

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



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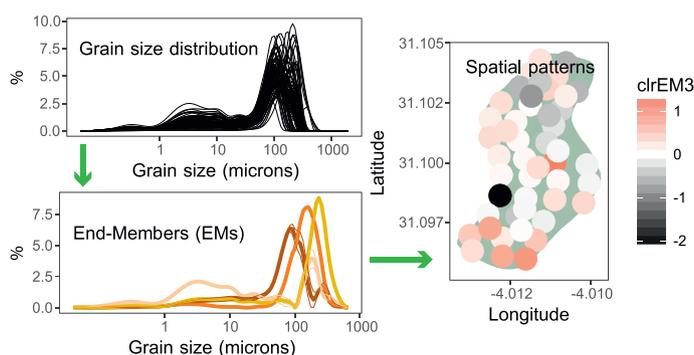
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HIGHLIGHTS

- 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.

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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 km² 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% H₂O₂ 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 $\pm 1.8 \mu\text{m}$ and $\pm 2.25 \mu\text{m}$ 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 \pm 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

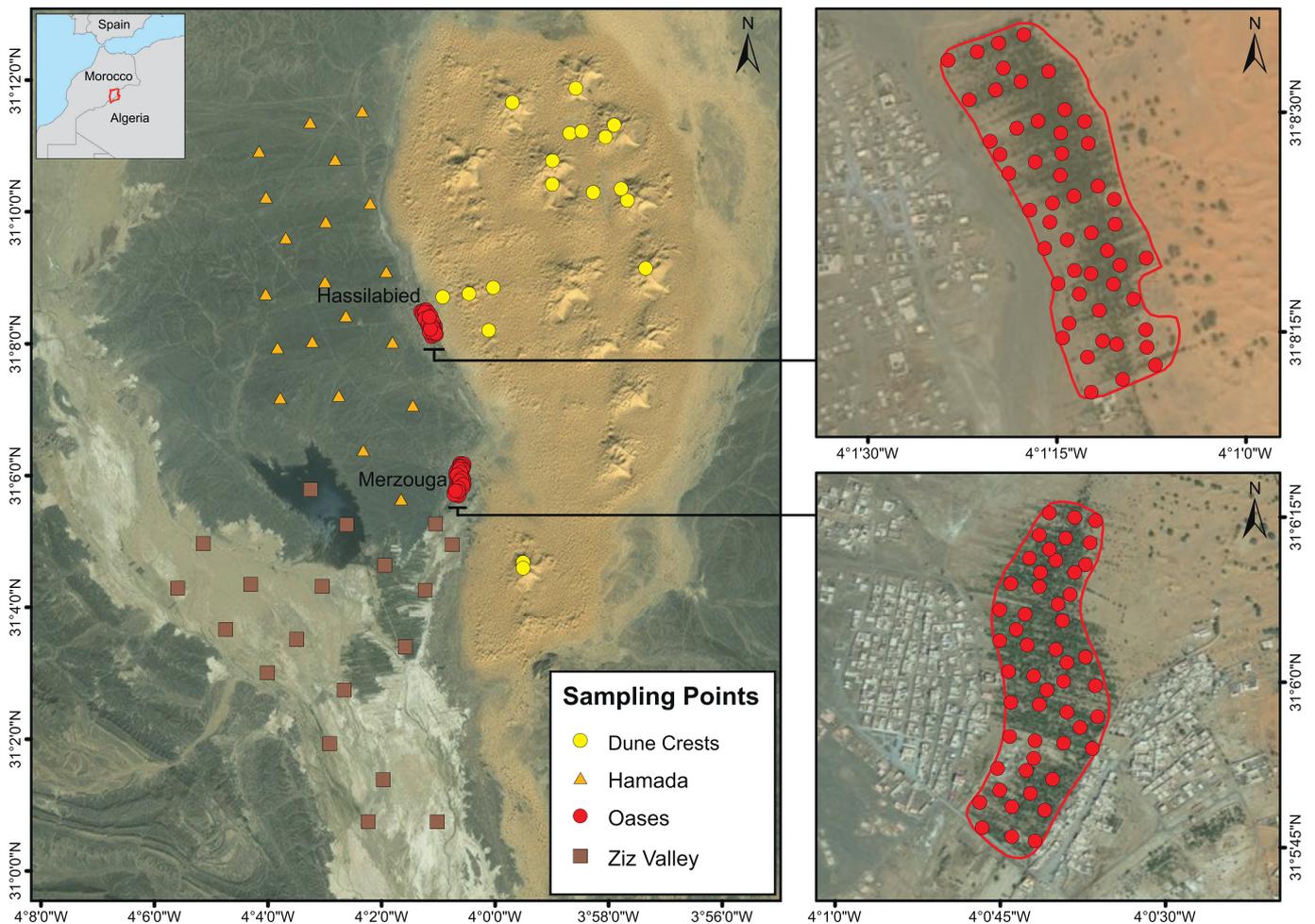


Fig. 1. Location of Erg Chebbi, the Hassilabiad and Merzouga oases and the sampling points. The images have been retrieved from Data ESRI, DigitalGlobe, GeoEye, i-cuved, USDA, FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo and the GIS User Community.

