EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2025, 26(11), 312–322
https://doi.org/10.12912/27197050/213427
ISSN 2719–7050, License CC-BY 4.0

Received: 2025.09.29
Accepted: 2025.10.21
Published: 2025.11.01

Evaluation of the mobility of barchan dunes and its effects in the palm grove of Jorf (southeast of Morocco)

Abdelfattah Ben Kacem[1*], M'hamed Amyay[1], Mahjoub Benbih[2]

[1] Laboratory of Geo-Environmental Analyses and Sustainable Development – Planning (LAGEA-DD), Sidi Mohamed Ben Abdellah University, Fès, Morocco
[2] Research Team: Geography, Planning, Demography, and Development, Ibn Zohr University, Agadir, Morocco
* Corresponding author's e-mail: abdelfattah.benkacem1@usmba.ac.ma

ABSTRACT

Sand dunes are among the most dynamic geomorphological forms. Their displacement rates vary according to morphological, climatic, topographic, and human factors. Sandy accumulations of different shapes, sizes, and ages encroach upon the palm grove and reduce its agronomic potential. Dune formations, especially barchan, result from wind action and have internal dynamics characterised by constant movement and morphological change. This article studies the barchans in the Jorf area, which extends across the Tafilalet plain in pre-Saharan Morocco, focusing on the Fezna site. The aim is to analyse the annual trends in the direction and movement of barchans that may threaten the sustainable use of land resources and nearby human settlements. The migration of twelve barchans was monitored using high-resolution satellite images from 2012 to 2024. The dune movement pattern was also examined. The migration rate of dunes at the Fezna site averaged 9.1 m per year toward the northeast during the study period, compared with an average of 24 m per year between 1951 and 1965. This difference is linked to the installation of protection and control systems against sand encroachment upstream rather than downstream.

Keywords: dune, sand encroachment, barchan, Tafilalet, Jorf, Fezna.

INTRODUCTION

The growing scale of sand encroachment and its impacts on ecosystems have attracted the interest of many scientists worldwide (Wang et al., 2022; Cai et al., 2025). Studies have mostly focused on defining the phenomenon, identifying its factors and processes, examining sand dynamics, and developing techniques to combat sand encroachment. Aeolian dunes cover about 6% of the Earth's surface, with 93% located in arid zones (Rahdari and Rodríguez-Seijo, 2021). They form large accumulations whose size, shape, orientation, and morphogenesis processes vary according to wind direction and intensity (Lancaster, 2023; Manzolli et al., 2023), topography, sand supply, and the granulometry of the local sandy material.

Current literature about dune dynamics indicates that the most studied type of dunes in terms of processes and movement is the barchan. It is considered a prototypical model for dune dynamics and provides a useful basis for studying dune morphology (Hersen, 2004), as the evolution of barchan dunes is the best understood (Tsoar et al., 2008; Livingstone et al., 2007). Barchans develop and evolve through the interaction of sand, wind, rainfall and drought, topography, and human activity (Callot and Crépy, 2018; Bristow and Duller, 2024).

Dune migrations, in particular, are one of the major processes in the external geodynamics of arid regions, essential for understanding dune movements and for the management of arid regions (Callot and Oulehri, 1996; Benbih et al., 2025). Barkhanate dunes are the most common dune form in the Tafilalet region, located in southeastern Morocco. These crescent-shaped dunes are very active (Génois et al., 2012; Elbelrhiti, 2005). The movement of dunes along the western edge of the Tafilalet plain, particularly near the

Jorf palm grove, poses a serious environmental and socio-economic threat. Determining the current rate of barchan dune migration and prevailing wind directions is therefore essential for assessing desertification risks and developing effective control or mitigation strategies.

To illustrate the mobility of barchan dunes and their potential for damage, this study focuses on the Jorf palm grove and its surroundings in the Tafilalet plain, which is one of the Moroccan regions most severely affected by desertification and sand encroachment. The latter results directly from land degradation driven by climatic aridity and unsustainable human activity (Benmohammadi et al., 2000; Benalla et al., 2003). This research analyses the migration rate of barchan dunes and examines their socio-economic and environmental impacts. High-resolution satellite imagery provides valuable data on the evolution of these dune formations in the Jorf area.

METHODS

Description of the study area

The Jorf sector lies in the pre-Saharan zone of southeastern Morocco (Figure 1). It is bordered by the Cretaceous hamada of Meski to the north, the Rissani palm grove to the south, the Arfoud palm grove to the east, and the eastern slope of the Anti-Atlas to the west. The study area is part of the Tafilalet plain, which includes the Rissani, Jorf, and Arfoud palm groves. These groves form part of the UNESCO Biosphere Reserve and are recognised as sites of biological and ecological

