Detection of sand encroachment patterns in desert oases

Arnald Puy*[1], Manuel Herzog[2], Pedro Escriche[3], Amou Marouche[4], Yousef Oubana[4], and Olaf Bubenzer[2]

[1]*Maritime Civilizations Department, Recanati Institute for Maritime Studies, University of Haifa, 199 Aba Khoushy Ave., Mount Carmel, 3498838 Haifa, Israel. Phone: 972-(0)-46647979. Fax: 972-(0)-48240493. E-Mail: arnald.puy@gmail.com*

[2]*Institute of Geography, University of Heidelberg, Im Neuenheimer Feld 348, D-69120 Heidelberg, Germany*

[3]*Centro de Estudios Rurales y de Agricultura Internacional (CERAI). Escuela de Capataces Agrícolas. Camí del Port s/n, 46470 Catarroja, Valencia, Spain*

[4]*Association Hassilabiad pour l'Environement, le Développement et la Cooperation. Ksar Hassi labiad 52202 Merzouga, Morocco*

Abstract

Desert oases are fragile agrarian areas highly vulnerable to sand encroachment. Identifying their degree of exposure to different sedimentary sources is therefore key to define strategies aimed at ensuring their conservation. Here we show how to tackle this issue using the case study of Erg Chebbi (Morocco), where two oases (Hassilabiad and Merzouga) surrounded by desert dunes, Hammada and alluvial sediments (Ziz Valley) sustain c. 4.000 inhabitants. We quantify the relative contribution of these three sedimentary sources to sand encroachment and assess the spatial distribution of their end-members in the oases by means of interviews, Particle Size Distribution (PSD), End-Member Modelling Analysis (EMMA) and the study of aeolian dynamics. We find that the most relevant contributor to sand encroachment is the Ziz Valley, followed by the Hammada, remote dust and the Erg dunes. Various depositional patches resulting from contrasting degrees of exposure to these different sedimentary sources are visible within the oases. Results suggest that any initiative disregarding the presence of such depositional heterogeneity within oases might be suboptimal in terms of efficacy against sand encroachment processes. Our approach will also help policy-makers define on more scientific grounds which sand source areas should be stabilized first in order to obtain the greatest reduction in sand encroachment in any given oasis.

Keywords: Drylands, Irrigation, Aridification, Climate Change, Sustainability

*Corresponding author. Current address: Centre de Recherches en Archéologie et Patrimoine, Université Libre de Bruxelles. Campus du Solbosch, Bâtiment A, rez-de-chaussée, CP175/01, Avenue F.D. Roosevelt 50, 1050 Bruxelles, Belgium.

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 fertile, ecologically rich agrarian fields. Attested at least since the Bronze Age, oasis agriculture has been a major pillar for the development of ancient civilizations and commercial routes (Barker and Gilbertson 2000; Beckwith 2009). Many oases that remain operative today originated in the past, such as those of Ras al Khaima, Masafi or Rustaq, in the Arabian Peninsula ($\geq$ 1000 BC)[1]. Currently, the relevance of oases for human welfare is evidenced by the approximately 150 milion people that benefit from oasis agriculture (Cheneval 2016), either through direct cultivation, trade or touristic services.

From an ecological standpoint, oases are also important at many levels. They act as important reserves of faunal and flora biodiversity as well as soil carbon and nitrogen stocks (F. R. Li et al. 2013; El-Saied et al. 2015). They are also a crucial stopover for birds, which might use oases to restore energy and their water reserves during migratory routes, for instance across the Sahara (Lavee et al. 1991; Schmaljohann et al. 2007). Finally, they create areas with significantly lower temperatures and higher humidity content, the so-called "oasis effect" (Oke 1987), a phenomenon that holds potential to allow permanent human settlement in otherwise highly hostile regions (Potchter et al. 2008).

However, due to their location in or at the fringes of deserts, oases are highly threatened by sand encroachment, e.g. the accumulation of sand grains carried by winds (Berque 2010). In oasian environments, sand 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; W. 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. crop selection, irrigation) and ecological (e.g. wind speeds and direction, sediment availability) variables. Such dynamic behavior 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 succesful in a given setting might underperform, fail or even backfire when exported to an apparently similar environment. This uniqueness urges

[1] see project OASIWAT. Origin, mutations and dynamics of Southeastern Arabia oases. Soil/water availabiity and management for the last 5 millennia (Research project funded by the French National Research Agency) http://www.cepam.cnrs.fr/oasiwat/project-presentation

for the development of a comprehensive, generic approach aimed at unfolding, for any oasian 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 most appropriate design for the shelterbelts. The second, their most convenient location.

