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Diverse sources of aeolian sediment revealed in an arid landscape in southeastern Iran using a modified Bayesian un-mixing model

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Diverse sources of aeolian sediment revealed in an arid landscape in southeastern Iran using a Bayesian un-mixing model

Abstract

Identifying and quantifying source contributions of aeolian sediment is critical to mitigate local and regional effects of wind erosion in the arid and semi-arid regions of the world. Sediment fingerprinting techniques have great potential in quantifying the source contribution of sediments. The purpose of this study is to demonstrate the effectiveness of fingerprinting methods in determining the sources of the aeolian sands of a small erg with varied and complex potential sources upwind. A two-stage statistical processes including a Kruskal-Wallis *H*-test and a stepwise discriminant function analysis (DFA) were applied to select optimum composite fingerprints to discriminate the potential sources of the aeolian sands from the Jazmurian plain located in Kerman Province, southeastern Iran. A Bayesian un-mixing model was applied to quantify uncertainties associate with the source contributions, and the model was evaluated by a goodness of fit (GOF) method. The results suggest that four geochemical properties (Cr, Co, Ni, and Li) were the optimum fingerprints for solving the Bayesian un-mixing model. The results show that there is great diversity in terms of the sources of sand, and that, contrary to expectation, sediments associated with an adjacent large ephemeral lake are the least significant in supplying sediment to the erg. Sand-sheet-derived sands and alluvial sediments dominate a majority of the samples, and are likely attributable to relatively short-distance aeolian flux, but substantial contributions from alluvial fans and terraces likely represent longer distance pathways. These results highlight the need to consider sediment provenance on a site-by-site basis. The GOF evaluation showed that the Bayesian un-mixing model is an effective method to aid aeolian sediment fingerprinting. This method may be applied to assess aeolian sediment sources in other desert regions with strong aeolian activities.

Key words: Sediment Fingerprinting, Aeolian Sediment, Bayesian un-mixing Model, Uncertainty, Jazmurian Plain.

1. Introduction

Desertification, or land degradation in the world's arid regions, is one of the world's most pressing environmental issues (Dregne et al., 1991; UN, 2015). The United Nations Convention to Combat Desertification (UNCCD, 1994) recognized several aspects of desertification leading to the loss of productivity of dryland soils including aeolian and water erosion. Desertification resulting from wind erosion and deposition, driven by changing climates (both drought and long-term climate changes) and human activities has been reported in different climatic regions worldwide (needs citations here). Drylands are typically highly susceptible to aeolian erosion and land degradation, due to interactions between the typically sparse vegetation, lack of moisture to bind the surficial sediments, and the susceptibility of the surface to disturbance and climate change (Ravi *et al.*, 2010). In many arid and semi-arid regions, deflated sand accumulates in dune fields (ergs), including parts of subtropical deserts and rain-shadowed zones of the mid-latitudes (Muhs, 2017). Although many studies have investigated aeolian dunes worldwide, much of the focus has been on the dune initiation (Luna et al., 2011), sedimentary structures (Yang et al., 2018), and palaeoclimatic implications of dated dune deposition (e.g. Lancaster et al., 2016; Thomas and Burrough, 2013; Leighton et al., 2014; Li and Yang, 2015; Du and Wang, 2014). Very little information is available on dune sediment provenance (Muhs, 2017), yet dune fields represent potential archives of information in regional sediment transport pathways, as they are effectively major sinks of the aeolian sediment regime.

Aeolian sediment transport fluxes in drylands are frequently complex, multi-directional and may involve multiple sources, sinks and pathways. Furthermore, they are often intimately linked to hydrological pathways, which themselves may operate only intermittently and unpredictably, in the form of ephemeral drainages and lakes (playas) (Al-Masrahy & Mountney, 2015; Bullard & Livingstone, 2002; Williams, 2015). Although terminal closed basins are often associated with aeolian sediment emissions, often in the form of dust (e.g. Gill, 1996), other studies have highlighted the role of dunefields as emission sources (Bullard *et al.*, 2008), and even alluvial fans as sources of nearby dune sands (Howard *et al.*, 1999). Moreover, not all basins may contribute equally as aeolian sources, perhaps most notably in the case of Saharan dust emissions, a disproportionate amount of which in now known to originate from the Bodélé Depression in Chad

(Washington and Todd, 2005), and such emissions may also have complex spatio-temporal dependency on localized hydrology (e.g. Dahmardeh Behrooz *et al.*, 2019). Therefore, identifying sources of aeolian sediment and quantifying the contribution of different sources represent critical steps for wind erosion control and management (Wang and Jia, 2013).

For the first time, Collins et al. (1997) applied a sediment fingerprinting method to quantify contribution sources of fluvial sediments. Consequently, many researchers applied this technique to quantify source contributions of fluvial sediments at various locations worldwide (e.g. Walling, 2005; Collins et al., 2010; Zhang et al., 2012; Smith and Blake, 2014; Le Gall et al., 2017; Tiecher et al., 2018; Habibi et al., 2019). Sediment fingerprinting is well-developed in the context of fluvial sediments, but only recently has this approach has been introduced to quantifying source contribution of aeolian sediments (Gholami et al., 2017a, b; Liu et al., 2016a; Wang et al., 2017; Dahmardeh Behrooz et al., 2019). The successful development of sediment fingerprinting methods for aeolian sediment deposits is important as it provides quantitative estimates of aeolian sediment with constrained uncertainties which can be applied to diverse dryland regions and environmental problems, especially where such transport fluxes may be complex and other methods of provenancing (e.g. detrital zircon U-Pb dating) may be difficult to apply (Gholami et al., 2017b). The effectiveness of multiple composite fingerprints to quantify the provenance of aeolian sediments reported by Liu et al., (2016a) suggested that these methods could be useful in other locations for studying provenance of aeolian sediments.

Geochemical characteristics of aeolian sediments deposited far from their source regions have been used as proxies for their potential sources (Wang et al. 2017). Criteria to determine sources are based on comparing the different geochemical properties of sediment samples and potential source samples. In recent years, numerous different sediment fingerprinting techniques have been developed to quantify sediment provenance, with hydrological applications most common at present (Walling, 2013; Wang et al., 2017). A wide range of properties have been employed in sediment fingerprinting studies including geochemical elements (Collins et al., 2012; Lamba et al., 2015; Liu et al., 2016a; Gholami et al., 2017a; Gholami et al., 2019), geochemical indicators (Vale et al., 2016), isotopic ratios (Douglas et al., 1995), radionuclides (Walling et al., 1999; Olley et al., 2012), organic elements (Walling et al., 1999; Gellis et al., 2009), magnetic properties (Russell et al., 2001) and physical signatures (Kouhpeima et al., 2010).

Results produced by sediment fingerprinting studies, however, may have various uncertainties (Walling, 2013). In recent years, techniques such as Bayesian models and Monte Carlo simulation were developed to evaluate uncertainties associate with sediment fingerprinting results (Collins et al., 2012; Cooper et al., 2014; Pulley et al., 2015; Lamba et al., 2015; Liu et al., 2016b; Abban et al., 2016; Cooper and Krueger, 2017; Nosrati et al., 2018; Habibi et al., 2019; Gholami et al., 2019). However, most of these studies focused on fluvial systems and the application of these modelling techniques to quantify source contribution of aeolian sediments is rare. Recently, Gholami et al. (2017b) successfully applied a Bayesian mixing model to assess uncertainties associated with results of aeolian sediment fingerprinting in the Yazd-Ardekan plain, Iran. Large parts of Iran (an area of about 24 million ha) are arid or semi-arid areas where wind erosion acts as an important geomorphological process over (Gholami et al., 2017a). About 25% of this area is occupied by dune fields, including the Yazd, Ashkzar, Kashan and Jazmurian ergs (Figure 1). Jazmurian erg and its surrounding areas at the southern border of Kerman and Sistan-Baluchestan Provinces, Iran, experience severe wind erosion (Rashki et al, 2017). The aim of this research is to test and evaluate the fingerprinting method to quantify sources of aeolian sediment in a dune field with a complex potential range of sand sources (a large playa, associated terminal fluvial channels, sand sheets and more distal alluvial fans), and to incorporate robust estimates of the uncertainties associated with the fingerprinting results using a Bayesian un-mixing model.

