2011). When the photos are converted to digital images and rectified they can be subjected to image analysis routines that generalize or classify the scene into the dominant surface covers. Objective discrimination of bare, open sand from most types of vegetation is straightforward in the majority cases due to the

marked contrast of relative brightness (e.g., digital number) of these cover types. Bare dunes appear as relatively bright areas (high digital number) and vegetation-covered sand appear as darker areas (low digital number) (Fig. 3). While aerial photographs continue to provide invaluable context for monitoring dune activity changes through time, additional information can be acquired with multispectral imagery.

Similar to aerial photographs, presence or absence of vegetation in a dune field is usually straightforward to identify and map with multispectral imagery (although see Section 2.1.3), which has led many investigators to focus efforts on extracting detail about the vegetation density, structure, and species. This information can be important for ascertaining the trajectory of dune activity, and for establishing relations between vegetation growth and aeolian sand transport. For example, Pinker and Karnieli (1995) collected characteristic spectral reflectance curves for several desert dune habitats and dominant desert vegetation. They subsequently used differences in the near-infrared range of the spectrum to map different vegetation types (see example from Ashdod Dunes, Israel in Fig. 4). Whereas in the natural color image all the areas of dense vegetation appear the same, the infrared bands are capable of highlighting trees and an area of the invasive species, *Acacia cyanophylla* (Labill.) Wendl. (Fabaceae) (both in red). In addition to detecting different successional stages across a vegetated or semi-vegetated dune field, the ability to resolve spatial patterns of vegetation types is important for linking empirical observations with numerical models, and for understanding the degree of forcing that would be required to reactivate stabilized or stabilizing dunes. In the numerical model of Baas and Nield (2007) it was found that the addition of two types of vegetation (shrubs and grasses) was necessary to form realistic parabolic and nebkha dunes. In this regard, multispectral imagery could and should be used to test this parameterization, and if needed, guide the refinement of the numerical growth characteristics. In a similar vein, the distribution of different vegetation functional groups (e.g., trees, shrubs, grasses) within a dune field can be used to infer the potential response to disturbance. For instance, during the pioneer stages of dune succession, early-stage colonizing plants tend to produce limited biomass on the dunes, which requires less disturbance for reactivation than dunes in late stages of succession, where greater biomass and pedogenic alteration render dunes more difficult to reactivate.

One of the most important advantages of multispectral imagery is that it can be used to develop vegetation indices (VIs), which accentuate the identification and spatial variation of types and densities of photosynthetically active dune plants. Although few studies have used VIs in relation to dune activity, Levin et al. (2006) found that
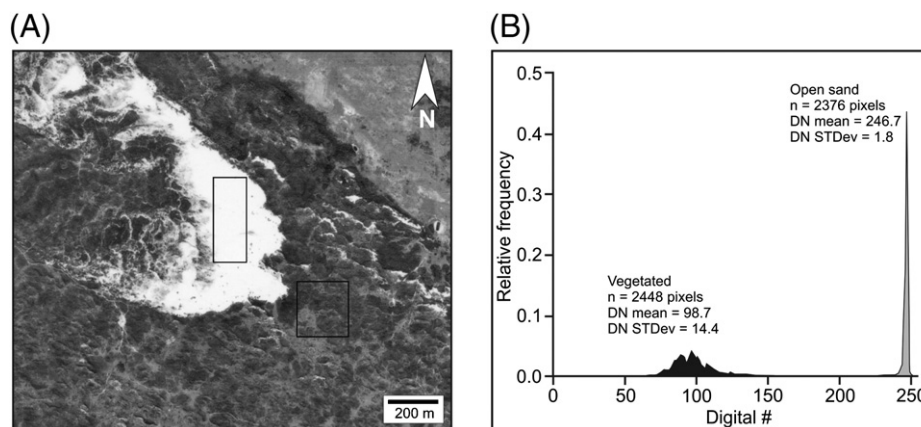
(A)

(B)

**Fig. 3.** The difference in relative brightness (digital number) of active and vegetation-stabilized sand dunes can be pronounced. From a scanned aerial photograph of the Elbow Sand Hills in Saskatchewan, Canada (A), we derive frequency histograms (B) that show marked differences in the relative brightness values of bare sand and vegetation. The locations of the samples are outlined in (A).
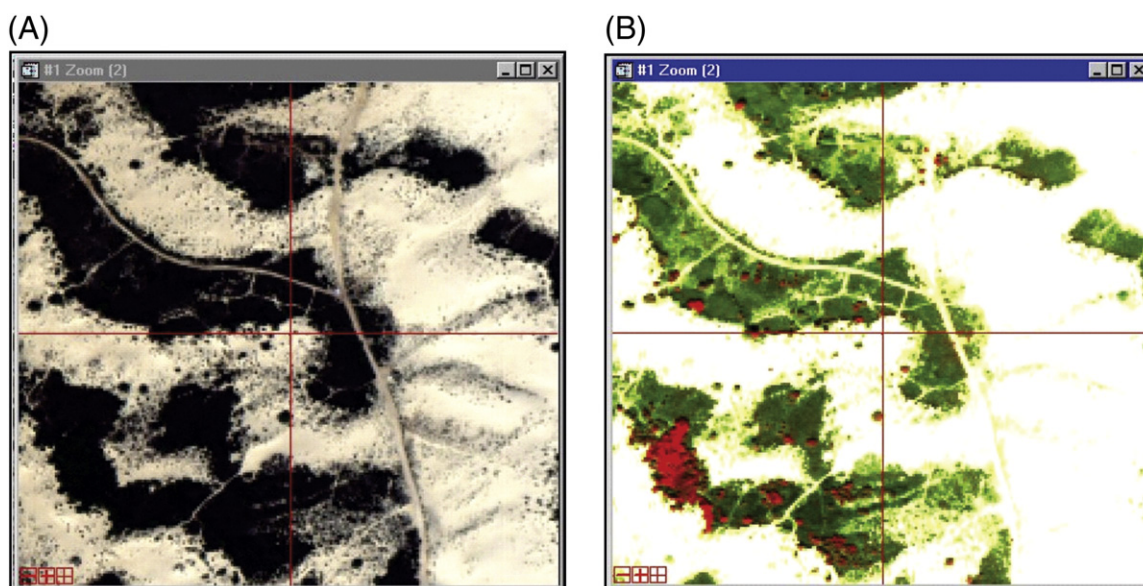
(A)    (B)



**Fig. 4.** An area in the dunes of Ashdod, Israel, as imaged by the airborne hyperspectral Compact Airborne Spectral Imager (CASI) sensor, in October 1999 (3 m spatial resolution). The image on the left is a natural color composite, while the image on the right is a false color composite. In the latter, areas in red represent trees and an invasive species, *Acacia cyanophylla* (Labill.) Wendl. (Fabaceae).

the Normalized Difference Vegetation Index (NDVI) and the Soil Adjusted Vegetation Index (SAVI) explained up to 78% of the aeolian transport rate on coastal dunes. They also developed a predictive model that incorporated SAVI and topographic variables in order to quantify the spatial pattern of sand transport and dune activity (see Fig. 8 in Levin et al., 2006). In our view, this type of approach is under-utilized in the context of predicting spatio-temporal patterns of aeolian sand transport and dune activity.