Here we show how to detect sand encroachment patterns in desert oases by means of an interdisciplinary approach 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. 150 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) (Figure 1, Supplementary Information). The Erg is surrounded by Hammada, a barren, flat landscape with a rocky surface that turns into dust after weathering and is easily blown away by the wind. To the W of Erg Chebbi, the Hammada is cut by the Wadi Ziz riverbed, an ephemeral river. Our case study is therefore a conspicuous example of an oasian environment susceptible to accumulate sand from more than one sedimentary source, a context 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 encrochment and precise its distribution within oases. We conclude by showing how this information can be used to improve our capacity to design better tailored, more adapted policies for oasis conservation in any oasian environment worldwide.

2 Materials and methods

2.1 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 wheather 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 minute interval and at 3 m above ground level.

2.2 Fieldwork

We conducted face-to-face, semi-structured interviews with 24 irrigators of the Hassilabiad oasis, thus sampling approximately half the population ($N \approx 50$). The aim was to know how irrigators 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. In this time slot most of the irrigators went to the oasis to conduct their agricultural tasks (Oubana, personal communication).

We carried out 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 Hammada soils and the alluvial sediments of the Wadi Ziz (Figure 1). Samples were collected from the dune crests in the Erg and from the first 30 cm of soil in the Hammada 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 sediment 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. Each sample was thoroughly mixed and stored in plastic bags for Particle Size Distribution (PSD) analysis in the laboratory.

2.3 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 seconds 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 $\pm$ standard deviation of the PIDS values for each of the sampling groups are presented in Table S1.

