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Portable wind tunnel experiments to study soil erosion by wind and its link to soil properties in the Fars province, Iran

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ABSTRACT

Soil erosion controlled by the wind effect on the surface, has been largely studied by field in-situ measurements as well as laboratory or numerical simulations. Nevertheless, more in-situ measurements and observations are needed to document this phenomenon for various desert areas. In the present study, we focus on the documentation of different properties of a wide range of semi-arid and arid soils of the Fars province, and how they control the soil erosion by wind. By improving our knowledge on soil properties which lead to the limitation of soil erosion by wind, it will be possible to better prevent wind erosion in the Fars province. Extensive wind tunnel experiments were conducted in 20 different arid and semi-arid regions. For each region, three wind tunnel experiments were done to encounter local soil variability. We determined threshold wind speeds for which soil erosion was observed. Other experiments were conducted at the same high wind speed, and duration conditions, allowing discussing soil erosion rates by wind regarding soil properties. As already documented in the literature, our results pointed out a significant negative power relationship between wind erosion rate and different soil physical properties, including soil surface gravel cover, the mean weight diameter (MWD) of soil particles, and soil clay and moisture contents. Moreover, a nonlinear relationship as a power function was found between the increase of soil organic carbon and the decrease of soil losses by wind in the studied semi-arid and arid soils. We determined critical values of these soil properties for which wind erosion in Fars province is limited under high wind speed conditions. Additionally, the effects of the electrical conductivity (EC), sodium adsorption ratio (SAR), and calcium carbonate equivalent (CCE) on wind erodibility were discussed at low and high concentrations and for different soil textures.

1. Introduction

Soil erosion by wind is a serious environmental problem in many arid and semi-arid regions; it is considered as a soil-degrading process (Webb et al., 2017) that affects over 500 million ha of land worldwide (Grini et al., 2005). In fact, wind erosion degrades soil by removing and emitting in the atmosphere fine soil particles that contain most of the soil organic carbon and nutrients (Van Pelt and Zobeck, 2007). The appraisal of this process at the soil-atmosphere interface is central to estimate of soil loss for soil conservation planning (Black and Chanasyk, 1989). The emission of top soil particles from land surfaces into the atmosphere impacts the soil productivity, and should also be considered for air quality and health issues (Webb et al., 2017; Pi and Sharratt, 2017; Pi et al., 2017).

Soil erosion by wind is a function of the soil erodibility and the wind erosivity (Chepil and Woodruff, 1963). It is a threshold phenomenon controlled by surface winds and soil properties.

There is a minimum wind stress that corresponds to a threshold velocity needed to initiate wind erosion on semi-arid and arid surfaces (Chepil, 1951; Gillette et al., 1982). Non-erodible elements such as vegetation and gravels on an erodible surface not only increase the apparent threshold wind velocity but also reduce the mass erosion rate. Even if the erosive action of the wind depends on its speed, several factors like the size and stability of the soil aggregates, clay content, and near-surface soil moisture affect the threshold velocity (Ravi et al., 2006).

The size and stability of soil aggregates are significant factors that affect the soil susceptibility to wind erosion (Colazo and Buschiazzo,

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2010; Négyesi et al., 2016). In general, soil aggregates are formed through the combination of mineral particles with organic and inorganic substances (Bronick and Lal, 2005; Mahmoodabadi and Ahmadbeigi, 2013). The binding of soil particles into stable aggregates is essential for the production of optimum soil tilth (Harris et al., 1966). Inter particle cohesion is a combined effect of the van der Waals force, liquid and chemical force, and electrostatic force. These effects are sensitive to soil properties, such as the particle shape and texture, the soil mineralogy, the packing arrangement, and the presence or absence of bonding agents such as soil moisture and soluble salts (Shao and Lu, 2000).

Soil texture can play a dominant role in the susceptibility of a soil surface to wind erosion (Belnap et al., 2007; He et al., 2008; Pasztor et al., 2016). Sandy soils are inherently more erodible than fine-textured soils, as they have less salt, clay and silt to enhance physical crusting and soil aggregation (Chepil, 1953; Colazo and Buschiazzo, 2010).

Soil moisture contributes to the binding forces keeping particles together (Cornelis et al., 2004) and to the soil aggregate formation (Webb and Strong, 2011) through adhesion and capillary effects (McKenna-Neuman and Nickling, 1989). The moisture of surface sediments is then one of the most significant factors governing the initiation of particle movement by the wind and hence the Aeolian transport rates (Dong et al., 2007).

Additionally, soil organic carbon is an important soil component (Mahmoodabadi and Heydarpour, 2014), which acts as a binding agent and as a nucleus in the formation of aggregates (Bronick and Lal, 2005). Accordingly, increase of soil organic carbon can enhance soil aggregate stability and formation (Mahmoodabadi and Ahmadbeigi, 2013) and, as a consequence, decrease soil erodibility (Bronick and Lal, 2005).

The effects of salinity (Mahmoodabadi et al., 2013) and sodicity (Ghadiri et al., 2004) on soil properties have been pointed out especially in arid and semi-arid regions. For instance, high levels of sodium enlarge soil erosion due to its destructive effect on soil structure (Ghadiri et al., 2004). Salts such as halite, lime and gypsum have different influence on soil erodibility by wind, which is related to factors like density (Ekhtesasi et al., 2003) and soil texture (Chepil, 1954; Tatarko, 2001).

In this study, we focus on wind erosion in Iranian semi-arid and arid areas of the Fars province located in the southwestern part of the country. Even if numerous studies investigated the link between wind erosion and soil properties, little is known about the controlling factors of the soil potential to wind erosion in the Fars province, and such a study could help us in wind erosion prevention and control programs. We propose to document physical and chemical properties of various natural semi-arid and arid soils of this region. Using an in-situ portable wind tunnel, threshold wind velocities for which soil erosion occurs are determined, and relationships between soil properties and wind erosion rates are studied under high wind speed condition.

2. Material and methods

2.1. Study area description of the in-situ measurement sites

Iran is located on the belt of arid and semi-arid regions of the world (Moradi et al., 2011) and suffers from dust events (Taghavi et al., 2017). Two-thirds of the country are within a dry climate (Zamani and Mahmoodabadi, 2013), and more than half of the Iranian provinces are suffering from critical wind erosion (Amiraslani and Dragovich, 2011; Rezaei et al., 2016). Frequent and intense dust sources are identified in Iran as for instance the Sistan Basin (Rashki et al., 2012), Al-Howizeh/Al-Azim marshes (Cao et al., 2015) and Kavir and Lut deserts (Rashki et al., 2015). Ginoux et al. (2012) also identified dust sources along the west coast of Iran.

Fars province is located in the south of the central region of Iran (Fig. 1a), from 27° 2′ to 31° 42′ northern latitude and 50° 42′ to 55° 36′ eastern longitude (Moradi et al., 2011). The area of this province is about 133.299 km^2, covering 8.1% of Iran. Based on De Martonne (1926) aridity index, all regions of Fars province are generally placed in arid and semi-arid classification (Nafarzadegan et al., 2012). Due to low annual precipitation, varying between 100 mm in the southern parts and > 400 mm in the northern parts (Nafarzadegan et al., 2012), and semi-arid and arid climate, draught is a common occurrence in this province (Tehrani et al., 2016), and many lakes of the province have been dried. Moreover, dust storms are of natural hazards in this province (Ghasem et al., 2012). Several intense dust storm events have been reported in this province, as for instance in summer (17 July 1998, 13 August 2001, and 28 August 2013) or spring (24 April 2008 and 28 February 2009), during which high wind speeds between 16 $m\,s^{-1}$ and 20 $m\,s^{-1}$ at the height of 10 m were measured. For example, the dust storm of 28 February 2009, reported in the southeast of the province, led to the decrease of visibility to 800 m (Mazidi et al., 2015).

