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Assessment of the distribution and activity of dunes in Iran based on mobility indices and ground data

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ABSTRACT

Sand dune movement causes severe damage to infrastructure and rural settlements in Iran every year. Identifying active dunes and monitoring areas with migrating sand are important prerequisites for mitigating these damages. With regard to this objective, the spatial variation of the wind energy environment based on the sand drift potential (DP) was calculated from 204 meteorological stations. Three commonly used dune activity models – the Lancaster mobility index (1988), the Tsoar mobility index (2005), and the index developed by Yizhaq et al. (2009) – were used for the evaluation of Iran's sand dune activity. The analysis of the indices showed that the dune activity was characterized by great spatial variation across Iran's deserts. All three models identified fully active dunes in the Sistan plain, the whole of the Lut desert, as well as in the Zirkuh Qaien and Deyhook regions, while the dunes in the northern part of Rig Boland, Booshroyeh and in the Neyshabor dunefields were categorized as stabilized dunes. For other dunes, the models show a less unified activity classification, with the Lancaster and Yizhaq models having more similar results while the Tsoar model stands more apart. Based on these model results and fields observations, a modified Lancaster mobility index has been applied to show a more realistic spatial variation of sand dunes activity in Iran's desert areas.

1. Introduction

Deserts cover 907,293 km^2 of Iran (Khosroshahi et al., 2009), and sand dune fields are scattered across the arid and rarely the semiarid areas of Iran. Sand seas or Ergs are also known as a "Reg", "Rig" or "Rek" in Iran, Afghanistan, Pakistan, and Tajikistan and the name "Registan" means "sand is accumulated". Very limited studies have been published regarding the sand dunes of Iran (e.g. Ekhtesasi and Dadfar, 2014; Feiznia et al., 2016; Mashhadi and Ahmadi, 2010); and dune morphology in relation to wind regime (Abbasi et al. 2019; Mashhadi et al., 2007; Mesbahzadeh and Ahmadi, 2012; Nazari et al., 2017) but no comprehensive reviews on a national scale are available to the English speaking international scientific community. Ehlers (1980) was the first one to provide a land use map of Iran showing sand dunes covering 182,900 km^2. Mahmmodi (2002) published a book (in Persian) entitled "Sand Seas Distribution of Iran" which covers around 35,385 km^2 (without considering sand sheets and the Nebka dunes). After that, Abbasi (2012) produced sand dune distribution maps using satellite images (Landsat 7 and 8), aerial photographs, Google Earth scenes integrated with field operations. The results of that study showed that the extraction and mapping of the dominance and morphology of sand dunes was carried out in a scale of 1:25,000, which revealed that dunes in Iran extended to 11 sand seas and 97 dune fields, which cover approximately 4.6 million hectares (Table 1). Most of the sand dunes in Iran occur in and around the Dasht-e Kavir and Lut deserts (Fig. 1). Dasht-e Kavir desert is mostly uninhabited and it is the largest desert in north-central of Iran, predominantly characterized by crusty salt ridges and salty marshlands. It is an important source of sand and dust storms during the dry season and therefore Rig Boland, Rig-e Jinn and the Rig-e Khartoran sand seas and several dune fields have formed in and around this desert (Fig. 1).

The Lut desert in southeastern Iran is surrounded by mountains, which affect the formation and morphology of the Yalan (Lut) sand sea. It is the largest sand sea in the country, formed by multidirectional winds and the special topography (Lorenz et al. 2015). A survey by the Kerman Agriculture Jihad Organization in 2018 estimated that sand storms lead to annual farmland and garden damages of $4.2 million (640 bln rial) in Rigan (IRNA, 2018) in the southern parts of the Lut desert, a county with a population of just 53,000.

The Jazmorian sand sea, as the second vast sand sea in the country, extends along the north and south of the Jazmorian ephemeral Salt Lake. It features dunes in two parts: one part located south of the

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Table 1
Important sand seas and dune fields in Iran (Abbasi, 2012).

The name of sand dune	Area (km^2)	%
Rig-e Yalan (Lut) sand sea	11,529	24
Rig-e Jazmorian sand sea	5588	12
Rig-e Jinn sand sea	4512	9.6
Rig-e Khuzestan sand sea	2614	5.6
Rig-e Shotoran sand sea	2612	5.5
Rig-e Zir kuhe Qaien sand sea	2208	4.7
Rig-e Khartoran sand sea	2081	4.4
Rig Boland sand sea	2013	4.3
Rig-e Sarakhs sand sea	813	1.8
Rig-e Booshroyeh sand sea	623	1.3
Sistan dunefields	641	1.4
Costal dune fields (Persian and Oman Gulf)	1039	2.2
Other dunefields	10,082	22
Total	46,355	100

ephemeral lake between Iranshahr and Galaeh Ganj in the Sistan and Baluchistan provinces, and a smaller part northwest of the desiccated lake, called the Rudbar dune field in the Kerman province. The Sistan sand dunes originate from the Hamouns ephemeral lakes in Iran and extend to the Registan sand sea in southern Afghanistan and are strongly influenced by the Sadobist Roozeh (the wind of 120 days) wind (Abbasi et al. 2019). In march 2016, a major sand storm in this region caused extensive socioeconomic disruptions and shifting sand damaged crops and urban infrastructures with a value of more than $71 million in the Sistan plain (Oshida, 2016).

Other dune areas in Iran include the Khuzestan sand sea, also known as the Karkheh sand sea, extending from Iraq into the Ilam and Khuzestan provinces in Iran, as well as costal dunes formed near the Persian Gulf and the Oman Sea beaches between the southern Iranian cities of Chabahar and Bushehr.

