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Study of dune fields by remote sensing

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Abstract. *Dunes usually appear in places with available sand, being found on beaches, in deserts, and even on Mars, where images of that planet show that dunes can be found ubiquitously over its surface. The dune fields have been undergoing natural changes caused by complex processes, of which wind action is largely responsible for the movement of the dunes. One of the consequences of the expansion of dune fields is the occurrence of desertification, a concern for populations living in arid and semi-arid areas. This work aims to describe the morphological changes that occurred in Lençóis Maranhenses and in the Moroccan region of Laayoune in order to better understand the dynamics of dune systems and the parameters that control their development, besides showing the morphological variations of the dunes and the factors that influence such modifications. For this, geological mapping is used through the application of remote sensing to monitor the interactions occurring between dunes. Using a multitemporal analysis, a series of satellite images were obtained, where these images were analyzed and the data were compared with laboratorial information. It is possible to observe differences in the morphologies and understand how the studied fields reached the present configuration.*

Keywords: *Dunes, Remote Sensing, Geomorphology, Dune Dynamics*

1. INTRODUCTION

In recent years, many studies have been carried out using data obtained with remote sensing. Remote sensing is a term used in the field of applied sciences and concerns the recording and analysis of interactions between electromagnetic radiation and the substances that make up planet Earth. The records are obtained through remote sensors that are present on Earth-observation satellites or through cameras on-board of aircrafts. A sensor on board the satellite generates a product of remote sensing called image, while an aerial camera, on board an aircraft, generates a product of remote sensing called aerial photography. There are a large number of remote sensing satellites on orbit around the Earth. Each of these satellites has distinct characteristics that depend on both the satellite and the sensor (Campbell and Wynne, 2011; Ralph D. Lorenz, 2014).

The work of Breed and Grow (1979) is a good example of analysis using remote sensing. It describes the different types and shapes of dunes, and presents the different varieties by degrees of similarity. Another interesting study is presented by Barbosa (1997) who made field and aerial observations where he noticed an average dune migration rate of 20 to 24 m per year. Concluding that in a period between 100 and 200 years a dune can migrate to the innermost portion of the dune field and that aeolian sedimentation is a recent phenomenon in the evolutionary history in the Quaternary coastal plain of the São Francisco River, located in the northeast region of Brazil.

The movement of the dunes is due to a phenomenon called saltation. In this phenomenon, the grain of sand that is carried by the wind, hits the ground and collides with other grains causing them to rebound and rise in the air while, at the same time, new grains can be ejected. As this happens, there is an increase in the number of grains bouncing around until a cloud of sand forms. This cloud hits the ground at a plane angle between 10° and 16°, depending on the grain size, its elevation height and the wind speed (Bagnold, 1974). Barchan dunes can connect themselves due to the increased supply of sand, causing the formation of wavy chains aligned perpendicular to the wind direction and giving rise to barchanoid chains, the most common form of dunes found in Lençóis Maranhenses. Longitudinal dunes are formed on the sides of barchan dunes and barchanoid chains during their migrations. These have morphological features similar to strands of sand. The parabolic dunes, as the name implies, have a shape similar to a parabola with a characteristic varying from "U" or "V". The formation of these dunes is related to the trapping of the arms of the barchans by the vegetation or by the humidity resulting from the rainy season. As a result of this entrapment, the convex side of the barchan is inverted and gives rise to the concave side of the parabola directed towards the wind (Gonçalves *et al.*, 2003; Ralph D. Lorenz, 2014).

Recently, Zhang *et al.* (2018) observed that dune interactions and asymmetric inflow conditions are mainly responsible for the asymmetry of barchans present in the dune field located in the Hexi Corridor, northwest China. Another recent study (Azzaoui *et al.*, 2020), made use of remote sensing to carry out analyzes of the sand dunes around the city of Tarfaya located in southern Morocco in the Sahara desert. The researchers automated the detection of barchan dunes through the application of computer vision based on machine learning. It is also possible to monitor the complex interactions that occur between these dunes. Thus, the purpose of this paper is describe the morphological changes that occurred in Lençóis Maranhenses and in region north the Laayoune in order to better understand the dynamics of dune systems, in addition to showing the factors that influence such changes. For this, remote sensing is used to monitor the interactions occurring between dunes, using a multitemporal analysis.

2. METHODS

In this section, we shall give an overall the two studied sites. Followed by the description of the satellites used to obtain the images that served as a means of analysis of the studied areas.

2.1 Study Area

Two areas were studied in this work. The first study area is located in the Lençóis Maranhenses National Park, in the Northeast region of Brazil, as shown in Fig. 1. More specifically located in the North Maranhense Mesoregion and Lençóis Maranhenses Microregion, between the following geographic coordinates: $02°30'26.9''$, $02°\ 41'\ 15.5''$, $02°40'0.3''$ and $02°\ 37'\ 6.24''$ latitude S, $43°\ 14'\ 12.7''$, $43°\ 02'\ 5.5''$, $42°51'14.5''$ e $42°\ 45'\ 31.13''$ longitude W.