Soil erosion by wind occurs during high wind speed events. These meteorological events are most of the time rare, leading to sporadic and pulsed dust particle emission in the atmosphere. In order to illustrate the occurrence of high wind events, the maximum wind speeds measured at three meteorological stations in the Fars province, including Shiraz (29° 32′ N and 52° 36′ E), Abadeh (31° 11′ N and 52° 40′ E), and Eghlid (30° 54′ N and 52° 38′ E) between 1990 or 1995 and 2017 are presented for each month in Fig. 2. High wind speeds higher than 7 $m\,s^{-1}$ and up to 30 $m\,s^{-1}$ (measured at 10 m height) are observed at these stations, even higher wind speeds being registered at Eghlid. These maximum wind speeds are generally associated with west to southwest directions at Shiraz, southwest but also west and north directions at Abadeh, and southwest direction at Eghlid (Fig. 2). The geographic locations of the three meteorological stations are shown in Fig. 1a.

In order to study soil erosion by wind using a portable wind tunnel in the Fars province, 20 arid and semi-arid regions were selected in the different geographic areas of the province, providing a variety of soils with different properties. Flat lands with as few vegetation, rock and pebble covers as possible and with no apparent crust were chosen. Fig. 1 presents the geographic locations (a) and general views of the 20 study regions in Fars province (b), which have different soil textures (fine, medium and coarse) and land use types: seasonal or abandoned agricultural fields, plains, rangelands, dried lakes or rivers. The average slope of soil surface is below 1%, and the majority of the studied regions have poor to moderate vegetation covers. The features of the studied regions, which were determined in the field, are listed in Table 1.

2.2. Wind tunnel experiments

Much of what we know about Aeolian processes comes from wind tunnel-based investigations (Gillette, 1978; Van Pelt and Zobeck, 2013). Mobile wind tunnels are essential tools for the field examination and quantification of wind erosion processes on natural non-imitated surfaces under standardized, quasi-natural wind conditions (Maurer et al., 2006). In fact, wind tunnels allow generating wind erosion for controlled conditions such as the area exposed to wind, soil surfaces, and wind speed, direction, and turbulence (Pi and Sharratt, 2017).

In order to determine wind erosion for the selected regions, a portable wind tunnel is used. This device was designed, constructed and calibrated in the Dry and Desert Regions Research Center of Yazd University of Iran. This wind tunnel is based on a previous version with a weaker wind generator (maximum wind speed of 12 $m\,s^{-1}$), which has been successfully used in previous studies (e.g. Azimzadeh et al., 2002; Ekhtesasi et al., 2003; Azimzadeh et al., 2008).

The portable wind tunnel used in this study consists of three main parts, including:

(1) A jet fan blower with 2-hp power, as a wind generator which can generate wind speeds in the range of 0.5–22 $m\,s^{-1}$ at the height of 0.25 m.

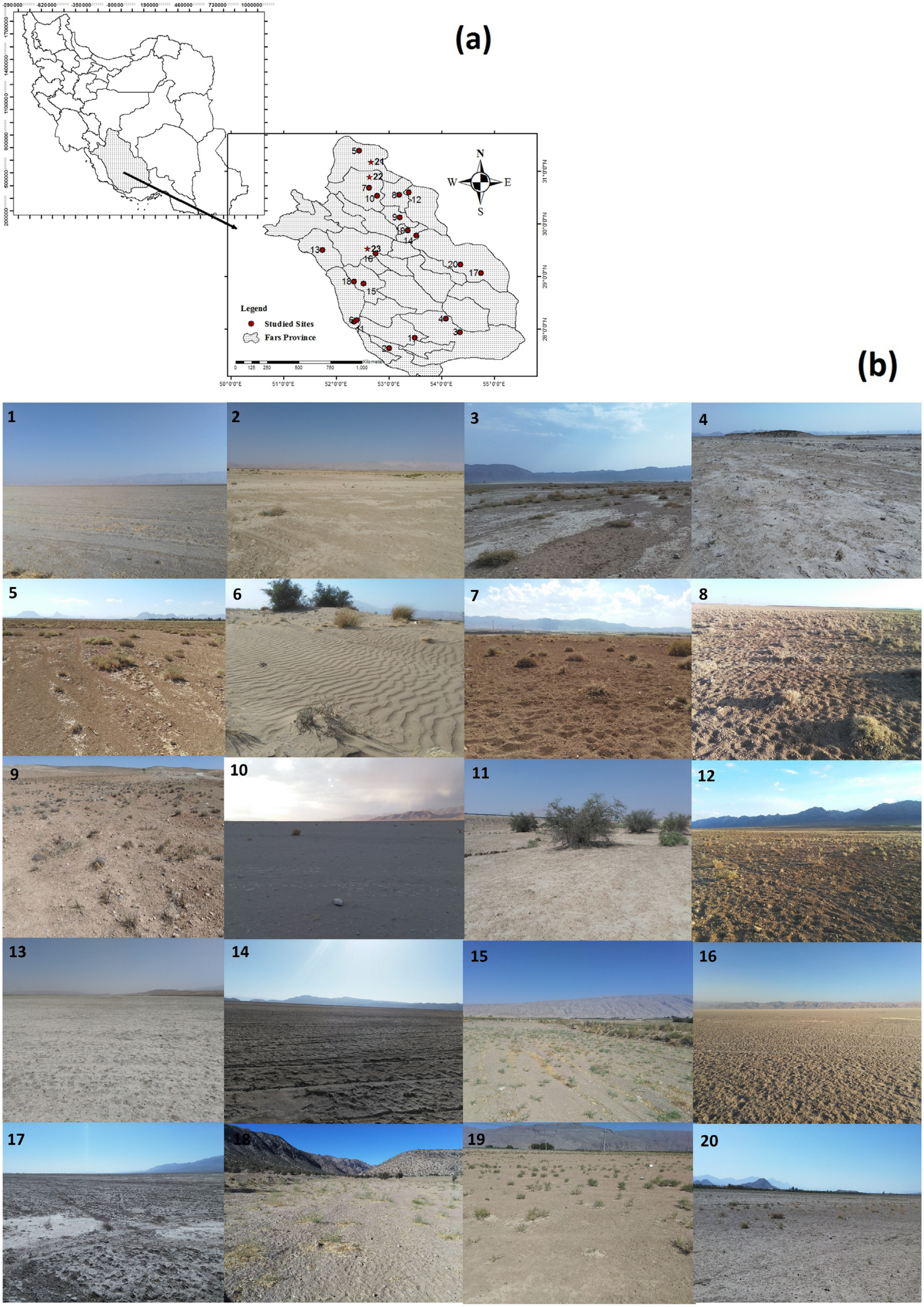

Fig. 1. Map of the Fars province in Iran: the geographical locations of the 20 studied areas (dots) and the 3 meteorological stations (stars) of Abadeh (21), Eghlid (22) and Shiraz (23) (a), and general views of the 20 studied regions in the Fars province (b).