In some dune fields, the effectiveness of vegetation in controlling sand availability is further enhanced by the presence of biological soil crusts. On Mars, the presence of abiotic crusts may also be important for limiting present-day dune activity (Schatz et al., 2006). On Earth, biological soil crusts are common in arid and semi-arid dune fields (e.g., Negev: Tsoar, 2008; Kalahari: Thomas and Dougill, 2007; China: Li et al., 2007). They can be formed by communities of several types of microphytes including mosses, lichens, fungi, green and blue-green algae, as well as bacteria. These crusts limit the availability of sand for transport by binding and protecting the surface. In typical cases, the uppermost layer of the soil surface is aggregated by

filaments of blue-green algae. Although the crusts are usually not thicker than 1–3 mm, their presence reduces aeolian entrainment by roughening the surface and aggregating particles (Marticorena et al., 1997).

In situ measurements of the spectral characteristics of biological soil crusts have found that, in cases, crusts have a unique spectral signature (for desert dunes in Israel: Karnieli and Sarafis, 1996; Karnieli, 1997; Karnieli et al., 1999; for coastal dunes in Israel: Levin et al., 2007; for semi-arid regions in Australia: O'Neill, 1994). However, the spectral signature of biological soil crusts can be influenced by wetting (O'Neill, 1994), the relative abundance and types of cyanobacteria, and absorption of iron oxide and clay minerals. Tsoar and Karnieli (1996) demonstrated that the spectral reflectance of crust can be used to assess the activity of dunes. Using multispectral imagery from Landsat MSS they measured a gradual decrease in the brightness of the Negev dunes between 1984 and 1989, which corresponded to an increase in crust and vegetation cover (Fig. 5). These changes were attributed to a decrease in the level of disturbance, while the adjacent Sinai dunes in Egypt were brighter, presumably
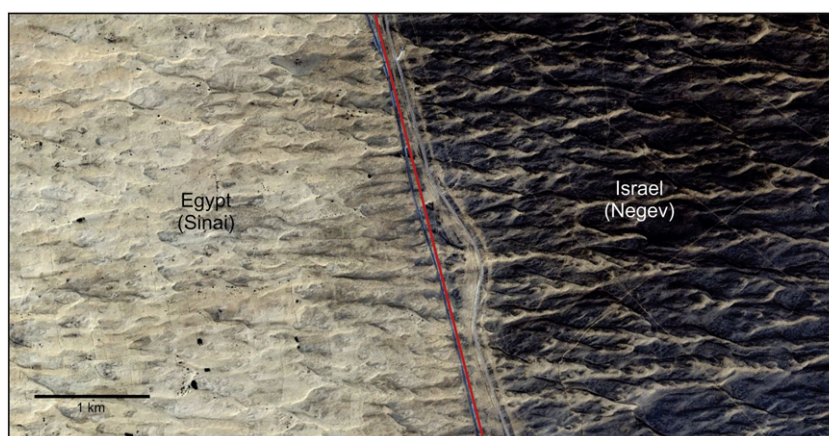


**Fig. 5.** Multispectral image of the border between Egypt and Israel showing the effects of disturbance on the level of dune activity (image source: Google™ Earth; image date: 04 Oct 2011). On the Israel side the dunes are darker because they are mostly stabilized by vegetation and crust, whereas dunes on the Egypt side are brighter because they are mostly active and bare. The difference is attributed to higher levels of anthropogenic disturbance on the Egypt side (see Tsoar and Karnieli, 1996).

due to more frequent human disturbances (trampling, cutting of vegetation and grazing) preventing crust and vegetation from colonizing the dunes. Levin et al. (in press) demonstrated that using high spatial resolution satellite imagery before and after rainfall, biological soil crusts could be identified, as they are quick to respond. Using Quick-Bird, Aster and Landsat imagery Levin et al. (in press) quantified the effects of wildfires in the Great Victoria Desert (Australia), and showed that while biological soil crusts are affected by fire, they can regenerate in a few years.

Despite progress in detecting crusts and various spectral details, their role in dune dynamics is not well-established in an empirical context. Simulation models suggest that crust can alter dune form, which may account for certain dune morphologies observed on Mars (Schatz et al., 2006); however, the association between crusts and dune form on Earth is, as of yet, largely unexplored. In this regard, the coupling of RS-based measurements of crust distribution and dune dynamics with field measurements of aeolian sand transport will be important for developing a greater quantitative understanding of crust effects on dune activity.

### 2.1.3. Challenges

While considerable progress has been made in the application of RS and SA to the quantification of sand availability, some aspects remain poorly resolved. In particular, the surface reflectance characteristics of partly vegetated dunes remain poorly parameterized. This topic is especially important because it limits the understanding of the interplay between abiotic and biotic processes during the intermediate states or transitions between dune activation and stabilization.

Presently, there are four key challenges: (1) the so-called 'mixed pixel' problem, (2) the effects of topography on reflection, (3) image commensurability, and (4) model parameterization.

The mixed pixel problem results from the fact that individual areas on sparsely-vegetated dunes consist of a mixture of different features or classes that are commonly below the resolution of the sensor. The process of resolving the proportion of reflectance from the sand and vegetation (including live and dead biomass) is referred to as spectral unmixing. Pixels are deconvolved into the spectral components that make up the total reflectance (e.g., Smith et al., 1990; Okin et al., 2001; Lucas et al., 2002). In two related papers Asner and colleagues demonstrated that the spectral reflectance of green

vegetation, dry biomass (e.g., non-photosynthetic vegetation), and bare soil can be separated within the shortwave infrared (2100–2400 nm), and that hyperspectral sensors can indeed unmix these spectral signatures at the pixel level in arid and semiarid ecosystems (Asner and Lobell, 2000; Asner and Heidebrecht, 2002). By establishing better estimates of vegetation cover on dunes it should be possible to relate these data to field-based measurements of aeolian sand transport (e.g., Thomas and Leason, 2005; Levin et al., 2006). In our view, this is a pressing research need that will extend the breadth of field-based measurements and models of vegetation-transport processes (e.g., Okin, 2008), and help in the refinement of numerical models that rely on assumptions about the spatio-temporal dynamics of vegetation in dune fields (e.g., Nield and Baas, 2008).

The second challenge is related to spatial differences in solar illumination that arise from the irregular shape of the dune terrain. This effect causes variations in the reflectance of identical vegetation types or covers due to shading. In the northern hemisphere, for example, steep south-facing slopes on recently stabilized dunes often appear brighter than those on north facing slopes (Fig. 6), but, without correction for terrain illumination, it is near impossible to determine if the difference in brightness is real or a topographic artifact. As digital terrain models become more widely available, topographic normalization could be used to improve image classifications of seral vegetation communities on dunes, especially at mid to high latitudes where terrain illumination effects are most pronounced. ATCOR is an example of a remote sensing application that offers the removal of topographic effects of shading (©DLR 2010) (Richter, 1998).