2. Material and methods

2.1 Study area

The study area is located in the Jazmurian Basin, in the Kerman Province of southeastern Iran (Figure 1). With the Jabal Albarez mountains to the north, and separated from the Gulf of Oman by the Makran mountains to the south, the Jazmurian Basin is a closed basin fed by the Bampur River from the east, and the longer Halil (Haliri) River to the west. The region is arid, receiving 100-200 mm rainfall annually, but with evapotranspiration of up to 2500 mm year^{-1} (Rashki, Arjmand & Kaskaoutis, 2017). Geologically, this area is covered by five Quaternary geological formations: (1) sand sheets (Q_s unit); (2) alluvial fine-grain sediments and dry river bed sediments (Q_{al} unit); (3) alluvial fans and terraces (Q_t unit); (4) mixtures of clay and salt (the dried lake-bed of Jazmurian lake, or Q_c unit) and (5) dune fields (Q_{sd} unit) (Figure 1, part B). The Q_s, Q_{al}, Q_t and Q_c geological units are assumed to be the potential sources of aeolian sediments for the small erg representing the deposition region, the Q_{sd} geological unit (Liu et al., 2016a; Gholami et al., 2017a, b). The area of the case study is 8050 km^2 and it consists of 1754 km^2 Q_t unit, 1443 km^2 Q_s unit, 1667 km^2 Q_c unit, 1887 km^2 Q_{al} unit and 199 km^2 Q_{sd} unit.

Jazmurian lake covers, at its maximum extent, about 1100 km^2 of the study area, but the lake is rarely inundated, and frequently completely dry; this has been the case since at least the earlier half of the 20^{th} century (Harrison, 1943). The lake has recently yielded sedimentological evidence of palaeoclimatic change since the Last Glacial Maximum, revealing a complex aridity history, with markedly wetter conditions during the early Holocene, with more minor excursions in moisture availability throughout the last 20 ka (Vaezi *et al.*, 2019).

Dominant winds in the western Jazmurian region are mainly from the southwestern, southern and southeastern directions (Figure 1, part E), though to the north and east they are more varied. Extensive droughts in the early 2000s caused the Jazmurian lake to completely dry and resulted in an increased frequency of dust events observed during 2001-2003. Dusty days in the Jazmurian Basin ranged from 91 in 1996 to 203 in 2003 (Rashki et al., 2017). Increasing in frequency and intensity of dust storms resulting from the desiccation of the lakes may raise serious problems for the regional climate, ecosystems and human health (e.g. Rashki et al., 2013b). The Jazmurian region is a main source of dust storms, and atmospheric dusts emitted from this area affect mostly both sides of the Sea of Oman, including the southeastern Arabian Peninsula and western Pakistan (Rashki et al., 2017).

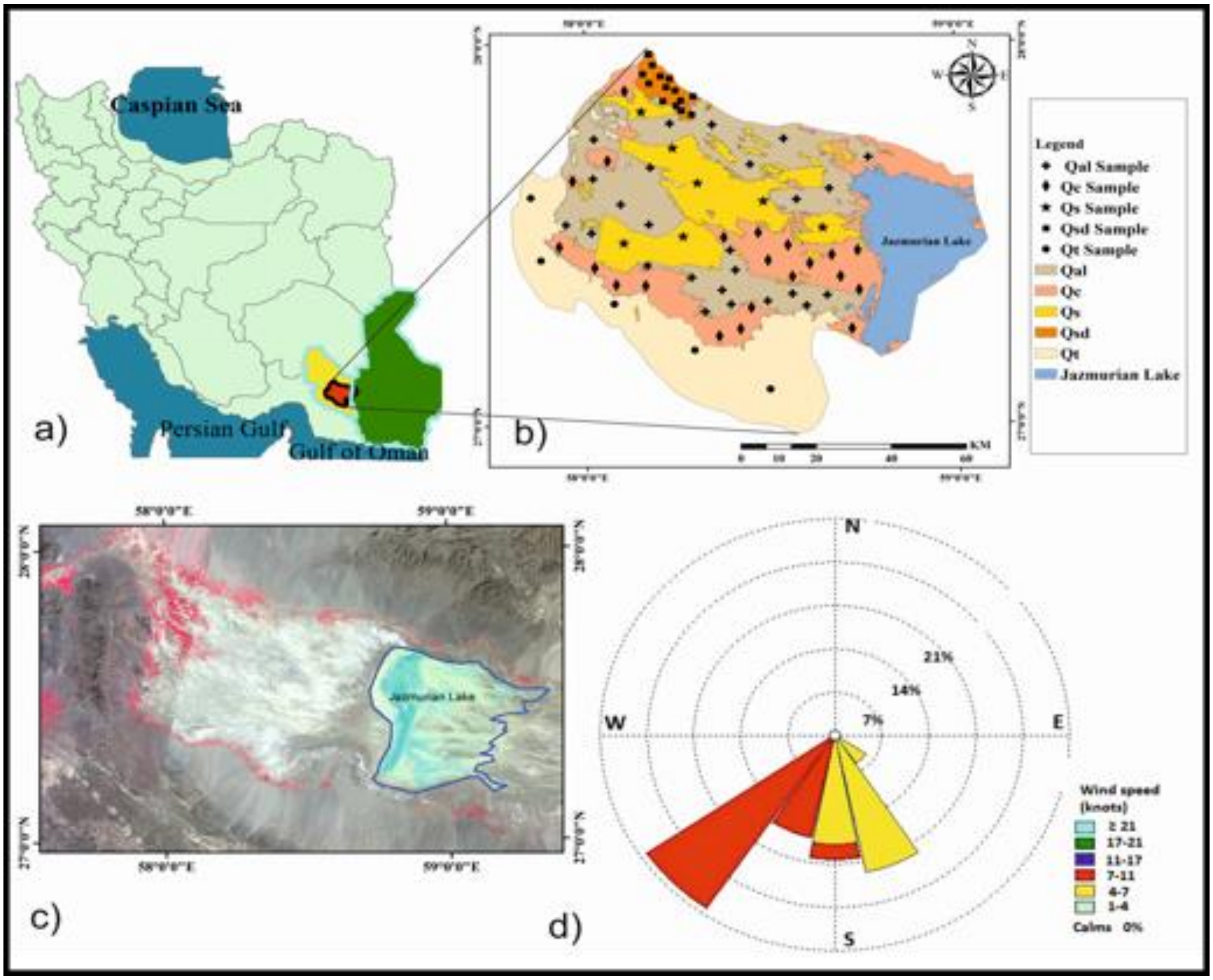

Figure 1. Location and geological map of the Jazmurian region, south of Kerman, Iran and sampling sites. a) Location of study area (with red color) at the map of Iran and south of Kerman province (Yellow color); b) Geological map of study area. Different colors represent different geological sites in the study area; c) Landsat image (February 2017) of study area; and d) Annual wind rose from Kahnouj station. Number of sampling points = 72.

2.2 Sampling and laboratory analysis

A total of 72 sediment and soil samples were collected from the upper 0-5 cm depth of the potential sources and deposition regions (Figure 1, part B) in winter 2017. Among these samples, 7 were collected from Q_s, 25 from Q_{al}, 5 from Q_t, 21 from Q_c source areas. Additionally, 14 samples were collected from the dune fields (Q_{sd}) as aeolian sediments (Figure 1, part C). Source samples collected from points that were: (*a*) clearly derived from the geological unit; (*b*) within the spatial coverage of the source area, broadly; and (*c*) influenced by wind erosion (Gholami et al., 2017b).

The grain size distribution of the samples was determined using the dry sieve method. The geochemical analysis of fingerprint properties focused on the 125- 410 μm fraction of the samples. This is the predominant range of grain size in the aeolian sediment deposition area, and sediments in this range are susceptible to aeolian transport (Field et al., 2010). The samples were digested with aqua regia (Collins et al., 2012) and analyzed for Ni, Cu, Co, Cr, Ga, Mn, P, Ba, Sr and Li using inductively coupled plasma optical emission spectroscopy (ICP-OES; Varian 730-ES model). The relative standard deviation (% RSD), based on three replicates for each determinant on each sample, was consistently ≤ 5%.

2.3 Potential sources of aeolian sediments

Selection of the optimum fingerprint involves quantitative assessment of the power of individual properties to identify the potential sources of sediment (Collins et al., 2010). A two-stage statistical procedure, which was introduced by Collins et al. (1997), was used to identify optimum composite fingerprints to discriminate potential sources of aeolian sediments. At the first step, the ability of potential sources' properties was investigated using the Kruskal-Wallis *H* test. At the second step, optimum composite fingerprints were selected by a stepwise discriminant function analysis (DFA). Wilks' lambda was used as the primary factor of discrimination in the stepwise DFA, which determined the optimum fingerprints as input parameters to the model. This two-stage procedure has been successfully applied by many studies for source fingerprinting of fluvial sediments (Walling et al., 1999; Stone et al., 2014; Zhou et al., 2016; Chen et al., 2016; Liu et al., 2016b) and more details of this method and its application to aeolian sediments may be found in Gholami et al. (2017a, b).