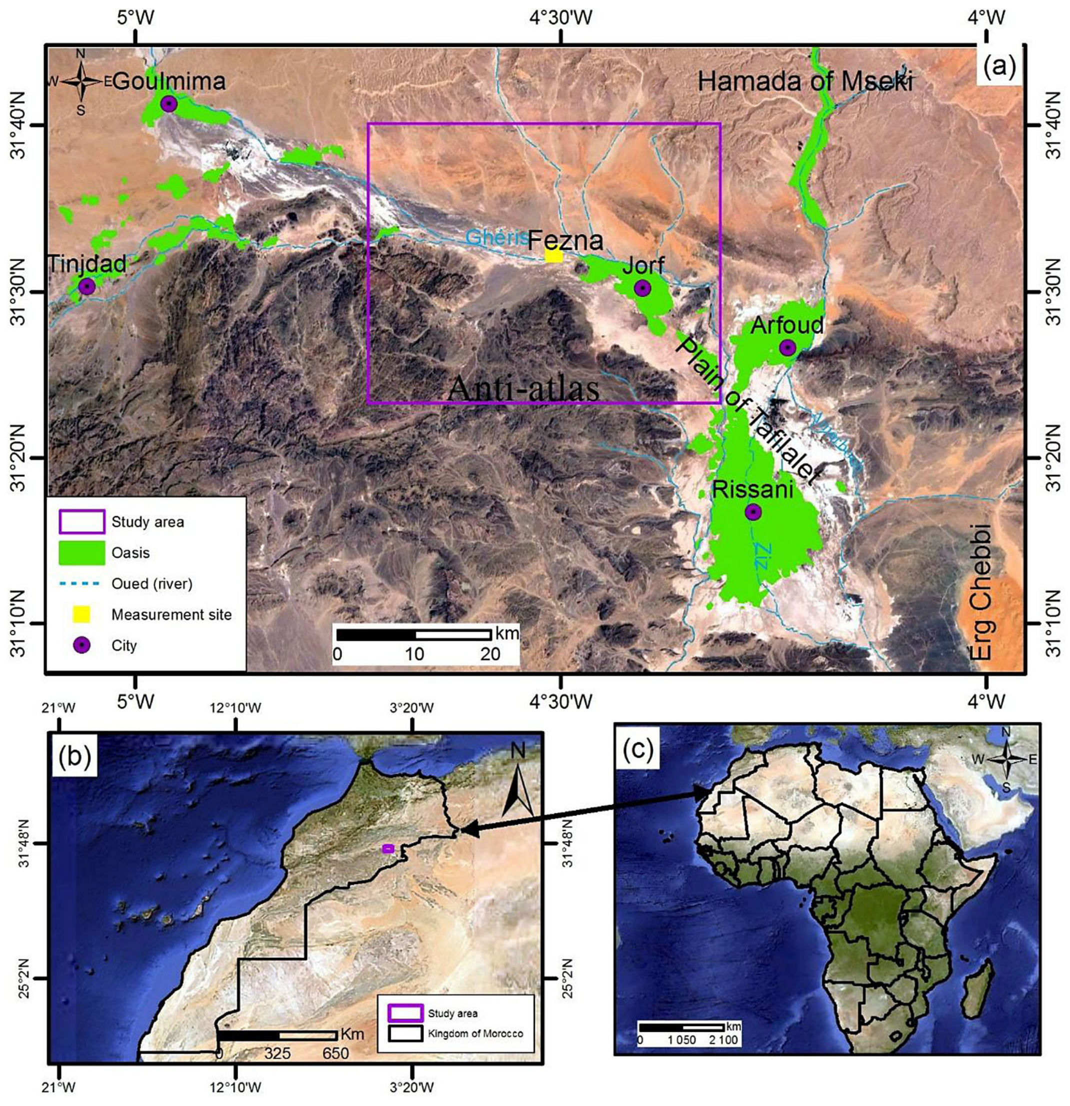

Figure 1. Location of the study area: (a) Jorf sector in in the Tafilalet plain, (b) an overview of Morocco map, (c) regional scale

interest (Laaouane and Ben Kacem, 2018). Administratively, the Jorf palm grove covers the communes of Arabe Essebbah Ghéris, Municipality of Jorf, and Fezna Ouled Jellal. These communes, under the Arfoud circle, have a combined population of 21,023 residents across 4.278 households (HCP, 2024). The experimental site selected for this study is a dune field located east of Qsar Fezna, northwest of the Jorf palm grove, and about 8 km north of Jorf town.

The Tafilalet plain was formed by the convergence of the Ziz and Ghéris rivers, which shaped this alluvial basin. Three main landforms can be distinguished: the plain, which is the most extensive and covers about 65% of the total area; the hamada; and the mountains, which occasionally appear as isolated peaks (Jbel Bine Jbilat, 854 m; Jbel Elgara, 809 m; Jbel Fezna, 926 m; and Jbel Elmenqara, 880 m). The lithological formations of the Jorf sector consist mainly of schist-sandstone layers that are highly susceptible to erosion. Quaternary deposits have left behind substantial alluvial accumulations that are sandy-silty in nature, providing a large reservoir of material that is easily mobilised by prevailing winds, especially during sandstorms. The sediments carried by the Ghéris and Ziz rivers and their tributaries are predominantly clay-sandy, making them highly sensitive to wind transport processes (Margat, 1958; Alali et al., 2013)

Aridity is the defining feature of the climate throughout southern Atlas Morocco (Joly, 1962; Akdim et al., 2017), where continental influences are predominant. The mean aridity index is 0.03 (Lamqadem et al., 2018). Maximum temperatures can reach 45 °C in summer, while winter minima range between –3 °C and 7 °C. Average annual rainfall is 67.7 mm (1967–2023), showing strong temporal variability. Potential annual evapotranspiration is about 1,200 mm (Navas et al., 2013). Wind conditions vary in both intensity and direction across seasons. Average monthly wind speed peaks at 9.1 m/s in May and June and decreases to around 5.8 m/s during winter (December–February). Wind rose data indicate a predominant southwest–northeast (SW–NE) direction associated with the Sahlé wind, along with secondary northeast–southwest (NE–SW, Chergui wind) and northwest–southeast (NW–SE) directions.

The population of Jorf has demonstrated the ability to exploit the advantages of their environment while adapting to its constraints. Through accumulated knowledge and practice, they have developed a highly complex and integrated agrosystem. This ingenuity is evident in spatial organisation, crop stratification, architectural forms, cultivation methods, and the diverse techniques used to mobilise water resources (Laaouane et al., 2019). Such achievements are also rooted in social organisations governed by a strict customary law that regulates not only human relations but also the management of economic and patrimonial resources.

Traditional oasis agriculture in the Jorf sector constitutes a key component of the desert environment. It embodies the knowledge and resilience of a society that has managed to thrive within an arid and settlement-constraining context (Hadeid et al., 2018; Hamamouche et al., 2018). Agriculture in the ancient palm groves is characterised as traditional and community-based, relying on local knowledge, solidarity, and collective labour and governed by social and communal norms (Lavie and Marschall, 2017). Historically, the Tafilalet region has played a central role in Morocco's history. It served as a major crossroads of trade and cultural exchange whose influence extended beyond regional boundaries. The city of Sijilmassa, now in ruins, stands as tangible evidence of this legacy. Tafilalet is also the birthplace of the Alaouite Dynasty, which continues to rule Morocco.