Third, consideration of image commensurability is important for multi-temporal studies. For example, as the spectral characteristics of vegetation can change throughout a season, it is vital for investigators undertaking multi-temporal studies to ensure that the spectral characteristics of vegetation are approximately equal. To determine the appropriate time for collecting hyperspectral imagery so that vegetation mapping over coastal dunes in the Netherlands could be most effective, Til et al. (2004) measured field spectra in two different periods early in the growing season. They found that at the end of May (e.g., earlier in the growing season) vegetation could be reliably classified with the greatest accuracy. Differences in the effectiveness of RS classifications throughout the season
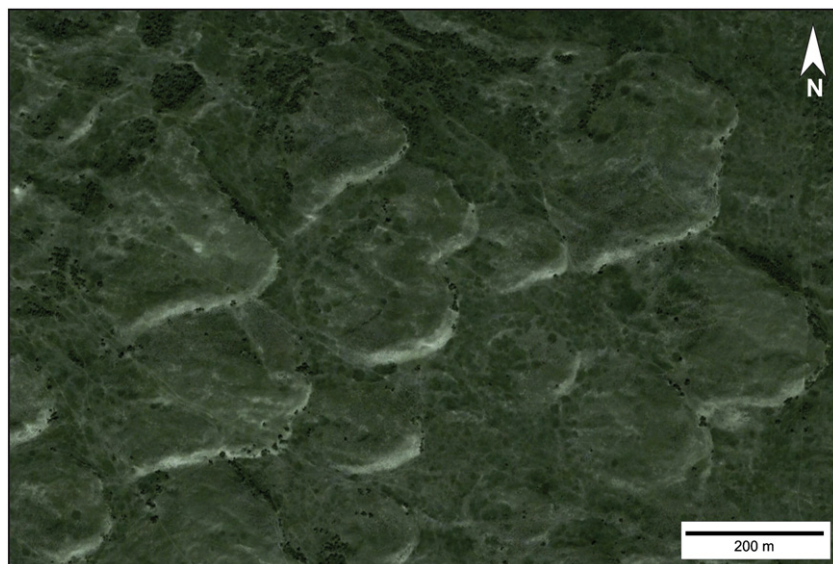


**Fig. 6.** This 2005 image shows the effects of topography on solar illumination. The vegetation-stabilized parabolic dunes (Great Sand Hills, Saskatchewan, Canada) have bright southeast-facing slopes, suggesting partial or complete exposure of bare sand. In contrast, the northeast-facing slopes are darker, but this might be an effect of topographically induced shading because the solar illumination was originating from azimuth 170°.

suggest that images from different times in the season may be incommensurate.

Finally, although RS analysis of vegetation and crusts has undergone significant evolution, linking these parameterizations to numerical dune field evolution models can be difficult. Although there is process-based research linking ground-based measurements of vegetation and crusts to wind erosion (see e.g. Shao, 2000), direct quantitative translation from RS data to ground-based measurements can be difficult. In cases, dune researchers can borrow from dust emissions researchers, who have integrated models and remote sensing of surface properties for some time (e.g., Lu and Shao, 2001; Shao and Dong, 2006; Yin et al., 2006; Bullard, 2010, among others). However, researchers of dune dynamics may require finer scale data than presently included in dust models and a research gap exists in translating RS parameterizations directly to increases in critical threshold and reduction in near surface shear stress. For example, Durán et al. (2008) related vegetation cover to shear stress partitioning by assuming that planimetric cover of vegetation is equivalent to the frontal area index. In other vegetated dune models, investigators have represented vegetation with non-dimensional "vegetation effectiveness" (Nield and Baas, 2008), further complicating direct comparison with RS data. The coupling of RS and models is important: RS offers a promising approach to improve vegetated dune models. The vegetation growth response to topographic change in some models is governed by simple "growth curves", which tend to be based on "trial-and-error" or qualitative rationales (see p. 731 in Nield and Baas, 2008). Multi-temporal RS data could be used to create empirical "growth curves", which could immediately improve vegetated dune models. What is needed, therefore, is a greater coupling between field-based and RS-derived measurements of vegetation response to erosion and burial at the scale of dunes or dune fields.

### 2.2. Dune form movement

Observable movement of a dune form provides an unambiguous indicator of active sand transport. Although it is relatively straightforward to qualitatively identify dune movement, devising a rigorous quantitative method that can be unambiguously applied requires much more care, especially given the diversity of dune forms that exist in natural environments.

The most widely used method involves measuring the distance between two lines representing successive positions of the dune (Gay, 1999) (also termed as "nose to nose", by Bailey and Bristow, 2004). Typically the edges of slipfaces, brink lines, or cuspate vegetation marks are used to represent the position of the dune (Jimenez et al., 1999; Levin et al., 2009). Several arrows/lines are drawn between the lines and the average length recorded. This method has been widely used (e.g., coastal dunes of Oregon: Hunter et al., 1983; coastal dunes of Alexandria, South Africa: Illenberger and Rust, 1988; coastal dunes of Ceara, Brazil: Jimenez et al., 1999). However, challenges can exist in reproducibility (Goudie, 1994, pp. 347–348): How densely should the arrows be drawn, in what direction do they point, and how can the starting and ending points of each arrow be objectively determined? In addition, the method assumes that all the different parts of the dune advance at the same rate, which may not be the case in stabilizing dunes. This method can result in an overestimation of the calculated advance rate (Levin and Ben-Dor, 2004).

Levin and Ben-Dor (2004) suggested using an area integration method to determine dune form movement to improve previous methods. The lines representing the dune at successive positions are joined, forming a polygon, which represents the displacement of the dune. This method avoids some of the subjectivity of drawing lines and results in improved measurements of dune movement (Levin and Ben-Dor, 2004). The linear method was suggested by

Bailey and Bristow (2004) to study the migration of the coastal parabolic dunes at Aberffraw, North Wales. They suggested fitting a best-fit linear trend line to the data points forming the polylines representing the dunes ridge positions. These trend lines represent the mean center point between the foremost point of the dune ridge at the nose and the rearmost trailing edge at the tips of the arms. The mean distance traveled by the dune is then derived from the distance between the center point of each trend line for a given dune ridge.

Recent advances in image-based cross-correlation methods demonstrate the potential to derive more objective measurements of dune form movement (Vermeesch and Drake, 2008; Necsoiu et al., 2009). The technique involves sub-pixel correlation of co-registered images, which yields a velocity field of dune displacements, and can also be used to derive an estimate of sand flux (discussed in Section 2.3).

The importance of dune form evolution has emerged as a top research priority in light of recent progress in numerical modeling and flume experiments (e.g., Schwämmle and Herrmann, 2003; Endo et al., 2004; Hersen et al., 2004; Durán et al., 2005; Hersen, 2005; Hersen and Douady, 2005; Durán et al., 2011; Katsuki et al., 2011). These approaches afford insight into dune dynamics and interactions and can be used to supplement the paucity of field observations. While these approaches are invaluable for overcoming temporal limitations and for developing hypotheses, there is a growing gap between simulations and geomorphological evidence because there are few real-world examples that have been used to verify and refine model and laboratory simulations. In some cases this has prompted debate as to the representativeness of model output (see Schwämmle and Herrmann, 2003; Livingstone et al., 2005; Schwämmle and Herrmann, 2005). Multi-temporal RS imagery and historical aerial photos enable us to study the long temporal baselines needed to document dune form interactions, and more importantly, for narrowing the gap between simulated and actual dune dynamics. In some instances, high-resolution, multi-temporal imagery freely available from Google™ Earth can provide sufficient observational evidence for testing model output.

### 2.3. Surface changes

The final method with demonstrated potential for inferring dune activity from RS data involves exploration of changes in the dune surface. Typically, the only process that moves sand on dune surfaces is aeolian transport (mass wasting is minimal, although possible; see Hugenholtz et al., 2007). Consequently, surface changes can be used as a reliable proxy for aeolian sand transport. Substantial advances have been made in evolving and adapting traditional RS techniques such as photogrammetry, and integrating newer RS technologies such as LiDAR.