compositions package (van den Boogaart et al., 2014) and followed the guidelines set forth by van den Boogaart and Tolosana-Delgado (2013). PSD data are a conspicuous example of compositional data (*CoDa*), e.g. vectors of positive components that constitute parts of a total, thus conveying only relative information. The sand, silt and clay fractions sum up to a constant (e.g. 100%) in each sample and any change in a given fraction leads to a change in the rest. Although this total sum constraint is of no real relevance as all compositional datasets are actually a simplification of a more complex reality, it forces any analysis to focus on the relative proportions between variables rather than on their absolute values. *CoDa* have thus to be transformed to log-ratios using either the additive log-ratio (*alr*), the centered log-ratio (*clr*) or the isometric log-ratio (*ilr*) transformation (Aitchison, 1986; Egozcue et al., 2003).

Here we used the *ilr* transformation to assess whether the Hassilabiad and Merzouga oases present significant differences in their soil texture. The *ilr* transformation uses an orthonormal basis based on balances to generate $D - 1$ contrasts and can yield non-interpretable *ilr* variables if the contrasts between the original variables have not been carefully selected. Aiming at creating meaningful balances with the highest discriminative power possible, we created the contrasts after inspecting a compositional biplot with the PSD data (Pawlowsky-Glahn and Egozcue, 2011). Components labelled “-1” were contrasted with components labelled “+1”, expressed here as [denominator | numerator] following Parent et al. (2014).

We also *clr* log-transformed the End-Member (EM) scores to better visualize in a map the relative contribution of each EM in

relation to the other EMs in the sample space (see Section 2.4). The *clr* transformation divides each variable by the geometric mean of all variables considered followed by a log-transformation. Unlike the *ilr* transformation, it yields D *clr*-transformed variables that are directly related to the original variables. However, it suffers from collinearity and singularity due to the use of a common divisor, an issue that requires the focus to be set on the single *clr*-transformed variables and not on their relations. *Clr*-transformed variables have been successfully used, for instance, to map elemental concentrations in agricultural soils of Europe (Reimann et al., 2012).

2.4. End-member modelling

We used End Member Modelling Analysis (EMMA) and the *EMMAgeo* package to discern how much sediment from each of the sedimentary sources surrounding Erg Chebbi encroaches in the Hassilabiad and Merzouga oases (Dietze et al., 2012; Dietze and Dietze, 2016). EMMA considers *CoDa* constraints and relies on the principles of eigenspace analysis and scaling to extract robust EMs from the PSD dataset, e.g. loadings representing grain size classes and scores reflecting the grain size composition in the sample space (Weltje and Prins, 2007). Although applied in many different contexts as a tool to analyze grain size distributions (Beuscher et al., 2017; Dietze and Dietze, 2016; Jiang et al., 2017; Weltje, 2012), the potential of EMMA for guiding policies against sand encroachment in desert oases has remained fully untapped as yet.

We defined the model based on the grain size distribution of the samples collected from the Hassilabiad and the Merzouga oases, and used the grain size distribution of the sedimentary sources for calibration purposes. We retained 105 grain size classes (0.039–653 μm) after discarding grain size classes that contained only zeroes ($n = 12$, 716–2000 μm). The weight transformation vector (l_w) was defined in a sequence of 100 values between 0 (l_{min}) and 0.033 (l_{max}) while the number of robust EMs (q_{max}) was set at 4 after measuring the model performance through combinations of different numbers of EMs (2–12) and l_w values. According to Weltje and Prins (2007) and Dietze et al. (2012), EMMA might create artificial modes where other EM modes overlap, a statistical artifact caused during the description of the variability of the data set. Hence only primary modes or modes not overlapping with other EM modes should be interpreted genetically (Dietze et al., 2016). The full R code for the model and the PSD dataset are available in Appendix A as Supplementary data.

2.5. Wind data

We retrieved wind data from the Jebel Brahim station (29.93° lat, –5.62° lon), located at the southern border of the Anti-Atlas, 150 km to the SW of Erg Chebbi (Schulz and Fink, 2016). The Jebel Brahim station is one of the fourteen automated weather stations set by the IMPETUS GLOWA project (University of Cologne) along a transect spanning the Atlas to the Northern Rim of the Sahara. The data collected by the Jebel Brahim station reflects the wind regime at the edge of the Saharan desert and can therefore be reliably used as a proxy for the wind regime in Erg Chebbi. We used data on wind speed and direction, collected by the station on a semi-regular basis between 2002–2011 at a 15 min interval and at 3 m above ground level.