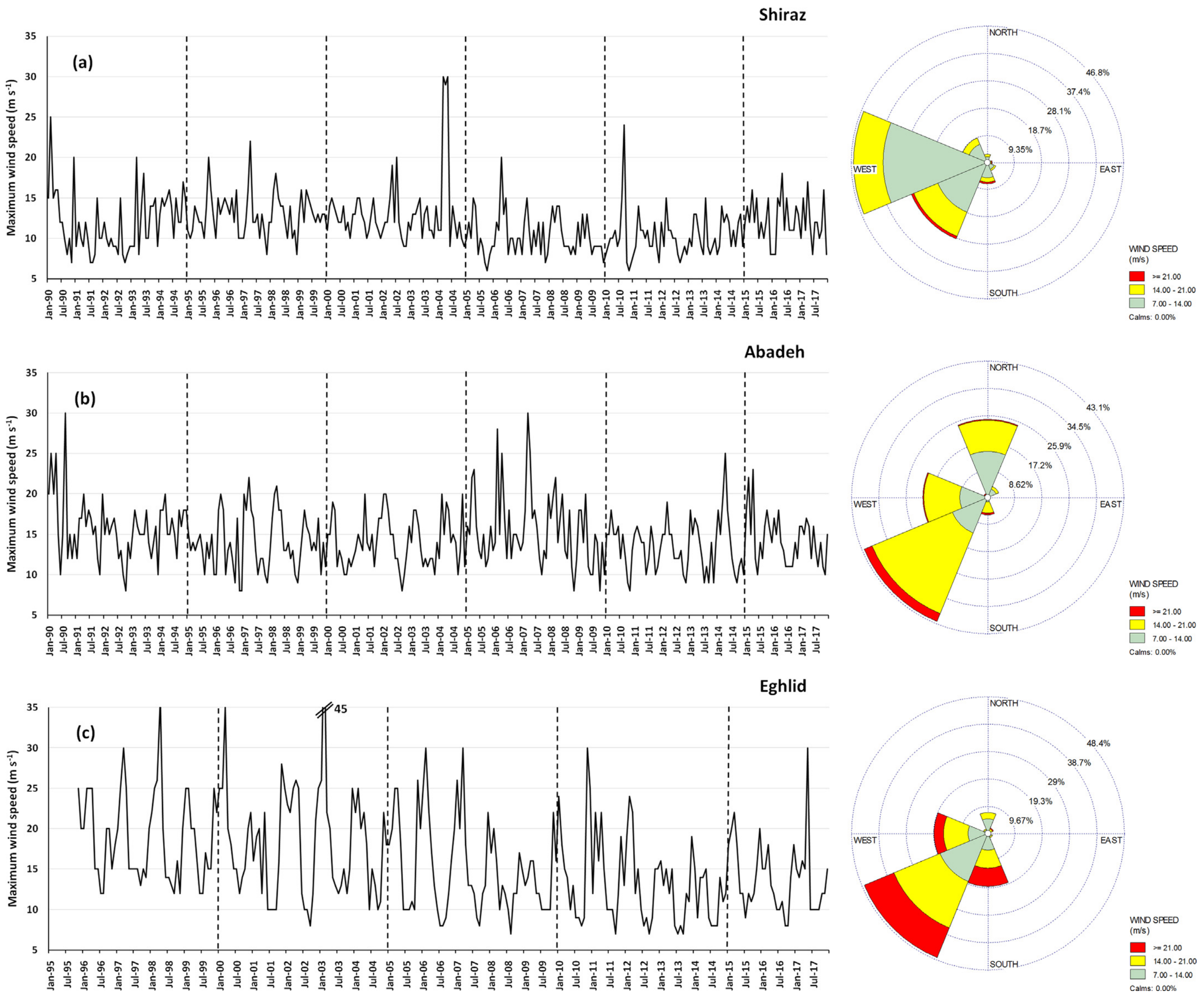

Fig. 2. Monthly maximum wind speeds (m s^{-1}) measured at 10 m height, between 1990 and 2017 at (a) Shiraz (29° 32′ N and 52° 36′ E), and (b) Abadeh (31° 11′ N and 52° 40′ E), and between the end of 1995 and 2017 at (c) Eghlid (30° 54′ N and 52° 38′ E) meteorological stations. Wind directions are presented for theses maximum wind speeds with wind rose plots for wind speed occurrences (in %) between 7 m s^{-1} and 14 m s^{-1} in light green, between 14 m s^{-1} and 21 m s^{-1} in yellow, and equal and higher than 21 m s^{-1} in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(2) A 2.5-m working section with a cross-sectional area of 0.3 m × 0.3 m, an air uniform-distributor at the beginning, and a test area by 1 m length and 0.3 m width at the bottom, directly placed on the undisturbed soil.

(3) An 8-m sediment collector which is made of plastic. The sediment collector has a special design which has made it affordable and easy to use. In fact, the sediment collector consists of two plastic tubes. An internal tube (with a length of 6 m and a diameter of 0.6 m) is placed in an external tube (with a length of 8 m and diameter of 1 m), and is open at the end. This two-layer cyclone sediment collector is connected to the end of the working section, and the wind generated inside the working section finally enters the internal tube. The end of the external tube is closed, and holes (with 0.1 m diameter) have been created on its top part to egress the wind flow. After the deposition of windblown sediment particles at the bottom of the sediment catcher, the “clean” wind exits through the holes on the outer tube. A schematic of the wind tunnel and views of the wind-tunnel setup deployed in the field are presented in Fig. 3.

In a first time, the portable wind tunnel is used to determine the threshold wind velocity for which soil erosion by wind is initiated at each measurement site. Following Belnap et al. (2007), the wind speed inside the wind tunnel can be gradually increased until a forward movement of the soil particles is observable across the surface.

In a second time, the portable wind tunnel is used to investigate the links between erosion rate and the soil properties. For this purpose, the same controlled wind speed and duration conditions are chosen for all the different undisturbed semi-arid and arid soils studied.

For each of the 20 studied regions, wind tunnel experiments are performed at three distinctive sites in order to consider local soil variability. Moreover, wind tunnel experiments and the subsequent soil samplings are done during summer when precipitation deficiency and high temperature are observed. For each run on the selected locations according to the given criteria, the portative wind tunnel is placed along the direction of the dominant wind of the region on the undisturbed soil surface. Then, the wind speed in the wind tunnel is successively increased to reach the threshold wind speed, and high

Table 1
Features of the 20 studied regions: soil texture; land use; average slope of the surface (%); vegetation cover status; the mean of measured soil erosion rates ($g\,m^{-2}\,s^{-1}$) for constant high wind speed of $15\,m\,s^{-1}$ at 0.25 m height, standard deviation (SD) and coefficient of variation (CV).

Region number	Soil texture	Land use	Average slope of the surface (%)	Vegetation cover status	Soil erosion rate by wind ($g\,m^{-2}\,s^{-1}$)		
					Mean	SD	CV (%)
1	Silty clay loam	Seasonal agricultural lands	< 1	Poor	0.30	0.04	11.98
2	Loamy sand	Abandoned agricultural lands	< 1	Poor	1.10	0.10	9.03
3	Clay loam	Abandoned agricultural lands	< 1	Poor	1.95	0.34	17.29
4	Silt loam	Plain	< 1	Poor	7.45	0.44	5.93
5	Loam	Rangeland	< 1	Moderate	3.04	0.26	8.60
6	Sand	Rangeland	< 1	Poor	10.31	0.55	5.31
7	Clay loam	Rangeland	< 1	Moderate	1.45	0.15	10.05
8	Loam	Rangeland	< 1	Moderate	0.86	0.32	37.24
9	Clay loam	Plain	< 1	Poor	0.19	0.03	14.29
10	Clay	Dried lake	< 1	Poor	1.64	0.04	2.66
11	Loamy sand	Dried river	< 1	Poor	4.72	0.39	8.21
12	Loam	Rangeland	< 1	Moderate	0.52	0.03	5.62
13	Silt loam	Dried lake	< 1	Poor	0.86	0.11	12.81
14	Sandy clay loam	Dried lake	< 1	Poor	1.56	0.05	3.07
15	Clay loam	Abandoned agricultural lands	< 1	Moderate	1.00	0.05	4.88
16	Sandy clay loam	Dried lake	< 1	Poor	1.46	0.05	3.37
17	Silty clay loam	Dried lake	< 1	Poor	0.36	0.03	8.28
18	Silt loam	Seasonal agricultural lands	< 1	Poor	0.96	0.15	15.62
19	Silt loam	Plain	< 1	Poor	0.32	0.06	17.89
20	Loam	Plain	< 1	Poor	0.27	0.02	5.94

wind speeds. Each wind tunnel experiment is carried out for 10 min, and the device is stopped. The deposited sediments in the catcher are collected, and then weighted in the laboratory. At each site, the erosion rate (E) ($g\,m^{-2}\,s^{-1}$) is determined by dividing the mass of sediment (g) by the test area (m^2) and event duration (s) to signify soil erodibility by wind (Liu et al., 2007). The mean value of the erosion rate of three sites within each region is calculated and considered as an indicator of soil erosion by wind (Table 1).

