Land degradation and sand dynamics in a steppe region (Nâama, south-western Algeria)

Degradación del suelo y dinámica de arenas en una región de estepa (Nâama, suroeste de Argelia)
Degradação do solo e dinâmica das areias na região de estepe (Nâama, sudoeste da Argélia)

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ABSTRACT

Land degradation is one of the most important environmental threats facing the international community. In North Africa, many semiarid and arid regions are suffering significant land degradation, which can be an impediment to sustainable development. Therefore; land degradation is monitored in a regional context for a better understanding of its causes and consequences. One of the main consequences is a notable increase in sand encroachment with negative environmental implications. For this reason, the dynamics of sands between south-eastern Morocco and the wilaya of Nâama, south-western Algeria, was studied. Sand samples gathered from six distinctive areas were subjected to physicochemical, colorimetric (redness index), morphoscopic (circularity), and geochemical analysis, and studied statistically using an analysis of variance (ANOVA), wind direction data, ternary plots and a hierarchical cluster of trace elements (K, Rb, Fe, Ti, Ca and Sr). In all areas, a clear dominance of the sand fraction appeared showing percentages ranging from 89 to 96%. Sampled areas were all carbonated, and the pH was alkaline, with close values ranging from 8.4 to 9. The mean circularity values ranged from 0.67 in Merzouga (Morocco) to 0.80 in El Aguer (Algeria). The lowest value of the redness index was noted in Merzouga with a mean value of 4. The Algerian areas showed an almost similar redness index with a value of 6 but the highest value was noted in Saadana with a value of 11. Geochemical approaches, based on ternary plots and dendrogram cluster indicating the abundance of major elements (Fe, Ca and K), were used as indicators of wind transport. Results suggested the existence of a Regional Wind Action System (RWAS) implicated in the transport of sand from south-eastern Morocco and its redistribution towards south-western Algeria. Merzouga was connected to all areas but particularly to nearby Saadana and Kasdir in the Algerian territory.

RESUMEN

La erosión del suelo es una de las mayores amenazas ambientales a las que se enfrenta la comunidad internacional. En el norte de África, varias regiones áridas y semiáridas están sometidas a procesos erosivos que impiden un desarrollo sostenible. El seguimiento de la erosión del suelo debe realizarse en un contexto regional para poder entender mejor sus causas y sus consecuencias. Una de las principales consecuencias es el notable incremento de invasiones de arena con negativas implicaciones ambientales. Por esta razón, en este trabajo se estudia la dinámica de las arenas entre el sureste de Marruecos y el wilaya de Nâama, suroeste de Argelia. Se presentan los resultados de los análisis físico-químicos, colorimétricos (índice de enrojecimiento), morfoscópicos (circularidad) y geoquímicos realizados en muestras de arena de seis localidades diferentes. Estos resultados se interpretaron mediante análisis de varianza (ANOVA), datos bibliográficos de la dirección del viento, plots ternarios y conglomerados jerárquicos realizados con las concentraciones de los elementos traza (K, Rb, Fe, Ti, Ca y Sr). En todas las zonas estudiadas domina la fracción arena con un rango de porcentajes del 89% al 96%. Las muestras eran carbonatadas y el pH

alcalino con valores comprendidos entre 8.4 y 9. Los valores medios de circularidad morfológica oscilan entre 0.6 en Merzouga (Marruecos) y 0.80 en El Aguer (Argelia). En las muestras recogidas en Argelia el índice de enrojecimiento fue muy similar, con valores de 6, pero el valor más alto se observó en Saadana, siendo de 11. El análisis geoquímico, interpretado mediante plots ternarios y dendrogramas, indicó que la abundancia de los elementos mayoritarios (Fe, Ca y K) puede ser indicadora del transporte eólico. Los resultados sugieren la existencia de un sistema regional de actuación eólica (RWAS) que implica el transporte de arena desde el sureste de Marruecos y su distribución a través del suroeste de Argelia, conectando Merzouga con todas las áreas pero especialmente con la cercana Saadana y Kasdir en Argelia.