2.4 Bayesian un-mixing model

In this study, we used a Bayesian un-mixing model, developed by Gholami et al. (2017b), to quantify source contributions of aeolian sediments. It is a full Bayesian model in that all hyperparameters are not fixed at a specific value and a prior distribution was selected for each hyperparameter. Compared to an empirical Bayesian approach, a full Bayesian model is more flexible and more complicated (Cooper et al., 2014). Further details of modelling procedure are given in Gholami et al. (2017b) and Habibi et al. (2019). Compared to the model used in Gholami et al. (2017b) and Habibi et al. (2019), which used a Centered Log Ratio (CLR) transformation, in this study, we used the Dirichlet distribution for source contributions (Fox and Papanicolaou, 2008). The Dirichlet distribution is a multivariate generalization of the beta distribution which satisfies the necessary boundaries constraints directly (that is, that all sources should sum to unity, and that all contribute between 0 and 1). It is thus simpler than the CLR transformation approach.

If $P = \{p_i, \dots, p_n\}$ follows the Dirichlet distribution with hyper-parameters $a_1, \dots, a_n > 0$, its density function is

$$f(P) = \frac{\Gamma(\sum_{i=1}^{n} a_i)}{\prod_{i=1}^{n} \Gamma(a_i)} \prod_{i=1}^{n} p_i^{a_i - 1} \qquad \text{(eq. 1)}$$

Here, $p_i, \dots, p_n \geq 0$ and $\sum_{i=1}^{n} p_i = 1$. Because there is no assumed prior information for the source contributions, we set hyper-parameters $a_1, \dots, a_n$ equal to one. Similarly, in this study, weakly or non-informative hyper-parameters were used as prior distributions.

Because of the structure of the model, directly sampling from the Dirichlet distribution was not possible. Therefore, a beta distribution was used according to the following steps to sample $P = \{p_i, \dots, p_n\}$ values from Dirichlet distribution (Gelman et al., 2004). First using $Beta(a_1, \sum_{i=2}^{k} a_i)$ distribution p1 was generated, then $p_2, \dots, p_{n-1}$ were simulated using $p_j = \left(1 - \sum_{i=1}^{j-1} \theta_i\right)\phi_j$, where ϕ_j was sampled from $Beta(a_j, \sum_{i=j+1}^{n} a_i)$ distribution. Finally, p_n was calculated as $p_k = 1 - \sum_{i=1}^{n-1} p_i$.

It is not possible to obtain posterior distribution functions directly, as the joint posterior of all parameters is complex and high-dimensional. However, the Bayesian un-mixing model defined above can be analyzed using Markov Chain Monte Carlo (MCMC) modelling, and the parameters can be derived using the WinBUGS package (Lunn et al., 2000). The model was run 20,000,000 times from the posterior distribution and the first 5,000,000 runs were considered as burn in. The model convergence during the runs was assessed by monitoring the trace plots of generated values (Gholami et al., 2017b).

2.5 Performance assessment of Bayesian un-mixing model

The goodness of fit (GOF) was used to evaluate the Bayesian un-mixing model performance according to Collins et al, (2012), and was calculated as follows:

$$GOF = 1 - \frac{1}{n} * \sum_{i=1}^{n} [\frac{(B_i - \sum_{i=1}^{m} A_j \,.\, X_{j.i}}{B_i}]^2 \qquad (eq.2)$$

Where B_i indicates concentration of optimum fingerprint property (*i*) in the dune field samples; A_j is mean concentration of optimum fingerprint property (*i*) in source category (*s*); $X_{j.i}$ indicates optimized percentage contribution from potential source category (*s*); *n* is number of optimum fingerprints (in this research, *n*=4); and *m* is number of potential sources for dune field samples (in this study, *m*=4).

3. Results

3.1 Discrimination sources of aeolian sediments

Results of the two-stage statistical procedure are showed in Tables 1 and 2. Table 1 presents the results of the Kruskal-Wallis *H*-test, which was used to assess the ability of the tracer properties to discriminate the four potential sources including Q_s, Q_{al}, Q_t and Q_c. The Kruskal-Wallis *H*-test (stage 1) showed that all of the 10 tracer properties could discriminate four potential sources at the 99% level of confidence (Table 1).

Table 1. Kruskal-Wallis *H*-test results for selecting fingerprints to distinguish potential aeolian sediment sources in the Jazmurian plain.

Tracers	Ni	Cu	Co	Cr	Ga	Mn	P	Ba	Sr	Li
Chi-Square	40.9	40.6	39.3	40.8	40.2	34.4	39.3	18.3	39.7	41.7
Sig	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*	0.00*

** Statistically significant at p <0.01*

All tracer properties passing the Kruskal-Wallis *H*-test were entered to stepwise DFA as stage 2 of the statistical verification. Table 2 shows that four optimum fingerprints were selected for modelling processes and to quantify source contribution of aeolian sediments. The four elements in question (Cr, Li, Ni and Co) are likely to reflect differing abilities to differentiate aspects of the region’s complex geological past. Chromium is most likely associated with the Remeshk ophiolite complex which lies unconformably to the south of the Jazmurian plain, whereas the commonly-associated nickel and cobalt are more likely attributable in origin to the metamorphic Deyader complex, also to the south (McCall, 2002). Lithium, meanwhile, is most abundant at the earth's surface as evaporite minerals associated with closed basins such as the Jazmurian plain, and its significance as a tracer probably relates to its ability to discriminate more local contributions.

Table 2. Stepwise DFA results for selecting the optimum fingerprints.

Step	Optimum fingerprint	Wilks lambda	*p*-value
1	Cr	178.9	< 0.001
2	Li	55.1	< 0.001
3	Ni	37.8	< 0.001
4	Co	30.2	< 0.001

The stepwise DFA was able to correctly classify 81% of the variance between the potential source samples. Although stepwise DFA results suggested that good source discrimination was achieved, samples collected from Q_s shown slightly overlap with the Q_{al} source samples when the first and second functions were plotted (Figure 2).

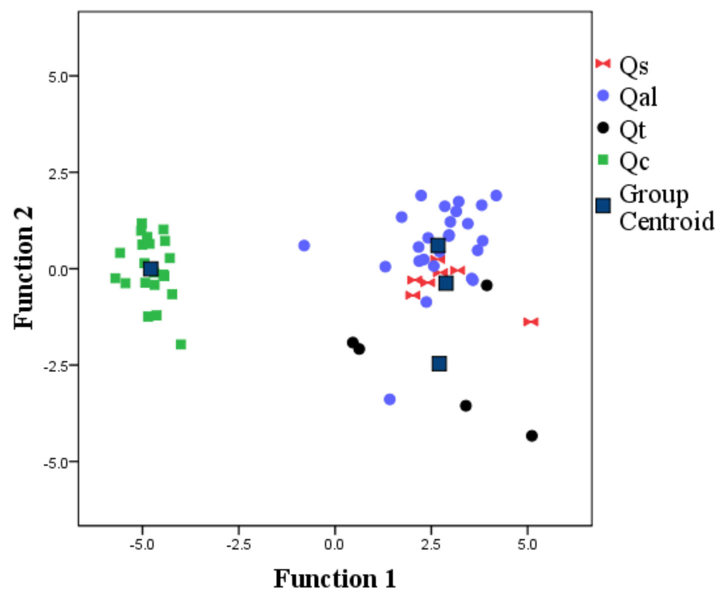

Figure 2. Two-dimensional scatter plot constructed from the first and second discriminant functions calculated using the stepwise DFA in association with the stepwise selection of the optimum fingerprints for discriminating potential sources of aeolian sediments in the Jazmurian plain, south of Kerman, Iran. Scatter plot shows distribution of samples collected from four

potential sources including Q_s, Q_{al}, Q_t and Q_c in the Jazmurian Plain. The stepwise DFA selected four optimum fingerprints (Cr, Li, Ni and Co) that provided a good discrimination between potential sources with 81% samples correctly classified in the four sources.