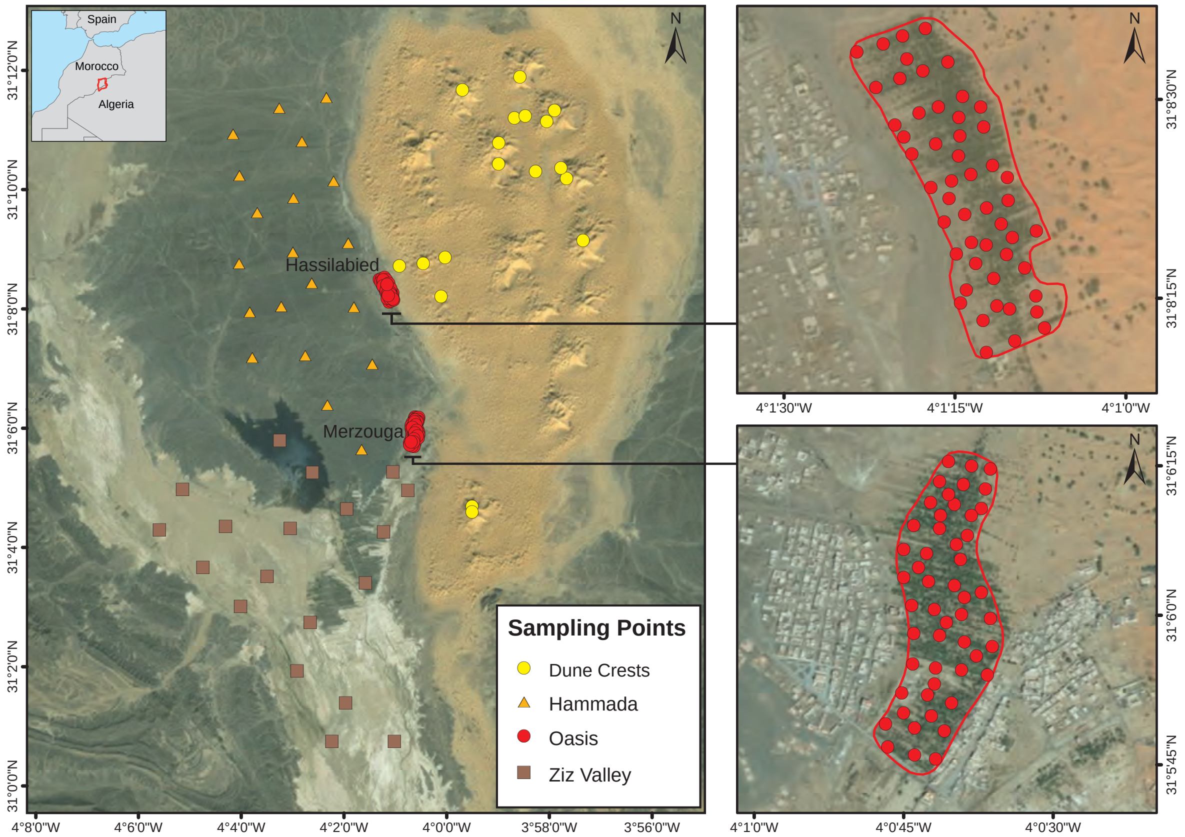

Figure 1: Location of Erg Chebbi, the Hassilabiad and Merzouga oases and the sampling points. The images have been retrieved from Data ESRI, DigitalGlobe, GeoEye, i-cuved, USDA, FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo and the GIS User Community.

2.4 Statistics

We conducted the statistical analyses in the *R* environment (Team 2016). For the analysis of PSD data we used the *compositions* package (Boogaart, Tolosana-Delgado, and Bren 2014) and followed the guidelines set forth by Boogaart and Tolosana-Delgado (2013). PSD data is 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 constrain 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 2.5). 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 forces any analysis to focus on the single *clr*-transformed variables and not on their relations. *Clr*-transformed variables have been succesfully used, for instance, to map elemental concentrations of agricultural soils in Europe (Reimann et al. 2012).

2.5 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 (E. Dietze, Hartmann, et al. 2012; M. Dietze and E. Dietze 2016). EMMA considers *CoDa* constraints and relies on the principles of eigenspace analysis and scaling to extract robust end-members (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; M. Dietze and E. Dietze 2016; Jiang et al. 2017; Weltje 2012), the potential of EMMA for guiding policies against sand encroachment in desert oasis 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 throught combinations of different numbers of EMs (2-12) and l_w values. According to Weltje and Prins (2007) and E. Dietze, Hartmann, 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 (M. Dietze, E. Dietze, et al. 2016). The full *R* code for the model is available as a Supplementary Information file.

3 Results

3.1 Wind dynamics

Figure 2 presents the aeolian data. The wind regime is bimodal, with winds blowing mainly from the SW–WSW / NE–ENE and maximum wind speeds ranging between 11.7–17.7 m/s. June, July and August show a higher contribution of winds blowing from the S–SE–E, while January presents a higher frequency of winds blowing from the NE. The monthly wind speed distribution can be found in Figure S1.