Data sources and preprocessing

Depending on the spatiotemporal scale of the study, various techniques worldwide monitor dune mobility and morphological changes. These include aerial photographs and satellite imagery (Bogle et al., 2015; Bouarfa and Bellal, 2018), and GPS measurements (Sbai and Mouadili, 2023a,b). Currently, drones and Lidar systems are commonly used (Robine et al., 2023; Ma et al., 2024).

In this study, the rate and direction of barchan dune mobility were determined using satellite images obtained freely via the Google Earth Pro platform. These images have a spatial resolution of 2 m (satellite Pleiades images from Google Earth Pro.). The analysis involved digitising dune deposits by creating KML files in Google Earth Pro, which were then imported and processed in vector format using ArcGIS for a final analysis.

Accurate measurement of barchan dune displacement requires identifying reference points (Figure 2). In this study, the right and left horns, the dune foot, and the avalanche face were selected as reference points. Monitoring at the Fezna site covered 12 years (2012–2024), divided into three time series (2012–2016, 2016–2020, and 2020–2024) to capture spatio-temporal variations in displacement rates.

Dune mobility measurements were coupled with climatic data (wind, precipitation, temperature, humidity, and evaporation) and sedimentological information to determine dune progression rates and the factors controlling sand movement variability. Surface mapping was used to measure silted agricultural areas (ha) across the Jorf palm grove. Field missions were conducted to validate results and assess the role of human activity, including interviews with local informants, particularly elders.

Auxiliary data was used to characterise the main drivers of dune mobility. Meteorological data were obtained from the Guir-Ziz-Ghéris Hydraulic Basin Agency (ABH, GZR) and the General Directorate of Meteorology (DGM), while socio-demographic information came from the High Commission for Planning (HCP).

RESULTS

Displacement rate of barchan dunes in the Fezna site between 2012 and 2024

Analysis of the results from high-resolution satellite images allowed accurate measurement of barchan dune movement (Table 1). Over the 12-year study period, the dunes migrated an average of 108.6 m, corresponding to an annual rate of 9.1 m/year. Mobility rates varied among individual dunes, with the highest displacement recorded at 11.3 m/year (B2) and the lowest at 6.1 m/year (B11). Examination of different reference points indicated that sand progression across morphological units (right horn, left horn, and dune foot) is relatively uniform. Specifically, the mean displacement rate was 110.2 m (9.18 m/year) for left horns, compared to 9.0 m/year for right horns and 8.98 m/year for dune feet.

The monitoring of barchan dunes displacement revealed significant variations both between the periods studied and among the individual dunes (Figures 3–4). At the Fezna site, the highest average displacement rate occurred during the second period (2016–2020), with a mean rate of 11.3 m/year, a maximum of 13.3 m/year (B15), and a minimum of 5.3 m/year (B22). The period 2012–2016 recorded the lowest average displacement rate, at 7 m/year, with the highest individual dune movement reaching 10.2 m/year (B18) and the lowest around 2.5 m/year. Between 2020 and 2024, the average displacement rate was approximately 9 m/year. Displacement rates also varied among dunes depending on their size and volume. For example, during the first period (2012–2016), dune B6, with an area of 488 m², exhibited an exceptionally high displacement rate of about 10 m/year, whereas the larger dune B11 (2004 m²) recorded a minimum average rate of 2.5 m/year over the same period.

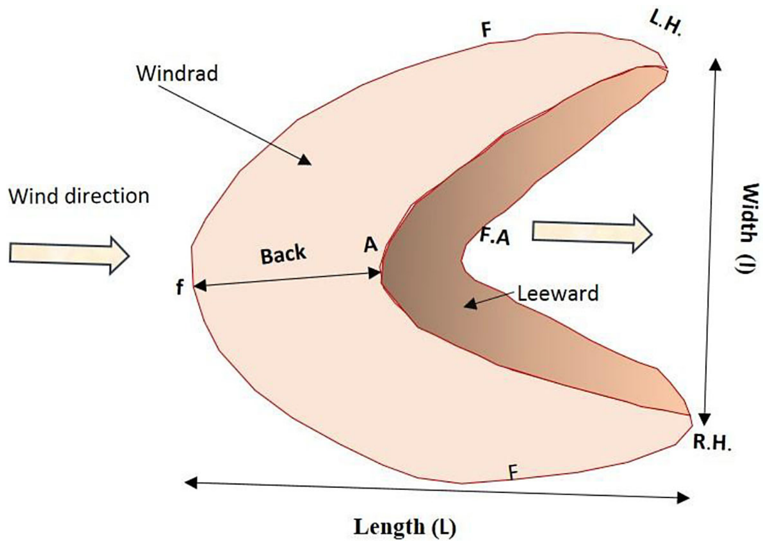

Figure 2. Morphological and morphometric units of barchan: f – foot, A – apex, F – flank, R.H. – right horn, L.H. – left horn, A.F. – avalanche face, L – length, W – width

Table 1. Mobility of the 12 barchans in the Fezna site between 2012 and 2024

Barchans	Right horn (m)	Left horn (m)	Foot (m)	Overall average displacement (m)	Annual average displacement (m/year)
B1	117	110	108	111.7	9.3
B2	132	123	152	135.7	11.3
B3	113	126	115	118	9.8
B4	69.7	109	88.4	89	7.4
B5	123	121	110	118	9.8
B6	134	132	120	128.7	10.7
B7	112	103	105	106.7	8.9
B8	136	121	122	126.3	10.5
B9	92.4	99.3	95.4	95.7	8
B10	95.6	97	88.6	93.7	7.8
B11	69.6	70.8	79	73.1	6.1
B12	98.6	110	112	106.9	8.9
Average	107.7	110.2	108	108.6	9.1