3.2 Apportionment source of aeolian sediments by the Bayesian un-mixing model

Uncertainty ranges of main source contribution of aeolian sediments were estimated by the Bayesian un-mixing model with 95% confidence limits (Table 3, Figure 4). The Q_{al} unit (alluvial and dry river-bed sources) was recognized as the main source to supply materials for sediment samples 1, 2, 3 and 6, with mean contributions of 37%, 36%, 29%, and 36%, respectively. For sediment sample 4, Q_s is the main source with mean contributions of 29%. For sediment sample 5, Q_t was recognized as main source and contribution ranged between 1-72% (with mean 29%). For sediment sample 7, about 33% of the materials came from the Q_{al} source (with contribution range 2-78%). The mean contributions from Q_s as main source for sediment samples 8, 9 and 10 were 38% (with contribution range 2-82%); 35% (with contribution range 2-79%); and 27% (with contribution range 1-68%), respectively. For sediment samples 11 and 12, the Q_s was the main source and its contribution ranges were 2-78% (with mean 34%) and 1-73% (with mean 31%), respectively. For sediment samples 13 and 14, the Q_c was recognized as the main source and its contribution ranges were 6-65% (with mean 37%) and 7-64% (with mean 37%), respectively. In the Bayesian model, the MC errors for all of aeolian sediment samples were less than 0.1% (Table 3), and the goodness of fit (GOF) values for 14 sediment samples ranged from 79% to 100% (Figure 3). The level of the MC error deviation is within the range proposed by Ntzoufras (2009).

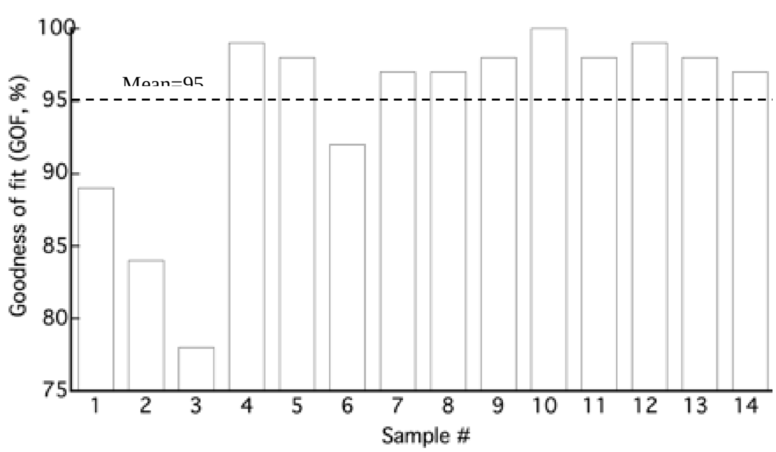

Figure 3. Goodness of fit (GOF) calculated for solutions of the Bayesian un-mixing model for the aeolian sediment samples

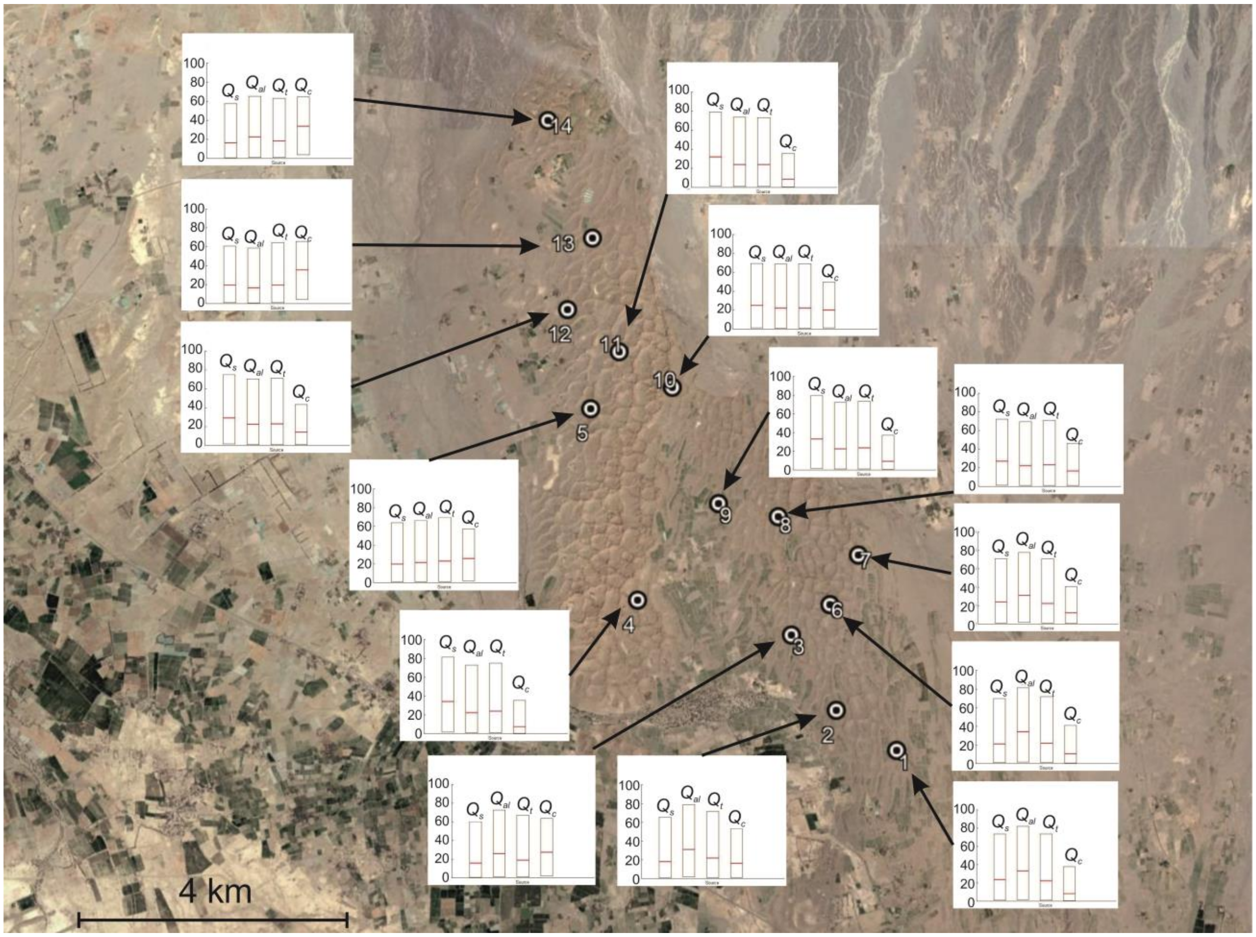

Figure 4. Source contributions for the fourteen samples from Jazmurian erg, expressed as 95% confidence intervals around a median. Note the general homogeneity of the sediment, with only Jazmurian lake-bed sediments (Q_c) typically less common, although locally abundant; especially in samples at the northern margin of the erg. Background imagery courtesy of Google Earth^{TM}.

Table 3: Uncertainty ranges (with 95% confidence limits) of source contributions for 14 aeolian sediment samples analyzed by the Bayesian un-mixing model.

Sediment	source	Mean %	Standard deviation	MC error ($\times10^{-4}$)	2.5%	median	97.5%
1	Qs	27	0.20	3.03	1	23	74
	Qal	36	0.23	3.29	2	33	82
	Qt	26	0.20	2.91	1	22	73
	Qc	11	0.10	1.43	0	8	38
2	Qs	22	0.18	2.60	1	18	65
	Qal	33	0.22	3.19	1	31	79
	Qt	26	0.20	2.84	1	21	71
	Qc	19	0.14	2.08	1	16	53
3	Qs	20	0.16	2.32	1	16	60
	Qal	29	0.20	2.79	1	26	72
	Qt	23	0.18	2.53	1	19	67
	Qc	28	0.17	2.42	2	27	64
4	Qs	29	0.20	2.84	1	27	72
	Qal	26	0.19	2.58	1	22	69
	Qt	27	0.19	2.74	1	23	71
	Qc	18	0.12	1.70	1	16	46
5	Qs	23	0.17	2.45	1	20	64
	Qal	25	0.18	2.46	1	21	66
	Qt	26	0.19	2.54	1	23	69
	Qc	26	0.15	2.02	2	26	57
6	Qs	25	0.19	2.77	1	21	70
	Qal	36	0.23	3.23	2	34	81
	Qt	26	0.20	2.83	1	22	72
	Qc	13	0.11	1.58	0	10	41
7	Qs	27	0.19	2.79	1	24	71
	Qal	33	0.21	2.92	2	31	78
	Qt	26	0.19	2.73	1	22	71
	Qc	14	0.11	1.48	1	12	41
8	Qs	36	0.23	3.38	2	34	81
	Qal	26	0.20	2.83	1	22	73
	Qt	28	0.21	2.99	1	24	75
	Qc	10	0.10	1.27	0	7	35
9	Qs	35	0.22	2.97	2	33	80
	Qal	26	0.20	2.77	1	22	72
	Qt	27	0.20	2.77	1	23	73
	Qc	12	0.10	1.39	0	9	37
10	Qs	28	0.19	2.77	1	25	69