2.3. Soil sampling and analysis

Besides the wind tunnel experiments, a 5-kg soil sample was collected at each site from the first 3 cm of topsoil from the nearest place to the point of the wind tunnel run. The collected soil samples were sent to the laboratory of Soil Physics and Chemistry of Soil Science Department of Shiraz University in Iran for analyzing different soil properties. In order to perform soil physical and chemical analysis, the soil samples were air-dried, and hand-sieved using a 2-mm sieve.

The measured physical properties include: the soil texture; content of sand (0.05–2 mm), silt (0.002–0.05 mm) and clay (< 0.002 mm) using hydrometer method (Gee and Or, 2002), and the particle size distribution by the dry-sieving method (Kemper and Rosenau, 1986). Both dispersed and non-dispersed size analyses are performed on the soil samples. The primary particle composition of the soil is obtained by a dispersed size analysis whereas non-dispersed size analysis is used to assess the state of aggregation of soil particles in the field (Feng et al., 2011). Using dry sieving data, the mean weight diameter (MWD) of soil particles is determined by using Eq. (1):

$$\mathrm{MWD} = \sum x_i w_i \qquad (1)$$

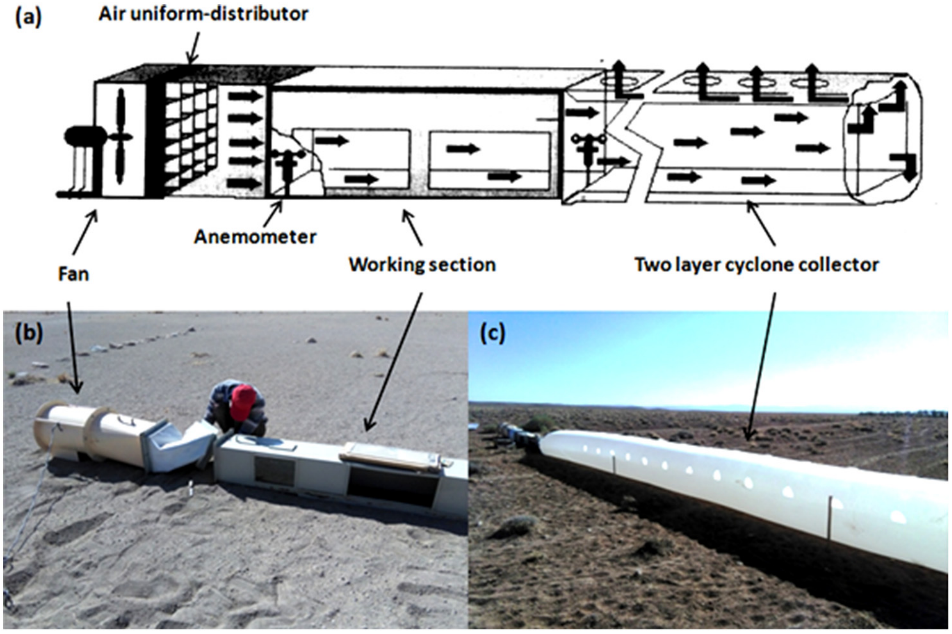

Fig. 3. Schematic of the portable wind tunnel used in the study (a, figure taken from Ekhtesasi et al., 2003), and views of the portable wind tunnel setup for in-situ experiments of the study in regions 10 (b) and 8 (c).

where x_i is the mean diameter of any particular size range of particles and w_i is the weight of particles in that size range as a percentage of the total sample.

In order to measure the soil initial moisture, another specific soil sample was collected at each site and wrapped in a plastic bag to avoid exposing to the air. The soil gravimetric moisture content is measured using the oven method (Page et al., 1992a). Furthermore, soil surface gravel (> 2 mm) cover of each point also is determined by photography method (Mahmoodabadi and Cerdà, 2013).

Regarding the soil chemical properties, soil organic carbon (OC) is measured as described by Walkley and Black (1934). The percentage of $CaCO_3$ equivalent (CCE) is determined using the titration method (Pansu and Gautheyrou, 2006). Also, pH-meter and EC-meter are used to measure the soil pH in saturated paste and electrical conductivity (EC) in saturated paste extract (Page et al., 1992b). Additionally, the amount of soluble cations is determined in the saturated paste extract, such as Na^{+} using a flame photometer, and Ca^{+2} and Mg^{+2} by titration method (Page et al., 1992b). With the obtained concentrations of these soluble cations, the sodium adsorption ratio (SAR in $(\text{meq L}^{-1})^{0.5}$) is calculated using Eq. (2) where the concentrations of soluble cations are expressed in meq L^{-1}:

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\frac{\mathrm{Mg}^{2+} + \mathrm{Ca}^{2+}}{2}}} \tag{2}$$

2.4. Data analysis

The statistical analysis of the data was done by using SPSS 16 software. Moreover, in order to find out the best relationship between soil erosion rate and the soil properties, the scatter plots were prepared using Excel, and the significance of the obtained relationships was analyzed by regression method and F test using SPSS 16.

3. Results and discussion

The soil erodibility is controlled by several concomitant factors; one of them could be inhibiting. In this section, the susceptibility of soil to wind erosion is assessed and discussed for 20 regions of the Fars province.

3.1. Soil properties of the studied areas

Characteristics and descriptive statistics of the studied soil properties are presented in Table 2, as the minimum, maximum and mean values, the standard deviation (SD) and the coefficient of variation (CV). With sand, silt and clay contents varying between few percents to several tens, we studied a large panel of different soil types that can be encountered in Iranian semi-arid and arid areas. Among these primary soil particles, the sand content shows the highest variation (CV: 62.61%), the variation of silt and clay contents being lower and nearly close to each other (CV: 49.49% and 43.50%, respectively). On the other hand, the MWD values point out the presence of quite large soil particle aggregates with the lowest variation for the different regions (CV: 25.23%). For this study, we limited the presence of rocks and large stones on the studied surfaces, and we considered surface gravel covers varying from 1.67% to 21.67%, for sandy to stony areas. Furthermore, moisture contents of soil samples are low, ranging from 1.07% to 3.96% for these semi-arid and arid regions in summer. In comparison with other attributes, the variations of SAR and EC data are very large, with the highest CV, 211.56% and 192.68%, respectively. Moreover, regarding that the studied regions consisted of saline and non-saline soils, the SAR and EC values exhibited the highest difference between maximum and minimum values (662 $(\text{meq L}^{-1})^{0.5}$ and 147.51 dS m^{-1}, respectively). The amount of OC ranged from 0.1% to 2.17% in the studied areas, which is in agreement with the average value of about 0.8% mentioned by Moshiri et al. (2017) for agricultural soils of Fars province.

Table 2
Statistical analysis of the measured soil properties, minimum, maximum, mean values, standard deviation (SD) and coefficient of variation (CV).