Climatic factors, wind and water erosion, population pressure, overexploitation of water resources, and over-grazing have been identified as the main reasons for desertification in Iran (NAP, 2005). A survey by the Iranian Forest, Rangeland and Watershed Management Organization (FRWO, 2004) reported that wind erosion causes annual damages of > 18.3 bln. USD. Therefore, the stabilization of sand dunes has been a major objective of programs to combat desertification during the past half century. The main method of dune stabilization in Iran is a combination of oil mulch spraying and tree plantation. This method, as a common technique for sand dune stabilization, has been used first on the Khuzestan sand dunes in 1958 and then on the Sabzevar dune fields in 1965 (NIOPDC, 1967). Oil mulch, which is a hydrocarbon colloid extracted from petroleum, stabilizes shifting sands, preserves soil moisture and assists to establish vegetation cover (Kowsar, et al., 1969). Amiraslani and Dragovich (2011) provided a list of major plant species used in Iran's desertification projects in different provinces of Iran. In order to control wind erosion and carbon sequestration, > 2 million hectares' of dry forests (mostly *Haloxylon* sp.) have been planted around and on top of Iran dunes during the last fifty years.

Sand dune activity is defined as changes in migration rates and/or variations in the amount of sand shifting on the dune itself (Thomas 1992). Bullard et al. (1997) provided a comprehensive literature review on various sand dune mobility models, as seen in Table 2. Wilson (1973) developed one of the earliest dune activity models, using annual average rainfall as a factor determining mobility. On a global scale he separated active from stable dunes by a precipitation threshold of 150 mm. Ash and Wasson (1983) presented two dunes mobility indexes (equations (1) and (2) in Table 2) based on precipitation as well as on actual and potential evapotranspiration in Australia, which was immediately modified by Wasson in (1984) by adding the percentage of time with wind speeds above the transport threshold parameter (W%) (equation 4). Lancaster (1987) adapted this model for dunes in the southwestern Kalahari (equation 5). One year later he simplified his dune mobility index (M) as he based it on W% and the ratio of precipitation to annual potential evapotranspiration as aridity index (P/PET) in 1988 (equation 6). He classified dunes as fully active ($M > 200$), active dune with inactive interdune areas ($200 > M > 100$), activity only on the dune crests ($100 > M > 50$), and inactive dunes ($M < 50$). The Lancaster mobility index (abbreviated LMI in this paper) is used widely in discussing dune activity under different climate conditions in the global sand seas and dune fields (e.g. Bullard et al., 1997; Gaylord and Stetler, 1994; Lancaster, 1997; Lancaster and Helm, 2000; Muhs and Maat, 1993; Muhs and Holliday, 1995; Muhs et al., 2003; Thomas, et al., 2005; Tsoar and Blumberg, 2002; Wang et al., 2005; Wolfe, 1997).

In more recent years, Tsoar (2005) developed an experimental model based on the assumption that the wind power is the most significant factor in sand dunes activity and thus his model uses the effective winds characteristics for different sand dune sites (equation 7). The model assumes that dunes are active under high wind power and vegetated under low wind power if rainfall is above 50 mm and there is no human pressure. Wind power, which grows with the cube of the wind velocity, is expressed as the drift potential (DP), which is generally calculated based on Fryberger and Dean's (1979) method according to this equation:

$$DP = V^2(V - V_t)t \qquad (10)$$

where DP is the sand drift potential in vector units (vu), V is wind velocity at 10 m above ground, V_t is the threshold wind velocity (set at 12 knots or about 6.2 m s^{-1}) under dry conditions and t is the time for which the wind speed was above the threshold.

The unidirectional index is the ratio of the resultant drift potential (RDP) to the drift potential (DP) and shows the directional variability of the wind (equation (11)).

$$RDP = (C^2 - D^2)^{0.5} \qquad (11)$$

$$C = \sum (VU)\,Sin(\theta)$$

$$D = \sum (VU)\,Cos(\theta)$$

The vector units (VU) in above formula represents the DP in each wind direction (in this paper, the wind directions were grouped into 16 direction classes of sand transport), θ is the midpoint angle of each wind direction class measured clockwise from 0° or 360° (north).

Tsoar (2005) indicated that when RDP/DP is high, the winds blows unidirectional and the wind energy is highly effective on the dune mobility, while a low RDP/DP exerts the effective wind on different slopes of dune. If RDP/DP stands close to 1 it indicates a narrow unidirectional drift potential, and if it stands close to 0 it indicates a wide multidirectional drift potential.

The Tsoar mobility index (TMI) is valid above 50 mm/yr rainfall and classifies dunes into "covered by vegetation or stabilized" ($M < 1$) and "uncovered by vegetation or active ($M > 1$). This model has been developed in 43 dune fields (e.g. in the Negev desert) and was also tested on coastal dunes in Ceará (Brazil). The DP ranged from 692 to 2173 VU and the annual rainfall went up to 1443 mm (Tsoar et al., 2009). Based on these tests the TMI concludes that vegetation will start covering the sand dunes when the wind power falls below 1000 DP (Tsoar, 2005).