	Qal	25	0.19	2.69	1	22	68
	Qt	26	0.19	2.67	1	22	69
	Qc	21	0.13	1.92	1	20	50
11	Qs	34	0.22	3.13	1	32	79
	Qal	28	0.20	2.74	1	24	73
	Qt	27	0.20	2.79	1	24	73
	Qc	11	0.10	1.37	0	8	36
12	Qs	31	0.21	3.01	1	29	75
	Qal	26	0.19	2.85	1	22	70
	Qt	27	0.19	2.86	1	23	71
	Qc	16	0.11	1.64	1	14	43
13	Qs	22	0.16	2.31	1	20	61
	Qal	20	0.16	2.32	1	16	59
	Qt	23	0.17	2.37	1	19	64
	Qc	35	0.16	2.20	4	35	66
14	Qs	20	0.15	2.21	1	16	57
	Qal	25	0.18	2.62	1	22	65
	Qt	22	0.17	2.41	1	18	63
	Qc	33	0.16	2.26	4	34	64

4. Discussion

The results of our study show that the 10 tracer properties were able to identify aeolian sediment sources at the 99% level of confidence. By using the stepwise discriminant function analysis, the number of tracers was reduced to four (Cr, Co, Ni and Li), yet these can still explain up to 81% of the variance between the sediment sources. Based on these four fingerprinting tracers, we applied a Bayesian un-mixing model to identify the relative contribution of the four potential sources to the aeolian sediment in the Jazmurian Plain, southeastern Iran. The performance of this model, evaluated by using the GOF, ranged from 78% to 100%. The fact that a majority of the GOF values was well above 80% suggested that the Bayesian model performed well in assessing the sediment sources in our study area (Zhou et al., 2016; Haddadchi et al., 2013).

The results of this study are in sharp contrast to studies which identified both marked spatial variability in the contributions of sources (e.g. Dahmardeh Behrooz *et al.*, 2019), and spatial variability of provenance in depositional environments, even at a localized scale (Gholami et al 2017b). At Jazmurian, the sources of the aeolian sediment in our study area are very diverse and no single source area had a contribution >40%. Desiccation of lakes in arid and semiarid areas may affect the frequency and intensity of aeolian sediment transport at local to global scales, and numerous studies have associated lake-beds with sources of aeolian emissions. These are reported from locations as diverse as Owens Lake, USA (Reheis et al, 2009), Hamoun lakes, Iran (Rashki et al, 2012; 2013a, b; Dahmardeh Behrooz et al., 2019), the Aral sea, Uzbekistan (Breckle et al, 2012), southern Africa (Prospero et al, 2002; and Mahowald et al, 2003), and Lake Eyre, Australia (Baddock et al, 2009). Here, however, materials for only two or three sand field samples come predominantly from the dried-bed of Jazmurian Lake (Q_c unit or mixture of clay and salt materials), despite its extensive outcropping upwind of the erg (samples 13 and 14; sample 5 has almost equal contributions from Q_c and Q_t).

Instead, this study shows the dunefield is supplied by a complex and diverse range of sources (Figure 4), and that most samples, fluvial and alluvial sediments (Q_{al} unit), alluvial fan and terrace sediments (Q_t unit), and sand sheets (Q_s unit), often contributing almost equally within the bounds of uncertainty, are the predominant sources for twelve of the samples studied. Sediments from the source area to Jazmurian erg are transported by winds that blow from the south and southeast (Figure 1), where the sources are represented by a more proximal mixture of alluvial (Q_{al}), lake-bed sediments (Q_c) and sand sheets (Q_s), with a more distal (~40 km) bajada of alluvial fans (Q_t) bordering the Makran mountains to the south. Spatial patterning of sediment sources within the dunefield sediment sources is limited (Figures 4 and 5), and only the sediment associated with the Jazmurian lake units (Q_c) show strong variance, being more abundant at the northern/western end of the erg. However, if the single largest mean contributions are considered (Figure 4), there is a weak trend in the data for samples in the eastern edge of the erg to have alluvially-derived material as the most abundant component, those to the center to have a more substantial component of sand-sheet derived sediments, and only those to the west containing larger contributions of lake-bed contributions. This observation likely reflects relatively local (km-scale) sediment sources and pathways, as this pattern mirrors the nature of the substrate surrounding the erg, with outcropping of lake-bed clays to the south-west, sand sheets to the south, and fluvial deposits to the south and east (Figure 5a). However, the presence of a considerable alluvial fan (Qt) component in all samples probably highlights the importance of a longer-distance transport component, over scales of 10 – 100 km (Figure 1), as local outcroppings of such deposits are very rare.

The aeolian sediment system in this region is a complex and interlinked interplay of sediment pathways and stores, affected by periodic fluvial events, and not simply a case of sediment deflating from an extensive ephemeral lake complex. Whilst the significance of dry fluvial and alluvial materials as an aeolian sediment source is well reported (e.g. Cohen *et al.*, 2010; Du, Wu & Tan, 2018), and Gholami et al., (2017b) revealed that Quaternary alluvial fans and terraces (alluvial sediments) are the main source of materials for sand fields in Yazd-Ardekan plain in Central Iran. Here it is clear that almost all components of the landscape have the capacity for aeolian sand mobilization at a range of scales. These findings are also in agreement with a recent study by Ahmady-Birgani et al. (2018), which reported that simultaneous actions of alluvial, fluvial and aeolian processes provide the majority of materials to the newly-formed sand fields associated with the desiccation of Lake Urmia in northwestern Iran.

It is worth considering noting that the age of the dunes at Jazmurian erg is unknown, and that absolute ages of Quaternary sediments from southern Iran are in general sparse. However, the dunes remain active within recent years (Figure 5b and 5c), with at least surficial mobilization of sands reshaping the surface of the dunes and interdunes. Where such longer records do exist, either in terms of dated terrestrial sequences (Kehl, Frechen & Skowronek, 2005; Kehl, Frechen & Skowronek, 2009; Rashidi *et al.*, 2019), or the recent lacustrine sequence from Jazmurian (Vaezi *et al.*, 2019), they reveal multiple periods of varying climate during the Late Quaternary, with likely periods of increased hydrological stress even during the Holocene. It is thus possible that not all source areas contribute equally to the dunefield contemporaneously, and that changing wind patterns on longer timescale may also contribute to the varied nature of the sands' origins.