RESUMO

A degradação do solo é uma das maiores ameaças ambientais que a comunidade internacional enfrenta. No norte da África, várias regiões áridas e semi-áridas são submetidas a processos de degradação que impedem o seu desenvolvimento sustentável. Assim, a degradação do solo é monitorizada em um contexto regional para melhor entender as suas causas e consequências. Uma das principais consequências é o aumento notável da invasão por areias com implicações ambientais negativas. Por esta razão, neste trabalho é estudada a dinâmica da areia entre o sudeste de Marrocos e Wilaya Nâama, sudoeste da Argélia. Amostras de areia colhidas em seis áreas distintas foram sujeitas a análises físico-químicas, colorimétricas (índice de rubefacção), morfoscópicas (circularidade) e geoquímicas. Os resultados foram interpretados usando análise de variância (ANOVA), dados da direção do vento, diagramas ternários e um conjunto hierárquico de concentrações de elementos (K, Rb, Fe, Ti, Ca e Sr). Uma clara dominância da fração areia ocorre em todas as áreas de estudo com uma concentração de 89 a 96%. Todas as amostras eram carbonatadas, com valores de pH entre 8,4 e 9. Os valores médios da circularidade morfológica variaram entre 0,67 em Merzouga (Marrocos) e 0,80 em El Aguer (Argélia). Os valores mais baixos do índice de rubefacção (valor médio de 4) foram observados nas amostras de Merzouga. As amostras colhidas nas áreas da Argélia apresentaram valores deste índice muito semelhantes (valor 6) mas o valor mais alto (11) foi observado em Saadana. A aproximação geoquímica baseada nos diagramas ternários e cluster de dendogramas indicaram a abundância de Fe, Ca e K, os quais foram usados como indicadores de transporte. Os resultados sugerem a existência de um sistema regional de ação do vento (RWAS), envolvido no transporte de areia desde o sudeste de Marrocos e a sua redistribuição ao longo do sudoeste da Argélia ligando Merzouga a todas as áreas, mas particularmente às áreas mais próximas de Saadana e Kasdir no território Argelino.

1. Introduction

With an area of 20 million hectares (Houyou et al. 2014), the Algerian steppe is one of the three main eco-climatic regions of the country and the largest area of rangeland of the North African countries. Steppe evokes vast arid expanses covered by very low, sparse vegetation (Le Houherou 1995; Aidoud et al. 2006). In recent decades, the Algerian south-western steppes have suffered from a decrease in rainfall and are under the threat of desertification, land degradation and increasing sand encroachment (Slimani et al. 2010). It is now well accepted that sand encroachment is linked to driving forces like wind and results from a very active morphodynamic process (Slimani et al. 2010; Ren et al. 2014; Hamdan et al. 2015).

Several works monitoring desertification and land degradation have mainly focused on the study of sand encroachment (Bagnold 1941; Dubief 1952; Sharp 1966; Callot 1987; Mainguet 1992). For over forty years, cartography, especially from satellite imagery, has been a reliable tool for better understanding sand encroachment phenomena. Significant studies have been carried out using aerial photographs (Smith et al. 1968) and Landsat images (Fryberger and Dean 1979) and, more recently, new approaches, including numerical modelling (Hersen 2004), field measurement (Hugenholtz et al. 2012) and geochemical methods have proved

to be powerful in identifying sand transport and its sources (Ren et al. 2014). These recent works had the double objective of showing not only the origin of the sand, but also the causes that led to its mobilization and reactivation (Capot-Rey 1970; Mainguet et al. 2008).

Mainguet (1992) proposed a theoretical framework called the Global Wind Action System (GWAS) and worked in the Sahel for several years to develop this concept and understand the sand dynamics better. The zone affected by GWAS can be divided into three main components: an ablation source area subjected to deflation providing fresh sandy material, a transit area, and an accumulation area. According to the same author, the Sahel was an area of wind accumulation during the Ogolian period (between 18000 and 12000 BP) but was reactivated as a sand-exporting zone during the catastrophic drought from 1968 to 1985 (Ozer et al. 2003). Adapting the GWAS to the movement sweeping from northern Egypt to the south, El-Baz (1988) initiated the Regional Wind Action System (RWAS), a concept that also seems more appropriate in the present work, given the regional scale of the study area.

The present study applies this original approach of wind and sand dynamics to the high plains of the wilaya (province in Arabic) of Nâama in south-western Algeria. The main objective is to study the potential specific processes of transport in relation to the sand dynamics in the study area, in order to assess the influence of allochthonous vs. autochthonous sand. Thus, the physicochemical, morphoscopic and colorimetric characteristics, and the geochemical composition of sand samples were studied. Statistical test such as ANOVA, wind direction data, ternary plot and hierarchical cluster of trace elements (K, Rb, Fe, Ti, Ca and Sr) were performed.

2. Materials and methods

2.1. Study area

The study area, a vast territory composed of high plains where the altitude can reach more than 1000 m (Slimani et al. 2010), is located in the south-west of Algeria (**Figure 1**). This large area of steppe is surrounded by salt lakes, sand accumulations, and mountains that form part of the Saharan Atlas range. Administratively, it belongs to the wilaya of Nâama.

The wilaya of Nâama is formed by tabular matching glacis having slopes ranging from 1 to 5%, and is crossed by a network of runoff channels that contribute significantly to the superficial soil erosion (Hirche 2010). The high plains lie between two mountain ranges, the Saharan Atlas in the south and the Tell Atlas in the north.

During the Quaternary period, the filling of a large subsidence zone with sediment generated a new landscape formed by depressions and different types of deposits, including dunes (Cornet et al. 1952). Recent dunes were built up during relatively dry periods of the last continental Quaternary period (Coque and Jauzein 1965).