Yizhaq et al. (2007) developed one of the most recent mathematical models for simulating dune activity with respect to wind power and vegetation cover (equation 8 in Table 2) and then further improved it based on wind power and precipitation rates (equation 9) under similar climatic conditions (Yizhaq et al., 2009). In these models, wind power determines the sand transport capacity, while the vegetation cover, which, in turn, is controlled by the precipitation, determines the amount of the sand available for transportation. Both models classify dunes as fixed, active or partially active, but fixed dunes can be reactivated during very strong winds and stabilized again once the wind

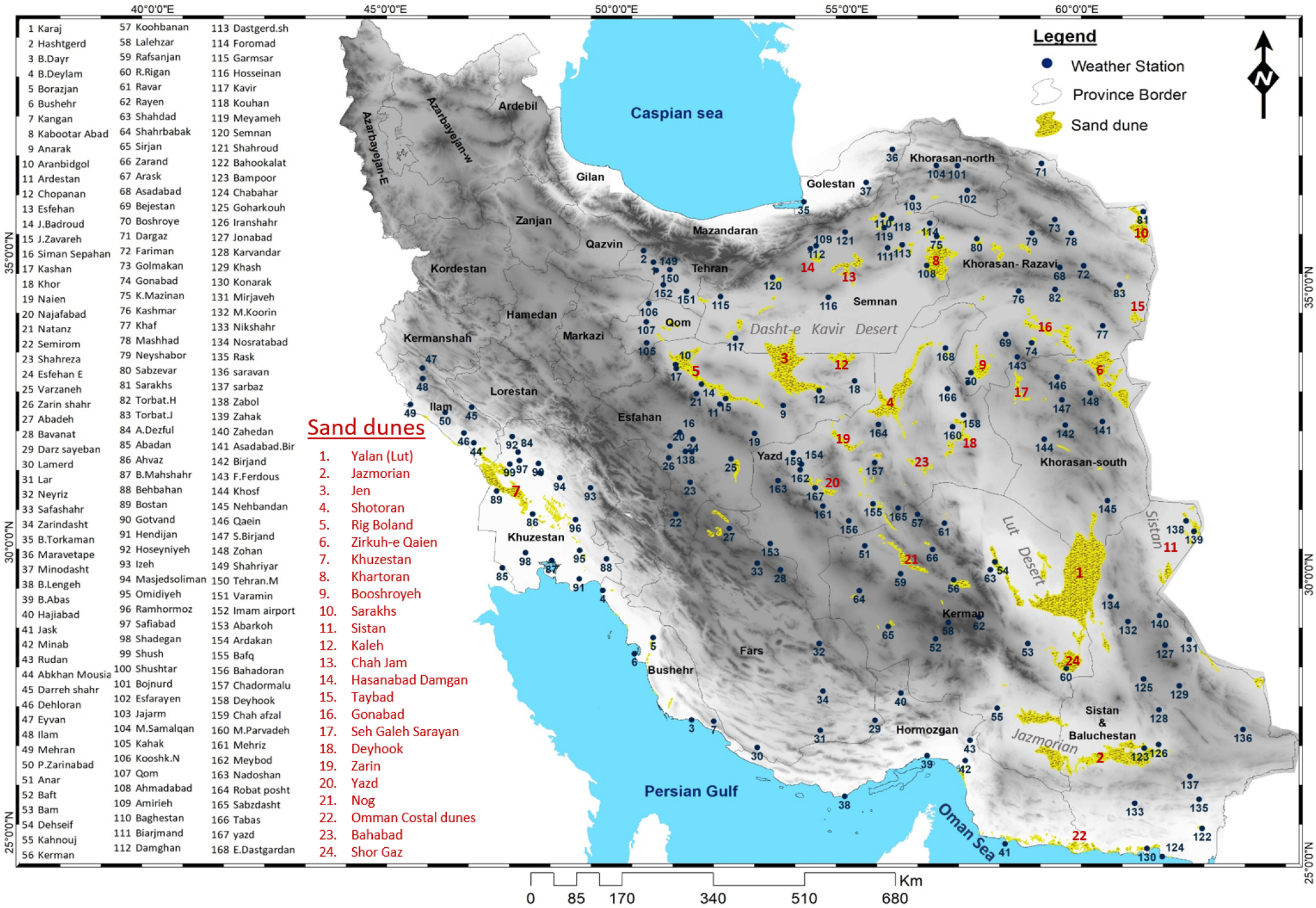

Fig.1. Sand dunes distribution and location of meteorological stations used in this study.

Table 2
Sand Dune Mobility Models.

Reference	Equation	Threshold Value	Region in which developed
Wilson (1973)	–	Dunes active when rainfall < 150	The world map
Ash and Wasson (1983)	$M = [5 \times 10 - 4(P)^2]/(\frac{AP}{PE})$ (1) $M = [3.8 \times 10 - 4(U)^4](\frac{AP}{PE})$ (2)	Mobility occurs when M ≥ 1.0	Australia
Talbot (1984)	$C = V^3/(P)^2$ (3)	C < 10, dunes inactive 5 < C < 10, limited aeolian activity C > 10, dunes active	Sahel
Wasson (1984)	$M = 0.21(0.13W + ln\frac{PET}{P})$ (4)	Mobility occurs when M ≥ 1.0	Australia
Lancaster (1987)	$M = 0{\cdot}25(0{\cdot}10\,W + ln\frac{PET}{P})$ (5)	Mobility occurs when M ≥ 1.0	Southwest Kalahari
Lancaster (1988)	$M = \frac{W\%}{P/PET}$ (6)	> 200, dune fully active 100–200, dunes active and interdunes inactive 50–100, crest areas only active < 50, dunes inactive	Southwest Kalahari , Namib, Mojave deserts
Tsoar (2005)	$M = \frac{DP}{1000 - \left(750\frac{RDP}{DP}\right)}$ (7)	M < 1 Covered by vegetation M < 1 Uncovered by vegetation	Several deserts
Yizhaq et al. (2007)	$\frac{dv}{dt} = \alpha(v + \eta)\left(1 - \frac{v}{v_{max}}\right) - \varepsilon DP\theta(v_c - v)v - \gamma\ DP^{2/3}\ v$ (8)		Several deserts
Yizhaq et al.,(2009)	$\frac{dv}{dt} = \alpha(p)(v + \eta)\left(1 - \frac{v}{v_{max}}\right) - \varepsilon\ DPg\ (v_c, v)v - \gamma\ DP^{2/3}\ v - \mu v$ (9)		Several deserts