The Lençóis Maranhenses National Park is limited to the north by the Atlantic Ocean and to the south by the dissected tablelands of the Barreiras Formation. To the east, it is limited to the Parnaíba-PI river and to the west to the bay of São José-MA. It has a total area of 155,000 ha, which is composed of sand dunes that occupy 2/3 of the total area and reach up to 30 meters in height. There are also lagoons located between the dunes, sandbanks, mangroves and a 70 km stretch of beach (UCs, 2011).

Figure 1: The study area: Lençois Maranhenses, NE Brazil. Landsat-8 image courtesy of the U.S. Geological Survey.

The second area is located in Western Sahara, in the southern region of Morocco, more specifically north of Laayoune (Fig. 2), close to the following coordinate: $27°32'$ N and $13°18'$ W. This region is characterized by relatively low air humidity and a semi-arid climate. Small fluctuations in the wind direction are characteristic of this region, which is a favorable factor for the development of barchans with a high degree of symmetry. Another factor is that the desert surface is relatively flat (Sauermann *et al.*, 2000; Maun, 2009).

2.2 Satellite Image Dataset

The images were obtained using Google Earth Engine, a cloud-based geospatial analysis platform that allows viewing and analyzing satellite images of planet Earth from geospatial data on Google's servers (Gorelick *et al.*, 2017).

For the analysis of the Lençóis Maranhenses region, the images used were selected from the LANDSAT 5-TM and

Figure 2: The study area: Laayoune, south of Morocco. Contains modified Copernicus Sentinel data 2021.

LANDSAT 8-OLI sensors. Landsat 5 was launched in March 1984 and decommissioned in May 2012, carrying the Multispectral Scanner (MSS) and Thematic Mapper (TM) sensors. While Landsat 8 was launched in March 2013 and carries the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) instruments. Like Landsat 5 before it was decommissioned, Landsat 8 orbits the Earth in a nearly polar orbit, synchronized with the Sun, circles the Earth every 99 minutes and maintains an altitude of 705 km with an inclination of 98.2°. Both satellites have a 16-day repeat cycle (U.S. Geological Survey, 2022).

Table 1 presents the bands that were used in the composition of the images obtained with Landsat 5, as well as the spectral and spatial resolution. The same is presented in Tab. 2, but for Landsat 8. Both have a spatial resolution of 30 m, showing a difference in wavelength.

Table 1: Spectral and spatial resolution of Landsat 5 image.

Bands	Spatial resolution	Wavelength
Blue	30 m	0.45-0.52 μm
Green	30 m	0.52-0.60 μm
Red	30 m	0.63-0.69 μm
Near Infrared	30 m	0.77-0.90 μm

Table 2: Spectral and spatial resolution of Landsat 8 image.

Bands	Spatial resolution	Wavelength
Blue	30 m	0.452-0.512 μm
Green	30 m	0.533-0.590 μm
Red	30 m	0.636-0.673 μm
Near Infrared	30 m	0.851-0.879 μm

The images for the study of the Laayoune region were obtained using the LANDSAT 5-TM and SENTINEL-2 satellites. The SENTINEL-2 mission is a high-resolution, wide-range, European multispectral imaging mission. The complete mission comprises twin satellites in polar orbit, but flying in the same orbit, phased 180° apart. It has an optical instrument with 13 spectral bands, an orbital band width of 290 km and a revisit time of 5 days (ESA European Space Agency, 2022). Table 3 presents the spectral and spatial resolution for SENTINEL-2, according to the spectral bands that were used to compose the studied images.

3. RESULTS AND ANALYSIS

The results obtained in this study are shown following geographical areas.

Table 3: Spectral and spatial resolution of SENTINEL-2 image.

Bands	Spatial resolution	Wavelength
Blue	10 m	490 nm
Green	10 m	560 nm
Red	10 m	665 nm
Near Infrared	10 m	842 nm

3.1 Lençóis Maranhenses

The dune system in presented in a period of 38 years, between 1984 and 2021, for which we observe several expanding regions and a few retracting ones in different positions along the inner edge. The positions of the observed changes are shown in the following figures.

Figure 3 is an image obtained by Landsat 5-TM dated from 06/20/1984 and presenting an enlarged view of the expansion of the dune area in Lençóis Maranhenses from 1984 to 2021. Figure 3 shows the region close to Travosa, while Fig. 4 presents the region between Travosa, Santo Amaro do Maranhão and Ibicuituba. In Fig. 5 it is possible to observe that in that region there was a retraction in the dune area. This retraction effect is associated with two factors, namely, the great proximity of this region to the coast and the some obstacles present in the relief.