Several studies have generated digital topographic data from hardcopy aerial photographs in order to resolve three-dimensional changes associated with dune activity (e.g., Brown and Arbogast, 1999; Ojeda et al., 2005). Brown and Arbogast (1999) applied digital photogrammetric methods to scanned stereographic aerial photographs in order to quantify erosion and deposition at a dune complex along the eastern shore of Lake Michigan. Despite relatively poor accuracy in the digital elevation models produced by the photogrammetric models (see Table 2 in Brown and Arbogast, 1999) the data provided a reasonable estimate of coarse-scale topographic changes during the timespan between photographs (1965–1987). From our own experience, high accuracy photogrammetrically generated digital elevation models of sand dunes from hardcopy aerial photographs are rare. Thus, accounting for errors in subsequent analyses with these data is paramount for qualifying interpretations.

New technologies allow direct collection of topographic data and improved spatio-temporal resolution. Several studies have applied multi-temporal LiDAR to resolve volumetric changes in dune fields.

Woolard and Colby (2002) used LiDAR data acquired in 1996 and 1997 to calculate volumetric changes of coastal dunes at Cape Hatteras, North Carolina, USA. Mitasova et al. (2004) investigated short-term dune activity changes at Jockey's Ridge, North Carolina, USA, by combining annual LiDAR elevation data (1997–2000) with quarterly field-based RTK GPS measurements. In addition to quantifying dune volumetric changes and migration, Mitasova et al. (2004) verified the effectiveness of dune mitigation strategies (sand fences) erected to slow dune migration and force an increase of dune height. Collectively, these investigations show the potential of monitoring dune activity changes with LiDAR. Away from coastal settings, dune form transition has been studied at White Sands Dune field using LiDAR (Reitz et al., 2010). A multi-temporal LiDAR dataset was used to assess erosion and deposition rates on dune surfaces along a morphological gradient. These data offered evidence to support modeling predictions that suggest the transition from barchan to parabolic dune occurs when surface change rates are approximately half the vegetation growth rate.

An alternative approach for quantifying three-dimensional changes of dune activity has been demonstrated by Vermeesch and Drake (2008). They used COSI-Corr software (Coregistration of Optically Sensed Images and Correlation, available for free to the research community; Leprince et al., 2007, 2008) with ASTER satellite images (also free for researchers). Vermeesch and Drake (2008) estimated the mass flux of migrating barchans on a pixel-by-pixel basis in the Bodélé depression of northern Chad. Although the method performed well for relatively large barchans, Vermeesch and Drake (2008) acknowledge that higher resolution satellite data could improve the analysis and extend the potential of this technique to smaller dunes.

It is important to recognize that in some settings it might be more effective to measure and monitor dune surface changes using field-based survey methods (GPS, Total station). In many remote dune fields RS-based data may be unavailable or too expensive to acquire at suitable resolution (e.g., LiDAR). Thus, by measuring surface changes on a representative sample of dunes it might be possible to resolve dune form modification that could not be resolved otherwise (e.g., Hugenholtz, 2010; El belrhiti and Douady, 2011). However, field-based surveying has limitations in terms of the resolution of data that can be acquired over large areas. In this regard, several emerging RS technologies, including the use of unmanned aerial vehicles (Fig. 7), could be important for overcoming some of the time and cost limitations associated with existing field- and RS-based methods.

## 2.4. Examining controls of dune activity

As the potential of RS and SA has become more established, the research scope has expanded to assess potential controls of changes in dune activity. Following the work of Gaylord and Stetler (1994), a number of papers began appearing in the literature relating climate variations to changes of dune activity, especially after 2002. Some of these studies document a link between dune activity and aridity. For instance, Marín et al. (2005) showed that the historical migration rates of parabolic dunes at the Great Sand Dunes National Monument in Colorado increased during droughts. Similarly, Thomas and Leason (2005) used Landsat™ to show that vegetation cover can decrease below a critical value of 14% over extensive areas in the southwestern Kalahari Desert during drought periods. This percentage of cover has been empirically associated with susceptibility of the linear dunes to aeolian transport, particularly on dune crests. In Canada, Hugenholtz and Wolfe (2005a) showed that the historical stabilization of several interior dune fields is partly explained by decreasing aridity in second half of the twentieth century. In Australia, Levin (2011) showed that dune stabilization on Fraser Island, Earth's largest sand island, could be attributed to a significant decrease in tropical cyclone frequency and intensity in eastern Australia since the early 1980s.

Using similar methodologies, a number of investigations detected anthropogenic influences on dune activity. In Israel, studies indicate a relation between dune stabilization in the second half of the twentieth century and concomitant changes in land management practices, particularly the suppression of various forms of disturbance (cutting of vegetation, grazing, and trampling: Tsoar and Karnieli, 1996; Tsoar and Blumberg, 2002; Kutiel et al., 2004; Levin and Ben-Dor, 2004; Seifan, 2009; Fig. 5). Mason et al. (2008) also detected anthropogenic influences on regional dune activity in northern China. Despite a marked decrease in wind power since the 1970s, which is expected to decrease mass flux across the dunes, Mason et al. (2008) measured an increase of dune activity (activation) at two of three sites, and inferred that anthropogenic factors, especially livestock grazing, played a role in counteracting the effects of declining wind power. A similar effect was noted at one of the seven sites investigated by Hugenholtz and Wolfe (2005a), where livestock trampling and over-grazing may have triggered dune activation locally during a drought (Fig. 8).

Despite progress in understanding the major controls of dune field activity, especially through the application of RS, relatively little is known about the role of dune field topography and organization on dune activity. Models suggest that dune fields self-organize into emergent patterns that lead to greater order, dune–dune spacing, and/or overall dune size (e.g., Werner, 1995). The pattern at any given time step reflects the boundary conditions and the constructional time leading up to that point. The widespread assumption that dune activity can be related directly to climatic conditions influencing vegetation growth belies the nonlinearity of dune field
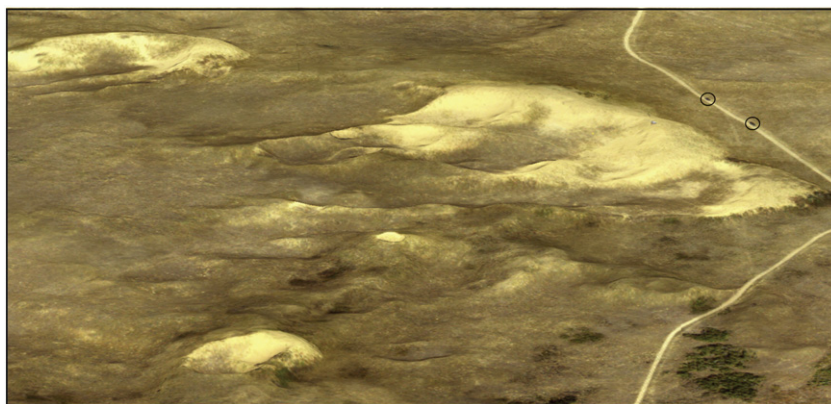