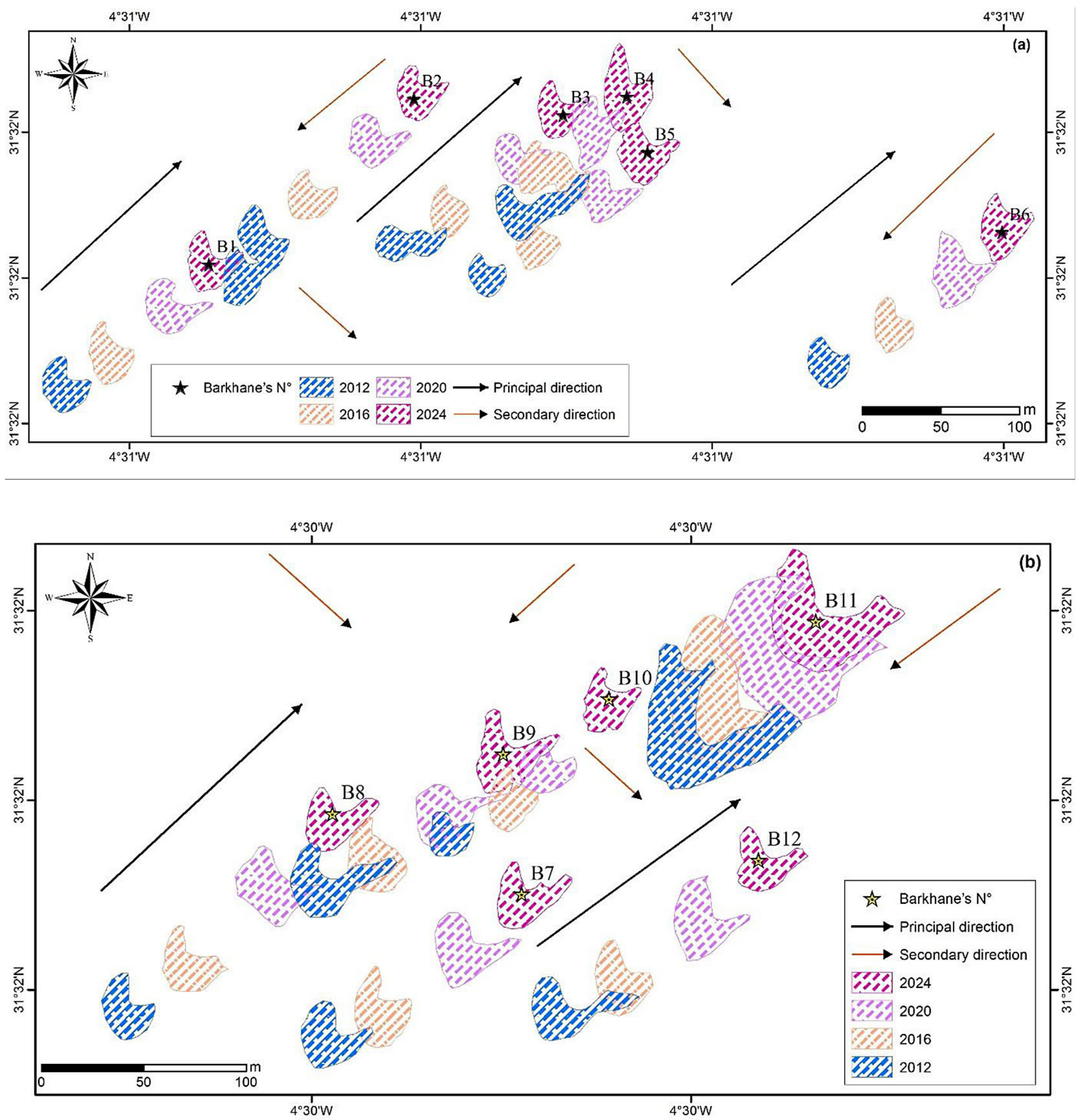

Figure 3. Morphological variations and mobility of barchan dunes in the Fezna site between 2012 and 2024 (a) from barchan 1 to barchan 6; (b) from barchan 7 to barchan 12

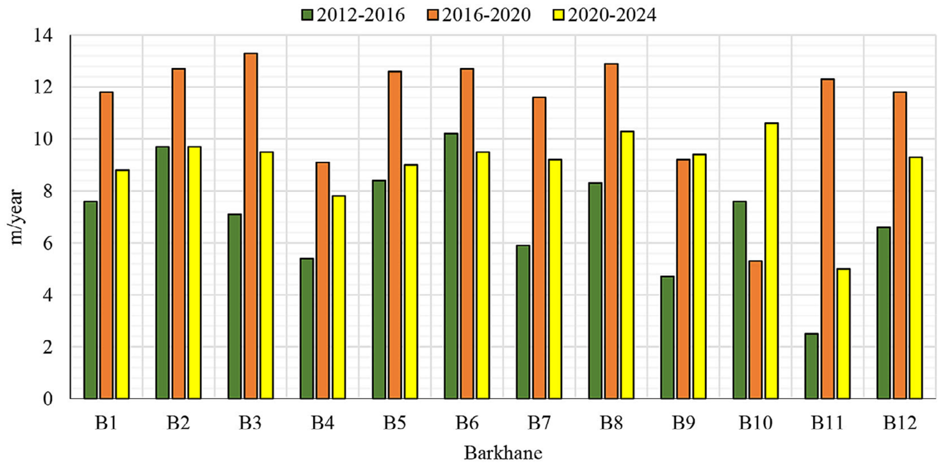

Figure 4. Temporal variations in the displacement rate of barchans in the site of Fezna

Variations in the orientation and migration direction of barchan dunes at the Fezna site

The determination of barchan dunes movement directions in the Fezna area was based on the monitoring and measurements described above, as well as on the orientation of the dunes (Table 2; Figure 5). Unlike classical wind roses, the dune displacement roses produced here do not represent the prevailing wind regime or potential sand transport, but rather the directions of active winds responsible for actual sand movement at the Fezna site. In this context, we observed a clear dominance of the southwest–northeast (SW–NE) direction, corresponding to the Sahlé wind, which accounts for 80% of movements. Field observations and dune monitoring also revealed the occurrence of the Chergui wind (NE–SW direction) at a frequency of 13%, and the northwest–southeast (NW–SE) direction at 6.7%. Although the Chergui wind is less frequent, it plays a crucial morphological role by significantly modifying the dune shapes created by the Sahlé wind, affecting ridge orientation, avalanche face slopes, and dune length.

