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Detection of sand encroachment patterns in desert oases. The case of Erg Chebbi (Morocco)

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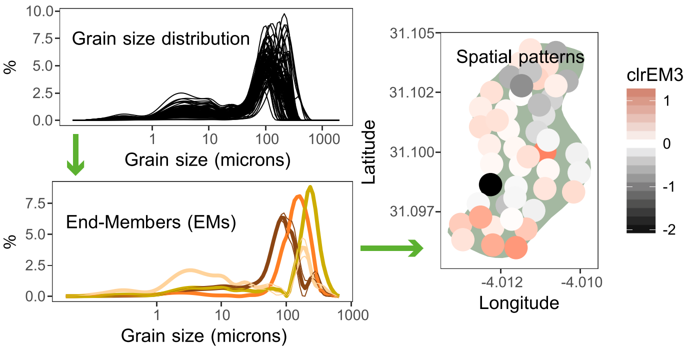
HIGHLIGHTS

- Desert oases agroecosystems are very vulnerable to sand encroachment.
- We show how to identify sand sources and areas of sand accumulation.
- We exemplify our approach with the case study of Erg Chebbi (Morocco).
- Our approach allows developing better tailored initiatives for oases conservation.

GRAPHICAL ABSTRACT



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ABSTRACT

Desert oases are fragile agrarian areas, very vulnerable to sand encroachment by wind. Ensuring their conservation highly depends on our capacity to identify sand encroachment patterns, e.g. the origin of sand and its spatial distribution in the irrigated plots. Here we show how to tackle this issue using the case study of Erg Chebbi (Morocco), where two oases (Hassilabiad and Merzouga) are surrounded by dunes, Hamada and alluvial sediments from the Wadi Ziz. We combine field interviews with the study of wind dynamics, sediment sampling, Particle Size Distribution (PSD) tests and End-Member Modelling Analysis (EMMA). We observe that the most relevant contributor to sand encroachment is the Wadi Ziz (30%), followed by the Hamada (28%), an undetermined source of dust (25%), and the Erg dunes (16%). These genetically different sediments cluster unevenly in the oases, indicating the existence of areas with contrasting degrees of exposure to sedimentary sources. The results allow to define on solid grounds which sand source areas should be stabilized first in order to obtain the greatest reduction in sand encroachment. Our approach also provides policy-makers with better tools to identify which spots are specially vulnerable to accumulate a specific sediment, thus allowing for a more nuanced management of sand in oasis environments.

1. Introduction

Oasis agriculture, e.g. the management of water flows to irrigate crops in desert environments, epitomizes the capacity of humans to turn barren lands into productive, ecologically-rich agrarian

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fields. Approximately 150 million people currently benefit from oasis agriculture (Cheneval, 2016), either through direct cultivation, trade or touristic services. Oases also play a non-negligible role as reserves of fauna and flora biodiversity as well as soil carbon and nitrogen stocks (Lavee et al., 1991; Li et al., 2013; El-Saied et al., 2015; Schmaljohann et al., 2007). However, due to their location in or at the fringes of deserts, oases are highly threatened by sediment encroachment, e.g. the accumulation of sand and silt grains carried by wind (Berque, 2010). In oasis environments, sediment encroachment destroys crops through burial or dehydration, reduces the water retention capacity of the soil and its nutrient pool and increases the chances of water stress due to plot thickening, slope modification and channel clogging. Upcoming climate change is likely to accentuate both the recurrence and the intensity of sand encroachment through the reactivation of dune fields (Thomas et al., 2005), a process that will be first felt in desert oases and will put them under serious risk of collapse.

Aiming at developing effective measures to ensure oasis conservation, major efforts have been invested on assessing the properties of different windbreaks and shelterbelts in protecting oases from sandstorms (Mohammed et al., 1996; Zhao et al., 2008). Our capacity to secure oasis sustainability has also been increased by studies on the physics of sand transportation and dune formation (Bristow et al., 2007; Kok et al., 2012; Weltje, 2012). However, sand encroachment in oases is a complex process defined by the unpredictable interaction of several social (e.g. agrarian practices) and environmental (e.g. wind speeds and direction, sediment availability) variables. Such dynamic behaviour renders the particularities of sand encroachment a highly context-dependent phenomenon, and one-size-fits-all policies against desertification unlikely to succeed. In other words: strategies that proved successful in a given setting might underperform, fail or even backfire when exported to an apparently similar environment. This uniqueness urges for the development of comprehensive approaches aimed at unfolding, for any oasis environment, the particularities of its processes of sand encroachment. We argue that the most pressing issues involve identifying how many sedimentary sources contribute sand or whether sand encroachment displays a spatially structured pattern: the first conditions the number of different grain sizes entering an oasis, their transportation pathways and therefore the global design of any sand-fighting strategy. The second, its spatial implementation.