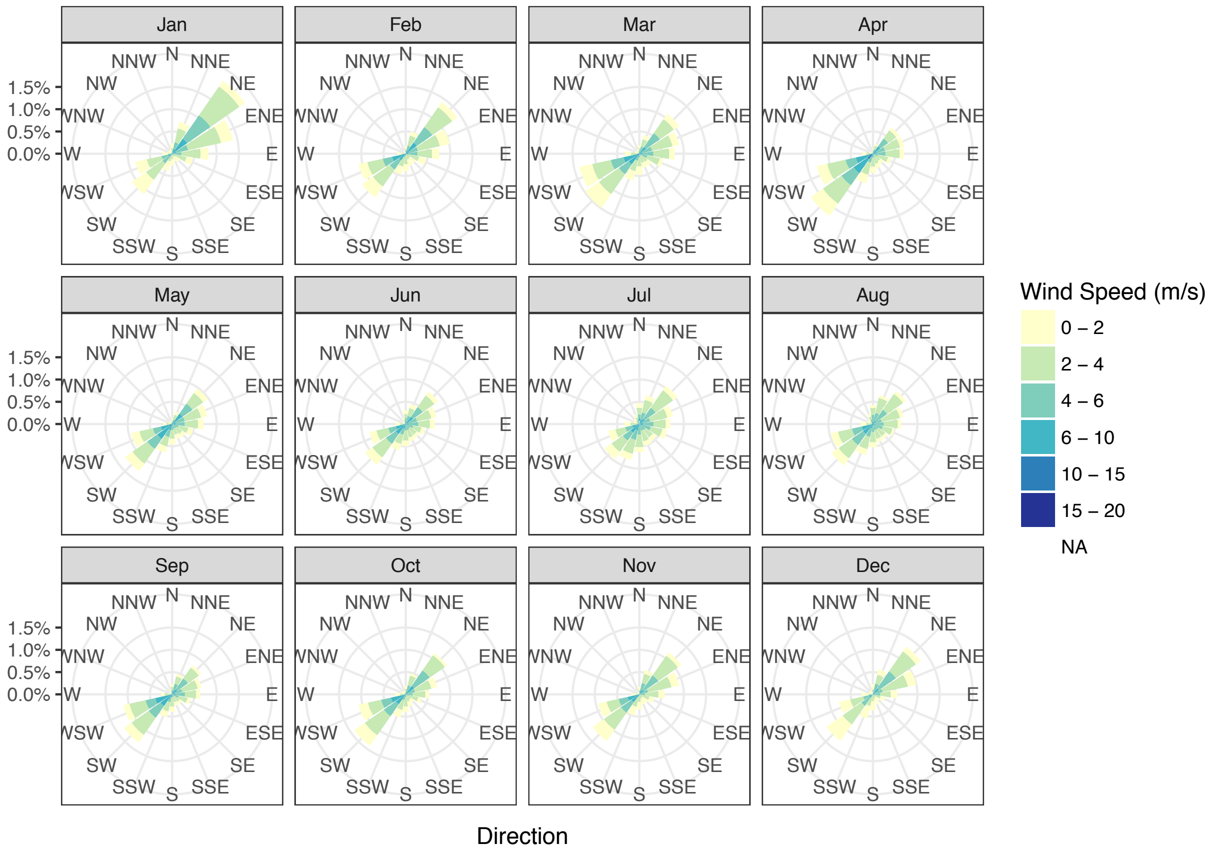

Figure 2: Wind roses plotting values for wind speed and direction collected between 2002–2011.

3.2 Interviews

Figure 3 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 W-E bring in finer, hotter, darker dust that 'burns' and dries the crops. Sandstorms blowing SW–WSW 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 E-W, but dustier. Some interviewees also explained that sandstorms blowing from the SE–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.

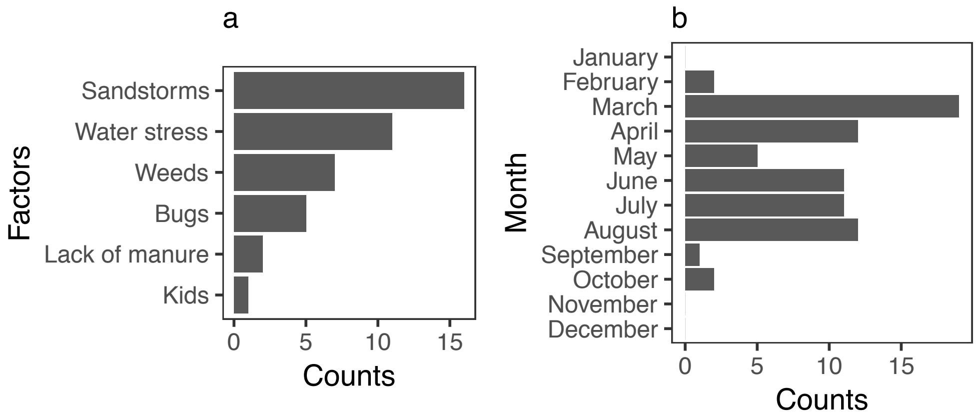

Figure 3: Bar plots with the results of the interviews. Interviewees were allowed to mention as many factors and months as they considered relevant. a) Noxious factors threatening the sustainability of the oasis. NA=1. b) Occurrence of sandstorms along the year. Six counts in June, July and August have been added to the bar plot to account for six irrigators that mentioned 'summer' instead than a specific month.

3.3 Sediment sampling

Figure 4 presents the grain size structure of the Hassilabiad and Merzouga samples. The fractions coarser than fine sand (>250 µm) were discarded due to the presence of zeroes, which pose serious difficulties when dealing with *CoDa* (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 balance [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 assesment 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 (Figure S2).

Figure 5 shows the spatial distribution of $ilr1$ values in Hassilabiad and Merzouga. Higher