2.2. Climate

The climate is arid-Mediterranean, characterized by a dry summer with high temperatures (Daget et al. 1988). In the study area, the network of reference climate stations is made up of three stations: Mecheria, El Bayadh and Ain Sefra (**Figure 1**). Climate data were gathered from the National Meteorology Office and covered a long period from 1970 to 2014 (ONM 2008).

Annual rainfall is generally low, ranging from 180 to 270 mm. The distribution of rainfall is very irregular, with a coefficient of variability ranging from 34 to 56%. Winters are cold and harsh while summers are hot and dry. The minimum temperatures occur in January, with average values ranging from -1.7 ºC in Ain Sefra to 7.3 ºC in Mecheria. July is the hottest month with average maximum values ranging from 33.8 ºC to 35.5 ºC. The dry period for both
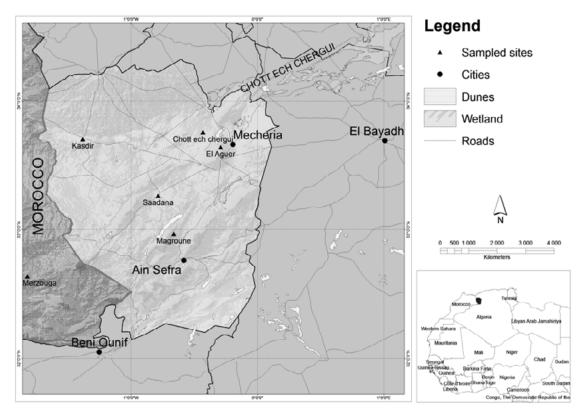
Figure 1. General location of the study area.

stations is about six months and the bioclimatic classification places the area in the medium-arid class with cold winters variant (Bagnouls and Gaussen 1953).

In an arid environment, the wind pattern is a climatic parameter of primary importance. The prevailing winds are generally governed by climate events and the orography. Wind also controls the formation of sand covers and can provoke sand storms. Therefore, the spatial and temporal variations of the wind activity are the main components of a study the dynamics of sands.

The results concerning wind activity were obtained from the National Meteorological Office ONM (2008). Wind directions at El Bayadh and Mecheria (ONM 2008) are presented by rose diagrams in **Figure 2(b)**; no data were gathered for Ain Sefra. Hirche (2010) showed that most of the winds were low speed (class: 1-5 m s^{-1}) at both stations with respectively 43.1% and 46.9%. The class of 6-10 ms^{-1} was non-negligible

with about a quarter of the total (23.5% and 22.9%). The strong winds were rare and present less than 2% at the two stations. The wind rose of frequency of speed shown in **Figure 2(c)**, underlines that wind speed is quite regular and oscillates between 3 and 4 m s^{-1}. The significant threshold of 4 m s^{-1} means that this speed is not exceeded until April. This could mean that a large proportion of the days have a higher wind speed, a fact that is well known to the local population, who fear spring sandstorms. In the study area, sandstorms most often occur in the form of dust winds. They were rare in the 1970s at both stations (El Bayadh: 3.2 days year^{-1}, Mecheria: 8 days year^{-1}), but the number of dust days has increased strongly since 1990 (Nouaceur 2008). Between 1990 and 1997, an average of 30 days per year was recorded in El Bayadh, reaching 119 days between 2001 and 2004. The same was observed in Mecheria, where 58 days were recorded between 1990 and 1997 and 136 days between 2001 and 2004 (Hirche et al. 2011).
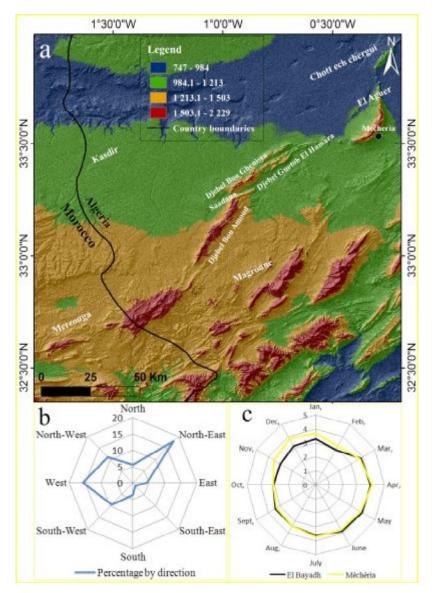
Figure 2. (a) Shaded Digital Elevation Model of the study area (in metre); (b) Wind rose diagram of percentages by direction at El Bayadh and Mecheria according to ONM (2008); (c) Wind rose diagram of Frequency analysis of wind speed (in ms-1) at El Bayadh and Mecheria according to ONM (2008).