**Fig. 7.** This image shows an oblique view of sand dunes using imagery and digital elevation data acquired from an unmanned aerial vehicle (UAV). The site is located in the Bigstick Sand Hills, Saskatchewan, Canada. This is an example of how emerging RS technologies can be used to develop high-resolution digital elevation data over wide areas. The elevation model was produced with digital photogrammetric methods using images acquired by the UAV (details on the process and accuracy of these data will be provided in a follow-up publication). The total field time required to perform the UAV survey was approximately 3 h. The circled objects are vehicles that provide a qualitative indication of scale.
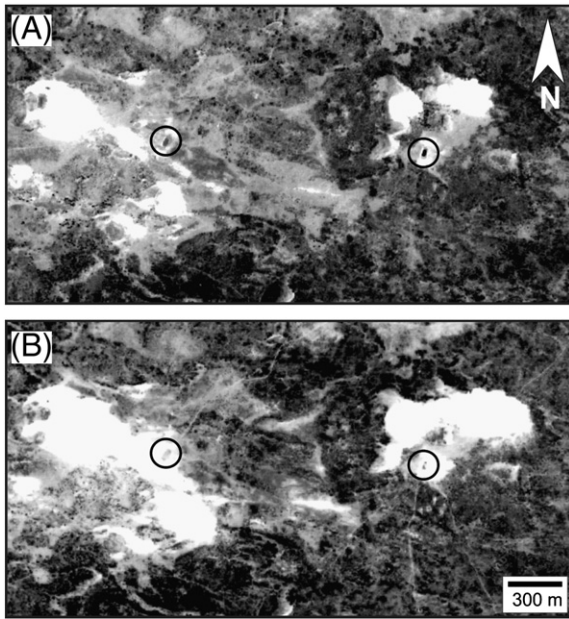
**Fig. 8.** These aerial photographs show an increase of dune activity, presumably due to over-grazing during drought. The circles show locations of dugouts that provide water for cattle. The photograph in (A) is from 1979, whereas (B) is from 1991 (Great Sand Hills, Saskatchewan, Canada). Dugouts attract cattle to the area and act as focal points for over-grazing disturbance, which was probably exacerbated during the 1987/88 drought.

evolution. For instance, it is widely documented that smaller dunes migrate faster than larger dunes for a given transport condition; thus, it could be argued that the smaller dunes should also stabilize faster than the larger dunes due to fetch and adjacency effects during vegetation colonization. For similar reasons, larger dunes with greater separation might stabilize more slowly. While these scenarios are essentially hypotheses, they raise the question of whether we can ignore spatial variations in dune size and organization, which occur in virtually all dune fields. In this regard, we envision future contributions by integrating numerical models with RS and SA of real dune fields.

## 3. Quantifying dune patterns and hierarchies

Among the most striking characteristics of dune fields is the regularity and 'pattern' that exists in topography. Early work quantifying dune field patterns focused on exploring dune allometric relations from field- or photograph-based measurements of dune dimensions. For barchan dunes, this approach established simple linear relations between the height, length, as well as the width and length of arms, with slight variations for different settings (cf. Hesp and Hastings, 1998). Similarly for linear dunes, allometric relations revealed linear relations between dune height and crest-to-crest spacing (Thomas, 1986; Lancaster, 1988b). When coupled with advances in numerical modeling, this type of approach also clarified some important morphological details for barchan dunes, especially the observation that the ratio of horn width to barchan width decreases with increasing dune width, which is important for the representation of barchan dune form in numerical models (Hersen et al., 2004). Thus, in the absence of collisions, the net effect is that small barchans get smaller as they migrate, while large barchans get larger.

Concurrent with research on the allometry of relatively simple dune forms and patterns, parallel progress was made in documenting complex dune field patterns arising from the superimposition of dune generations (Lancaster, 1992; Warren and Allison, 1998; Lancaster

et al., 2002). At all stages, but particularly in the last decade, RS and SA have spurred progress in understanding dune field patterns and hierarchies by increasing objectivity and allowing quantification of dune field topography.

### 3.1. Metrics of dune field pattern

An objective and standardized method for quantifying dune field pattern has been a longstanding goal of aeolian geomorphologists. Most studies of dune field pattern have been based on interpretation of optical images, from both aerial and satellite platforms. Important initial contributions to the quantification of pattern were made by Bullard et al. (1995) and Al-Dabi et al. (1997). Bullard et al. (1995) developed a classification scheme by mapping and classifying linear dune planimetric pattern variability from aerial photographs in the southwestern Kalahari. The method mimics early investigations of fluvial drainage basin patterns (e.g., Howard, 1967); however, Bullard et al. (1995) included a statistical assessment using four pattern variables of linear dunes: y-junction frequency, termini frequency, orientation, and wavelength. Their statistical assessment added to the rigor and objectivity of previous studies (e.g., Mabbutt and Wooding, 1983; Thomas, 1986; Wasson et al., 1988). In a separate but complimentary investigation, Al-Dabi et al. (1997) used Landsat images to resolve spatial and temporal changes of dune density patterns in northwestern Kuwait. They showed an increase in the area of the dune field as well as the rate of dune formation shortly after the 1991 Gulf War, suggesting that surface disturbance contributed to an increase of sand supply.

An appraisal of dune fields as emergent self-organizing complex systems (Werner, 1995, 1999, 2003; Werner and Kocurek, 1997, 1999; Kocurek and Ewing, 2005) expanded interest in resolving dune field patterns and pattern controls, with RS and SA providing the geospatial backbone for these investigations. Ewing et al. (2006) provided the first comprehensive example using measurements of digitized points and lines representing dune positions at four dune fields (White Sands, New Mexico, USA; Algodones, California, USA; Agneitir, Mauritania; Namib, Namibia). Digitized points were used to represent dune defects, which denote dune terminations or breaks in pattern, while lines digitized along dune crests were used to measure dune spacing, orientation, and length. Cumulative probability distributions (CPDs) provided a statistical description of different dune generations, denoted qualitatively by inflections or gaps in the CPDs for defect density, crest length, crest spacing, and crest orientation. The absence of inflections in the CPDs of dunes at White Sands indicates a relatively simple dune field pattern comprising a single generation, whereas at least two generations were determined from CPDs of the other locations, indicating more complex patterns comprising multiple dune generations. Subsequent applications of these metrics by Ewing and Kocurek (2010a,b) and Ewing et al. (2010) have been used to explore effects of dune field boundary conditions on pattern development and different types of dune–dune interactions. The latter is especially important because it provides a more direct link between bedform pattern and the processes leading to a particular type or stage of pattern development (also see Rachal and Dugas, 2009).

A complimentary approach for resolving dune field patterns was introduced by Wilkins and Ford (2007). They applied nearest neighbor analysis – a SA method originally developed by ecologists – in order to resolve temporal changes in dune field pattern and to detect the degree of randomness of dune field pattern, expressed by the spatial arrangement of a population of points representing individual dunes within the dune field. Their analysis revealed a non-random pattern in the organizational state of the Coral Pink Sand Dunes, Utah, USA. Bishop (2007) extended the application of nearest neighbor analysis to dunes on Mars and found a qualitative relation between the level of organization and the morphology of dunes that

dominate a given area of interest. Bishop (2007) went on to suggest that the nearest neighbor index, or *R*-statistic, may indicate a dimensionless "geographical signature" of crescentic dune self-organization in the circumpolar region of Mars. A similar conclusion was proposed by Bishop (2010) for mega-barchanoid dunes in the Rub' Al Khali Desert, Saudi Arabia.

### 3.2. Analyses of dune topography

The use of DEMs to examine dune topography directly continues to advance. Topography can be analyzed in more detail than metrics of dune field pattern. For example, shading effects assessed by satellite imagery can be used as a metric of topographic variability. Using this approach, Levin et al. (2004) demonstrated that the slope and aspect of bare sand dunes can be extracted from the shading using two Landsat images, one acquired in winter and the other in summer (representing different sun zenith and azimuth angles). Access to standardized global elevation datasets suitable for examining dunes in three-dimensions has only recently become a reality and has the potential to stimulate advances in topographic analysis. The first high spatial resolution global DEM was produced within the Shuttle Radar Topography Mission (SRTM), with an absolute accuracy of $\pm 16$ m and an elevation posting approximately every 30 m (Werner, 2001). Blumberg (2006) demonstrated that megadunes can be viably characterized with SRTM data. More recently, the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) was released on 29 June 2009 (second version released October 2010: http://www.gdem.aster.ersdac.or.jp/).