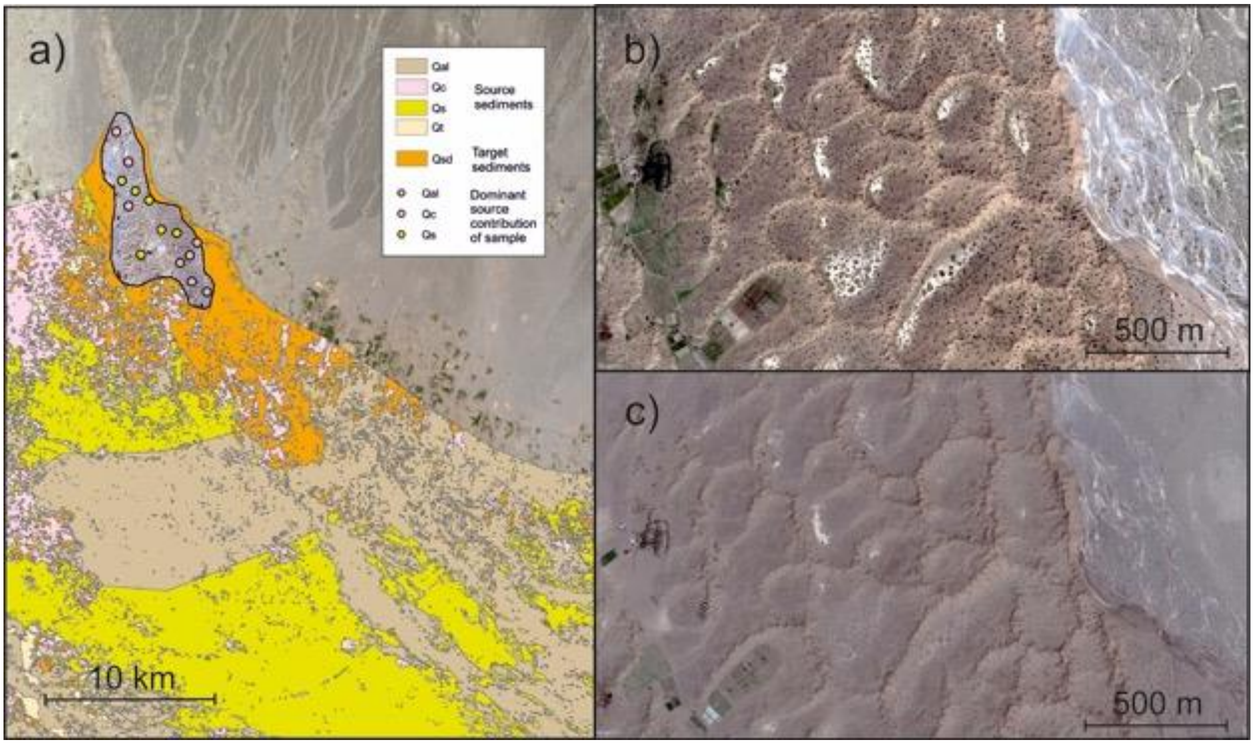

Figure 5. Localized variance in the major source contributions to the sands of the dune field are likely associated with spatio-temporal variance in local sources. a) The dominant component of the target samples, whilst never markedly more than other contributions, does seem to relate to shorter distance transport with some east-west variance evident across the erg. b) The dunefield's modern activity is evident by comparison with an image (courtesy of Google Earth^{TM}) from March 2011, revealing bright interdunes, presumably rich with evaporites, with c) a comparable image from March 2012, showing the interdunes buried beneath blown sand. To the west of this image, fields are similarly covered, and dune crests in the southeast corner have moved on the order of ~10 m.

In terms of managing land degradation, this study highlights the potential for using sediment provenancing studies to better inform potential land management of aeolian desertification, and crucially, highlights the need to make such assessments on a site-by-site basis. The Jazmurian erg is adjacent to a large dryland lake system, which serves as the terminal basin for local hydrological activity across a sand-rich landscape, and which varies in extent on a range of timescales and is thus associated with extensive deposition of lacustrine sediments and evaporites. It might seem tempting to immediately ascribe that as the dominant source of aeolian sediments for Jazmurian erg (e.g., Gill, 1996). Yet establishing the provenance of the sediments of Jazmurian erg has revealed that the sands of the dunes are from a wide range of local sources, with substantial contributions from all major local landscape elements. This includes both short (km-scale) and longer (10-100 km scale) contributions; focusing on managing the lake-bed's contribution would be to overlook the majority of actual source material. Mitigation efforts to minimize aeolian desertification at Jazmurian need to focus on a holistic approach to sand stabilization.

5. Conclusions

Sediment fingerprinting is an effective tool to quantify source contribution of aeolian sediments. Results of our study show that aeolian, fluvial and alluvial processes are the main sediment supplier's for dune fields in the Jazmurian plain of Iran. Like other modeling methods, results produced by fingerprinting method are associated with uncertainties. Therefore, quantifying uncertainty related to source contribution of aeolian sediment is essential for environmental management. Here, we introduced a novel Bayesian un-mixing model to quantify uncertainties associated with source contribution of aeolian sediments. The performance of the revised model was satisfactory, as suggested by GOF.

Our study found that the sediment sources for the Jazmurian erg are diverse and likely represent complex, multiphase sediment pathways, with evidence for sand transport at a range of spatial scales. This finding, in contrast to other studies which have revealed sometimes singular dominant landscape elements in terms of aeolian emissions, highlights the need investigate aeolian transport pathways on a site-by-site basis, as there is marked spatial and temporal variability in the consistency of sediment pathways. This knowledge can inform mitigation strategies for the protection of agricultural and other land uses. The fingerprinting method and the uncertainty evaluation approach proposed by this study has the potential to be applied to other arid and semiarid systems, where aeolian sediment transport is a concern for aeolian desertification, air quality, human health, and nutrient cycling.

Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this article.

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References

Abban, B., Papanicolaou, A. N., Cowles, M. K., Wilson, C. G., Abaci, O., Wacha, K., Schilling, K., and Schnobelen, D. (2016). An enhanced Bayesian fingerprinting framework for studying sediment source dynamics in intensively managed landscapes. Water Resource Research, 52, 4646-4673. doi:10.1002/2015WR018030.

Ahmady-Birgani, H., Agahi, E., Ahmadi, S. J., and Erfanian, M. (2018). Sediment source fingerprinting of the Lake Urmia Sand Dunes. Scientific Reports, 8:206, 1-15. doi:10.1038/s41598-017-18027-0

Al-Masrahy, M. A. & Mountney, N. P. (2015) 'A classification scheme for fluvial–aeolian system interaction in desert-margin settings'. *Aeolian Research*, 17 pp. 67-88.

Baddock, M. C., Bullard, J. E., and Bryant, R. G. (2009). Dust source identification using MODIS: a comparison of techniques applied to the Lake Eyre Basin, Australia. Remote Sens Environ, 113:1511–28.

Breckle, S.W., Wucherer, W., Liliya, A., Dimeyeva, L. A., Nathalia, P., and Ogar, N. P. (2012). Aralkum - a man-made desert: the desiccated floor of the Aral Sea (Central Asia). Springer; pp. 486.

Brewer, M. J., Filipe, J. A. N., Elston, D. A., Dawson, L. A., Mayes, R. W., Soulsby, Ch., and Dunn, S. M. (2005). A Hierarchical Model for Compositional Data Analysis. Journal of Agricultural, Biological, and Environmental Statistics, 10(1), 19–34. doi:10.1198/108571105X28200

Bullard, J., Baddock, M., McTainsh, G. & Leys, J. (2008) 'Sub-basin scale dust source geomorphology detected using MODIS'. *Geophysical Research Letters*, 35 (15),

Bullard, J. E. & Livingstone, I. (2002) 'Interactions between aeolian and fluvial systems in dryland environments'. *Area*, 34 (1), pp. 8-16.

Chen, F., Fang, N., and Shi, Z. (2016). Using biomarkers as fingerprint properties to identify sediment sources in a small catchment. Science of the Total Environment, 557-558, 123–133. doi:10.1016/j.scitotenv.2016.03.028.

Cohen, T. J., Nanson, G. C., Larsen, J. R., Jones, B. G., Price, D. M., Coleman, M., and Pietsch, T. J. (2010). Late Quaternary aeolian and fluvial interactions on the Cooper Creek Fan and the association between linear and source-bordering dunes, Strzelecki Desert, Australia. Quaternary Science Reviews, 29, 455-471.

Collins, A. L., Walling, D. E., and Leeks, G. J. L. (1997). Fingerprinting the origin of fluvial suspended sediment in larger river basins: combining assessment of spatial provenance and source type. Geografiska Annaler, 79, 239–254.

Collins, A. L., Zhang, Y., Walling, D. E., Grenfell, S. E., and Smith, P. (2010). Tracing sediment loss from eroding farm tracks using a geochemical fingerprinting procedure combining local and genetic algorithm optimisation. Science of the Total Environment, 408(22), 5461–5471. doi:10.1016/j.scitotenv.2010.07.066

Collins, A. L., Zhang, Y., Walling, D. E., Grenfell, S. E., Smith, P., Grischeff, J., … Brogden, D. (2012). Quantifying fine-grained sediment sources in the River Axe Catchment, southwest England: Application of a Monte-Carlo numerical modelling framework incorporating local and genetic algorithm optimisation. Hydrological Processes, 26 (13), 1962–1983. doi:10.1002/hyp.8283.

Cooper, R. J., and Krueger, T. (2017). An extended Bayesian sediment fingerprinting mixing model for the full Bayes treatment of geochemical uncertainties. Hydrological Processes. doi: 10.1002/hyp.11154.