Soil property	Unit	Min.	Max.	Mean	SD	CV (%)
Sand	%	9.56	89.56	39.05	24.45	62.61
Silt	%	4.72	60.72	36.81	18.21	49.46
Clay	%	3.72	45.72	24.14	10.50	43.50
Mean weight diameter (MWD)	mm	0.20	0.60	0.40	0.10	25.23
Soil surface gravel cover	%	1.67	21.67	8.21	4.62	56.30
Gravimetric soil moisture content	%	1.07	3.96	2.70	0.75	27.88
Organic carbon (OC)	%	0.10	2.17	0.77	0.56	72.91
Electrical conductivity (EC)	dS m^{-1}	0.59	148.10	27.96	53.88	192.68
Sodium adsorption ratio (SAR)	$(\text{meq L}^{-1})^{0.5}$	0.39	662.38	104.93	221.97	211.56
Calcium carbonate equivalent (CCE)	%	23.75	85.00	52.05	16.63	31.96

Before discussing the effect of the soil properties on the wind erosion rate, we first investigated if linear relationships could be found between some of the measured soil properties (Fig. 4). This may point out hidden effects of different parameters on soil erodibility, keeping in mind that soil erodibility is controlled by several concomitant factors. Sand content decreased when soil clay content increased (Fig. 4a) ($R^2 = 0.54$, $P < 0.001$). Moreover, the soil analyses pointed out that soil moisture (Fig. 4b) and OC contents (Fig. 4c) increased for high clay contents ($R^2 = 0.62$, $P < 0.001$, and $R^2 = 0.43$, $P < 0.001$, respectively). Furthermore, EC was strongly correlated to SAR values for the studied soils ($R^2 = 0.95$, $P < 0.001$). EC and SAR parameters followed the same trend in the soils analyzed (Fig. 4d). Even if it is not simple to directly connect the content of primary particles to the MWD, as illustrated for the clay content in Fig. 4e ($R^2 = 0.3$, $P < 0.001$), large MWD values were observed for low sand contents (Fig. 4f, $R^2 = 0.45$, $P < 0.001$) and high values of clay and silt contents. Additionally, CCE increased for high values of sand particles in the soil samples ($R^2 = 0.40$, $P < 0.001$) (Fig. 4g). On the other hand and as expected, no relationship was found between the surface gravel coverage and the soil clay content (Fig.4h). This illustrates that there is no hidden effect between these two parameters when their relationships with soil erosion rate are discussed.

3.2. Estimation of threshold wind speeds

Using the portable wind tunnel, soil erosion by wind was observed for wind speeds between 5 m s^{-1} and 12 m s^{-1} (at 0.25 m), depending on the soils of the 20 studied areas. If we consider a logarithmic wind profile and a wide range of roughness length generally observed for desert areas, from 10^{-5} m to 5 10^{-3} m (i.e. Gillette et al., 1982; Greeley et al., 1997; Marticorena et al., 1997; Laurent et al., 2005), a wind speed of 5 m s^{-1} at 0.25 m corresponds to wind speeds between 6.8 m s^{-1} and 9.7 m s^{-1} at the height of 10 m. Likewise, a wind speed of 12 m s^{-1} at 0.25 m corresponds to higher wind speeds at 10 m, between 16.4 m s^{-1} and 23.3 m s^{-1} for common roughness values mentioned previously. For the semi-arid and arid regions of the Fars province, soil erosion is associated with high wind speed events. Even if these winds are rare, they can be observed at different meteorological stations of this province as illustrated in Fig. 2.

3.3. Erosion rates and influence of soil properties

The highest threshold wind speed measured for wind tunnel

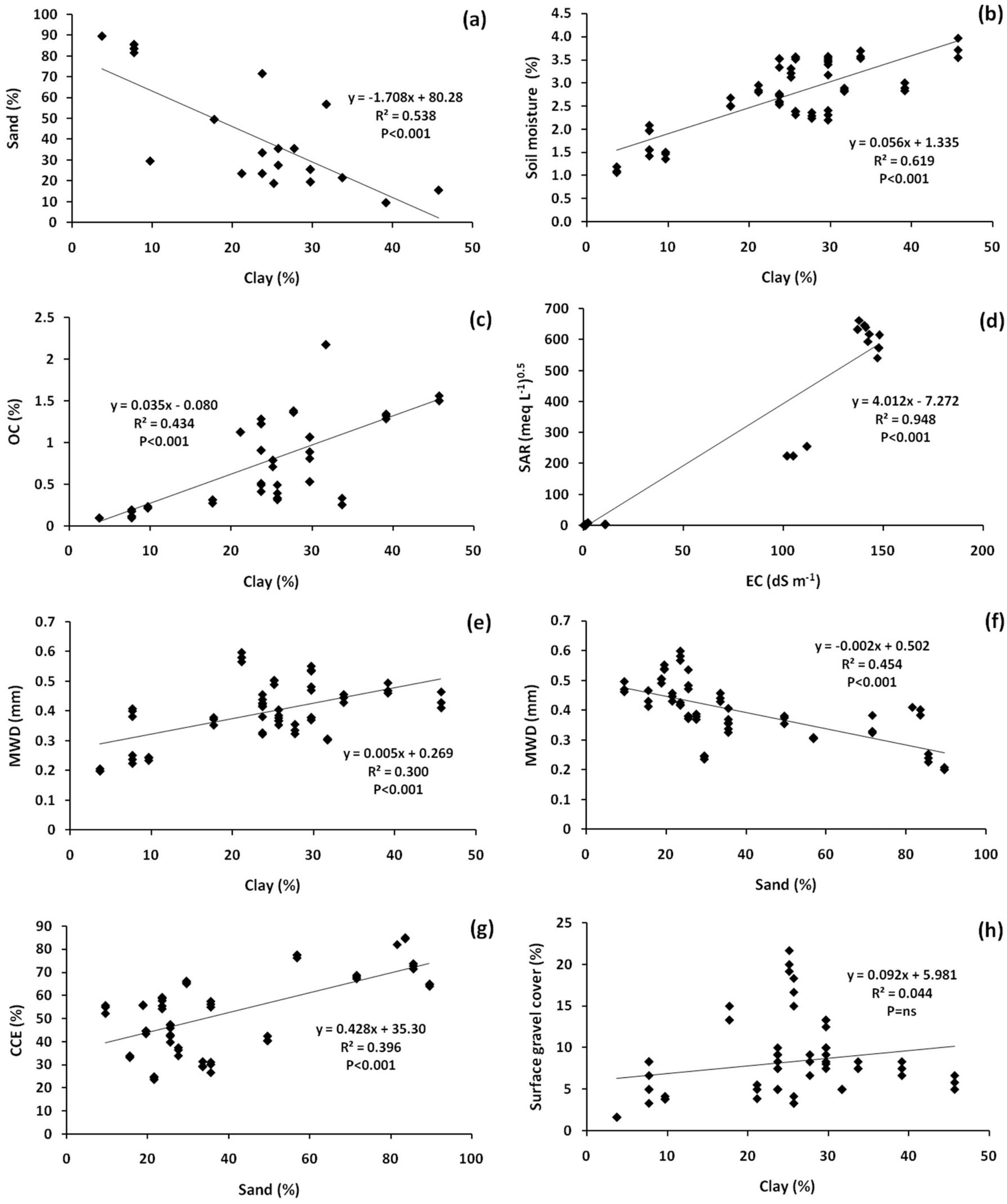

Fig. 4. Relationships between (a) sand and clay contents, (b) clay and soil moisture contents, (c) clay and OC contents, (d) SAR and CE, (e) MWD and clay content, (f) MWD and sand content, (g) CCE and sand content, and (h) surface gravel cover and clay content for the soil analyzed in all the studied regions (ns: not significant).

experiments on the natural and undisturbed soil surfaces of the studied sites was 12 $\mathrm{m\,s^{-1}}$ at the height of 0.25 m. Given that winds are considered erosive when they reach a speed further than a threshold velocity (Zobeck and Van Pelt, 2014), after some pre-tests, we chose a high wind speed of 15 $\mathrm{m\,s^{-1}}$ at the height of 0.25 m to conduct all in-situ wind tunnel experiments in order to study the wind erosion rate as a function of the natural soil properties of the 20 regions of the Fars province.