2.3. Soil sampling and laboratory analyses

Representative sites, principally constituted of sandy cover and dunes, were selected and 32 sand samples were gathered at six locations: Merzouga in south-eastern Morocco and Magroune, Saadana, Kasdir, El Aguer and Chott ech chergui in the wilaya of Nâama south-western Algeria (**Table 1**). Sand samples were collected from the surface to a depth of 20 or even 30 cm using a small plastic shovel at a rate of a few hundred grams for each sample.

Sand samples were air dried and sieved prior to analysis. Gravels (> 2 mm) and fine particles (< 2 mm) were separated to calculate the percentage of each fraction (Loveland and Whalley 1991). The particle size distribution was determined by the pipette method after the elimination of organic matter with H_2O_2 and dispersion with sodium hexametaphosphate (Loveland and Whalley 1991). pH and the EC (electrical conductivity) were measured potentiometrically in a 1:2.5 soil:water suspension. $CaCO_3$ equivalent was determined by Bascomb's method (Bascomb

Table 1. Geographical coordinates and number of samples of the sampled areas

Areas (number of samples)	Latitude (N)	Longitude (W)
Merzouga (3)	31°14'70.91"	3°58'12.77"
Magroune (5)	32°59'32.02"	0°43'18.80"
Saadana (9)	33°17'12.40"	0°56'29.80"
Kasdir (7)	33°37'34.20"	1°29'70.60"
El Aguer (4)	33°44'56.13"	0°18'53.40"
Chott ech chergui (4)	34°00'49.80"	0°24'44.80"

1961) modified by Barahona and Iriarte (1984). Organic carbon (OC) was analysed by wet oxidation using Tyurin's method (Tyurin 1951). Cation and cation-exchange capacity (CEC) were determined with 1 N ammonium acetate and Na-acetate (Soil Conservation Service 1972).

Morphoscopic and colorimetric features were studied for each sand sample (over a minimum of 100 grains), in a binocular magnifying glass equipped with a scanning system managed through Imagej® software (Abramoff et al. 2004). Image processing determined the mean circularity of each sample. The degree of sheen was defined relative to the brightness of the surface of the sand grain and its ability to reflect light (Cailleux and Tricart 1959). A redness index (RI) was calculated as: Hue x chroma) / Value (Munsell 1954; Hurst 1977, in Ortiz et al. 2002).

Geochemical analysis was performed to measure the concentrations of trace and major elements (Fe, Ca, K, Rb, Ti and Sr) using an X-ray fluorescence (XRF) analyser, NITON XLt 792.

2.4. Statistical analysis

The differences in the means of the physicochemical, geochemical and morphoscopic parameters in the sand samples were analysed using a one way ANOVA procedure in SPSS software 20.0 (IBM SPSS Inc., Armonk, NY, USA). The mean ± 2 median absolute deviations (MAD) (Tukey 1977) of different samples were separated by Duncan's test (P < 0.05).

3. Results

3.1. Physical and chemical characterization of the study area

Statistically, the measured factors did not indicate significant differences. **Tables 2 and 3** show the one-way ANOVA and list the mean and SD of the main physicochemical factors linked to the sampled areas.

The physical properties and the available water were also studied. In all areas, a clear dominance of the sand fraction appeared (**Table 2**), showing percentages ranging from 89 to 96%. No significant statistical difference was noted (P = 0.280). No gradient appeared between Merzouga and Chott ech chergui. Silts and clays, representing the fine fraction, were present in very modest amounts in most samples. The percentages of coarse and fine silts ranged from 0.15 to 1.40% and from 0.02 to 2.15%, respectively, while those of clays ranged from 1.60 to 5.44%. No significant statistical difference was found.

The chemical analyses are shown in **Table 3**. Significant differences (P = 0.001) can be noted with respect to pH values. Sampled areas were all carbonated, and the pH was alkaline, with close values ranging from 8.4 to 9 (Soil Conservation Service 1972). Small differences were found in the areas of Magroune and Saadana, indicating pH values slightly higher than in other areas. However, the proportions of calcium carbonates were moderately low, with values varying

between 1 and 7.3% (Marañés et al. 1994). In general, the electrical conductivity showed very low values (Hamed et al. 2008). The values varied between 0.04 and 3.64 dS m^{-1}, ranging from non- to very slightly saline (Soil Survey Division Staff 1993), as measured in samples gathered in the salted area of Chott ech chergui, without any statistically significant differences. Organic carbon percentages remained very low, with less than 1% (Marañés et al. 1994). The first result was the absence of any gradient from Merzouga to Chott ech chergui.