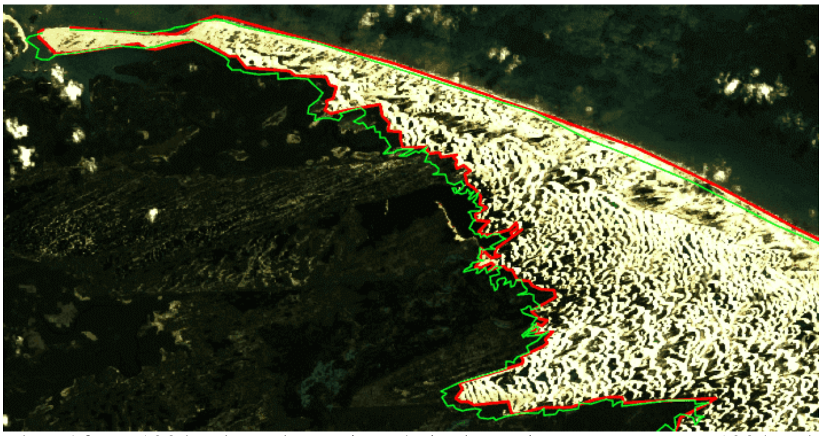

Figure 3: Image of Landsat 5 from 1984 enlarged prominently in the region near Travosa: 1984-red, 2021-green. Landsat-5 image courtesy of the U.S. Geological Survey.

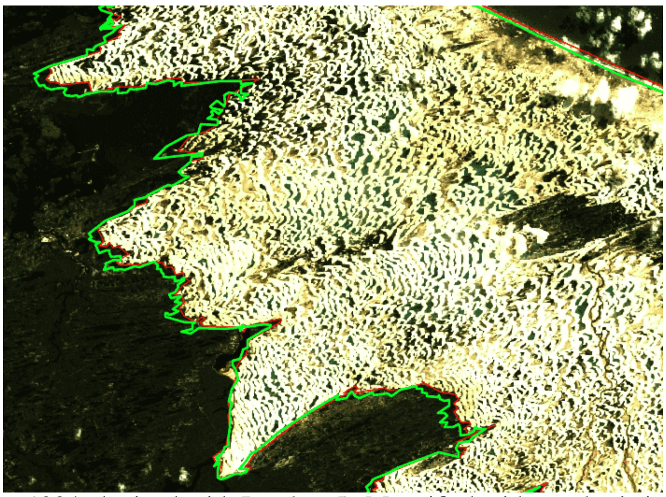

Figure 4: Satellite image from 1984 obtained with Landsat 5. Magnified with emphasis in the region between Travosa, Santo Amaro do Maranhão and Ibicuituba: 1984-red, 2021-green. Landsat-5 image courtesy of the U.S. Geological Survey.

Figure 6 presents three images of a specific area of Lençóis Maranhenses. Fig. 6a dates from 1984 and was obtained by Landsat 5, Fig. 6b and Fig. 6c are from 2021 and were obtained by Landsat 8, with the only difference that in the third image an edge detection filter was applied and the geometry of a specific dune was selected. It is an image processing

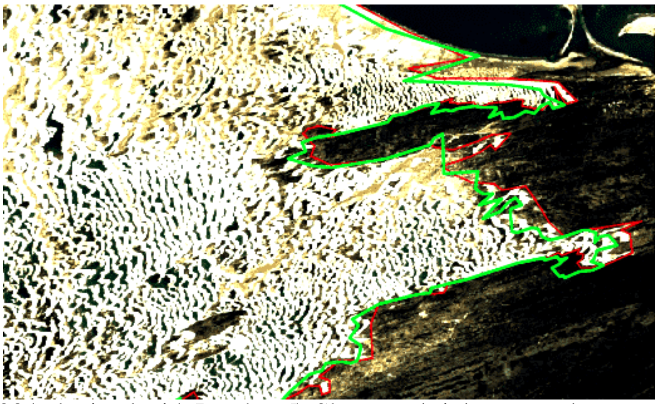

Figure 5: Satellite image of 1984 obtained with Landsat 5. Shows a shrinkage area between the year 1984 (red) and 2021 (green). Landsat-5 image courtesy of the U.S. Geological Survey.

(a) Landsat 5: 1984. (b) Landsat 8: 2021. (c) Edge detection: 2021.

Figure 6: Image set showing the different position of a dune for the years 1984 and 2021. In image (c) edge detection was applied to highlight the geometry of the dune being evaluated. Landsat-5 and Landsat-8 image courtesy of the U.S. Geological Survey.

technique that aims to determine points in a digital image where the light intensity undergoes a sudden change. The distance that the dune traveled between 1984 to 2021 was measured, showing that it moved about 273 meters.