3. Results

3.1. Interviews

Fig. 2 shows the results of the interviews. We interviewed 22 males and 2 females, with the mean age being 56.4 ± 16.3 years. Irrigators considered sandstorms as the most threatening factor for the sustainability of the oasis, followed by water stress and weeds. March–April and the summer season were alluded to as the periods of the year with the highest occurrence of sandstorms. Many irrigators differentiated between sandstorms blowing SW–WSW from

those blowing NE–ENE in terms of grain size inputs and impact on agricultural tasks: they noted that sandstorms blowing from the SW–WSW bring in finer, hotter, darker dust that ‘burns’ and dries the crops. Sandstorms blowing from the E transfer coarser, reddish sand from the dunes into the oasis, clogging the channels, burying the crops and thickening the plots. Sandstorms blowing from the NE bring the same material as those blowing from the E, but dustier. Some interviewees also explained that sandstorms blowing from the SW–WSW can have some positive side-effects in the management of the oasis: the wind carries dust that can be mixed with the soil to improve fertility, and if strong enough, it can push the sand encroached to the easternmost area of the oasis out of the agricultural zone.

3.2. Sediment sampling

Fig. 3 presents the grain size structure of the Hassilabiad and Merzouga samples. The fractions coarser than fine sand ($>250 \mu\text{m}$) were discarded due to the presence of zeroes, which pose serious difficulties when dealing with *CoDa* (van den Boogaart and Tolosana-Delgado, 2013). The biplot explains a high degree of variance (>0.9) and most observations are very well represented by the two first principal components ($\cos^2 > 0.75$). The samples from Hassilabiad are more dominated by fine sand, very fine sand and very coarse silt particles. The samples from Merzouga present higher values in medium silt, fine silt, very fine silt and clay. The separation between these two grain size groups is clear and allows setting a robust threshold for particles that behave similarly. Following the first axis of the biplot, we balanced [csilt, msilt, fsilt, vfsilt, clay | fsand, vfsand, vcsilt] to obtain a proxy for the proportion between the fine and the coarse fractions, or *ilr1* (see Table S2 for the complete Sequential Binary Partition, SBP). This *ilr*-transformation placed the data on the Euclidean space and set the ground for a statistical assessment of the differences in grain size between the oases, which we conducted via a Bayesian *t*-test. The results evidenced that Hassilabiad and Merzouga have convincingly very different mean grain sizes ($\mu_1 - \mu_2 = 0.99$), with the former and the latter presenting respectively a much coarser soil texture and a much larger grain size variability (Fig. S2).

Fig. 4 shows the spatial distribution of *ilr1* values in Hassilabiad and Merzouga. Higher (or positive) *ilr1* scores indicate a higher weight of the fine sand, very fine sand and very coarse silt fractions (e.g. the coarse fraction is more dominant). Lower (or negative) *ilr1* scores reflect a higher weight of the coarse silt, medium silt, fine silt,

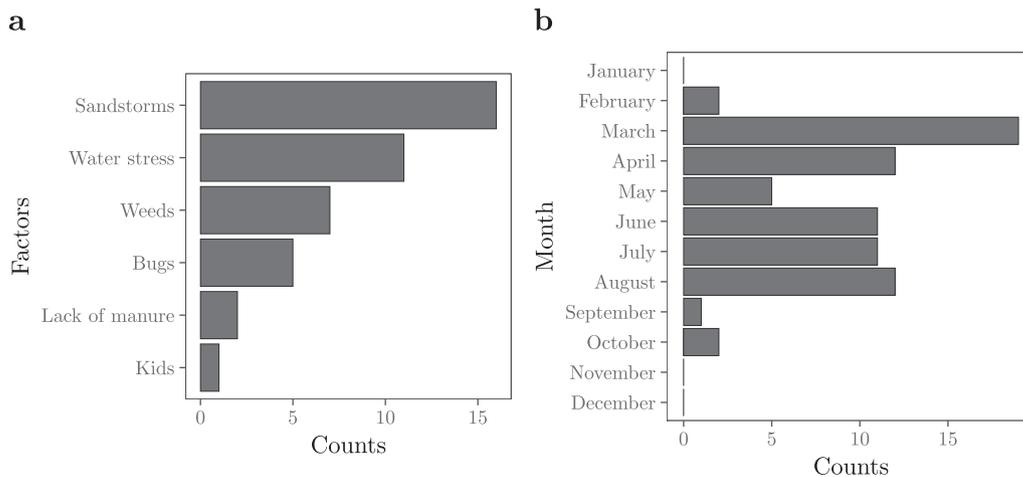


Fig. 2. Bar plots with the results of the interviews. Interviewees were allowed to mention as many factors and months as they considered relevant. a) Factors threatening the sustainability of the oasis. NA = 1. b) Occurrence of sandstorms along the year. Six counts in June, July and August have been added to the bar plot to account for six irrigators that mentioned ‘summer’ instead than a specific month.