Table 2. Physical properties and available water of sand samples (n = 32)

Areas	Sand (%)		Coarse Silt (%)		Fine Silt (%)		Clay (%)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Merzouga	95.10	2.99	0.15	0.02	0.02	0.01	1.60	0.18
Magroune	92.47	1.70	0.90	0.48	1.38	0.64	4.45	0.73
Saadana	94.21	0.93	0.20	0.05	0.92	0.27	3.86	0.53
Kasdir	90.68	1.89	0.81	0.46	0.99	0.55	5.44	0.63
El Aguer	95.69	1.07	0.45	0.25	0.34	0.26	2.14	0.13
Chott ech chergui	89.93	4.40	1.41	0.91	2.15	1.49	4.83	2.26
	P = 0.280		**P = 0.304**		**P = 0.400**		**P = 0.069**	

Table 3. Chemical properties of sand samples (n = 32)

Areas	CaCO$_3$ (%)		pH		EC (dS m^{-1})		OC (%)		CEC (cmol$_c$ kg^{-1})	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Merzouga	2.60	0.12	8.70ab	0.14	0.04	0.01	0.74	0.01	0.21	0.11
Magroune	1.00	0.06	9.00b	0.07	0.07	0.01	0.62	0.02	0.53	0.04
Saadana	1.22	0.25	9.00b	0.05	0.07	0.01	0.10	0.02	0.39	0.03
Kasdir	4.64	2.21	8.40a	0.14	0.47	0.25	0.11	0.05	0.21	0.07
El Aguer	1.37	0.10	8.60ab	0.16	0.06	0.01	0.24	0.20	0.45	0.03
Chott ech chergui	7.36	4.12	8.60ab	0.16	3.64	3.52	0.11	0.05	4.31	4.17
	P = 0.102		**P = 0.001**		**P = 0.211**		**P = 0.665**		**P = 0.205**	

a,b letters indicate mean significant differences between areas.

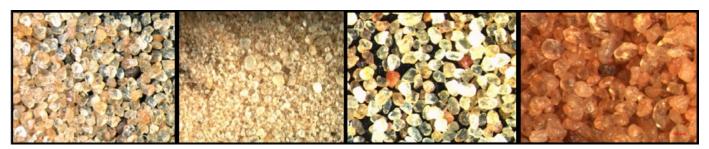### 3.2. Morphoscopic and colorimetric characterization

In general, the sand showed different morphoscopic and colorimetric characteristics (**Table 4**). The mean circularity values ranged from 0.67 in Merzouga to 0.80 in El Aguer (**Figure 3**, photographs (a) and (b)). In all areas, no statistically significant difference was noted. Kasdir, Magroune, Chott ech chergui and Saadana showed sand grains with very similar circularity values.

Table 4. Morphoscopic and colorimetric features of sand samples

Areas	Circularity (Abramoff et al. 2004)		Redness Index (RI) (Ortiz et al. 2002)		Degree of Sheen (Cailleux et Tricart 1959)
	Mean	SD	Mean	SD	
Merzouga	0.67	0.05	4a	0.01	notable brightness
Magroune	0.72	0.04	6a	0.01	very moderate shine
Saadana	0.74	0.02	11b	0.67	very low brightness
Kasdir	0.70	0.03	6a	0.01	very bright
El Aguer	0.80	0.02	6a	0.75	very bright
Chott ech chergui	0.77	0.01	6	0.50	very bright
	P = 0.168		**P = 0.01**		

a,b letters indicate mean significant differences between areas.

The lowest value of the redness index was noted in Merzouga, and the highest in Saadana (**Figure 3**, photographs (c) and (d)). Samples from Magroune, Kasdir, El Aguer and Chott ech chergui had an almost similar redness index but with a statistically significant difference (P = 0.01). Very bright quartz particles were found at Kasdir, El Aguer and Chott ech chergui.

a. Merzouga quartz grains less circularity.

b. El Aguer quartz grain notable circularity.

c. Merzouga less redness quartz grains.

d. Saadana red quartz grains.

Figure 3. Microphotographs of the morphoscopic and colorimetric features of quartz grains.

3.3. Geochemical characterization

The abundances of major and trace elements in sand samples are shown in **Table 5**. Fe, Ca and K are considered as major elements, Sr and Ti as minor elements and Rb as a trace element. Fe, Rb and Sr showed very low mean values with respect to reference values for the earth's crust in general (Wedepohl 1995). Merzouga, Magroune and Chott ech chergui had the highest concentrations of Fe, ranging from 3 165 to 3 432 ppm, without any statistically significant differences compared to Fe. K and Ti mean values were moderately low, ranging from 4 193 to 8 729 ppm for K and 472 to 1 614 ppm for Ti. Ca presented the most contrasting means; its lowest values were noted in Magroune and Merzouga with 6 835 and 8 687 ppm respectively. Saadana and El Aguer showed mean values half those of the references. The highest mean Ca values were measured at 30 695 and 37 742 ppm, in Kasdir and Chott ech chergui respectively.