Role of the climate and sandy material in the mobility of barkhanes in Jorf

Wind is a key climatic agent in dune morphogenesis, distribution, and mobility (Tsoar et al., 2009; Mainguet et al., 2006). The Tafilalet plain is highly vulnerable to sandstorms and dust events due to its location. Each year, from February to July, the season of strong winds, locally called Maoussem Elaajaj, begins. High wind speeds, extreme temperatures, very low relative humidity, and elevated evaporation accompany sandstorms in the Jorf area. For instance, during a sandstorm on 25 May 2023, wind speeds exceeded 24 m/s. The critical threshold for sand mobilisation and dune morphological change ranges from 4 to 6.25 m/s (Bagnold, 1941; Fryberger, 1979). During the same event, the maximum temperature reached 43.2 °C, and relative humidity dropped to 16.5%. Evaporation was also exceptionally high in June 2023, reaching 403.2 mm, compared to an annual average of approximately 235 mm.

Analysis of sedimentary data from the sandy material identified four sand fractions: coarse, medium, fine, and very fine, occurring in varying proportions (Table 3). In the Jorf sector, the sand is composed of 79.4% fine sand, 11.2% very fine sand, and 6.8% medium sand.

Environmental and socioeconomic impacts of sand encroachment

In pre-Saharan Morocco, the traditional oasis agricultural system represents an important heritage. Historically, oasis agriculture has played a central role in maintaining ecological, social, and cultural balance (Hadeid et al., 2018; El Khoumsi et al., 2017). The Jorf palm grove, due to its location, acts as a barrier against particle-laden winds and contributes to their deposition at the edge of the grove (Figures 6–7).

Quantifying the socio-economic impact of sand encroachment is essential to assess its adverse effects. Surveys and interviews with farmers in the Jorf palm grove, combined with analysis of aerial imagery, indicate that dune sand has invaded 351 hectares, including more than 20 percent of

Table 2. Orientation and direction of movement of the barchan dunes in the site of Fezna

Situation	Direction of movement	Observation tool
28/09/2011	SW-NE	Pleiade satellite
01/03/2012	NE-SW	Pleiade satellite
23/09/2012	SW-NE	Pleiade satellite
15/10/2012	SW-NE	Pleiade satellite
19/11/2012	SW-NE	Pleiade satellite
20/07/2013	NE-SW	Pleiade satellite
07/08/2013	SW-NE	Pleiade satellite
11/02/2016	SW-NE	Pleiade satellite
18/02/2016	NW-SE	Pleiade satellite
08/11/2018	SW-NE	Pleiade satellite
10/10/2020	SW-NE	Pleiade satellite
31/10/2022	SW-NE	Pleiade satellite
23/08/2023	SW-NE	On ground
03/04/2024	SW-NE	Pleiade satellite
30/05/2025	SW-NE	On ground

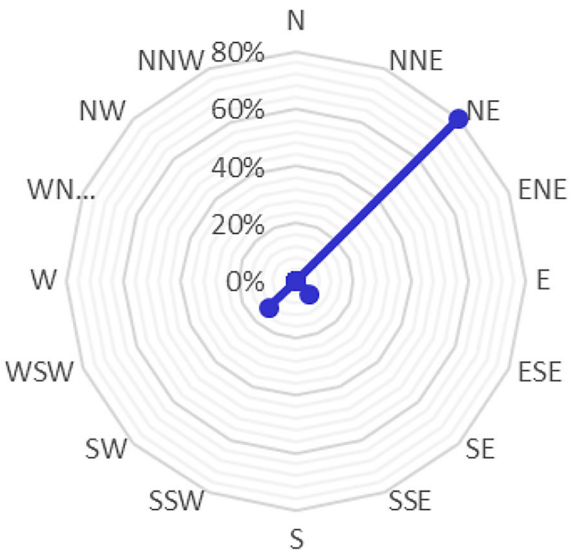

Figure 5. Rose of movement of the barchans in the site of Fezna from 2011 to 2025

Hannabou, 18 percent of Elmenqara, and 12 percent of Fezna (Table 4). According to Laaouane and Ben Kacem (2018), the financial value of this lost agricultural heritage amounts to 14,040,000 DH. Maintaining each hectare of cultivable land requires the labour of eight people, which represents a significant loss of working days that exacerbates local precarity and drives migration. Furthermore, surveys conducted in 2023 indicate that 35 percent of farmers in the Qsours de Jorf plan to leave their land, with 46 percent of them choosing the city of Fès as their destination.

Table 3. Relative proportions of the different types of sands contained in the sites constituting the Jorf sector

Sand proportion %	Sand proportion %
Coarse sand	2.6%
Medium sand	6.8%
Fine sand	79.4%
Very fine sand	11.2%

DISCUSSION

The mobility of free dunes is common in arid zones where sandy material is abundant (Dłużewski and Woronko, 2024). Plains and depressions in the Moroccan pre-Sahara are particularly favourable for wind-driven sedimentation (Mainguet et al., 2010). Several studies have documented the migration rates of barchan dunes in the Jorf area (Chemin, 1984; Kabiri et al., 2003). Chemin (1984) analysed the spatiotemporal evolution of sand encroachment and the progression of barchans to the west of the Hannabou palm grove. Using aerial photographs from 1951 to 1965, this study detected a displacement of 320 m, corresponding to an annual rate of 24 m. Kabiri and colleagues examined the wind regime, dune migration, and sand transport at the Elkraire site between 2000 and 2003 (Kabiri et al., 2003; Navas et al., 2013). Their results indicated an average displacement rate of 15 to 28 m/year toward the palm grove, that is, in a northeast direction.