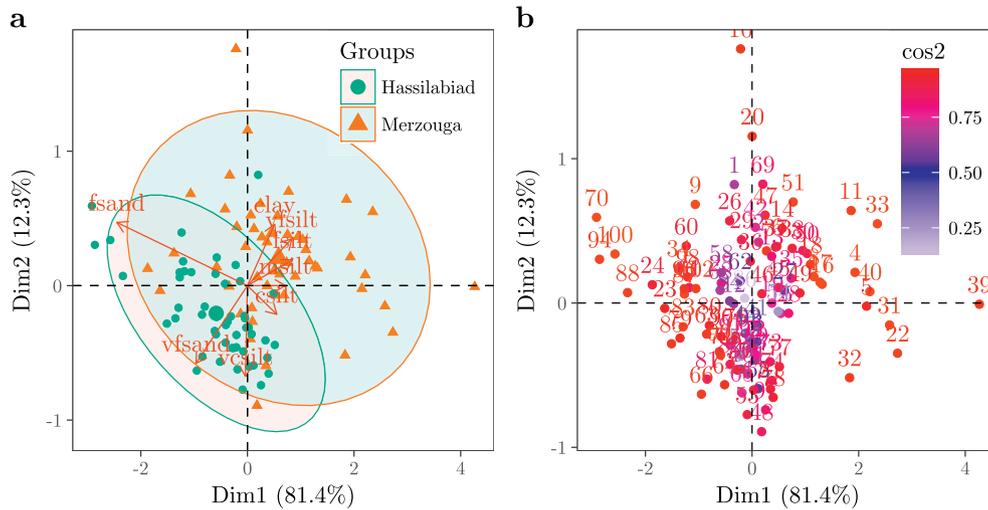


Fig. 3. Texture of the Hassilabiad and Merzouga samples. a) Biplot with the 95% confidence ellipses. b) Quality of representation of the samples in the PCA space.

very fine silt and clay fractions (e.g. the fine fraction is more dominant). Hassilabiad presents higher *ilr1* values and the highest scores concentrated in the southeasternmost stretch of the oasis. Merzouga shows the highest and lowest *ilr1* scores clearly clustered in the northernmost and southernmost area of the oasis.

3.3. EMMA

Fig. 5 summarizes the EMMA output. The final model explains 84% of the total variance in grain size, with the mean column-wise (class-wise) and row-wise (sample-wise) explained variance R^2 being 0.82 and 0.9 respectively. Clay is the class with the highest R^2 (0.85 ± 0.07 , $n = 50$), while coarse sand is the one with the lowest (0.5 ± 0.05 , $n = 3$). Almost all the samples from Merzouga show $R^2 > 0.9$, while for Hassilabiad there are 31 (60.7%), 10 (19.6%), 3 (5.8%) and 8 (15.6%) samples showing $R^2 \geq 0.9$, $0.9 > R^2 \geq 0.8$, $0.8 > R^2 \geq 0.7$ and $R^2 < 0.7$ respectively (Fig. 5A–B). The modes of the End Members (EMs) were set at 83 (EM 1, 83.8 μm , very fine sand), 90 (EM 2, 161.16 μm , fine sand), 91 (EM 3, 176.92 μm , fine sand) and 94 (EM 4, 234.93 μm , fine-medium sand) after defining lower and upper limits for each EM mode by means of stem and bar plots.

The variance explained by the EMs is similar for EM 1–EM 3 (30–25%), and much lower for EM 4 (16%). As shown in Fig. 5C, all EM, except EM 3, are unimodal and show a single peak. The main peak of EM 3, which concurs with the overlapping of peaks from EM 2 and

EM 4, is reasonably a statistical artifact due to EMMA’s orthogonality and linear constraints (Dietze et al., 2014). We thus considered the secondary peak between 1–30 μm as more representative of EM 3.

Fig. 5C–D allows to robustly relate EM 1, EM 2 and EM 4 to the local sedimentary sources. EM 1 concurs with the coarser sediment collected in the Ziz Valley and therefore is a proxy for the Ziz very fine sand, whereas EM 2 reflects the fine sand deflated from the Hamada. EM 4 represents the contribution of fine to medium sand grains from the Erg Chebbi dune crests. As for EM 3, it reflects clay to coarse silt, a grain size fraction also present in the Hamada and Ziz samples. We considered EM 3 a possible surrogate for either remote dust deposition or dust inputs from the Ziz (Ref. Discussion section).