Table 3. Chemical properties of sand samples (n = 32)

Elements (ppm)	Sr		Rb		Fe		Ti		Ca		K	
Areas	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Merzouga	18.5ab	1.9	8.80	1.40	3432	422	472a	39.62	8687a	225	5249	173.05
Magroune	14.6a	1.2	13.76	1.43	3165	356	1614b	211.01	6835a	810	8729	945.99
Saadana	14.6a	1.7	12.96	1.32	2783	310	1130ab	134.61	14335a	2645	7173	748.95
Kasdir	32.7b	7.6	10.20	1.59	2587	549	971ab	146.68	30695b	8085	6072	1163.73
El Aguer	15.2a	1.5	7.37	1.67	1632	320	1050ab	80.29	15410a	1469	4193	990.27
Chott ech chergui	33.6b	8.9	13.88	2.13	3327	429	1541b	305.69	37742b	3012	8059	1482.12
	P = 0.016		P = 0.075		P = 0.180		P = 0.009		P = 0.001		P = 0.093	

a,b letters indicate mean significant differences between areas.

4. Discussion

4.1. Climate

The results underlined that the study area had an arid climate with high variability that could lead to a succession of dry years and thus exacerbate the arid conditions. Several authors, e.g. Coudée Gaussen (1994) and Rognon (1989, 1996), have shown that, in arid regions, dry soil quickly becomes vulnerable to wind erosion. The presence or absence of vegetation can reduce or increase the effect of wind speed on the soil surface. Slimani et al. (2010) noted that partial or total disappearance of perennial plants exposed the soil to wind erosion and altered its composition.

A second important result is the preponderance of westerly winds. In south-east Morocco, and specifically the wilaya of Tafilalet (including the area of Merzouga), the dominant wind blows from the south-west towards the north-east. This confirms our data, in which the wind blew mainly from the west (34%) and from the north (28%), wind from the south representing only 14% of the total (**Figure 2(b)**). These winds, occurring in spring, are involved in the transport and redistribution of sand. The accumulation of sand in the south-western steppe could be caused by the existence of a sand/wind corridor oriented WSW-ENE, which produces a sand flux (Dubief 1952, in Slimani et al. 2010). The low contribution of south winds invalidates the theory of desertification of the Algerian steppes by the southern Sahara. Nevertheless, a category of very dry, strong, high-speed wind

(Han 2007) called the Sirocco (Chhili for the local population) can have a catastrophic impact on agriculture. It is observed that the process of wind deflation is due to the conjunction of several factors, the most important of which is low vegetation cover and soil dryness as a consequence of anthropozoic degradation (ill-considered clearing, overgrazing, abandonment, etc.) or persistent drought. The huge increase of livestock (sheep) has led to a serious diminution of vegetation cover and biomass. As a result, the repeated passage of animals on the sandy loamy soils favours their scattering. In addition, after a drought, the upper level of the soil becomes powdery and easily transportable by the wind (Coudée Gaussen 1994; Rognon 1994). These winds can also be spectacular, as was the case with the sand storm in Algeria in February 2004 (Nouaceur 2008).

According to the sand corridor theory, the sand flux coming from Merzouga would be canalized by the dominant winds through the corridor created by the mountains in the region of Saadana (**Figure 2(a)**). The sand-laden winds would continue to Kasdir and Magroune, finally reaching Chott ech chergui and El Aguer. The hypothesis of Moroccan origin, for at least some of the sand, is reinforced and seems plausible.

4.2. Sand physical and chemical properties

The results for the physical and chemical properties of the samples are summarized in **Tables 2 and 3** respectively. The pH value measured in Magroune and Saadana was 9. Kasdir, Chott ech chergui and El Aguer, did not show mean pH values higher than Merzouga, Magroune and Saadana. In an arid environment, the alkaline nature of sand samples cannot be considered surprising (values ranging between 8.2 and 8.3 are considered normal) (Han 2007, in Abbasslou et al. 2013). Gommeaux (2008) noted that the characteristics of the soil in Merzouga resulted more from the aridity than the bedrock.

In all samples, carbonate rates were very low. Samples gathered in Chott ech chergui and Kasdir showed very modest $CaCO_3$ values (7.36 and 4.64%, respectively). The remaining measurements showed almost insignificant

rates. During the sampling campaign, scattered shells were found in the sand covers. Makhlouf (1992) noted that, in arid territories, winds deposit shell debris, which could be a non-negligible source of carbonates.