Definitions: M = mobility, P = annual precipitation, PE = annual potential evapotranspiration, AP = actual annual evapotranspiration, C = wind erosion factor, U = V–Vt, V = mean annual wind speed, Vt = threshold wind velocity, W = percent of time wind above transport threshold, DP = drift potential, v = the dynamical variable representing areal vegetation cover density, ε = stands for the vegetation tolerance to sand erosion and deposition, γ = proportional constant of vegetation types, η= A spontaneous growth cover parameter,

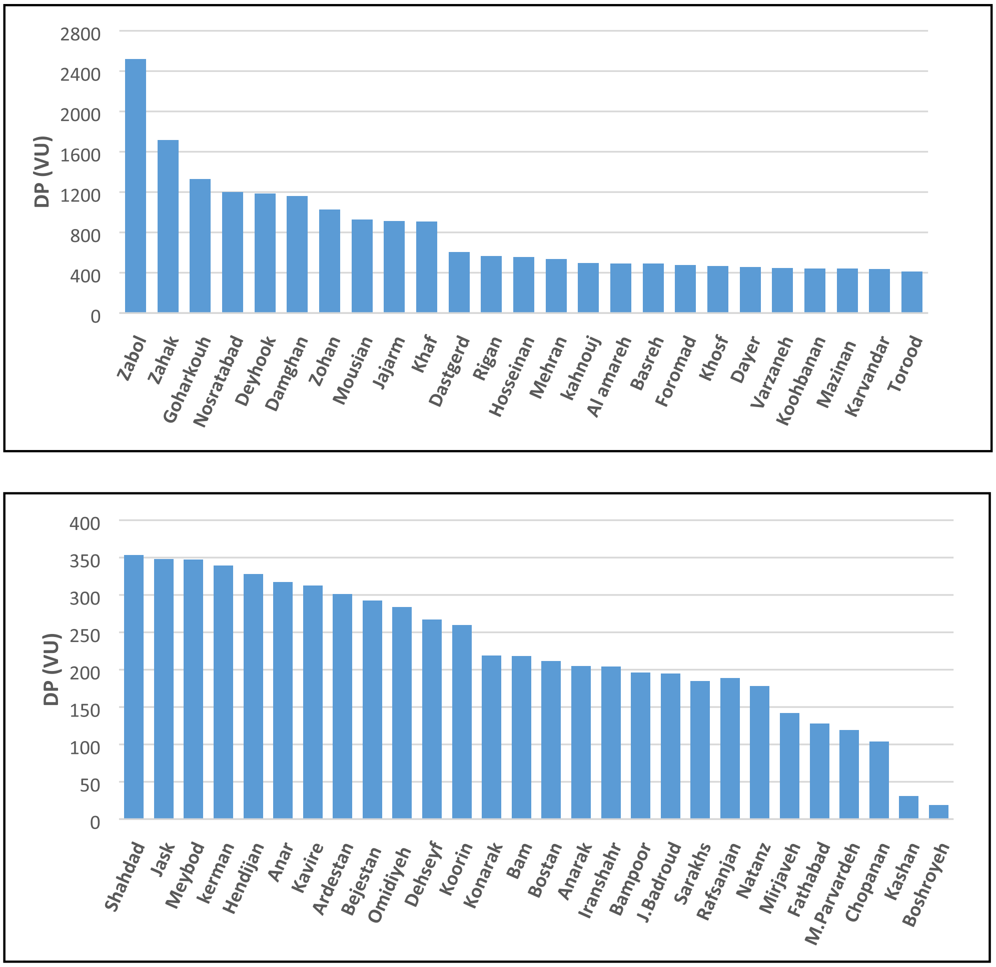

Fig. 2. Annual drift potential (DP) at selected meteorological stations near sand dunes in Iran.

power decreases (Yizhaq et al., 2009).

Ashkenazy et al. (2012) investigated the future activity of currently fixed dune fields in the Kalahari and in Australian deserts based on Yizhaq's model in two climate change scenarios and demonstrated that both dunes fields remain stable until the end of the 21st century because the DP will stay small and precipitation will remain above the minimal threshold necessary for vegetative growth.

The aim of this study is to provide an integrated analysis of the spatial variations of the wind energy based on DP and sand dune activity in Iran. In order to assess the dune activity, the Lancaster mobility index (LMI), the Tsoar mobility index (TMI) and the Yizhaq model were applied and compared. Based on the results of this comparison and supported by extensive field observations, the Lancaster mobility index has been modified to better represent the activity of the Iranian dunes.

2. Material and methods

In order to determine the distribution of sand dunes in Iran, we used sand dune maps in scale 1:25 000 that provided by Research Institute Forests and Ranglands Iran (Abbasi, 2012). The speed and direction of hourly wind data were recorded in intervals for 1 or 3 hourly for 24 h per day at height of 10 m above the ground were obtained from 204 meteorological stations (near 39 million records) in and around Iran deserts (Fig. 1) from Iran Meteorological Organization (IMO). The data cover the period 1994 to 2013, but some stations are shorter due to data limitations.

The percent time wind above transport threshold (W%), was considered 12 knots or 6.2 m s^{-1}, were also calculated for weather stations. Potential evapotranspiration (PE) values were generated using Thornthwaite's (1948) method using calculator online (http://ponce.sdsu.edu/onlinethornthwaite.php). Sand drift potential (DP), Resultant drift potential (RDP) and the ratio of RDP/DP have been calculated using Fryberger and Dean (1979) method according to equations (10) and (11). The spatial variation of DP was interpolated using ordinary kriging in geostatistical method with ArcGIS software version 10.3 (ESRI Inc.).