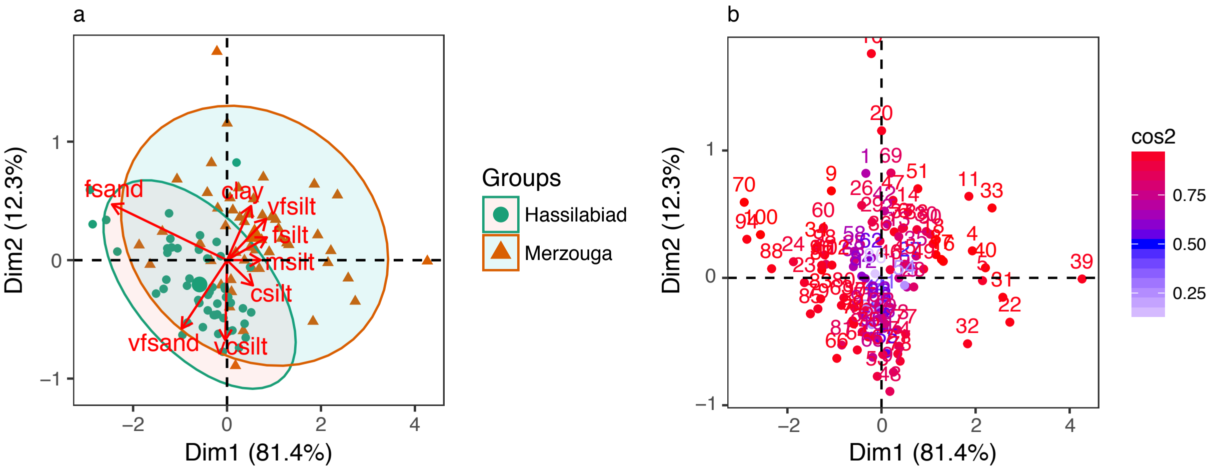

Figure 4: Texture of the Hassilabiad and Merzouga samples. a) Biplot. b) Quality of representation of the samples in the PCA space.

(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, very fine silt and clay fractions (e.g. the fine fraction is more dominant). Hassilabiad presents higher $ilr1$ values but no clear spatial pattern in the distribution of scores. Merzouga shows the highest and lowest $ilr1$ scores clearly clustered in the northernmost and southernmost areas of the oasis.

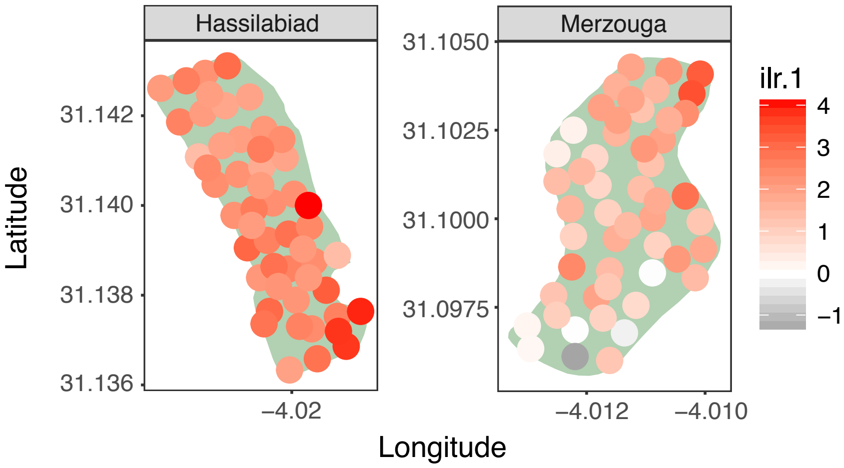

Figure 5: Spatial distribution of $Ilr1$ scores.

3.4 EMMA

Figure 6 summarises 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 $(0.85 \pm 0.07, n = 50)$, while coarse sand is the one with the lowest $(0.5 \pm 0.05, n = 3)$. 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 (Figure 6A–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 Figure 6C, 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 (E. Dietze, Maussion, et al. 2014). We thus considered the secondary peak between 1 – 30 µm as more representative of EM 3.

Figures 6C-D allow 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 dust encroaching during sandstorms blowing SW–NE. EM 2 reflects the coarser sediment deflated from the Hammada that deposits on the oases during winds blowing W–E. EM 4 represents the contribution of sand grains from the Erg Chebbi dune crests carried to the oases by strong winds blowing E–W. As for EM 3, it reflects clay to coarse silt, a grain size fraction also present in the Hammada and Ziz samples. We considered EM 3 a surrogate for remote dust deposition (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 Figure 7. 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 that 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 Hammada sediment (EM 2). No areas within the oasis seem to accumulate more Ziz or Hammada 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 Hammada sediment (EM 2), while the southernmost stretch is more prone to accumulate remote dust (EM 3). Compared to Hassilabiad, the presence of sand coming from the dunes in the Merzouga oasis is almost non-existent (EM 4).