3.3.1. *Erosion rates*

The erosion rates (E) obtained for the same constant high wind speed and duration (15 $\mathrm{m\,s^{-1}}$ at 0.25 m during 10 min) varied over almost 2 orders of magnitude, the mean values varying from 0.19 to 10.31 $\mathrm{g\,m^{-2}\,s^{-1}}$ (Table 1). The coefficient of variation (CV) associated to the mean erosion rate from three measurements in each region is often below 15%. The highest CV, of about 37%, was obtained for the rangelands of region 8 (E = 0.86 $\mathrm{g\,m^{-2}\,s^{-1}}$) (Table 1). The low dispersion of the three measurements generally observed for each region pointed out the similar conditions encountered, including both soil properties and in-situ measurement procedure.

Among these regions, rangelands of the region 6 with the shifting sands (Fig. 1b) showed the highest wind erosion rate (10.31 $\mathrm{g\,m^{-2}\,s^{-1}}$). Soils of this region are considered as coarse-textured soils (sand) with a poor vegetation cover (Table 1). This region presents the lowest gravel cover (1.7%), the lowest clay content (3.7%) and soil moisture (1.1%). Actually, this area is called as the most critical wind erosion region of

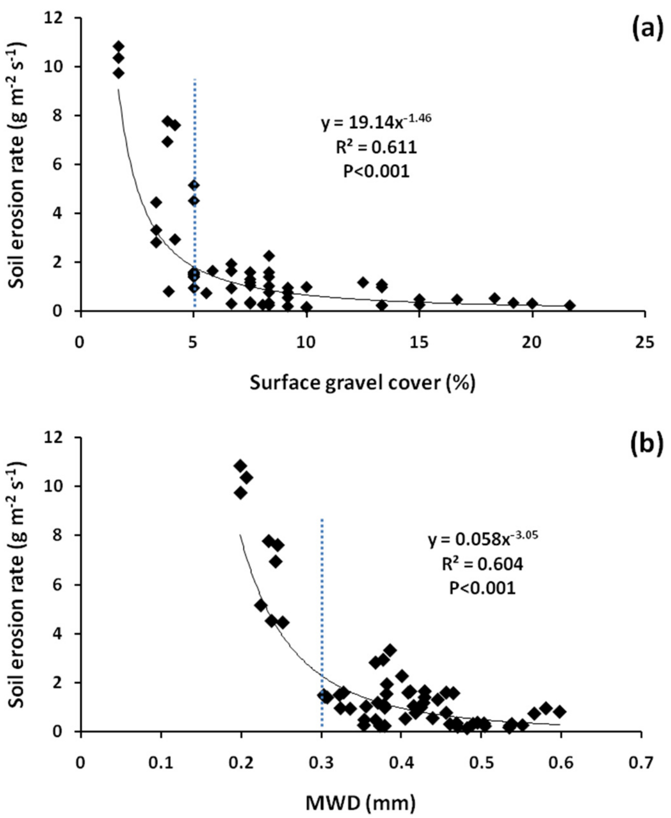

Fig. 5. Influence of (a) the percentage of soil surface gravel cover, and (b) the mean weight diameter (MWD) of soil particles on the soil erosion by wind for the 60 wind tunnel measurements performed in the 20 studied regions (dotted lines indicate estimated critical values).

the Fars province (Rezaei et al., 2016), which is verified by our in-situ wind tunnel measurements. On the opposite, the clay loam soils in the plains of region 9 with a poor vegetation cover produced the lowest erosion rate (0.19 $g\,m^{-2}\,s^{-1}$), which are > 50 times less erodible than the region 6 soils for the same air flow conditions. The surface gravel coverage is 9.7% for this region, and the soils are rich in clay (29.7%) with a soil moisture 3 times higher than in region 6 (3.4%).

3.3.2. *Influence of soil physical properties on soil erodibility by wind*

3.3.2.1. Soil surface gravel cover. The effect of soil surface gravel cover percentage on the wind erosion rate for the semi-arid and arid soils of the Fars province is illustrated in Fig. 5a. A negative power relationship was found between soil surface gravel cover and wind erosion ($R^2 = 0.61$, $P < 0.001$). The coverage of the surface with gravels, even partially, inhibited strongly the soil susceptibility to wind erosion. The presence of gravels provides a strong protection of the soil against wind erosion (Marticorena et al., 1997). The non-erodible elements on the surface cover a part of the erodible surface and reduce the wind shear stress by absorbing wind momentum near the surface (Marshall, 1971; Mu, 2010; Feng et al., 2011). This partition of the shear stress between rough elements and the erodible surface reduces the soil erodibility by wind.

Goossens (1994) stated that a critical cover density exists for soil surface covered with pebbles or gravels, for which the erosion threshold is increased and the underlying surface protected. In the present study, a soil surface gravel cover higher than 5% (Fig. 5a) can powerfully prevent the soil erosion by wind.

3.3.2.2. Aggregate size distribution. The effect of MWD, as an index of particle size distribution, on soil erodibility by wind was investigated (Fig. 5b). The soil erosion rate decreases significantly for high MWD values, following a power function ($R^2 = 0.60$, $P < 0.001$) (Fig. 5b). Previous studies pointed out a lower erodibility of soil with increasing MWD of soil particles (Ćirić et al., 2012; Zamani and Mahmoodabadi, 2013; Sirjani and Mahmoodabadi, 2014; Kheirabadi et al., 2018). Moreover, Farid Giglo et al. (2014) stated that soils with robust aggregates and with a high proportion of large aggregates are stable soils. Additionally, erodible soils may be protected by soil aggregates (Fryrear et al., 1994). Mackinnon et al. (2004) implied that the presence of soil aggregates on the soil surface, shelter the surface against wind erosion by creating a large increase in threshold friction velocity as the surface roughness increases.

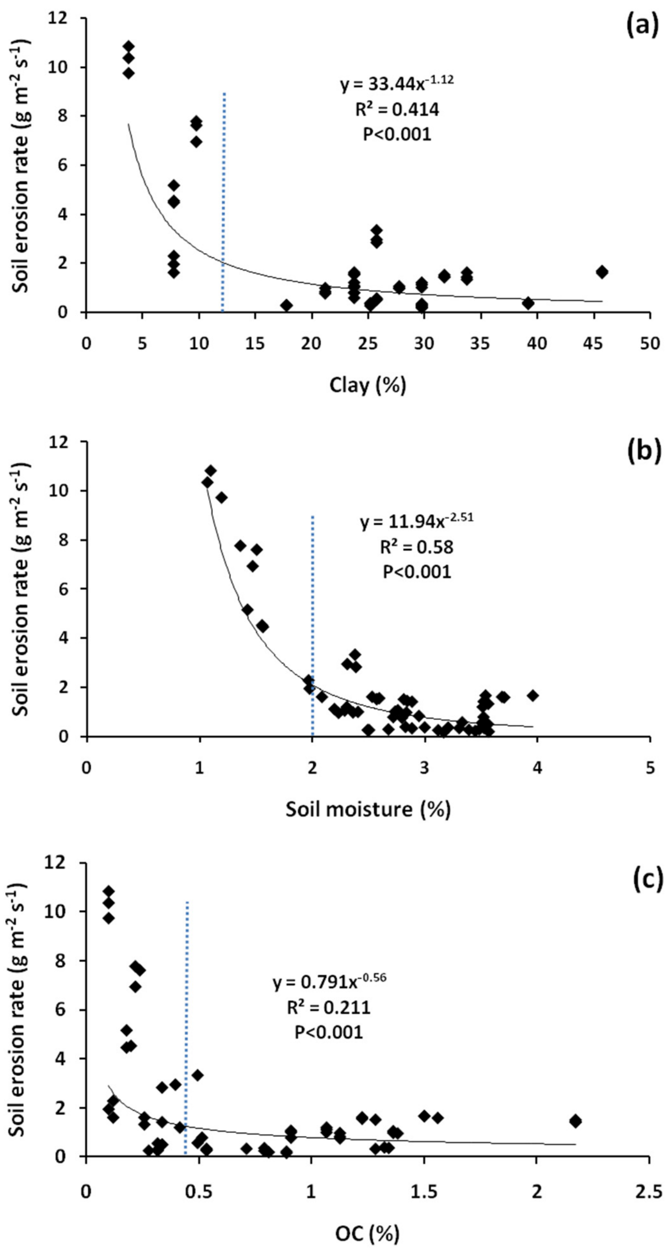

Fig. 6. Influence of (a) soil clay content, (b) initial soil moisture content and (c) soil organic carbon (OC) on wind erosion rate (dotted lines indicate estimated critical values).