The winds in the Lençóis Maranhenses region are strongly unidirectional, thus, barchan and barchanoid shapes are commonly found in this region. In addition to the wind, the movement of sand is controlled by the amount of water present in the soil. Soil with high humidity increases the adhesion of sand particles, which produces an additional resistance of the grains to the action of the wind. Another important point that must be observed in the Lençóis Maranhenses region is how the sand of the dunes interacts with the lagoons. The sand in this region can be moved by jumping through the interdunes when they are dry, the drying of these ponds occurring in summer and autumn. If the ponds never dried up, the dunes would shrink as they advanced. Thus, the existence of the dune field in this region depends on the seasonality of the rains, which occur between December and May (Maun, 2009).

3.2 Laayoune

In the Laayoune region, some dunes were selected and the movement of these dunes between 2011 and 2021 was analyzed. Figs. 7 and 8 show the dunes that were analyzed. From Fig. 7, we measured the displacement of the smaller and larger dunes was measured. For the larger dunes, the displacement between 2011 and 2015 was approximately 85 meters and between 2015 and 2021 it was 149 meters. For the smaller dune, the displacement was 141 m between 2011 and 2015, and 241 m between 2015 and 2021. Fig. 8 presents the second analyzed dune. For this dune, there was a displacement of 104 m between 2011 and 2015, and 165 m between 2015 and 2021.

The most frequent period of wind in this region varies between the months of April and August, with its maximum occurring in the months of June and July. The winds that blow from NNE are the main cause of sand propagation, controlling the orientation of the dunes (Aydda *et al.*, 2018; Maun, 2009).

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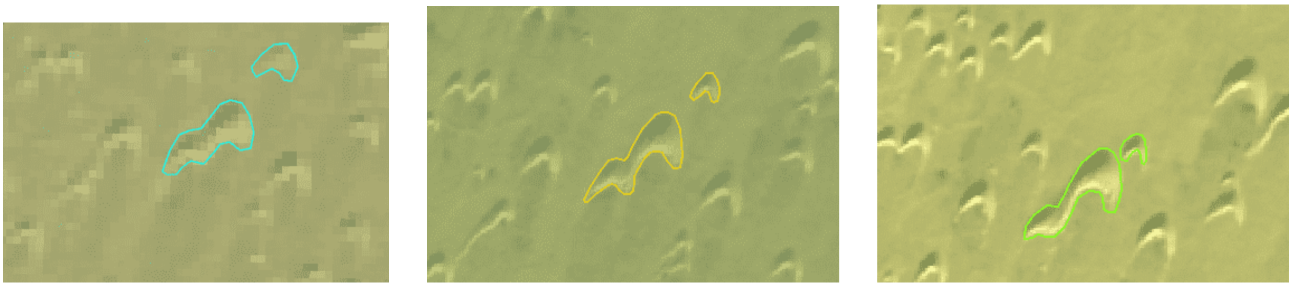
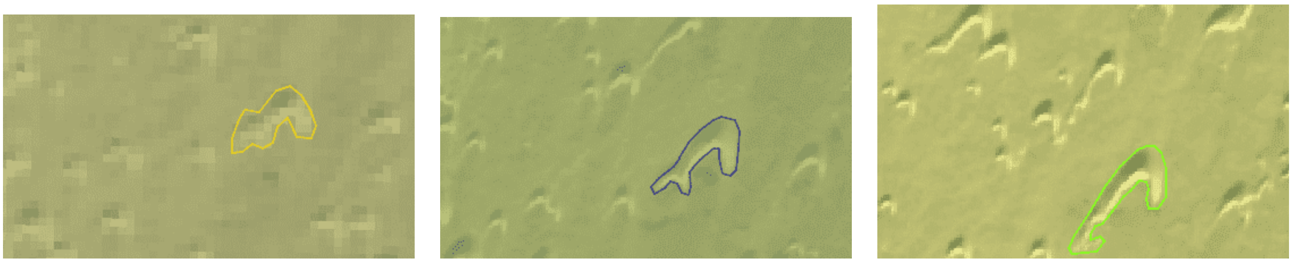


(a) Landsat 5: 2011 (b) SENTINEL-2: 2015 (c) SENTINEL-2: 2021

Figure 7: Geometry 1: Image set showing the different position of a dune for the years 2011, 2015 and 2021. Landsat-5 image courtesy of the U.S. Geological Survey. Contains modified Copernicus Sentinel data 2015 and 2021.



(a) Landsat 5: 2011 (b) SENTINEL-2: 2015 (c) SENTINEL-2: 2021

Figure 8: Geometry 2: Image set showing the different position of a dune for the years 2011, 2015 and 2021. Landsat-5 image courtesy of the U.S. Geological Survey. Contains modified Copernicus Sentinel data 2015 and 2021.

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