4 Discussion and conclusions

Desert oases can accumulate a wide range of different sand grains. Wind currents of varying speed and blowing in different directions incorporate diverse grain sizes from one or more sedi-

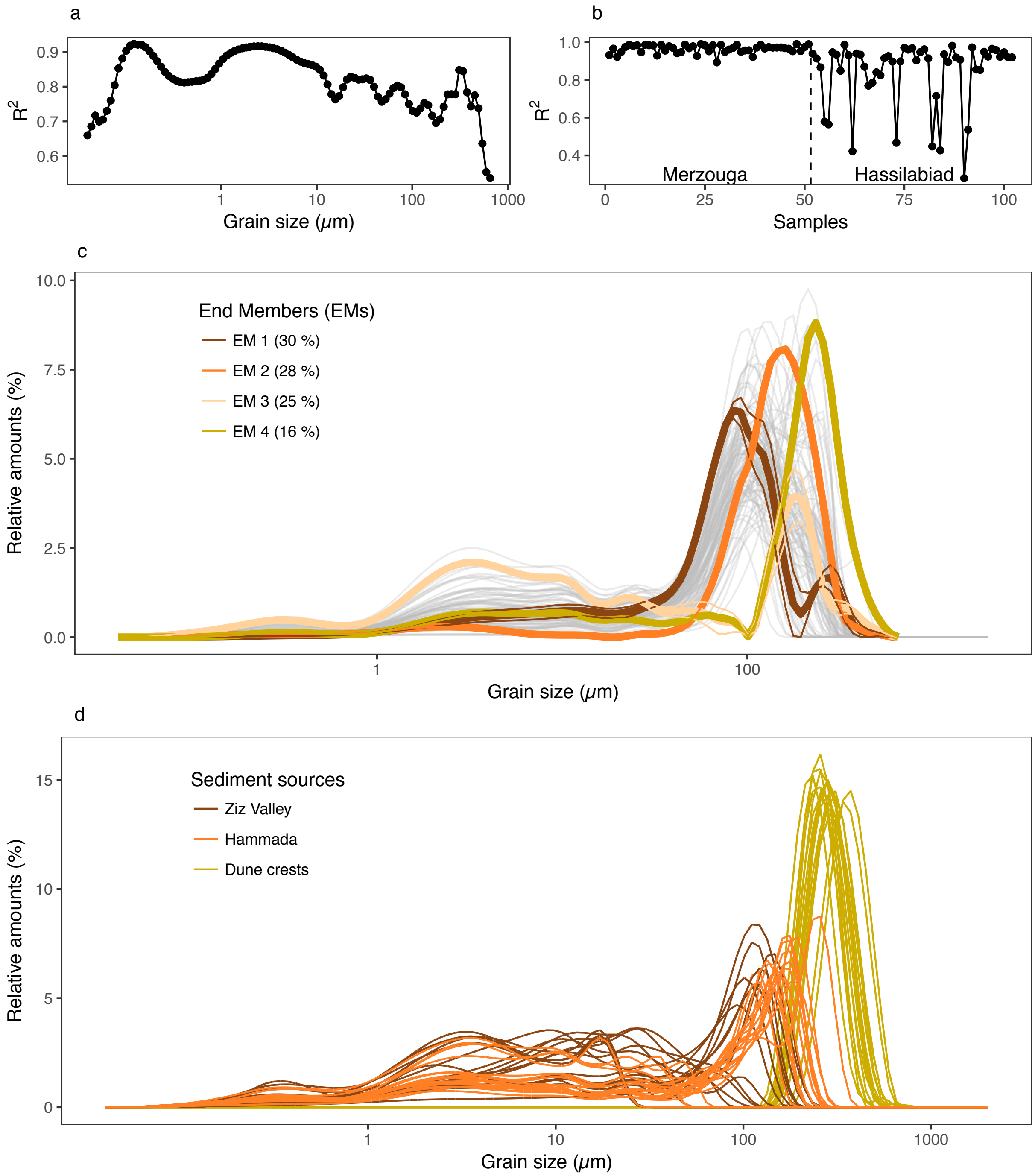

Figure 6: Results of the End-Member Analysis (EMMA). a) Class-wise explained variance (82%). b) Sample-wise explained variance (90%). c) End-Members (EMs) identified in the samples collected in the Hassilabiad and Merzouga oases. The mean values of the EMs are represented with thick, colored lines while 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 reflect the amount of explained variance. d) Grain size distribution of the sediment sources.