The EC values were generally in the 0.04 to 3.64 dS m^{-1} category (Abbaslou et al. 2013). The highest value (3.64 dS m^{-1}) was measured at Chott ech chergui. The sandy samples had the lowest salinities ranging from 0.04 to 0.45 dS m^{-1}. Hamed et al. (2008) noted that a sandy soil had the lowest salinity and the lowest EC. This confirms that the EC is closely linked to the nature of the soil and the variability of the salinity. The CEC is directly linked to organic matter and to types of clay. Chott ech chergui samples showed the highest mean CEC value (4.31 cmol$_c$ kg^{-1}) with mean clay of 4.83%. Saadana, Kasdir and Magroune also revealed very close mean clay values (**Table 2**). Gommeaux (2008) highlighted the very lowest values of CEC measured in Merzouga. According to him, this is related to the very low clay and organic matter contents. Slimani et al. (2010) noted that, in the steppic region of the 'Rogassa plateau' in south-western Algeria, the study of the soil constituents showed significantly lower than average amounts of fine particles (silts, and clays) and organic matter, inducing an alteration of the physicochemical properties of the soil. The same study highlighted the generalized accumulation of sand, due to the increase in sand inputs from neighbouring steppes.

The values of pH, $CaCO_3$, EC and CEC seem to depend on the arid conditions, where the wind appears to be a major transport and dispersal factor. El Aguer and Chott ech chergui concentrate the highest percentages of fine fractions, which are very sensitive to wind action (Youssef et al. 2012). This leads to think that the wind dynamics is involved in the transport of sand. Kasdir and Chott ech chergui are rich in clays and silts. Their proximity to chotts (local term meaning saline wetlands) (**Figure 1**) makes a supply of very fine sediments possible and the coarse fraction is almost absent or very little represented, only a few tenths of a gram in some samples. The amounts of available water are negligible outside the area of Chott ech chergui.

4.3. Sand morphoscopic and colorimetric properties

Morphoscopy is a reliable tool for studying sand. It involves examining the shape and the appearance of quartz grains (degree of sheen) (Cailleux and Tricart 1959).

In all areas sampled, sub-rounded and well-rounded shiny quartz grains were dominant but the colour of the grain differed (**Table 4**). The grains inherit an original form from their native habitat and are then shaped by their environment (Marshall et al. 2012).

The rounded shape of the quartz grains is very characteristic of quartz particles transported and rolled by winds over long distances. A subsequent stay in water gives the quartz particles a shiny appearance (Le Ribault 1977; Makhlouf 1992; Mainguet 1995; Rognon 1996; Alali et al. 2014).

Thus, the quartz grains of Chott ech chergui and El Aguer showed higher sphericity than quartz grains sampled at Magroune, Saadana and Kasdir and grains from Merzouga showed the lowest values, suggesting transport over a short distance (**Figure 3**, microphotographs (a) and (b)). Therefore, it seems that the sand accumulations in Chott ech chergui and El Aguer are the result of wind transportation from a relatively distant sand source. Sands gathered in Saadana, Kasdir and, to a lesser degree Magroune, confirmed the same trend, but the sand source seemed to be closer. Magroune, where there is an imposing field of dunes, could be an accumulation area. Morphoscopic criteria seem to distinguish Merzouga as a sand exporting area.

The sands gathered in Merzouga had an average redness value of 4, which is a moderate value corresponding to a reddish yellow colour (7.5YR5/8). Observation of the quartz grains with a magnifying glass showed sub angular to sub rounded, uncoated quartz grains. This could indicate newly formed sand, and is a rare alteration (Adnani et al. 2016).

Kasdir, Chott ech chergui and El Aguer exhibited a mean of redness index of 6 and Munsell chart values ranging from light red (2.5YR6/6) in Kasdir to yellowish red (5YR5/8) in El Aguer. Here, winds deposited sand particles in the saline depressions. In such a confined hydromorphic, anaerobic and reducing environment, the quartz grains are washed and discoloured by the dissolution of iron oxide (FeO) (Makhlouf 1992). It appears that the orange-red colour and the moderate shine of the sand result from a brief stay in a humid area. Magroune had yellowish quartz grains (Bensaid 2006). With a mean value of 11, the redness index (RI) clearly singularized Saadana, where the sand is red (2.5YR5/8). Saadana is in a natural corridor oriented SW-NE, where intensive wind activity is noted. This area is wedged in the gaps between Djebel (mountain in Arabic) Bou Amoud, Djebel Bou Ghnissa and Djebel Guetob El Hamara (**Figure 2(a)**). When winds laden with sand penetrate between the Djebels, their speed doubles under the Venturi effect. The sand is discharged when wind activity decreases on reaching the mountains (Andreotti et al. 2002; Navas et al. 2009). Under the effect of wind forces, the surfaces of the grains are abraded and they become covered with a very thin reddish layer formed by free iron oxides, (Walker 1979; Adnani et al. 2016). The Saadana area appears to offer the conditions necessary (intense wind activity, sandstone mountains oriented SW-NE in the direction of dominant wind) to allow the sand to acquire its red colour. As stated above, the shine of quartz grains is evidence of a transition in a humid environment. In Kasdir, Chott ech chergui and El Aguer, very bright quartz was observed. In Merzouga, Magroune, and Saadana the quartz grains showed notable, moderate and very low brightness, respectively (**Table 4**).