Three sand dune models, the Lancaster mobility index (LMI), Tsoar mobility index (TMI) and Yizhaq model (Equations 6, 7 and 9 in Table 1), were calculated and compared to assessment dunefield activity for each station around Iran's deserts.

Finally, according to winds characteristics and dunes activity in some parts of Iran's desert, we modified Lancaster model regarding to wind power and sand transport feature in Iran.

The spatial variation of mobility indexes was interpolated using ordinary kriging in geostatistical method with ArcGIS software version 10.3 (ESRI Inc.).

3. Results

3.1. Spatial variability of sand drift potential

Climatic conditions in Iran are mainly controlled by the pressure systems of the westerly cyclones, the Siberian high pressure and the southwest Monsoon airstreams (Kehl, 2009). During the dry season, when sand and dust storms are a common phenomenon, four wind regimes are predominant in Iran's deserts: (I) the Shamal wind from

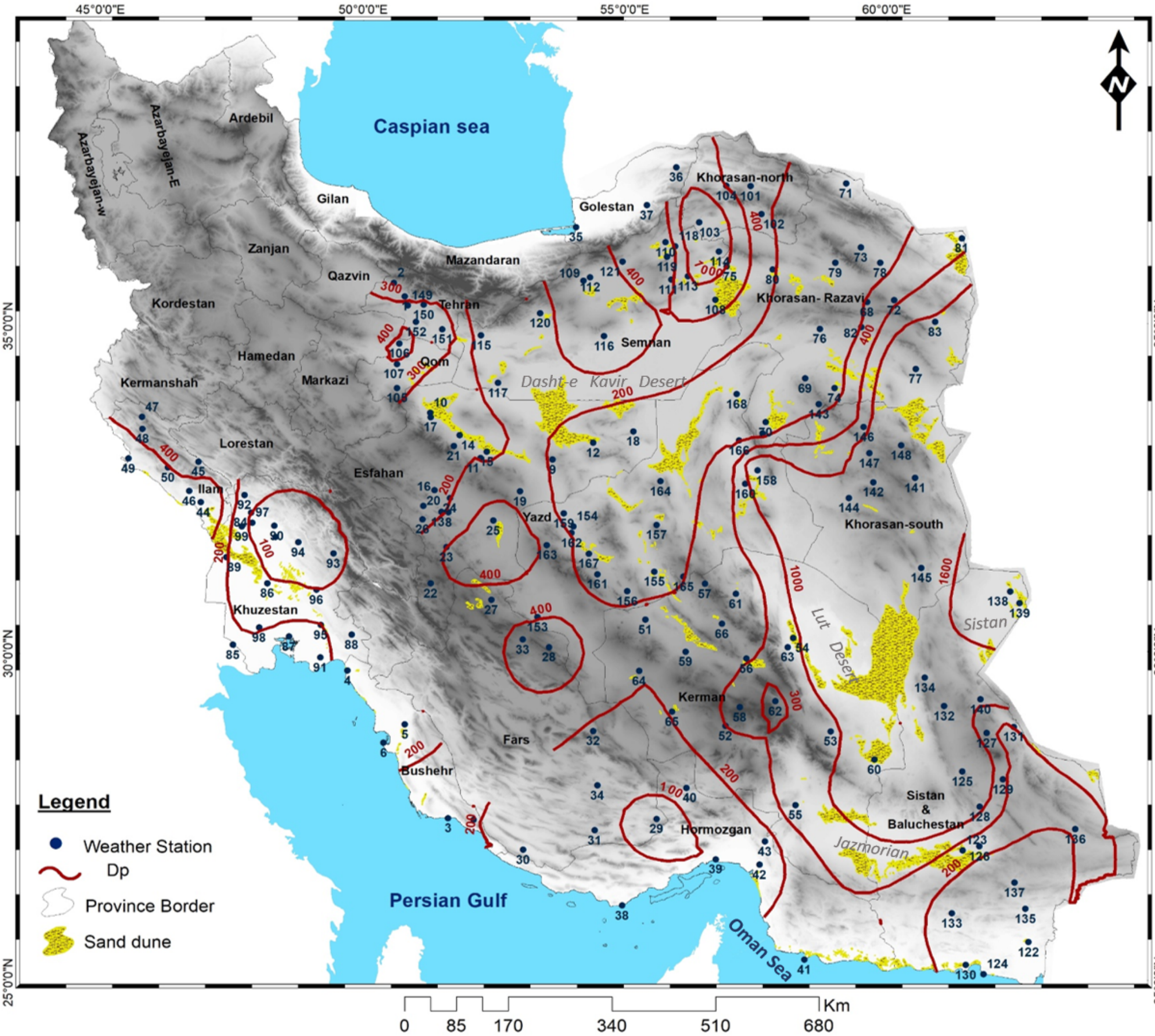

Fig. 3. Spatial variation of sand drift potential (DP in vu) in Iran's deserts.

northwestern direction, which covers most parts of Iran and Iraq, (II) westerly cyclones or the prevailing westerlies, which blow from the west to the east in the middle latitudes, (III) the Sadobist Roozeh wind as a very strong northerly or northwesterly wind covering the east and southeast of the country, and (IV) an intense southwesterly wind or monsoon, which dominates over the eastern parts of the Oman Sea (Abbasi et al. 2019; Alizadeh-Choobari, Zawar-Reza and Sturman, 2014; Chaichitehrani and Allahdadi, 2018; Bou Karam et al., 2017; Garzanti et al., 2013; Rashki et al., 2019; Shao et al., 2011; Yu et al., 2016).