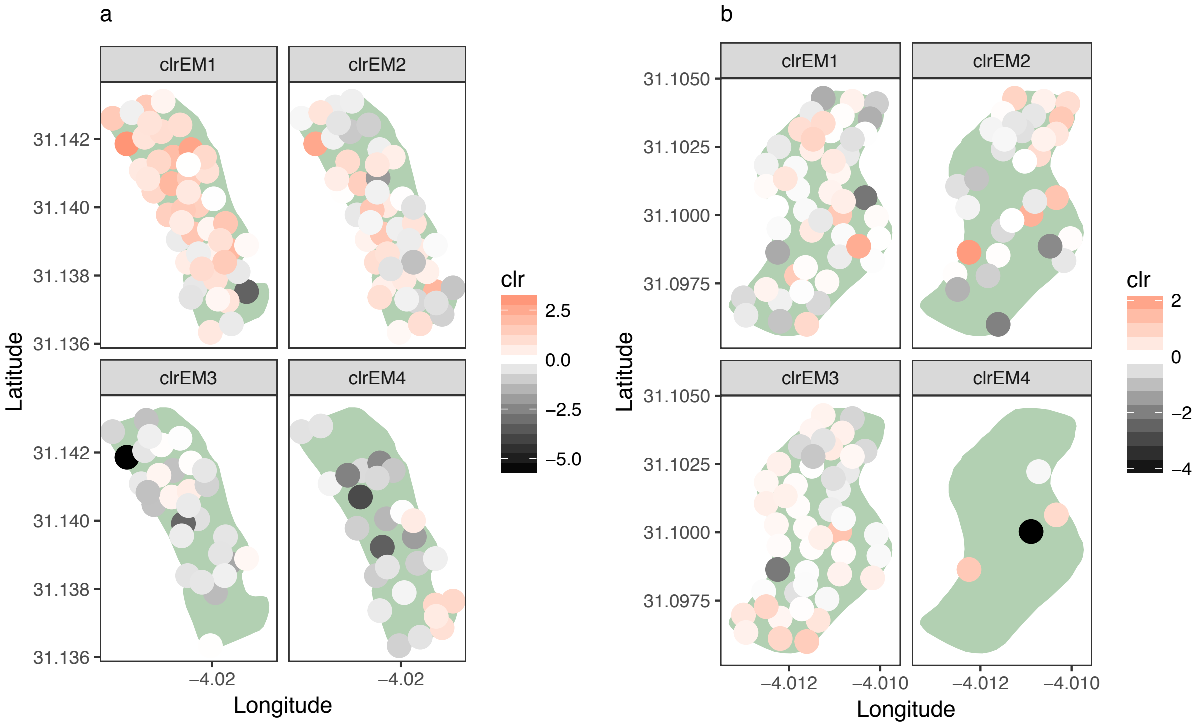

Figure 7: Spatial distribution of *clr*-transformed EM scores. Those EM scores that yielded zeroes were not *clr*-transformed and have not been plotted. a) Hassilabiad. Number of samples not plotted due to zeroes: EM 1 = 4 (7.8%), EM 2 = 3 (5.8%), EM 3 = 21 (41.1%), EM 4 = 24 (47%). b) Merzouga. Number of excluded sample points: EM 1 = 2 (3.9%), EM 2 = 19 (37.2%), EM 3 = 4 (7.8%), EM 4 = 47 (92.1%).

mentary sources and distribute the resulting mixture unevenly over the irrigated plots. A given stretch of land within an oasis might also collect well-sorted sediments carried from the same source in discrete transportation events. Such episodes of deposition get mixed in the oases by farming activities and bioturbation, hampering the assesment of how exposed a terrain is to specific sand encroachment processes. This in turn obstructs the development of effective, custom-designed strategies against desertification. Here we show how to combine field interviews, Particle Size Distribution (PSD), End-Member Modelling (EMMA) and wind analyses to overcome this issue and unmix the contribution of different sedimentary sources to the grain size distribution of oases soils.

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 Hammada (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. However, we argue here that EM 3 likely reflects background deposition of remote dust. Its range and mode is consistent with that of 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 Saharan dust (4–32 µm) (Van Der Does et al. 2016). We also rule out a possible local fluvial origin for EM 3 because the mode between 1–30 µm characterizing EM 3 appears simultaneously in the samples collected from the Ziz Valley and the Hammada (Figure 6C), the latter an area without any relevant fluvial input.

Our work in Erg Chebbi has far-reaching implications for oasis conservation policies in desert environments. Firstly, it suggests that even relatively small oases (15–20 ha) in close proximity ($\sim$ 4 km away) might display contrasting patterns of sand encroachment. The Hassilabiad oasis, for instance, presents a much coarser soil texture, a higher proportion of Ziz and Hammada sediment, and an area with a relatively large presence of sand from the Erg dunes. In contrast, the Merzouga oasis shows a finer texture but two areas with a proportionally higher accumulation of remote dust and Hammada sediment (Figure 7).