Referring to the results obtained at the Fezna site (Figures 3–4) and to the studies conducted by Chemin (1984) and Kabiri et al. (2003) (Table 5), it is possible to conclude that the displacement rate of barchan dunes in the Jorf sector has decreased between 1950 and 2024. All studies consistently highlight the dominance of the southwest–northeast direction (Sahlé wind). The northeast–southwest (Chergui) and south–north directions are less significant for annual dune migration but play a notable role at the morphodynamic level. Although the work of Chemin (1951–1964) and Kabiri (2000–2003) provides important information about dune system dynamics, these results no longer reflect current displacement rates. This is due to significant socio-spatial changes in the Hannabou, Elkraire, Elbouia, and Fezna sectors, particularly in land use and silting control. Protection systems against silting, installed upstream instead of at downstream termini where dunes meet the edge of the palm grove, have

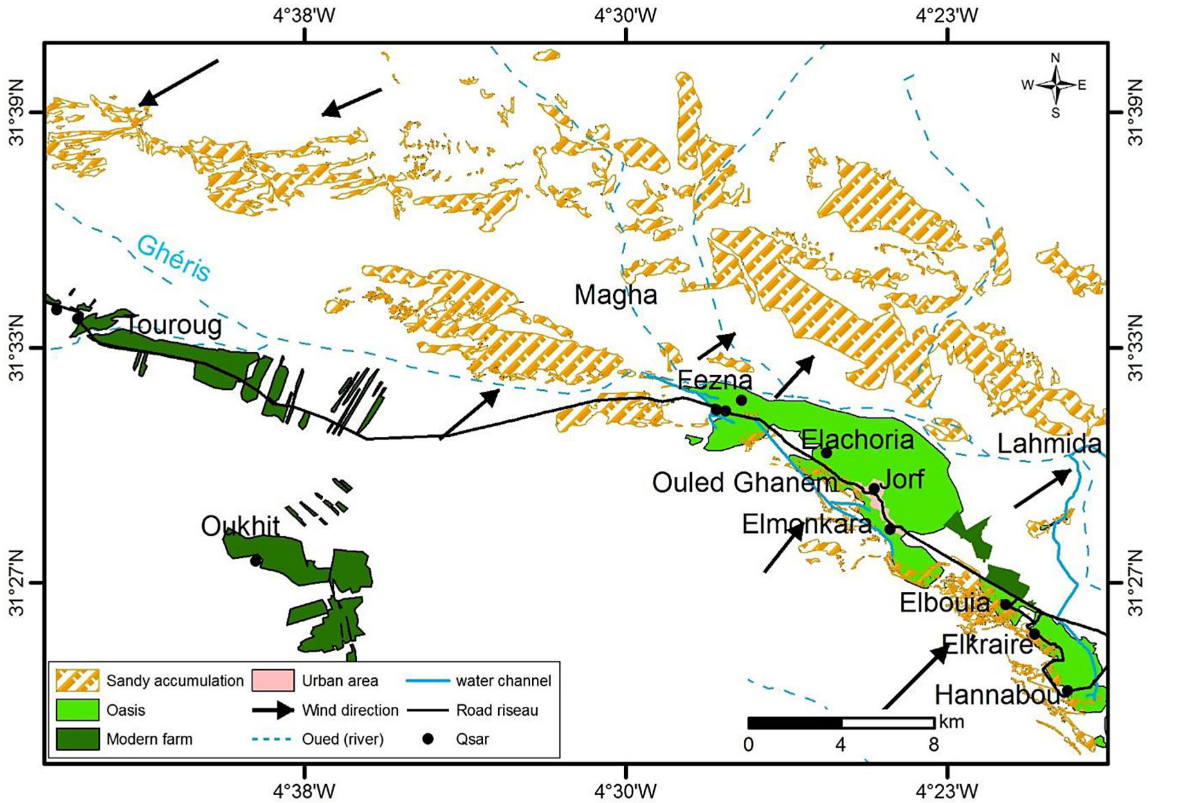

Figure 6. Sand encroachment of the palm grove, the Qsours and the infrastructure in the Jorf sector

Figure 7. Photographic views illustrating the reclamation of agricultural land and infrastructure in Jorf: (a) Elbouia, (b) Elkraire, (c) Ouled Ghanem, (d) road linking Elkraire and Elbouia

Table 4. Area of cultivable land invaded by sandy accumulation

Territorial Commune	Site	Agricultural area invaded by the dunes (ha)
Arabe Essebbah Ghéris	Hannabou	73.5
	Elkraire	41.4
	Elbouia	45.4
Municipality of Jorf	Elmonkara	62
	Ouled Ghanem	25.1
Fezna	Elaachoria	59.9
	Fezna	43.7

Table 5. Rate and direction of movement of the barchan dunes in certain sites in the Jorf sector

Site	Period of study	Annual movement	Direction of migration	Type of dune	Author
Hannabou	1951–1965	24 m/yr	Southwest–northeast	Barkhane	(Chemin, 1984)
Elkraire	2000–2003	Rate from 15 to 28 m/yr	Southwest–northeast	Barkhane	(Kabiri et al., 2003 ; Navas et al., 2013)

reduced wind-driven saltation and partially stabilised wind deposits. Furthermore, studies of sand encroachment impacts in the Rissani palm grove indicate that sand has invaded 390 hectares, with over 80 percent affecting the western front. The financial value of this lost agricultural heritage is estimated at 15,600,000 DH (Laaouane and Ben Kacem, 2018).