Methods for direct analysis of topography remain underdeveloped. Hugenholtz and Barchyn (2010) presented two SA methods to illustrate the potential of using digital elevation data to resolve dune generations and for quantifying spatial variations of sand supply. The first example used a method known as residual relief separation (similar to Hillier and Smith, 2008) to separate the topography of smaller superimposed dunes from underlying host bedforms. This bedform configuration, which is often referred to as mega-dunes, is common in major sand seas with high sand supply and represents a hierarchical system of bedforms evolving at different scales. Previous efforts have relied on RS imagery to resolve different dune generations (e.g., Lancaster et al., 2002); however, the proliferation of digital topographic data provides a more objective framework for distinguishing the different length scales that make up the dune complex. In this regard, the approach developed by Hugenholtz and Barchyn (2010) is a first step in characterizing dune pattern hierarchies more objectively. The second example presented by Hugenholtz and Barchyn (2010) was an attempt to map the equivalent sand thickness (EST) concept proposed by Wasson and Hyde (1983) (Fig. 9). EST refers to a conceptualization of dune field sand supply that is contained in the dunes. The method developed by Hugenholtz and Barchyn is mainly based on filtering procedures that smooth the dataset and create different digital layers representing the subdune topography and dune height. The resulting output is a map showing the spatial distribution of EST (Fig. 9). This method was recently applied also by Yang et al. (2011) to study the formation of Earth's highest sand dunes, in China. In our view, the next step is to develop a more complimentary approach that facilitates hypothesis testing about dune field pattern controls by linking EST derived from real-world topography to that derived from simulated dune field topography.

The direct use of DEM data remains one of the most important avenues for future research. Topography can be used as initial conditions for dune field-scale computational fluid dynamics simulations (e.g. Jackson et al., 2011; Liu et al., 2011). Reitz et al. (2010) used multi-temporal LiDAR data from White Sands, New Mexico to validate a numerical dune model. Data such as these show incredible promise for analyzing dune forms as three dimensional objects and examining morphodynamics.
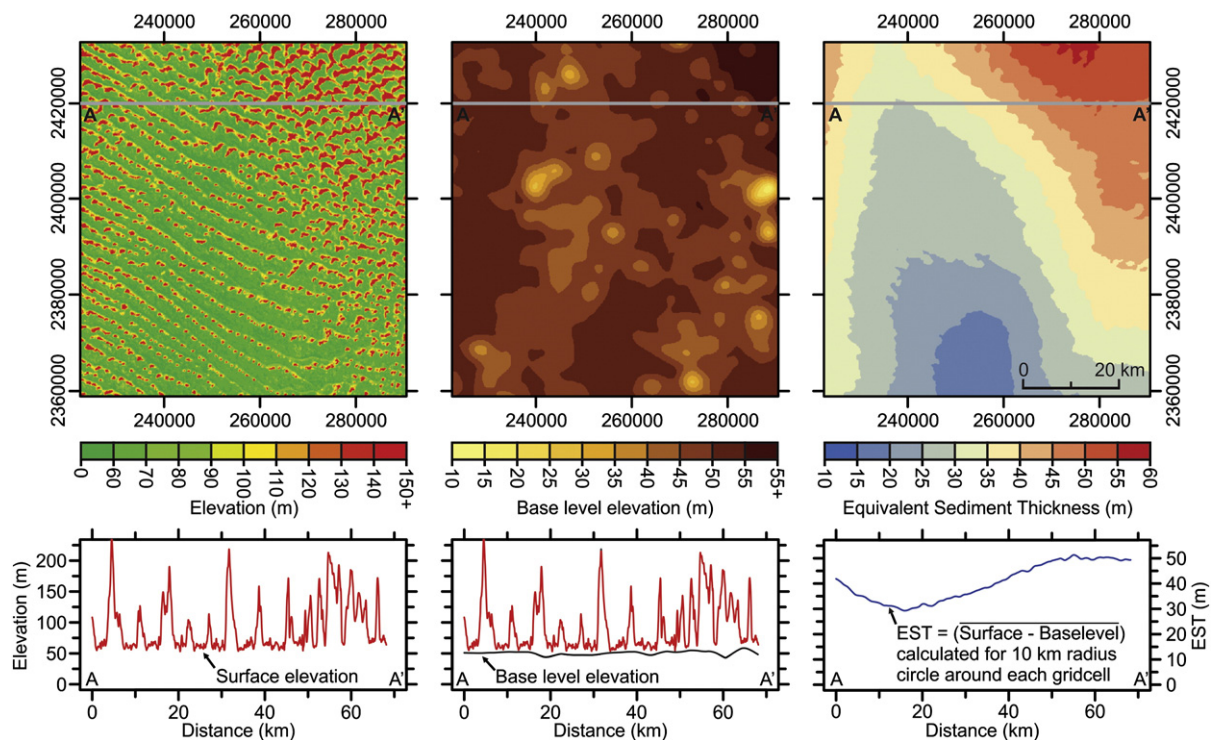


**Fig. 9.** The sequences of images illustrate the process of deriving a map of Equivalent Sand Thickness (EST; Wasson and Hyde, 1983). The details of the GIS procedures are outlined by Hugenholtz and Barchyn (2010). The smoothed topography representing the inter-dune baselevel surface is subtracted from the original topography to yield a dune height map. The latter is then filtered approximating the local EST for a 10 km radius around each grid cell. Here we use ASTER GDEM data to map EST for a section the Rub' Al Khali Desert in Saudi Arabia (center of map is approximately 21° 33′ 38.34″ N, 54° 37′ 24.39″ E).

## 3.3. Challenges

Due to the relative infancy of SA and many RS datasets, there are a number of looming challenges that require careful consideration. The bulk of SA efforts have been performed by using landform objects to represent individual dunes (e.g., points and lines of Ewing et al., 2006; Wilkins and Ford, 2007; Bishop, 2007, 2010). Discretization of dunes as objects invariably raises some fundamental and tricky questions: Where does a sand dune begin and end? What spatial resolution is needed to accurately characterize dune features? Although the first question may seem straightforward for some simple dune morphologies, the process becomes highly subjective when attempting to assign points, lines or polygons to features representing dune amalgamations or linked dune forms (Fig. 10). Moreover, consideration of the spatial resolution needed to identify dune features is, thus far, essentially arbitrary because it is pre-defined according to the resolution of available data.

Despite a growing number of alternative approaches, the pattern of aeolian dune fields is still considered mostly within the longstanding tradition in geomorphology of treating landforms as objects. This is known as *specific geomorphometry*, whereby landforms are denoted as points, lines, polygons, or symbols. While this approach can be reliable for some dunes that have process-based arguments to support delineation (*bona fide landforms* following Deng, 2007), such as well-dispersed barchans on non-sandy substrates, there are no consistent process-based arguments to support the delineation of all types of aeolian dunes (referred to as vague landforms, or *semantic landforms* following Deng, 2007). The example of dunes at White Sands in Fig. 10 serves to illustrate the ambiguity and subjectivity in identifying dunes and defining their boundaries. Depending on the context or perspective, the feature in Fig. 10 may be considered as a discrete dune produced by lateral linking (Ewing and Kocurek, 2010b), or as a series of laterally-linked dunes. The problem for pattern analysis arises in the subjective decision-making process that assigns points, lines, or polygons to represent one of more features. The resulting pattern metrics are therefore conditioned by observer bias, and may not be reproducible. Moreover, the observer's decision on how to identify dunes will be influenced by the resolution of available imagery, which adds yet another layer of subjectivity. Ultimately, these issues may be reconcilable; however, aeolian geomorphology is not alone, other disciplines face similar challenges.