In addition, the irregular topography and large mountain ranges in and around Iran's deserts affect the surface winds, sand transport and dune formation. Alborz and Zagros, the two main mountains ranges surrounding Iran's deserts, and other small mountain ranges, like Karkas, Kuhbanan, Makran, Barez and Bazman mountains, are located into the central deserts of Iran. The Sadobist Roozeh wind accelerates into a corridor between the Hindu-Kush Mountains in Afghanistan and the Bageran and Ahangran Mountains in southern Khorasan (Abbasi et al. 2019; Whitney, 2006). Zir kuhe Qian, Sistan and Registan and a part of Yalan (Lut) sand seas are formed by this Sadobist Roozeh wind. In addition, several dune fields are formed in association with topography obstacles e.g. Rig-e Jinn, Zirkuh Qaien, Rig-e Talhe, Rig-e Kuhe Gogerd and the Booshroyeh sand dunes.

The spatial analyses of the drift potential showed considerable variation from high to low energy environments in the arid and semi-arid areas of Iran between 1994 and 2013 (Fig. 3). Fryberger and Dean (1979) classified the wind energy environment based on DP (vu) into high (DP > 400), moderate (200 < DP 〈400) and low (DP 〈200). The highest levels of annually DP occurred in the Sistan plain with 2,516 and 1,716 (vu) in Zabol and Zahak (Abbasi et al. 2019). High wind energy environment also occurs in the eastern and southern Lut desert (Nosratabad, Karvandar, R. Rigan, Khusf), the northern and central part of Dasht-e Kavir desert (Hosseinan, Damgan, Torood, Kalateh Mazinan, Dastgerd Shahroud), Zir Kuh Qaien region (Zohan, Khaf, Asadabad), the western of Jazmorian (Kahnoj), Deyhook in Yazd province and the western edge of Khuzestan border (Abkhan Mousian), as seen in Fig. 2.

Moderate wind energy environment covers most of Iran's deserts e.g. the central-west part of Dasht-e Kavir desert (Kavir or Caravanserai Shah Abbasi), the western and southwestern parts of the Lut desert

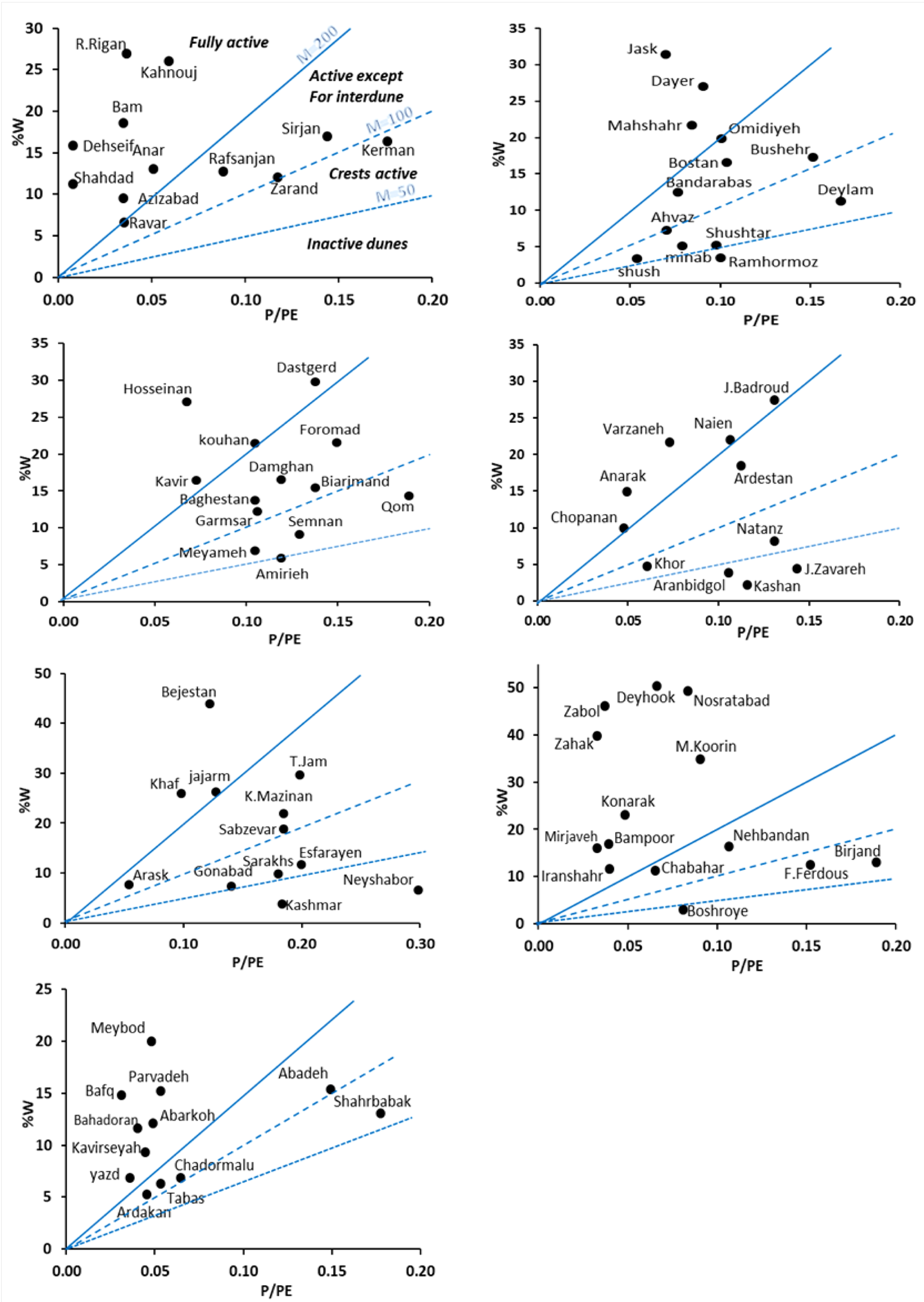

Fig. 4. Dune field mobility in Iran's deserts based on Lancaster's (1988) index.