CONCLUSIONS

This study combined morphological, meteorological, and environmental data to analyse the mobility and impact of active sand dunes at the Fezna site in Jorf. The findings indicate that the Fezna barchan field remains active, although the rate of dune migration has slowed over time. Climatic aridity, sand availability, flat topography, and human activity are the main factors influencing dune dynamics along the western edge of the palm grove. Dune migration has major consequences, threatening the stability of the oasis agrosystem and nearby settlements. These results are essential for developing effective dune control and land management strategies.

Acknowledgments

The authors sincerely thank the farmers and local residents of the Jorf and Fezna regions for their cooperation and valuable insights during this study.

REFERENCES

1. Akdim, B., Laaouane, M., Sabiri, A. (2017). Morocco's Southeast (Presahara). In *Research association work on sustainable land management: On the sidelines of the publication of the 2013 report of the national programme to combat desertification, updating and adaptation to zonal specificities* 79–112. Rabat. *(in French)*
2. Alali, A., Benmohammadi, A. (2013). Sand encroachment in the plain of Tafilalet (south-east of Morocco). *Larhyss Journal*, *16*, 53–75. *(in French).*
3. Bagnold, R. A. (1941). *The physics of blown sand and desert dunes.* Methuen.
4. Benalla, M., Alem, E.M., Rognon, P., Desjardins, R., Hilali, A., Khardi, A. (2003). Les dunes du Tafilalet (Maroc): Dynamique éolienne et ensablement des palmeraies. *Sécheresse*, *14*(2). *(in French)*
5. Benbih, M., Ouammou, A., Nmiss, M., Naitsi, H., Boukdoun, A. (2025). Contribution of geographic information systems (GIS) to the geodynamic monitoring of barkhanes in the Middle Draa, Morocco. *Geomatics and Land Management*, *2*(1), 174–184. https://doi.org/10.34874/PRSM.GGT-2025.V2.N1.3867 *(in French).*
6. Benmohammadi A., Benmohammadi L., Ballais J.L., Riser J. (2000). Analysis of anthropic and natural interrelations: their impact on the resurgence of sand encroachment and desertification in southeastern Morocco. *Drought; 11*(4). 297–308. (in French).
7. Bogle R., Redsteer M.H., Vogel, J. (2015). Field measurement and analysis of climatic factors affecting dune mobility near Grand Falls on the Navajo Nation, southwestern United States.

Geomorphology, 228(1), 41–51. https://doi.org/10.1016/j.geomorph.2014.08.023

8. Bouarfa, S. and Bellal, S.A. (2018). Assessment of the Aeolian sand dynamics in the region of Ain Sefra (Western Algeria), using wind data and satellite imagery. *Arabian Journal of Geosciences, 11*(3), article no. 56. https://doi.org/10.1007/s12517-017-3346-9
9. Bristow, C.S. and Duller, G.A.T. (2024). The structure and chronology of a star dune at Erg Chebbi, Morocco, reveals why star dunes are rarely recognised in the rock record. *Scientific Reports, 14*(1), article no. 4464. https://doi.org/10.1038/s41598-024-53485-3
10. Cai L., Ding G.D., Qu M., Zhang Y., (2025). Sand barriers promote the accumulation of soil nutrients in sandy areas under different ecological conditions: A meta-analysis. *Journal of Environmental Management,* 381. https://doi.org/10.1016/j.jenvman.2025.125235
11. Callot, Y., Crépy, M. (2018). The role of sand supply in linear dune dynamics: a paradigm shift? Cross-approach of modelling contributions and field observations (Erg de Fachi-Bilma, Niger, Chad): *Geomorphology: Relief, Processes, Environment, 24*(3), 225–235. https://doi.org/10.4000/geomorphologie.12365 (in French).
12. Callot, Y. and Oulehri, T. (1996). Geodynamics of the Aeolian sands in the north-western Sahara: relations between aerology and geomorphology. *Geodinamica Acta, 9*(1), 1–12. https://doi.org/10.1080/09853111.1996.11417259 (in French).
13. Chemin, M.C. (1984). Sand encroachment in the palm groves of southeastern Morocco. Need for a local, regional and synoptic approach to understanding the effects of wind dynamics. Case studies. *Works of the Institute of Geography of Reims, 59–60,* 111–130 (in French).
14. Dłużewski, M., Woronko, B. (2024). In the Land Dunes of the Kampinos National Park. *In World Geomorphological Landscapes: Vol. Part F2267*. https://doi.org/10.1007/978-3-031-45762-3_30
15. El Khoumsi W., Hammani A., Kuper M., Bouaziz A. (2017). The sustainability of the oasis system in the face of groundwater resource deterioration: the case of the Tafilalet palm grove. *Revue Marocaine des Sciences Agronomiques et Vétérinaires* 5(1), 41–51. (in French).
16. Elbelrhiti, H. (2005). Morphodynamics of barkhanes: a study of the dunes of southwest Morocco. *Doctoral thesis. Université Denis Diderot – Paris VII*, 154 (in French).
17. Fryberger, S.G. (1979**)**. Dunes form and wind regime. In: McKee, E.D. (edition) A study of global sand seas. *U.S. Geological survey Professional paper*, 137–169.
18. Génois, M., Hersen, P., Pont, S., Grégoire, G. (2012). When dunes move together, the structure of deserts emerges. *arXiv Preprint*, *arXiv:1211.7238*, 1.
19. Hadeid, M., Bellal, S. A., Ghodbani, T., Dari, O. (2018). Agriculture in the Sahara of southwest Algeria: Between modern agricultural development and the permanence of traditional oasis agriculture. *Cahiers Agricultures, 27*(1), 15005. https://doi.org/10.1051/cagri/2017060 (in French).
20. Hersen, P. (2004). *Morphogenesis and dynamics of the barchanes* (Doctoral thesis, University Paris VII). (in French).
21. Joly, F. (1962). *Study on the relief of the southeast of Morocco.* From the Scientific Institute Chérifien, Geology and Physical Geography Series, No. 10. Rabat (in French).
22. Kabiri, L., Boudad, L., Krimou, A., Khardi, A., Elmrani, L. (2003). Preliminary study of the dynamics of continental dunes in the Moroccan southeast. *Sécheresse, 14*(3), 149–156. (in French).
23. Laaouane, M., Ben Kacem, A. (2018). Sand encroachment in the palm grove of Rissani (Tafilalet, Morocco): Diachronic follow-up, impact study, and control strategy. *Geography of Morocco, 33*, 66–86. (in French).
24. Laaouane, M., Ben Kacem, A., Akdim, B. (2019). Characterization of sand encroachment in the palm grove of Rissani (Tafilalet, Morocco). *Geomaghreb, 15*, 1–21. (in French).
25. Lamqadem, A. A., Pradhan, B., Saber, H., Rahimi, A. (2018). Desertification sensitivity analysis using the MEDALUS model and GIS: A case study of the oases of Middle Draa Valley, Morocco. *Sensors (Switzerland)*, *18*(7), 2230. https://doi.org/10.3390/s18072230
26. Lancaster, N. (2023). *Geomorphology of desert dunes.* Cambridge University Press. Second Edition, pp 333. https://doi.org/10.1017/9781108355568
27. Lavie, E., Marshall, A. (2017). *Oases and globalization: Ruptures and continuities.* Springer-Verlag, 255.
28. Livingstone, I., Wiggs, G. F. S., Weaver, C. M. (2007). Geomorphology of desert sand dunes: A review of recent progress. *Earth-Science Reviews, 80*(3–4), 239–257. https://doi.org/10.1016/j.earscirev.2006.09.004
29. Ma, D., Tian, Z., Zhu, C., Wang, Y. (2024). A comprehensive approach to evaluate coastal dune evolution in Haiyang, China. *Frontiers in Marine Science, 11, 1–15.* https://doi.org/10.3389/fmars.2024.1326317
30. Mainguet, M., Dumay, F., Kabiri, L. (2006). Use of indicators for desertification in the oasis settlements. *Rapport inédit, Programme OTAN réf. 981994*, 62.
31. Mainguet, M., Dumay, F., Kabiri, L., Rémini, B. (2010). Prodromes of desertification in the oasis of