Cooper, R. J., Krueger, T., Hiscock, K. M., and Rawlins, B. G. (2014). Sensitivity of fluvial sediment source apportionment to mixing model assumptions: A Bayesian model comparison. Water Resourecs Reaserch, 50: 9031-9047. doi:10.1002/2014WR016194.
Dahmardeh Behrooz, R., Gholami, H., Telfer, M. W., Jansen, J. D., and Fathabadi, A. (2019). Using GLUE to pull apart the provenance of atmospheric dust. Aeolian Research, 37, 1-13. https://doi.org/10.1016/j.aeolia.2018.12.001
Dong, Z. B., Chen, G. T., He, X. D., Han, Z. W. & Wang, X. M. (2004). Controlling blown sand along the highway crossing the Taklimakan Desert. Journal of Arid Environments, 57 (3), pp. 329-344.
Douglas, G. B., Gray, C. M., Hart, B. T., and Beckett, R. (1995). A Strontium isotopic investigation of the origin of suspended partculate matter (SPM) in the Murray-Darling river system, Australia. Geochimica et Cosmochimica Acta, 59 (18), 3799-3815. https://doi.org/10.1016/0016-7037(95)00266-3
Dregne, H., Kassas, M., and Rozanov, B. (1991). A new assessment of the world status of desertification. J. Animal . Sci, 69, 2463-2471.
Du, J. H., and Wang, X. L. (2014). Optically Stimulated Luminescence dating of sand-dune formed within the Little Ice Age. Journal of Asian Earth Sciences. http://dx.doi.org/10.1016/j.jseaes.2014.05.012
Du, S., Wu, Y., and Tan, L. (2018). Geochemical evidence for the provenance of aeolian deposits in the Qaidam Basin, Tibetan Plateau. Aeolian Research, 32, 60-70. https://doi.org/10.1016/j.aeolia.2018.01.005
Field, J. P., Belnap, J., Breshears, D. D., Neff, J .C., Okin, G. S., Whicker, J. J., Painter, T. H., Ravi, S., Reheis, M. C., and Reynolds, R. L. (2010). The ecology of dust. Frontiers in Ecology and the Environment, 8(3); 423-430. https://doi.org/10.1890/090050
Fox, J. F., and Papanicolaou, A. N. (2008). An un-mixing model to study watershed erosion processes. Advances in Water Resources, 31, 96–108. doi:10.1016/j.advwatres.2007.06.008
Gellis, A. C., Hupp, C. R., Pavich, M. J., Landwehr, J. M., Banks, W. S. L., Hubbard, B. E., Langland, M. J., Ritchie, J. C., and Reuter J. M. (2009). Sources, transport, and storage of sediment in the Chesapeake Bay Watershed. U.S. Geological Survey Scientific Investigations Report 2008-5186: 95.
Gelman, A., Carlin, J. B., Stern, H. S., and Rubin, D. B. (2004). Bayesian Data Analysis, 2nd Ed., Chapman & Hall.
Gholami, H., Jafari TakhtiNajad, E., Collins, A.L., Fathabadi, A. (2019). Monte Carlo fingerprinting of the terrestrial sources of different particle size fractions of coastal sediment deposits using geochemical tracers: some lessons for the user community. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-019-04857-0
Gholami, H., Middleton, N., NazariSamani, A. A., and Wasson, R. (2017a). Determining contribution of sand dune potential sources using radionuclides, trace and major elements in central Iran. Arab J Geosci, 10:163. doi. 10.1007/s12517-017-2917-0.
Gholami, H., Telfer, M. W., Blake, W. H., and Fathabadi, A. (2017b) Aeolian sediment fingerprinting using a Bayesian mixing model. Earth Surf. Process. Landforms, doi: 10.1002/esp.4189.
Gill, T. E. (1996). Eolian sediments generated by anthropogenic disturbance of playas: human impacts on the geomorphic system and geomorphic impacts on the human system. Geomorphology, 17 pp. 207-228.

Habibi, S., Gholami, H., Fathabadi, A., and Jansen, J. D. (2019). Fingerprinting sources of reservoir sediment via two modelling approaches. Science of the Total Environment, 663, 78-96. https://doi.org/10.1016/j.scitotenv.2019.01.327

Haddadchi, A., Ryder, D., Evrard, O., and Olley, J. (2013). Sediment fingerprinting in fluvial systems: review of tracers, sediment sources and mixing models. International Journal of Sediment Research, 28, 560-578. doi.org/10.1016/S1001-6279(14)60013-5

Harrison, J. V. (1943) 'The Jaz Murian Depression, Persian Baluchistan'. *The Geographical Journal*, 101 (5/6), pp. 206-225.

Howard, D. A., Ramsey, M. S., Christensen, P. R. & Lancaster, N. (1999) 'Identification of sand sources and transport pathways at the Kelso Dunes, California, using thermal infrared remote sensing'. *GSA Bulletin*, 111 (5), pp. 646-662.

Kehl, M., Frechen, M. & Skowronek, A. (2005) 'Paleosols derived from loess and loess-like sediments in the Basin of Persepolis, Southern Iran'. *Quaternary International*, 140-141 pp. 135-149.

Kehl, M., Frechen, M. & Skowronek, A. (2009) 'Nature and age of Late Quaternary basin fill deposits in the Basin of Persepolis/Southern Iran'. *Quaternary International*, 196 (1-2), pp. 57-70.

Kouhpeima, A., Feiznia, S., Ahmadi, H., Hashemi, S. A., and Zareiee, A. R. (2010). Application of quantitative composite fingerprinting technique to identify the main sediment sources in two small catchments of Iran. Hydrology and Earth System Sciences, 7, 6677–6698. doi.org/10.5194/hessd-7-6677-2010

Lamba, J., Karthikeyan, K. G., and Thompson, A. M. (2015). Apportionment of suspended sediment sources in an agricultural watershed using sediment fingerprinting. Geoderma, 239-240, 25–33. doi:10.1016/j.geoderma.2014.09.024.

Lancaster, N., Wolfe, S., Thomas, D., Bristow, C., Bubenzer, O., Burrough, S., Duller, G., Halfen, A., Hesse, P., Roskin, J., Singhvi, A., Tsoar, H., Tripaldi, A, Yang, X., and Zarate, M. (2016). The INQUA Dunes Atlas chronologic database. Quaternary International, 410, 3-10. https://doi.org/10.1016/j.quaint.2015.10.044

Le Gall, M., Evrard, O., Dapoigny, A., Tiecher, T., Zafar, M., Minella, J. P. G., Laceby, P., and Ayrault, S. (2017). Tracing sediment sources in a subtropical agricultural catchment of southern Brazil cultivated with conventional and conservation farming practices. Land Degradation and Development, 28(4), 1426-1436. https://doi.org/10.1002/ldr.2662

Leighton, C. L., Thomas, D. S. G., and Bailey, R. M. (2014). Reproducibility and utility of dune luminescence chronologies. Earth Science Reviews, 129, 24-39. http://dx.doi.org/10.1016/j.earscirev.2013.11.007

Li, H., and Yang, X. (2015). Spatial and temporal patterns of aeolian activities in the desert belt of northern China revealed by dune chronologies. Quaternary International, xxx, 1-11. http://dx.doi.org/10.1016/j.quaint.2015.07.015

Liu, B., Niu, Q., Qu, J., and Zu, R. (2016a). Quantifying the provenance of aeolian sediments using multiple composite fingerprints. Aeolian Research, 22, 117-122. dx.doi.org/10.1016/j.aeolia.2016.08.002

Liu, B., Storm, D. E., Zhang, X. J., Cao, W., and Duan, X. (2016b). A new method for fingerprinting sediment source contributions using distances from discriminant function analysis. Catena, 147, 32–39. doi:10.1016/j.catena.2016.06.039.

Luna, M. C. M. de M., Parteli, E. J. R., Duran, O., and Herrmann, H. J. (2011). Model for the genesis of coastal dune fields with vegetation. Geomorphology, 129, 215-224. https://doi.org/10.1016/j.geomorph.2011.01.024

Lunn, D. J., Thomas, A., Best, N., and Spiegelhalter, D. (2000). WinBUGS - a Bayesian modelling framework: concepts, structure, and extensibility. Statistics and Computing, 10:325--337.

Mahowald, N. M., Bryant, R. G., del Corral, J., and Steinberger, L. (2003). Ephemeral lakes and desert dust sources. Geophys Res Lett, 30:1074. http://dx.doi.org/10.1029/2002GL016041

McCall, G. J. H. (2002). A summary of the geology of the Iranian Makran. Geological Society, London, Special Publications, 195**,** 147.