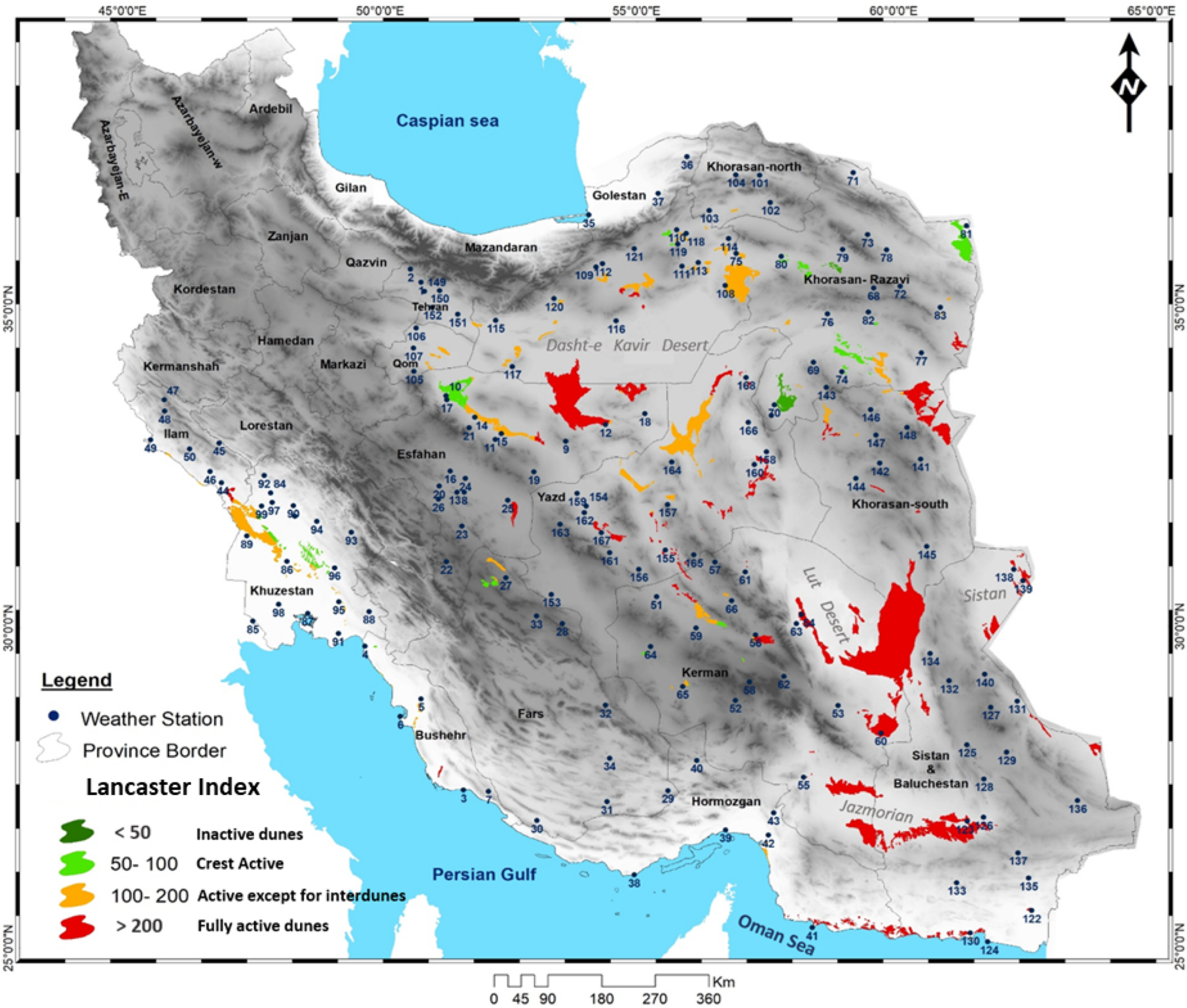

Fig. 5. Sand dune activity in Iran's deserts based on Lancaster's (1988) mobility index.

(Shahdad, Daheseyf, Mohammadabad Koorin, Bam), the southeastern and western parts of the Khuzestan province (Bostan, Mahshahr, Omidiyeh, Hendijan) and the Omman sea coast from Jask to Konarak.

A low energy wind environment can be found in the southwest of Dasht-e Kavir desert (Kashan, Aran Bidgol, Natanz, Janglbani Badroud, Jangalbani Zavareh), the eastern part of Jazmorian (Bampoor, Iranshahr), Sarakhs, Ferdous, Booshroyeh, Gonabad and the central and northern parts of Khuzestan province (Ahvaz, Shush, Shushtar and Ramhormoz), Sabzevar and Neyshabor region.