This patchiness likely reflects the existence of areas more or less prone to accumulate specific wind-blown sand/silt grains. The volume of sediment encroaching in a given oasis spot, as well as its dominant grain size, is a function of several social-ecological factors that interact at the oasis and the plot level, e.g. degree of palm tree development and exposure to wind, wind speed and direction, vegetation cover, soil humidity or human activity, among many others (Kok et al. 2012; Wan et al. 2013; M. Zhao et al. 2011). The interplay of these factors, whose values vary across space, create contrasting patterns of exposure to different sedimentary sources, a sort of depositional mosaic formed under a single depositional environment. This observation is in line with further evidence showing that seemingly uniform agrarian areas present great ecological variability when assessed with the appropriate level of detail (Horden and Purcell 2000; Puy 2014). Policies aimed at fighting sand encroachment might therefore obtain sub-optimal results if they overlook this spatial heterogeneity when selecting the design and location of their sheltering structures. In other words: the existence of depositional patches renders the setting of evenly-spread sheltering structure/s inefficient against sand encroachment processes. Better results might be achieved once protection belts are placed and devised according to the depositional heterogeneity existing within oases: spots prone to accumulate fine/medium sand grains deposited via saltation or surface creep (e.g. 0–30 cm agl) might benefit from receiving special protection with checkerboards (Berque 2010; Bo and Zheng 2013). Sectors more exposed to finer sand particles travelling in suspension (e.g. >50–100 cm agl), on the other hand, should be protected with higher structures, such as trees (e.g. *Eucalyptus microtheca*) or shrubs (Mohammed et al. 1996), either within or at the boundaries of the affected areas.

Tailoring shelterbelts to specific depositional patches is especially required in oasis exposed to different sedimentary sources/grain sizes. Although this might be the case of most Moroccan oases (Escriche, personal communication), governmental initiatives for oasis conservation such as the *Plan Maroc Vert* or the *Programme de Développement Territorial Durable des Oasis du Tafilalet (POT)* still consider oasis as homogeneous agrarian areas (PNUD 2018). The same applies for the strategies against desertification fostered by the Ministère de l'Environnement et du Développement Durable of Tunis (Durable 2018). In China, on the other hand, policies against desertification rely on the assumption that different areas of the oasis (e.g. centre, inner, edge) demand different conservation measures (Shiming and Gliessman 2016). We argue that this more nuanced approach to oasis sustainability might benefit from including the spatial identification of sand encroachment patterns as a tool to subdivide areas of intervention within oasis on more solid grounds.

Secondly, our study stresses the need to consider the eventual positive side-effects derived from specific sand encroachment processes. 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). Depending on the sediment source, sandstorms might also transfer minerals and nutrients that are not readily available in-site. If the oases soils are well structured and not easily eroded, sandstorms transferring dust or very fine sand are a non-negligible supply of soil nutrition (Feng Rui Li et al. 2004). 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 (Figure 5). 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 (X. Li and H. Zhang 2014). Setting a transitional area with sparse vegetation between such coarse soils and the Erg dunes could also help improve soil quality: transitional areas slow down wind speeds and trap coarser grains, thus increasing the relative proportion of finer grains passing through (K. Zhang et al. 2017). 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) that need to be thoroughly considered for a well-educated management decision. In any case, detecting areas of natural coarse/fine material accumulation might provide practitioners with better tools to ameliorate the physical conditions of oasis soils.

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, End-Member (EM) loadings suggest that the strongest contributor of sediment to the oases is the Ziz Valley (30%), followed by the Hammada (28%). The Erg dunes are comparatively negligible (16%) (Figure 6C). Any initiative aiming at reducing sand encroachment at the regional level should therefore prioritize protecting the oases from the Ziz inputs, which collects during sandstorms blowing SW–NE. 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; Mohammed et al. 1999; W. 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; Kloprogge and Sluijs 2006).

Combat desertification and reverse land degradation is one of the Sustainable Development Goals of the United Nations for 2030 (United Nations 2015). In many arid regions of the world tackling sand encroachment is the major spearhead for achieving agrarian sustainability. 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 how fine-grained data on these two factors can be collected and used to inform policies aiming at managing agrarian areas in desert environments. Better, more tailored strategies against sand encroachment might be developed once the link between sediment sources, transportation pathways and depositional patches is properly understood and quantified on a case-by-case basis.

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