Muhs, D. R. (2017). Evaluation of simple geochemical indicators of aeolian sand provenance: Late Quaternary dune fields of North America revisited. Quaternary Science Reviews, 171, 260-296. doi.org/10.1016/j.quascirev.2017.07.007

Ntzoufras, I. (2009). Bayesian modelling using WinBUGS. John Wiley & Sons, Inc: Hoboken, New Jersey.

Nosrati, K., Collins, A. L., and Madankan, M. (2018). Fingerprinting sub-basin spatial sediment sources using different multivariate statistical techniques and the Modified MixSIR model. Catena, 164, 32-43. https://doi.org/10.1016/j.catena.2018.01.003

Olley, J., Burton, J., Smolders, K., Pantus, F., and Pietsch, T. (2012). The application of fallout radionuclides to determine the dominant erosion process in water supply catchments of subtropical South-east Queensland, Australia. Hydrological Processes, 27(6), 885-895.doi.10.1002/hyp.9422

Prospero, J. M., Ginoux, P., Torres, O., Nicholson, S. E., and Gill, T. E. (2002). Environmental characterization of global sources of atmospheric soil dust identified with the Nimbus 7 total ozone mapping spectrometer absorbing aerosol product. Rev Geophys, 40: 2–31

Pulley, S., Foster, I., and Antunes, P. (2015). The uncertainties associated with sediment fingerprinting suspended and recently deposited fluvial sediment in the Nene River Basin. Geomorphology, 228, 303–319. doi:10.1016/j.geomorph.2014.09.016.

Rashidi, Z., Sohbati, R., Karimi, A., Farpoor, M. H., Khormali, F., Thompson, W. & Murray, A. (2019) 'Constraining the timing of palaeosol development in Iranian arid environments using OSL dating'. *Quaternary Geochronology*, 49 pp. 92-100.

Rashki, A., Arjmand, M., and Kaskaoutis, D. G. (2017). Assessment of dust activity and dust-plume pathways over Jazmurian Basin, southeast Iran. Aeolian Research, 24, 145-160. http://dx.doi.org/10.1016/j.aeolia.2017.01.002

Rashki, A., Eriksson, P. G., Rautenbach, C. J. D., Kaskaoutis, D. G., Grote, W., and Dykstra, J. (2013a). Assessment of chemical and mineralogical characteristics of airborne dust in the Sistan region, Iran. Aeolian Research, 90; 227-236. http://dx.doi.org/10.1016/j.chemosphere.2012.06.059

Rashki, A., Kaskaoutis, D. G., Goudie, A. S., and Kahn, R. A. (2013b). Dryness of ephemeral lakes and consequences for dust activity: The case of the Hamoun drainage basin, southeastern Iran. Science of the Total Environment, 463-464; 552-564. http://dx.doi.org/10.1016/j.scitotenv.2013.06.045

Rashki, A., Kaskaoutis, D. G., Rautenbach, C. J. D., Eriksson, P. G., Qiang, M., and Gipta, P. (2012). Dust storms and their horizontal dust loading in the Sistan region, Iran. Aeolian Research, 5; 51-62. doi:10.1016/j.aeolia.2011.12.001

Ravi, S., Breshears, D. D., Huxman, T. E., and D'odorico, P. (2010). Land degradation in

drylands: Interactions among hydrologic-aeolian erosion and vegetation dynamics. Geomorphology, 116**,** 236-245.
Reheis, M., Budahn, J. R., Lamothe, P. J., and Reynolds, R. L. (2009). Compositions of modern dust and surface sediments in the Desert Southwest United States. J Geophys Res, 114: F01028. http://dx.doi.org/10.1029/2008JF001009
Russell, M. A., Walling, D. E., and Hodgkinson, R. A. (2001). Suspended sediment sources in two small lowland agricultural catchments in the UK. Journal of Hydrology, 252, 1–24. doi.org/10.1016/S0022-1694 (01)00388-2
Smith, H. G., and Blake, W. H. (2014). Sediment fingerprinting in agricultural catchments: A critical re-examination of source discrimination and data corrections. Geomorphology, 204, 177–191. doi:10.1016/j.geomorph.2013.08.003.
Stone, M., Collins, A. L., Silins, U., Emelko, M. B., and Zhang, Y. S. (2014). The use of composite fingerprints to quantify sediment sources in a wildfire impacted landscape, Alberta, Canada. Science of the Total Environment, 473-474, 642–650. doi:10.1016/j.scitotenv.2013.12.052.
Thomas, D. S. G., and Burrough, S. L. (2013). Luminescence-based dune chronologies in southern Africa: Analysis and interpretation of dune database records across the subcontinent. Quaternary International, xxx, 1-16. http://dx.doi.org/10.1016/j.quaint.2013.09.008
Tiecher, T., Paolo, J., Minella, J. P. G., Evrard, O., Caner, L., Merten, G. H., Capoane, V., Didone, E. J., and dos Santos, D. R. (2018). Fingerprinitng sediment sources in a large agricultural catchment under no-tillage in southern Brazil (Conceicao river). Land Degradation and Development. In press. https://doi.org/10.1002/ldr.2917
United Nations (2015). Transforming Our World: The 2030 Agenda for Sustainable Development. New York: UN Publishing.
UNCCD, (1994).United Nations convention to combat desertification in those countries experiencing serious drought and/or desertification, particularly in Africa (pp. 1–2). Geneva: United Nations Environment Programme for the Convention to Combat Desertification (CCD).
Vaezi, A., Ghazban, F., Tavakoli, V., Routh, J., Beni, A. N., Bianchi, T. S., Curtis, J. H. & Kylin, H. (2019) 'A Late Pleistocene-Holocene multi-proxy record of climate variability in the Jazmurian playa, southeastern Iran'. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 514 pp. 754-767.
Vale, S. S., Fuller, I. C., Procter, J. N., Basher, L. R., and Smith, I. E. (2016). Characterization and quantification of suspended sediment sources to the Manawatu River, New Zealand. Science of The Total Environment, 543, 171–186. doi:10.1016/j.scitotenv.2015.11.003
Walling, D. E. (2005). Tracing suspended sediment sources in catchments and river systems. Science of the Total Environment, 344 (1-3), 159–184. doi:10.1016/j.scitotenv.2005.02.011.
Walling, D. E. (2013). The evolution of sediment source fingerprinting investigations in fluvial systems. Journal of Soils and Sediments, 13 (10), 1658–1675. doi:10.1007/s11368-013-0767-2.
Walling, D. E., Owens, P. N., and Leeks, G. J. L. (1999). Fingerprinting suspended sediment sources in the catchment of the River Ouse, Yorkshire, UK. Hydrological Processes, 13, 955-975. doi. 10.1002/(SICI)1099-1085(199905)13:7<955::AID-HYP784>3.0.CO;2-G
Wang, H. & Jia, X. (2013) Field observations of windblown sand and dust in the Takimakan Desert, NW China, and insights into modern dust sources. Land Degradation & Development, 24 (4), pp. 323-333.

Wang, G., Li, J., Ravi, S., Scott Van Pelt, R., Costa, P. J. M., and Dukes, D. (2017). Tracer techniques in aeolian research: approaches, applications, and challenges. Earth-Sciences Reviews, 170, 1-16. https://doi.org/10.1016/j.earscirev.2017.05.001

Washington, R. & Todd, M. C. (2005) 'Atmospheric controls on mineral dust emission from the Bodélé Depression, Chad: The role of the low level jet'. *Geophysical Research Letters*, 32 (17),

Williams, M. (2015) 'Interactions between fluvial and eolian geomorphic systems and processes: Examples from the Sahara and Australia'. CATENA, 134 pp. 4-13.

Yang, L., Dong, Y., and Huang, D. (2018). Morphological response of coastal dunes to a group of three typhoons on Pingtan Island, China. Aeolian Research, 32, 210-217. https://doi.org/10.1016/j.aeolia.2018.03.009

Zhang, Y. S., Collins. A. L., and Horowitz, A. J. (2012). A preliminary assessment of the spatial sources of contemporary suspended sediment in the Ohio River basin, United States, using water quality data from the NASQAN program in a source tracing procedure. Hydrological Processes, 26, 326-334. doi: 10.1002/hyp.8128

Zhou, H., Chang, W., and Zhang, L. (2016). Sediment sources in a small agricultural catchment: A composite fingerprinting approach based on the selection of potential sources. Geomorphology, 266, 11-19. dx.doi.org/10.1016/j.geomorph.2016.05.007