Aiming at detecting sand encroachment patterns in the oases, we assessed the spatial distribution of the *clr*-transformed EM scores. The results are presented in Fig. 6. Higher positive (resp. lower negative) *clr* scores indicate that the EM in question is more (resp. less) dominant than the geometric mean of all EMs. *Clr* values close or equal to 0 imply a similar or exact ratio between a given EM and the geometric mean of all EMs. Empty areas reflect patches that do not accumulate the sediment in question, or where the presence of the sediment is negligible from a statistical point of view. In the Hassilabiad oasis, the sediment from the Ziz (EM 1) is clearly the one encroaching the most, followed by the Hamada sediment (EM 2). No areas in the oasis seem to accumulate more Ziz or Hamada sediment than others. The southeasternmost area of the oasis, however, does show a significant accumulation of sand from the Erg (EM 4). As for the Merzouga oasis, no EM is clearly dominant. There is an area of relatively high accumulation of Ziz sediment (EM 1), to the north of the oasis. The northernmost area shows the highest proportion of Hamada sediment (EM 2), while the southernmost stretch is more prone to accumulate dust from EM 3. Compared to Hassilabiad, the presence of sand coming from the dunes in the Merzouga oasis is almost non-existent (EM 4).

3.4. Wind dynamics

Fig. 7 presents the aeolian data summarizing the frequency of main wind nodes and speeds for each month. The wind regime is mostly bimodal, with winds blowing mainly from the SW–WSW/NE–ENE and maximum wind speeds ranging between 11.7–17.7 m/s. This speed range is enough to initiate and maintain aeolian transport at larger distances in all detected wind directions (Kok et al., 2012). The wind blowing from the SW–WSW is consistently strong in all months and is likely responsible for transferring sediment from the

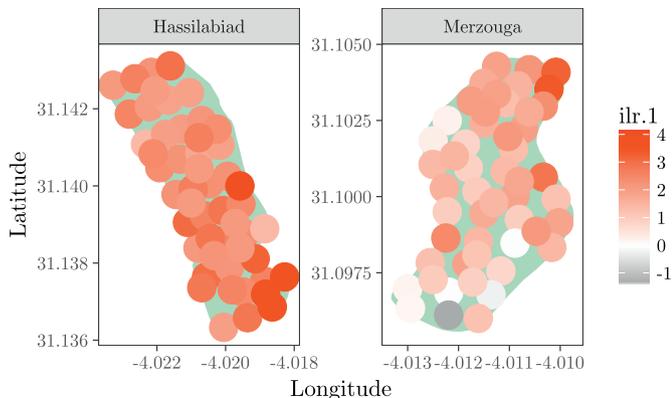


Fig. 4. Spatial distribution of *Ilr1* scores.