Following our results, soil particles with MWD larger than 0.3 mm can significantly inhibit wind erosion rate in the studied regions within the Fars province (Fig. 5b).

3.3.2.3. Soil texture. Due to the important role of clay particles on different soil properties such as soil moisture (Fig. 4b), and since the sand and clay contents are complementary to describe the soil primary particles (Fig. 4a), we present here the effect of clay particles on soil erodibility by wind (Fig. 6a). Our results indicate that the soil loss rate by wind is strongly related to the soil clay content ($R^2 = 0.41$, $P < 0.001$) (Fig. 6a). Unlike sand particles, clays and silts can increase aggregation in the soil (Ćirić et al., 2012). Clay is a key factor in increasing cloddiness (Perfect et al., 1993) as well as in reducing erodibility (Chepil, 1953) and the soil loss by wind (Leys et al., 1996). Aba Idah et al. (2008) stated that soils with high clay content have a low erodibility factor due to the higher binding and inter-binding forces that help in resisting detachability of soil by wind and water. Diouf et al. (1990) showed in laboratory conditions that adding a small amount of bentonite clay to a sandy soil could decrease soil erodibility by wind. Likewise, silt particles can also limit the erodibility of soil. In fact, they are responsible not only in clod formation, but also in surface crust forming (Chepil, 1953). From our results, we can estimate that clay contents between 10 and 15% in semi-arid and arid Iranian soils can strongly reduce soil erodibility by wind. This range is in agreement with the works of Chepil (1953) in which soil clay contents higher than 15% significantly decreased wind erosion. On the other hand, Chepil (1953) implied that clay contents higher than 40% can result in increasing soil erodible fractions. Regarding the maximum clay contents being about 46% (Table 2) only for one region in our study, we cannot discuss the effect of very high clay quantities on soil erodibility.

Our results also pointed out that soils with the same textures, for instance, the silt loam soils don't have similar soil erodibility (ranging from 0.32 to 7.45 $g\,m^{-2}\,s^{-1}$) (Table 1). The soil erodibility is controlled by different surface and soil properties at the same time (such as the percentage of gravel particles on the soil surface, the size of the soil aggregates, and the soil texture). The discussion of the effect of each soil parameter on the soil erodibility should be done keeping in mind the influence of the other parameters.

3.3.2.4. Soil moisture content. The effect of the initial gravimetric soil moisture content on the rate of wind erosion is presented in Fig. 6b. The higher soil moisture contents considerably limit the wind erosion rates, and a power function describes this relationship ($R^2 = 0.58$, $P < 0.001$). The negative effect of soil moisture on erodibility by wind was pointed out in many studies (e.g. Chepil, 1956; Bisal and Hsieh, 1966; McKenna-Neuman and Nickling, 1989; Chen et al., 1996; Fecan et al., 1999; Han et al., 2009). This is related to the cohesive forces of the adsorbed water film surrounding the soil particles through adhesion and capillary effects. This increases the resistances of particles to wind erosion (Wiggs et al., 2004). According to the Fig. 6b, at first the erodibility of the soil samples reduces rapidly with increasing soil moisture percentage up to 2%, and then the decreasing of the erosion rate gets slower and finally becomes almost constant. Soil moisture contents above 2% can significantly resist wind erosion in the region studied here. From wind tunnel experiments, Chen et al. (1996) indicated that soil gravimetric moisture contents > 4–6% can obstruct wind erosion of sandy loam soils. Furthermore, Han et al. (2009) showed that wind erosion of sand can be greatly decreased at gravimetric soil moistures above 0.8%. The results of Wang et al. (2014) on a thawed soil indicated that soil gravimetric moisture content around 2.61% is critical to prevent wind erosion. As illustrated by Fecan et al. (1999) and Wang et al. (2014), the soil type and the primary particle contents of clay, silt and sand have an important role on these soil critical moisture values.

3.3.3. Influence of soil chemical properties on soil erodibility by wind

3.3.3.1. Organic carbon. With respect to the importance of OC on the soil aggregate stability (Mahmoodabadi and Ahmadbeigi, 2013), the effect of OC on wind erodibility of the soils was assessed (Fig. 6c). There is a significant negative relationship between OC and wind erosion rate, and it follows a power function ($R^2 = 0.21$, $P < 0.001$) (Fig. 6c). This means that the presence of OC in the soils can reduce the soil susceptibility to wind erosive agent. Soil organic matter is often associated with high levels of aggregation as well as structural stability (Tatarko, 2001). The results of Farid Giglo et al. (2014) indicated that OC was the most important factor in increasing the stability of aggregates. Fryrear et al. (1994) found that with increasing OC, soil erodible fractions decreased. Furthermore, Colazo and Buschiazzo (2010) indicated that the dry aggregate stability and soil erodible fraction in the semi-arid Argentinean Pampas soils were related to OC. In fact, due to binding individual particles, OC can intensify soil aggregation (Skidmore and Layton, 1992; Fryrear et al., 1994) and the soil dry aggregate stability (Colazo and Buschiazzo, 2010; Mahmoodabadi and Ahmadbeigi, 2013), leading to wind erosion reduction (Chepil, 1950). Considering Fig. 6c, the critical value of OC, which can resist wind erosion for the semi-arid and arid regions of the Fars province, is about 0.4%.

3.3.3.2. Soil salinity and sodicity. The electrical conductivity (EC) and the sodium adsorption ratio (SAR) showed the same tendency, and their values for the studied soils were significantly correlated ($R^2 = 0.95$, Fig. 4d). We only present the relationship between EC and the erosion rate in Fig. 7a.

Considering the very large range and variation of EC values (Table 2), it was plotted using a logarithmic scale in Fig. 7a. Moreover, since the studied regions showed very different EC values, they were classified in three groups, including: 14 regions with very low salinity values ($\leq 1\ dS\,m^{-1}$); 2 regions with soil salinity between 2 $dS\,m^{-1}$ and 12 $dS\,m^{-1}$; and 4 regions with very saline soils, EC values being higher than 100 $dS\,m^{-1}$. The effect of EC on the wind erosion rate was therefore analyzed separately for these three groups. For the soils with a salinity up to 1 $dS\,m^{-1}$, an increase of EC led to intensify exponentially the soil losses by wind ($R^2 = 0.72$, $P < 0.001$). The erosion rates measured for the two groups, $2 < EC < 12\ dS\,m^{-1}$, and EC >