The counterpart to *specific geomorphometry* is *general geomorphometry* — a form of spatial analysis based on the variability of topography without identifying landform objects. Although this approach is largely under-utilized in aeolian geomorphology, parallel progress in resolving bedform patterns in marine and fluvial settings provides invaluable perspective on its potential application to aeolian dune fields. Methodologies outlined in two recent studies stand out. van Dijk et al. (2008) compared geostatistical (factorial kriging) and spectral filtering (Fourier analysis) as methods to discriminate different sub-aqueous bedform hierarchies detected in bathymetric data from the North Sea. The outcomes are similar to the residual relief separation technique used by Hugenholtz and Barchyn (2010); however, the methodology is based on objective, automated approaches, whereas the approach developed by Hugenholtz and Barchyn (2010) involves some user input. In a similar study, Cataño-Lopera et al. (2009) applied wavelet transform (WT), which is another form of spectral filtering, in order to investigate morphological characteristics of bedforms generated in laboratory tanks. While wavelet techniques have been applied for assessing aeolian transport phenomenon in the time domain (Baas, 2006), application of WT to the space domain is relatively new. Results from both studies illustrate the potential of signal processing methods for characterizing the morphology, size, and spatial variability of bedforms objectively. Moreover, Cataño-Lopera et al. (2009) point out that this type of analysis can be used to compare bedform characteristics generated from computer models with those generated in flumes or under natural conditions. Objective methods that can be used to gauge model output are essential for refining the representativeness of the latter (Baas and Nield, 2010). At present, aeolian geomorphology is lacking these validation tools,
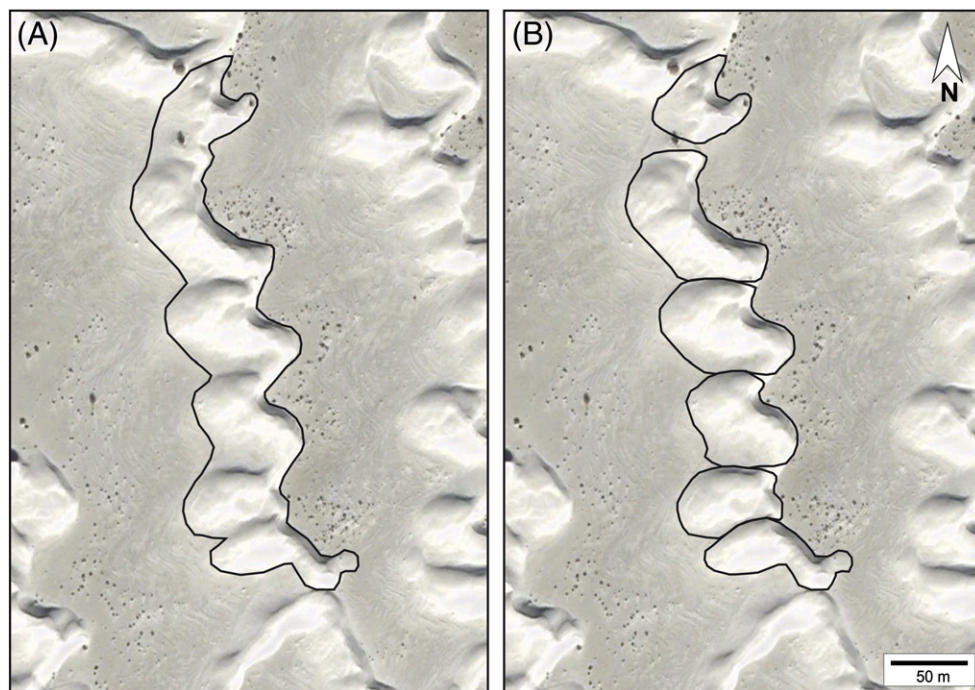


**Fig. 10.** Defining the boundaries of sand dunes for the purpose of spatial analysis can add a high degree of subjectivity to the outcome. Here we show two contrasting interpretations of the boundaries of dunes at White Sands, New Mexico, USA (image source: Google™ Earth; image date: 01 Feb 2007). There is no correct interpretation. Consideration of the topography in a general sense could overcome these subjective definitions of dune boundaries by avoiding prescriptive decisions about discrete or compound dunes.

while models of bedform development and evolution continue to rapidly emerge.

## 4. Extra-terrestrial dunes

For obvious reasons, remote sensing has played a vital role in investigations of dunes and dune fields on other planetary surfaces. Although the bulk of literature is devoted to dune mapping and inference of wind regimes, there has also been a recent shift towards quantitative methods in order to resolve spatial patterns and contemporary processes operating on the dunes (Fenton, 2006; Bishop, 2007; Bourke et al., 2008; Ewing et al., 2010; Silvestro et al., 2010). Thus, many of the same factors that propelled recent advances in research on terrestrial dunes (e.g., image resolution, software, and data availability) have also contributed to advances for other planetary bodies, especially Mars. A number of imaging sensors have been sent to Mars since 1964, providing a wealth of information about the distribution and morphology of dunes. Images from five major imaging programs (Mariner 9; Viking; Mars Global Surveyor, MGS; Mars Odyssey; and Mars Reconnaissance Orbiter, MRO) reveal that dunes are widespread on Mars, with a range of terrestrial look-a-like dune morphologies (e.g., barchan, linear, transverse, and dome), as well as some morphologies that have yet to be classified.

By combing RS and SA, Hayward et al. (2007a,b) constructed the Mars Global Digital Dune Database (MGD$^3$) in an attempt to resolve planet-wide patterns of atmospheric and sedimentary processes that shaped the surface landforms of Mars. The MGD$^3$ comprises a geospatial database containing information on the locations and areal extent of major dune fields (>1 km$^2$) between 65°N and 65°S latitude, and includes a classification of dunes according to terrestrial taxonomic terminology, as well as dune centroid and slipface orientations. These metrics have served as proxies for the prevailing wind direction in the last instance of dune morphological adjustment (dune centroid azimuth is a metric for dune fields found in craters; it refers to the geodesic azimuth of the line connecting the centroid of the crater to the centroid of the dune field). Hayward et al. (2009) compared dune centroid azimuths and slipface orientations to Martian GCM and mesoscale model output of near surface winds. They found that dune centroid azimuths agreed with GCM modeled wind direction and with mesoscale modeled mean wind speed, while slipface orientation had some correspondence to mesoscale wind speed but very little agreement with GCM modeled wind direction.