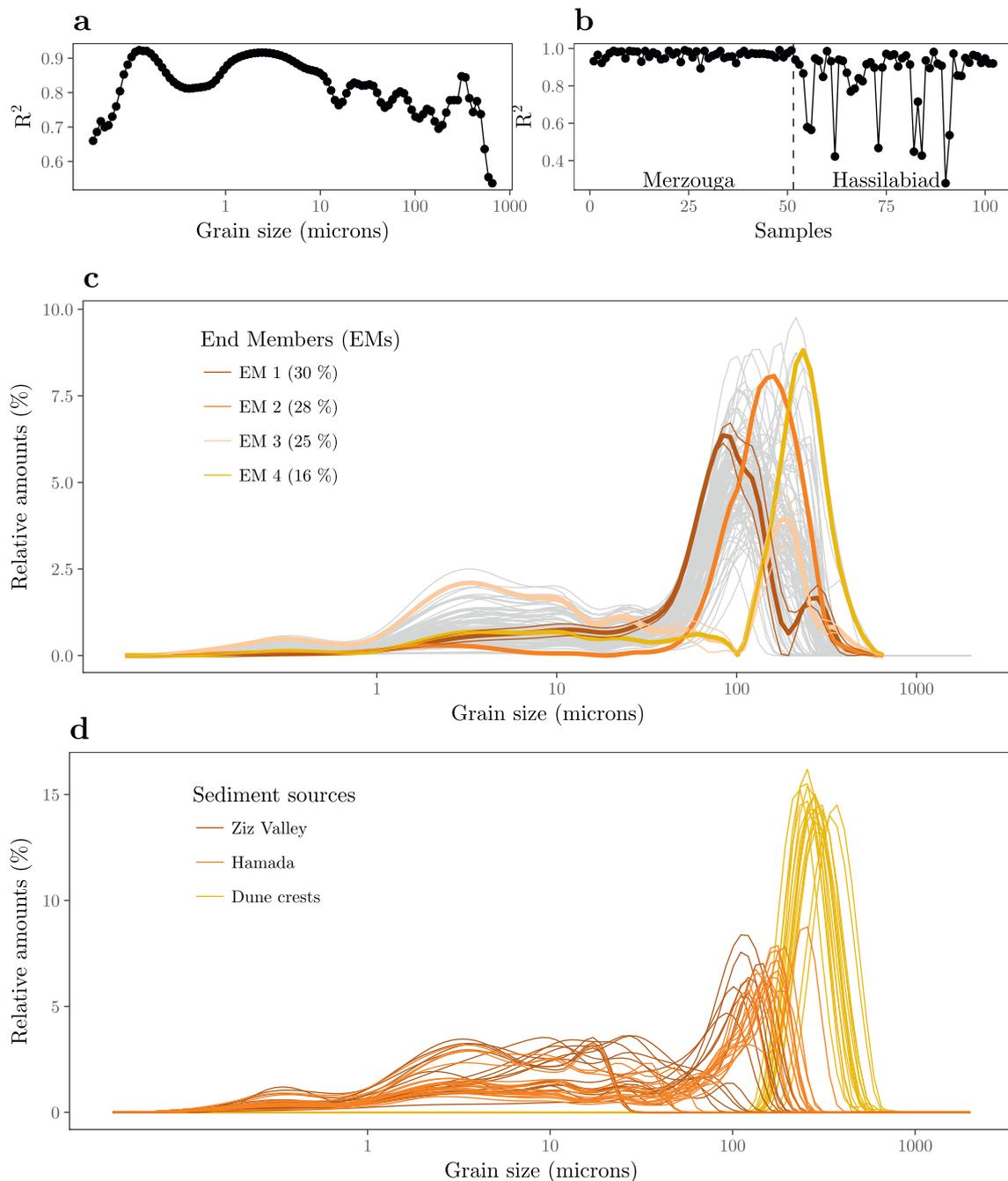


Fig. 5. Results of the End-Member Analysis (EMMA). a) Class-wise explained variance (82%). b) Sample-wise explained variance (90%). c) End-Members (EMs) identified in the samples collected from the Hassilabiad and Merzouga oases. The mean values of the EMs are represented with thick, colored lines whereas the first and second quartiles appear as thin, colored lines. The grain size distribution of the oases samples appear in grey in the background. In the legend, the percentage in parentheses reflects the amount of explained variance. d) Grain size distribution of the sedimentary sources.

Ziz (EM 1) and the Hamada (EM 2) to the oases. The wind blowing from the NE and ENE/S is not as frequent and might explain the deposition of sand from the Erg dunes (EM 4). The monthly wind speed distribution can be found in Fig. S1.

4. Discussion

4.1. The origin of the sediment encroaching in the oases

We found that most of the sediment encroaching in the Hassilabiad and Merzouga oases is local in origin. The largest proportion

(58%) is very fine sand and fine sand coming respectively from the Ziz Valley (EM 1) and the Hamada (EM 2) during winds blowing from the SW–WSW. A much smaller proportion (16%) is fine to medium sand coming from the Erg dunes, transported during winds blowing from the ENE–NE (EM 4). The rest (25%, EM 3) is clay to coarse silt (1–30 μm , mode at 4 μm), whose provenance could not be readily linked to any local sedimentary source nor wind direction. We suggest here two possible origins for EM 3. Firstly, it might be dust deposited by the Ziz that is later on transported from the Hamada to the oases by sandstorms blowing SW–WSW. Such hypothesis requires the Hamada to be mainly an aggradation form that binds

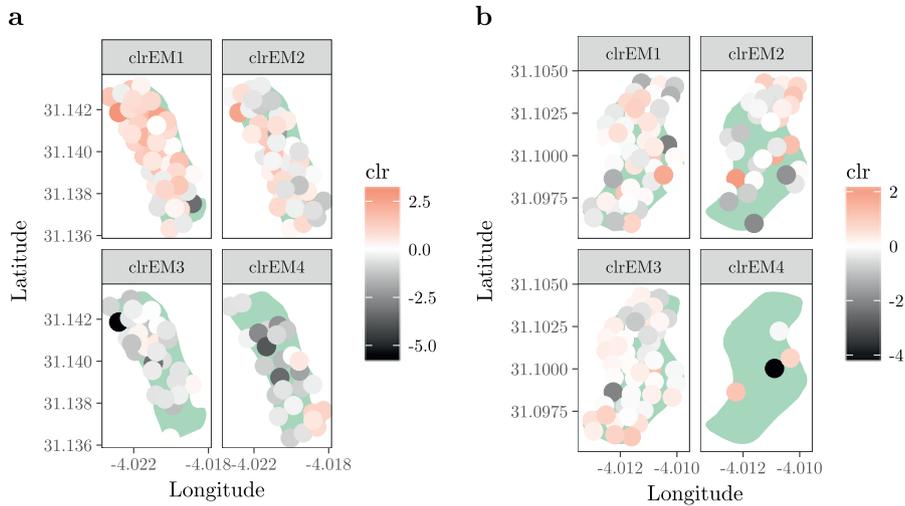


Fig. 6. Spatial distribution of *clr*-transformed EM scores. Those EM scores that yielded zeroes were not *clr*-transformed and have not been plotted. a) Hassilabiad. Number of samples not plotted due to zeroes: EM 1 = 4 (7.8%), EM 2 = 3 (5.8%), EM 3 = 21 (41.1%), EM 4 = 24 (47%). b) Merzouga. Number of samples not plotted due to zeroes: EM 1 = 2 (3.9%), EM 2 = 19 (37.2%), EM 3 = 4 (7.8%), EM 4 = 47 (92.1%).