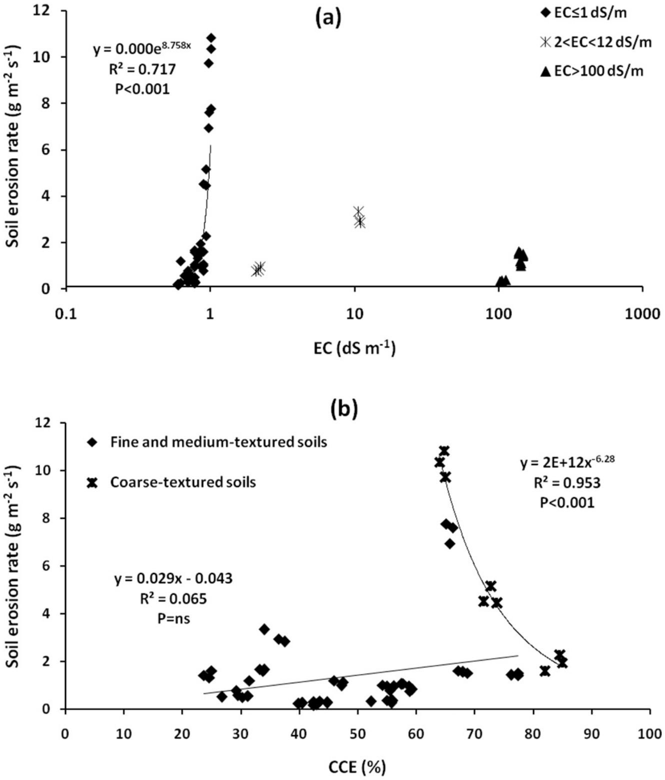

Fig. 7. Dependence of wind erosion rate to (a) soil electrical conductivity (EC), and (b) soil calcium carbonate equivalent (CCE).

100 dS m^{-1}, are lower than the maximum values measured for the first group, but due to the limited number of data, it is difficult to discuss the effect of salinity on the erosion rate for EC values higher than 2 dS m^{-1} (Fig. 7a). Moreover, this first study will need more investigations depending on the type of salts.

Moosavi and Sepaskhah (2012) mentioned that salinity has adverse effects on soil physical properties, and Tejada and Gonzalez (2005) pointed out it affects the soil structural stability. So, an increase of salt concentration in soil can make it more susceptible to erosion (Ghadiri et al., 2004).

On the other hand, Abrol et al. (1988) stated that excess salts keep the clay in saline soils in a flocculated state. Moreover, according to Warrence et al. (2002), salinity can have a flocculating effect on soils, causing fine particles to bind together into aggregates. They also declared that this flocculation is generally enhanced when the soil solution salinity exceeds a value of about 1.5 dS m^{-1}.

The same trends are observed for the sodicity. Our measurements indicated that the erosion rate increased exponentially with sodicity values from 0.4 to 1.6 (meq L^{-1})$^{0.5}$. For sodicity values between 3 and several hundreds of (meq L^{-1})$^{0.5}$, lower erosion rates were observed. The sodicity or an accumulation of dispersive cations such as Na$^+$ in soil solution and exchange phase can also influence soil properties such as structural stability (Mahmoodabadi et al., 2013; Yan et al., 2015). In fact, an increase of SAR can increase clay dispersion (Moosavi and Sepaskhah, 2012), leading to the reduction of soil aggregate stability (Farid Giglo et al., 2014).

Our results pointed out contradictory effect of both salinity and sodicity on soil erodibility by wind. They can induce an increase of the erosion rate for low values ($\leq$1 dS m^{-1} for the salinity and $\leq$1.6 (meq L^{-1})$^{0.5}$ for the sodicity), and a decrease for higher values, but this last issue should be investigated more in details.

3.3.3.3. Calcium carbonate equivalent. The effect of soil calcium carbonate equivalent (CCE) on wind erosion rate is presented in Fig. 7b. Previous studies mentioned that the effect of CCE on soil erosion rate varies according to the soil texture; fine and medium-textured soils are represented differently from the coarse-textured soils. While an increase of CCE contents showed no significant effect on the soil erosion rate of fine and medium textures ($R^2 = 0.07$, P = ns), large amounts of CCE (> 60%) showed a significant negative influence on soil erosion by wind ($R^2 = 0.95$, $P < 0.001$) for three regions with soil containing high levels of sand particles (> 80%), including sand and loamy sand soils (Fig. 7b). Chepil (1954) concluded that calcium carbonate could improve aggregation only in sandy and loamy sand soils, and consequently, it could reduce wind erodibility of these soils. Tatarko (2001) also stated that on sand and loamy sand soils, increases in calcium carbonate resulted in increased aggregation and stability. In fact, calcium carbonate acts as a mild cementing agent similar to silt-sized quartz in these soils (Tatarko, 2001). But in the case of other soils in arid areas, Chepil (1954) showed that increase in calcium carbonate caused a substantial disintegration of soil cloddiness and a decrease in the stability of clods on soils other than sands and loamy sands. In contrast with these results, Colazo and Buschiazzo (2010) didn't observe any significant relationship between calcium carbonate and both soil dry aggregate stability and soil erodible fractions even in sandy and loamy sand soils. They declared that it was may be due to the low amount of calcium carbonate in most of their studied soils, which was < 10 g kg^{-1}. These different results point out the difficulty to study the effect of CCE on soil erodibility, which can be dependent on its concentration in soil and the soil texture.

4. Conclusions

Extensive in-situ measurements were done using a portable wind tunnel for 60 experimental locations of 20 different arid and semi-arid regions of the Fars province, Iran. Using this device, the threshold wind speeds at which soil erosion occurs were estimated for these desert areas. They varied from 5 to 12 m s^{-1} at 0.25 m height, i.e. 10-m wind speeds between 6.8 and 9.7 m s^{-1}, and 16.4 and 23.3 m s^{-1}, respectively; such high wind speeds being measured in natural conditions by meteorological stations of the Fars province. These threshold wind speeds point out the large difference of sensibility to wind erosion of the semi-arid and arid areas of the Fars province. Wind tunnel experiments were also conducted at the same high wind speed (15 m s^{-1} at the height of 0.25 m) and duration conditions to study soil erosion rates by wind regarding soil properties. As it was previously shown for other arid areas, high values of the soil surface gravel cover percentage, the soil MWD, the clay and soil moisture contents, and the soil organic carbon significantly reduced the erodibility of the studied soils by wind. In fact, the measurements conducted at a 15 m s^{-1} constant wind speed (at 0.25 m height) pointed out that the soil with high surface gravel coverage percentage and soil MWD present the lower soil erosion rates both following a power function ($R^2 = 0.61$, $P < 0.001$ and $R^2 = 0.60$, $P < 0.001$, respectively). Our measurements also allowed us to establish nonlinear relationships as power functions between the increase of the relative soil clay content as well as the soil moisture content, and the decrease of the soil erosion rate ($R^2 = 0.41$, $P < 0.001$ and $R^2 = 0.58$, $P < 0.001$, respectively). Moreover, we found a negative power relationship between soil organic carbon and soil losses by wind ($R^2 = 0.21$ and $P < 0.001$). These results are in agreement with previous studies on the susceptibility of soils to wind erosion performed in semi-arid and arid areas worldwide. Critical values of these soil properties, for which soil erosion by wind is inhibited, were proposed for the regions of the Fars province: 5% for the soil surface gravel cover, 0.3 mm for the soil MWD, between 10 and 15% for the soil clay content, 2% for the gravimetric soil moisture content, and 0.4% for the soil organic carbon. These critical values being obtained for a high constant wind speed; more investigations are still needed to determine how these values may vary under different wind speed conditions. Furthermore, for soil salinity increase up to 1 dS m^{-1}, as well as for soil sodicity up to 1.6 (meq L^{-1})$^{0.5}$, soil erodibility can be reinforced. The effects of higher salinity and sodicity values on the erosion of the soils of the Fars province need more investigations. Our results also indicated that the soil texture should be considered to evaluate the effect of CCE contents on soil erodibility.

Even if more investigations are needed in other experimental conditions, our results are definitively a first step to document, and eventually prevent, soil erosion by wind in the semi-arid and arid areas of the Fars province.

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