Tafilalet in Morocco and specific local solutions. In *Global environmental change, disasters and security: Threats, challenges, vulnerabilities and risks OTAN 5*, 901–919.

32. Manzolli, P.R., Portz, L.C., Fontán-Bouzas, A., Bitencourt, V., Alcántara-Carrió, J. (2023). Contribution of reverse dune migration to stabilisation of a transgressive coastal dune field at Lagoa do Peixe National Park dune field (south of Brazil). *Remote Sensing, 15*, 3470. https://doi.org/10.3390/rs15143470
33. Margat, J. (1958). The water resources of the palm groves of Tafilalet. *Economic Bulletin of Morocco, 22*, 1–20. (in French).
34. Mestoul, D. (2021). Dynamics of silting in the Gourara in southern Algeria: Origins, anthropogenic factors of aggravation, and prospects. *Geomorphologie: Relief, Processus, Environnement, 27*(1), 53–67. https://doi.org/10.4000/geomorphologie.15346 (in French).
35. Navas, A., Sadiki, A., Machin, J., Gaspar, L., Kabiri, L., Faleh, A. (2013). Soils in the country of Ziz (Moroccan southeast): Characteristics and aspects of degradation. *Info-Print: El Kadissia-Lido–Fez*, 106. (in French).
36. Pedrosa, A., Claudino-Sales, V. (2023). Dune migration at Canoa Quebrada, northeast Brazil. *Contributions to the Social Sciences*, *16*(7), 7058–7078.
37. Rahdari, M. R., Rodríguez-Seijo, A. (2021). Monitoring sand drift potential and sand dune mobility over the last three decades (Khartouran Erg, Sabzevar, NE Iran). *Sustainability (Switzerland)*, *13*(16), 9050. https://doi.org/10.3390/su13169050
38. Robin, N., Billy, J., Nicolae Lerma, A., Castelle, B., Hesp, P. A., Rosebery, D., Fauny, C., Deparis, J., Marieu, V., Bouchet, C., Miot da Silva, G. (2023). Natural remobilization and historical evolution of a modern coastal transgressive dunefield. *Earth Surface Processes and Landforms*, *48*(5), 1064–1083. https://doi.org/10.1002/esp.5535
39. Sbai, A., Mouadili, O. (2023a). Contribution of the GPS in the study of dune dynamics: Examples in eastern Morocco. *Physio-Géo*, *19,* 113–131. https://doi.org/10.4000/physio-geo.15944 *(in French).*
40. Sbai, A., Mouadili, O. (2023b). Using the GPS station to study wind and coastal morpho-dynamics in northeastern Morocco. *Journal of Geographical Research*, *6*(1), 28–38. https://doi.org/10.30564/jgr.v6i1.5270
41. Tsoar, H., Blumberg, D. G., Wenkart, R. (2008). Formation and geomorphology of the north-western Negev sand dunes. In *Arid Dune Landscapes* 25–49. Springer. https://doi.org/10.1007/978-3-540-75498-5_3
42. Tsoar, H., Levin, N., Porat, N., Maia, L. P., Herrmann, H. J., Tatumi, S. H., Claudino-Sales, V. (2009). The effect of climate change on the mobility and stability of coastal sand dunes in Ceará State (NE Brazil). *Quaternary Research*, *71*, 217–226.
43. Wang L., Wu, Q., Fu, Z., Jiang, G., Liu, Y., Xu, K., (2022). Aeolian sand accumulation and land desertification over the past 1,500 years as revealed by two aeolian dunes in the Beiluhe Basin on interior Qinghai-Tibet Plateau, SW China. *Quaternary International*, *613,* 101–117. https://doi.org/10.1016/j.quaint.2021.11.01