finer sediment and thickens the soil underneath. In this scenario, the wind-blown dust from the Ziz is incorporated in the Hamada, remobilized by the small fluvial channels cutting the rocky plateau and finally transported to the oases through aeolian processes. The presence of the secondary EM 3 mode (1–30 μm) in the Hamada and Ziz samples supports this interpretation. Secondly, it is also possible that EM 3 reflects background deposition of exogenous dust. Its range and mode is consistent with that of desert loess sediments in the fine silt and clay fraction (2–22 μm) transported in high suspension clouds over large distances (Jiang et al., 2017; Vandenberghe, 2013). Perisaharan loess deposits have been identified in the Moroccan south-Atlas piedmont, c. 1000 km to the SW of Erg Chebbi (Caude-Gaussen, 1987). The range and mode of EM 3 also concurs

with that shown by the Saharan dust (4–32 μm) (Van Der Does et al., 2016). In this scenario, 25% of the total sediment encroaching in the oases comes from a remote sedimentary source. Further geomorphological work on the Hamada and direct sampling of the Saharan loess deposits might allow to rule one of these hypotheses out.

4.2. Implications for policy-making

Our work in Erg Chebbi has three important implications for oasis conservation policies in desert environments.

Firstly, it shows how to identify areas specially exposed to receive specific sand grains. The Hassilabiad oasis, for instance, presents a much coarser soil texture, a higher proportion of Ziz and Hamada

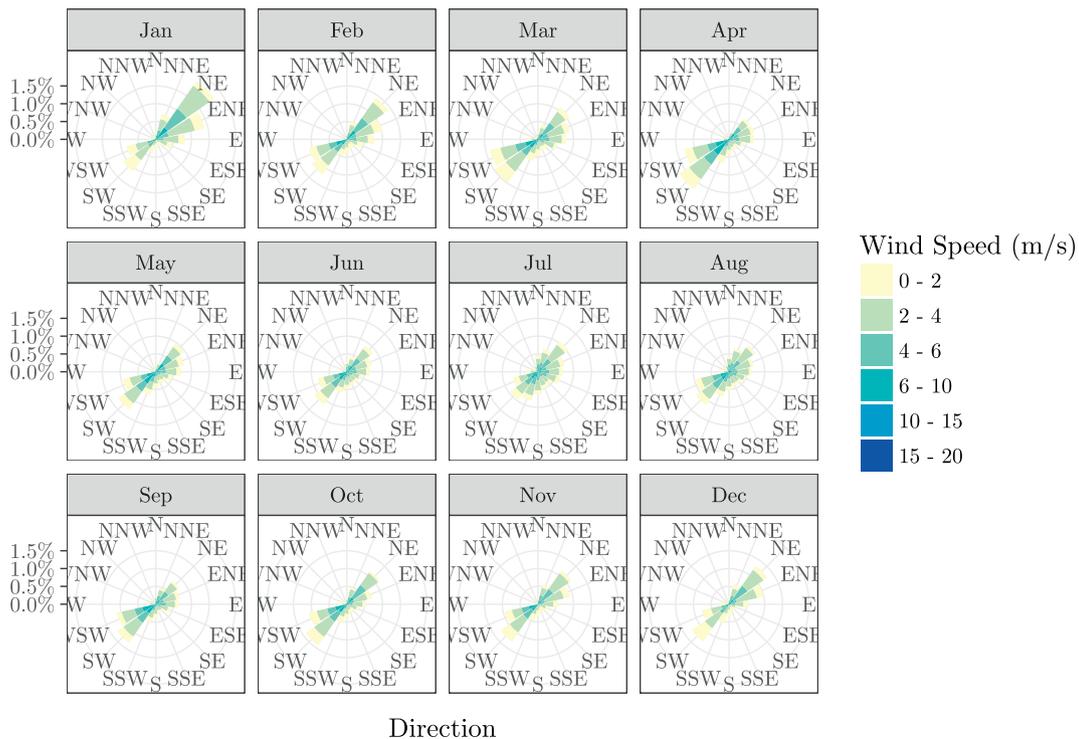


Fig. 7. Wind roses plotting data for wind speed and direction collected at the Jebel Brahim station (29.93° lat, –5.62° lon, 150 km to the SW of Erg Chebbi) between 2002–2011.