The suitability of using dune orientation metrics to validate and refine near-surface windflow models of Mars hinges on the assumption that the dune orientations are not simply relic features of a former wind regime. There are examples in Canada, for instance, where the orientation of relic dunes is northwesterly, while modern wind direction is southeasterly (Wolfe et al., 2004). Thus, signs of contemporary dune mobility on Martian dunes are required to validate their use as indicators of present-day wind direction, but only if the activity is consistent with the morphological interpretation of wind direction. Indeed, many signs of isolated present-day aeolian transport are apparent on Mars (Bridges et al., 2007; Sullivan et al., 2008; Reiss et al., 2010; Silvestro et al., 2010; Hansen et al., 2011). However, evidence of widespread, present-day dune activity and migration is thus far limited. Fenton et al. (2005) observed changes in the brightness of crestal regions of dunes in the Proctor Crater and interpreted this as a sign of contemporary crest reversal. Additional signs of present-day dune activity were documented in the Rabe Crater. Fenton (2006) noted the appearance of bright streaks on a dune slipface and interpreted these features as grainflows indicating sand transport and dune migration. Similarly, shrinking and disappearing dome dunes in north polar region of Mars were interpreted as signs of active saltation by Bourke et al. (2008). Silvestro et al. (2010) showed evidence of ripple migration on the surface of dunes in the Nili Patera and inferred dune migration from changes in the dune base-ground surface contact and in the development of streaks representing grainflows on the slipface. More recently, Hansen et al. (2011) showed that the morphology of northern polar dunes on Mars is modified by seasonal sublimation of $CO_2$ and aeolian sediment transport. Collectively, the evidence suggests aeolian saltation is occurring; however, there remains some uncertainty as to whether the dunes are actively modified by aeolian erosion and deposition, or if the observed changes are simply an effect of sediment bypassing over indurated (crusted) dunes (cf. Schatz et al., 2006). Thus, some dunes on Mars may have surface activity, but whole dunes might not be mobile. In our view, three-dimensional changes of dunes on Mars will provide the only unequivocal evidence of present-day dune mobility and validate the use of dunes to infer present-day wind directions.

Attempts to understand sedimentary processes acting on Martian dunes have relied mostly on developing analogies with terrestrial dunes. In this regard, RS has been invaluable for comparing the diversity of dune morphologies between the two planets (e.g., Breed et al., 1979b; Schatz et al., 2006; Bourke, 2010). However, recent advances in the spatial resolution of image data from Mars, mainly from the High Resolution Imaging Science Experiment (HiRISE), have prompted several important contributions inferring both past and contemporary processes. Several studies have recently applied HiRISE images to document contemporary activity of gullies on dune lee slopes (Diniega et al., 2010; Gardin et al., 2010; Reiss et al., 2010; Hansen et al., 2011). These features are indicative of secondary processes responsible for denuding dune lee slopes and, in some locations, are argued to be evidence for recent liquid water flow on the surface of Mars. While the exact transport mechanism is debatable (cf. Diniega et al., 2010; Reiss et al., 2010), the ability to resolve gully changes is nonetheless remarkable. In similar vein Ewing et al. (2010) recently have shown how SA of dune and ripple patterns on Mars can lead to a morphodynamic interpretation of primary wind fields and secondary flow modifications yielding a complex reticulate pattern. It may be possible in the near future to measure volumetric displacements of dunes on Mars, which would improve the quantification of present-day aeolian transport and morphodynamic interpretations. To this end, the release of high resolution digital terrain models (DTM) of Mars created photogrammetrically from HiRISE stereo pairs is an important step forward (see Fig. 2).

## 5. Conclusions and outlook

The purpose of this review was to highlight recent progress in the application of RS and SA to the understanding of dune activity, patterns, and extra-terrestrial dunes. Although it may be too early to suggest that a paradigm shift has emerged from the growing application of these technologies (cf. Livingstone et al., 2007), it is clear that substantial progress in the quantitative characterization of dune field form and morphodynamic interpretation has occurred.

A longstanding research challenge in aeolian geomorphology, in our view, has been the issue of form and process, and how to reconcile the spatio-temporal scales involved in dune field evolution with the limitations of our brief observational record and empirical perspective. While RS and SA do not provide an immediate, or the only, solution to this challenge, they offer a synoptic perspective and platform from which to help guide field-based research and validate modeling efforts. We surmise that it will soon be possible to use these technologies to develop a coupled topography–climate–sediment–ecosystem model to predict real-world dune field morphodynamics. Whereas current models simulate artificial topography, we believe the next generation of models will use real topography to simulate the effects of different climate change scenarios (e.g., Pelletier et al., 2009). Research highlighted in this review shows that some of the input

parameters are already available, including sand availability (Scheidt et al., 2010) and topography (Hugenholtz and Barchyn, 2010). Moreover, we need not look far for examples of other input data that can be incorporated into the model, including output from global climate models (e.g., Thomas et al., 2005), three-dimensional boundary layer airflow models of complex terrain (e.g., Liu et al., 2011), and ecosystem response models of vegetation and soil dynamics (e.g., Mangan et al., 2004). Ultimately, this type of modeling relies on the interoperability of different modules and ongoing refinement of process rules and parameterizations.

Continued progress in the application of RS and SA for resolving dune field dynamics will depend, in part, on the ability to address some of the research challenges outlined in this review. Four technical issues stand out from our review and assessment of the literature. First, the application of RS imagery to estimate the effects of vegetation cover on aeolian transport during the early stages of dune stabilization is currently under-developed, yet this is crucial for parameterizing a growing number of numerical models capable of simulating the effects of vegetation on dune and dune field dynamics. While there are many different research approaches available to address this issue, investigations that combine RS-based image analysis with field-based measurements of vegetation cover, structure, and aeolian transport rate are probably the most suitable and transferable to models because they consider similar spatio-temporal scales.

Second, observational evidence of dune form evolution is lagging behind progress in simulation models. In this regard, a major challenge is to link the temporal baseline of RS data to the appropriate scale of dune dynamics. For highly dynamic dune fields this requires high-resolution imagery at relatively short (i.e., monthly) intervals, while other dune fields might require decadal intervals or longer. Although there are a few notable examples of detailed observational records regarding dune form evolution (e.g., Ewing and Kocurek, 2010b; Reitz et al., 2010; Hansen et al., 2011), there are immediate opportunities to expand this effort with high-resolution RS data and SA methods. Moreover, there are opportunities to move from two-dimensional to three-dimensional descriptions (e.g., Vermeesch and Drake, 2008; Reitz et al., 2010).

Third, progress in developing and applying objective and reproducible SA methods for characterizing dune field pattern has been limited thus far. Parallel progress in the application of general geomorphometric techniques in allied branches of Earth-surface science provides some guidance on how to address this issue for dune fields. A variety of general geomorphometric variables could be calculated within a standardized local window (see Baas and Nield, 2010; Hugenholtz and Barchyn, 2010) for each pixel in a study area and summarized within a statistical framework. Statistical techniques could be used to reduce collinearity and isolate the metrics that characterize the most variability dune field (Baas and Nield, 2010). We believe there are many opportunities to use or adapt existing metrics to the field of study, but acknowledge that an applicable framework has yet to be developed.

Fourth, greater emphasis on three-dimensional topographic changes in dune fields is essential for developing a better understanding of spatio-temporal patterns of dune field activity, both on Earth and Mars, and for validating and refining numerical models predicated on transport equations that give rise to spatial variations of erosion and deposition. This is especially important, in our view, for reconciling the specific mechanisms leading to contemporary changes on Martian dunes, and for clarifying dune–dune interactions, dune field-scale sand budgets, and dune form evolution. Fortunately, a number of existing and emerging technologies (and methodologies) are available for this type of research, including photogrammetry (e.g., HiRISE digital terrain models), LiDAR and synthetic aperture radar (e.g., TerraSAR-X and TanDEM-X).

In addition to the foregoing technical issues, we believe that future progress in the application of RS and SA in aeolian geomorphology partly depends on the expanding availability (e.g., low or zero cost and accessibility) of high-quality geospatial data. Significant progress has been made in recent years with the release of global datasets, many of which are available at no cost or restrictions to users worldwide via electronic download (see Table 1). Furthermore, many geospatial software packages and customized toolsets are free and available in open source format (e.g., microdem, GRASS, SAGA, MultiSpec). Continued progress will partly depend on the availability of data and the development or adoption of SA techniques that quantify important dune system characteristics.

## Acknowledgements

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