The study of the circularity and redness of the sand, and the shine of the quartz grains suggest that the six areas could be categorized as follows: a sand source area in Merzouga, two transit areas at Kasdir and Saadana, and accumulation areas in Magroune, Chott ech chergui and El Aguer.

4.4. Sand geochemical properties

The sand showed a geochemical composition with trace elements, such as copper, lead, nickel-boron, arsenic, fluorine, chlorine and bromine, which are the inheritance of the rock alteration. Several studies have used variations in the abundance of trace elements as an indicator of wind transport (Ren et al. 2014).

The output of the one way ANOVA showed mixed results (**Table 5**). The area of Merzouga exhibited lower mean values (e.g. of Ti) than those measured in the downstream areas (Saadana and Kasdir).

However, major elements can be good indicators for understanding the spatial variation of aeolian sand (Ren et al. 2014) so geochemical approaches, based on ternary plots indicating the abundance of major elements (Fe, Ca and K), were used as indicators of wind transport. The ternary plot of Fe, Ca and K showed that all areas were chemically similar (**Figure 4**). They are organized in a curve starting at Merzouga and continuing through Kasdir, El Aguer and Chott ech chergui. Saadana lies in the intermediate area. Magroune is close to Merzouga and Saadana but has a slightly eccentric location.

According to the fieldwork, the pattern emerging from the ternary plot distinguishes six areas and appears to refine the results of the morphoscopic and colorimetric study. Merzouga on one side, and Saadana and Kasdir on the other, confirm their status as source and transit areas respectively. Geochemical similarities indicate Chott ech chergui and El Aguer as accumulation areas.
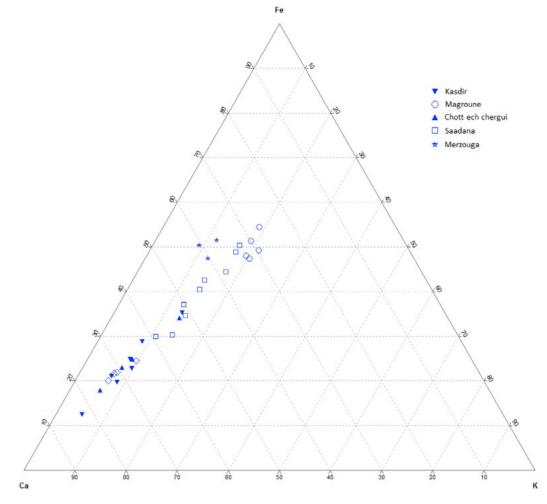

Figure 4. Ternary plot of Fe, Ca and K abundances in moles.

Following this, a hierarchical cluster analysis was applied (**Figure 5**). Based on the Ward method (Ward 1963) and the city block distance, it was conducted to discriminate samples by using trace elements. The dendrogram clearly shows that the sand samples of Merzouga are very similar to those of Saadana and Kasdir. Those of Saadana and Kasdir are closely related to the sands of Chott ech chergui and El Aguer. Sheltered from the winds blowing from the south-west, Magroune appears to be spared the sandy inputs of wind.
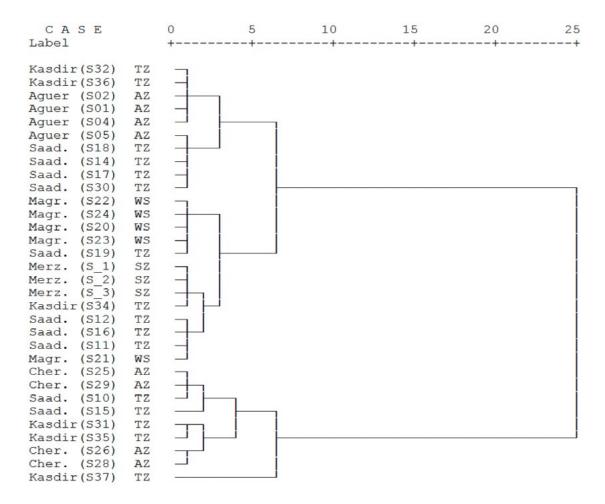

Figure 5. Cluster dendrogram by Ward's method (City-block distance) of samples according to geochemical concentrations.

5. Conclusions

The study of the sand dynamics in the semiarid wilaya of Nâama in south-western Algeria, allowed a Regional Wind Action System (RWAS) to be established, formed by a sand source, and sand transit and accumulation areas.

Recurrent droughts, and highly variable and decreased rainfall, promoted the reactivation of sand stocks. The dominant winds, with a WSW to ENE direction, play a significant role in the transport of sand from south-eastern Morocco and its redistribution towards the north-west, which is consistent with the physico-chemical and geochemical analysis presented in this study.

Understanding the dynamics of the sands, along with other anthropic factors, could lead to another paradigm in the fight against desertification and land degradation.

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