sediment, and an area with a relatively high presence of sand from the Erg dunes. In contrast, the Merzouga oasis shows a finer texture but three areas with a proportionally higher accumulation of remote dust, Ziz and Hamada sediment (Fig. 6). The chances of a sediment collecting in a given oasis spot are defined by the interaction of several social-ecological factors, e.g. plot location, its exposure to main wind speeds and sedimentary sources, degree of palm tree development, vegetation cover, soil humidity or human activity, among others (Kok et al., 2012; Wan et al., 2013; Zhao et al., 2011). These factors vary within oases and create spatially heterogeneous depositional environments. The sedimentary patchiness detected in Hassilabiad and Merzouga is reasonably a structural feature of desert oases and suggests that the setting of evenly-spread, uniform sheltering structures might be a suboptimal approach against sand encroachment. Better results might be achieved by placing and devising sand-protecting structures according to the requirements of specific vulnerable spots. Checkerboards, for instance, can effectively protect areas exposed to receiving fine/medium sand grains via saltation or reptation (Berque, 2010; Bo and Zheng, 2013). However, they are inappropriate for areas vulnerable to fine dust deposited via suspension. In those cases, developing higher structures such as trees or shrubs is a much better option (Mohammed et al., 1996). Currently, and unlike in China (Shiming and Gliessman, 2016), oasis conservation policies in Morocco and Tunis regard oases as homogeneous areas and do not subdivide sectors of intervention based on their unequal exposure to sand encroachment (Ministère de l'Environnement et du Développement Durable, 2018; PNUD, 2018).

Secondly, the identification of sand encroachment patterns might allow to develop more nuanced approaches to sand management. Coarse soils might actually benefit from collecting finer sediment, as explained by the Hassilabiad irrigators. The aeolian deposition of finer sediment contributes to increase the water, nutrient and organic matter retention capacity of the soil, thus making it less vulnerable to wind erosion (Brady and Weil, 2008). Such process of natural soil transportation might save farmers from having to fully import finer soils from elsewhere, a common but highly labour-demanding strategy to improve soil quality in arid environments (Ackermann et al., 2005; Keeley, 1985). In Hassilabiad, soils in most need of a higher proportion of finer sediments are those located to the southeasternmost reach of the oasis, while in Merzouga they are located to the north (Fig. 4). Keeping these soils wet during sandstorms blowing W–E might increase the proportion of wind-blown fine particles settling in the plots while preventing saltation and dust emission (Li and Zhang, 2014). It has also been suggested that specific spots within oases might behave as attractors of aeolian dust during non-storm events given the appropriate combination of surface roughness, humidity and human activity (Wan et al., 2013). Taking advantage of natural aeolian sediment deposition processes to improve soil texture might however come with trade-offs (e.g. drying/burial of crops, over-irrigation) that need to be thoroughly considered for a well-educated management decision.

Thirdly, our work shows how to rank sedimentary sources in terms of their contribution to sand encroachment. This holds great potential as a tool to know on scientific grounds which external areas of intervention should be prioritized in order to lead to the greatest reduction in sand encroachment. This is especially relevant for regions where the scarcity of economical, environmental and/or human means preclude launching a systematic fight against desertification. In the case of Erg Chebbi, EM loadings suggest that the strongest contributor of sediment to the oases is the Ziz Valley (30%), followed by the Hamada (28%). The Erg dunes are comparatively negligible (16%) (Fig. 5C). Any initiative aiming at reducing sand encroachment at the regional level should therefore prioritize protecting the oases from the Ziz inputs. This might involve not only setting high sheltering structures (e.g. trees, shrubs) on the westernmost boundary of the oases, but also implementing initiatives

directly in the Ziz or at the transitional zones between such area and the oases (Mohammed et al., 1996, 1999; Zhao et al., 2008). If used alongside already established policy-making tools, such as participatory approaches, EM loadings can help make much more informed decisions during the discussion of the priorities set (Berque, 2010). This is highly relevant in order to prevent Type III errors or framing mistakes, common in environmental policy analysis and characterized by properly solving the wrong problems (Dunn, 2001; Klopogge and Sluijs, 2006).

5. Conclusions

Combat desertification and reverse land degradation is one of the Sustainable Development Goals of the United Nations for 2030 (United Nations, 2015). Whether we succeed partially depends on our capacity to identify areas of preferential intervention and the most adequate initiatives to protect oases from sand inputs. Our study shows, using the case study of Erg Chebbi (Morocco), how fine-grained data on these two factors can be collected and used to inform policies aiming at better managing agrarian areas in desert environments. In Erg Chebbi, initiatives aiming at maximizing the reduction in sand encroachment should prioritize stabilizing the sediment blown away from the Wadi Ziz, which collects in the oases much more than the sand from the Erg. We have also observed that the oases are by no means uniform depositional areas, but a cluster of sedimentary patches unevenly exposed to receive sand from different sources. Policies aiming at fighting sand encroachment should adapt the location and design of shelterbelts to the specific spatial distribution of the different grain sizes accumulating in the oases. Better, more tailored strategies against sand encroachment might be developed once the link between sedimentary sources, transportation pathways and depositional patches is properly understood and quantified in oasis environments on a case-by-case basis.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2018.05.343>.

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