Here we show how to detect sand encroachment patterns in oases agroecosystems by combining aeolian analysis, field interviews, sediment sampling, Particle Size Distribution (PSD) tests and End-Member Modelling Analysis (EMMA). We exemplify our approach using the case study of Erg Chebbi (Tafilalt/Taouz region, South-East Morocco, 31.13° lat, −4.02° lon), a dune field extending over c. 110 km^2 that stores a moderate amount of groundwater used by local communities to irrigate the oases of Hassilabiad (16 ha) and Merzouga (21 ha) (Fig. 1, Supplementary Information). The Erg is surrounded by Hamada, a large rocky, unvegetated plateau that spreads over dozens of kilometers in the Sahara, Australian deserts and Libya (Goudie, 2004). To the west of Erg Chebbi, the Hamada is cut by the Wadi Ziz riverbed, an ephemeral river. Our case study is therefore a conspicuous example of an oasis environment susceptible to accumulate sand from more than one sedimentary source, a setting that requires a precise evaluation of the risks posed by each sand source before effectively implementing any sand-fighting strategy. In the paper we illustrate how to quantify the relative contribution of each sedimentary source to sand encroachment and precise its spatial distribution in the oases. We conclude by showing how this information can be used to improve our capacity to design better tailored, more nuanced policies for oasis conservation in desert environments.

2. Materials and methods

2.1. Fieldwork

We conducted face-to-face, semi-structured interviews with irrigators of the Hassilabiad oasis on September 2016. The aim was to know how they perceived sandstorms in terms of their effect on the oasis, main features, provenance and yearly occurrence. Since neither a list of irrigators nor any irrigation registry was available as a sampling frame, we systematically interviewed all the subjects that we found working in the oasis between 09.00–14.00 h. According to one of the authors (Yousef Oubana), most of the irrigators went to the oasis to conduct their agricultural tasks in this time slot. This strategy allowed us to interview 24 irrigators, thus sampling almost half the population ($N \approx 50$).

We carried out a systematic sediment sampling of the Hassilabiad and Merzouga oases and the three main sedimentary sources of the region: the Erg Chebbi star-shaped dunes, the Hamada sediment and the alluvial sediments of the Wadi Ziz (Fig. 1). Samples were collected from the dune crests in the Erg and from the first 30 cm of sediment in the Hamada and the Ziz. As no prior information on grain size variability within each group was available prior to sampling, we followed Small et al. (2002) and collected c. 20 samples per sedimentary source. The sample size collected from the oases was defined after a prospective Bayesian power analysis (1500 simulations) with the Region Of Practical Equivalence (ROPE) for the effect size set at (−0.5, 0.5) (Kruschke, 2013), as we considered a small to medium difference in texture between Hassilabiad and Merzouga to be irrelevant for policy purposes. We decided to collect 51 soil samples in each oasis, reaching a mean power of 0.95 [95% highest density interval (HDI) = 0.93–0.96]. We drew sampling transects following the direction of the palm tree rows and added random sampling points between transects until achieving the desired sample size. Sediment samples from the oases were collected from the first 30 cm of the soil to ensure that they reflected recent processes of sand encroachment. Each sample was thoroughly mixed and stored in plastic bags for Particle Size Distribution (PSD) analysis in the laboratory.

2.2. PSD analysis

We carried out PSD analysis in a Coulter LS 230 at the Laboratori de Sedimentologia, Facultat de Ciències de la Terra, Universitat de Barcelona, Spain. PSD tests were conducted on the <2 mm soil fraction after air-drying the samples at room temperature for 48–72 h. Organic matter and carbonates were removed with solutions of 10–15% H_2O_2 and HCl respectively. We decalcified all the samples prior to measurement to prevent secondary carbonates formed as a consequence of irrigation from biasing the grain size distribution of the oases samples. We also applied a 50 ml sodium polyphosphate solution to avoid flocculation and the formation of aggregates. Ultrasounds were not used to circumvent undesired effects such as re-aggregation or ghost signals (Machalett et al., 2008). Each run in the Coulter was set at 60 s and the retained value averaged the values provided by the device during this time span, with the limits for the mean and the standard deviation being within ±1.8 μm and ±2.25 μm respectively. The obscuration level was measured with a Polarization Intensity Differential Scatter (PIDS) unit. The resulting 117 grain classes ranged from 0.039 to 2000 μm and were defined using Gradistat (Blott and Pye, 2001). The mean ± standard deviation of the PIDS values for each of the sampling groups is presented in Table S1 of the Supplementary Information file.

2.3. Statistics

We conducted the statistical analyses in the *R* environment (R Core Team, 2018). For the analysis of PSD data we used the