3.2. Lancaster mobility index

The long-term mean annual rainfall for the arid and semi-arid regions in Iran is 141 mm (Modarres and da Silva, 2007) and at the stations selected for this study the annual precipitation ranged from 31 mm in Shahdad (western Lut desert) to 298 mm in Shushtar in Khuzestan, with an average of 144 mm. The annual potential evapotranspiration was calculated at 1572 mm/yr, with a range between 789 and 3969 (mm/yr) in Foromad and Shush, respectively. Fig. 3

Analysis of the LMI revealed a considerable spatial variation over the Iranian sand dune system from very active to inactive categories (Figs. 4 and 5), following the distribution of the wind power, precipitation and potential evapotranspiration. Fully active dunes (LMI > 200) were detected in the whole Lut desert, due to the low precipitation of 30–40 mm, high evapotranspiration (in the western and southern parts) and frequent strong winds (in the eastern part). Other regions with fully active dunes were the central and southern parts of Dasht-e Kavir as well as in the whole of Sistan, Baluchistan, and in some parts of the Yazd and Khorasan provinces. In Sistan, for example, the combination of the 120 days wind, which enables sand transport during 40–46% of the time, low precipitation (53–103 mm) and a high potential evapotranspiration (1230–1608 mm/yr) leads to the formation of active dune fields. Especially the values of the potential evapotranspiration in Sistan and western Afghanistan are among the highest rates recorded around the globe (Afghan Institute of Meteorology, 1978; Dittmann, 2014).

Regarding to the LMI, the Shotoran, Rig-e Jinn, Deyhook, and Sagand sand dunes in central Iran were fully active dunes as well. These results were confirmed by field observations with the exception of the southern part of Rig-e Jinn (Chopanan).

In addition, the costal dunes in the Omman Sea region from Konarak to Jask are fully active because of moderate to high percentages of wind speeds above the transport threshold (23–31%), rainfall (97–196 mm) and a high potential evapotranspiration (2002–2491 mm/yr).

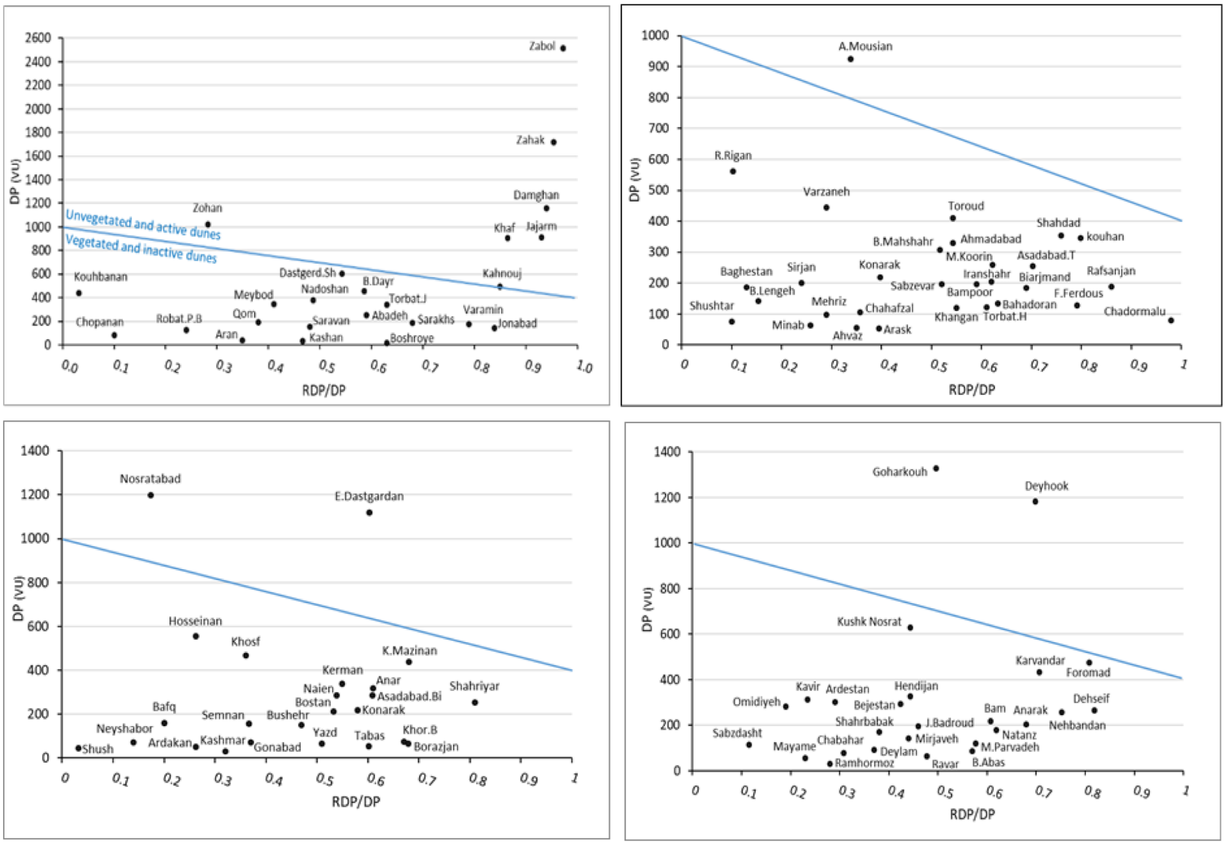

Fig. 6. Dune field mobility in Iran's deserts based on Tsoar's (2005) index.

There is considerable variation of dune activity in the Jazmorian sand sea so that the Iranshahr and Bampoor meteorological stations, in the eastern part, were classified as fully active due to high evapotranspiration. But field observations rather indicate that these dunes are inactive because of the low frequency of wind speeds above the transport threshold (12–17%) and existing vegetation cover. Due to summer rainfall, which was created by the SW-monsoon system in Baluchistan (Babaeian, 2017; Saligheh and Sayadi, 2017), *Capparis decidua* trees stabilized the western parts of the Jazmorian sand dunes, as shown by Keneshloo and Damizadeh (2015). The activity of dunes generally increased towards the central and western part because the frequency of higher wind speeds increased to 26% at the Kahnouj meteorological station.

The Khuzestan sand sea extends from Iraq into the Ilam and Khuzestan provinces in Iran. The Iraqi part, Ilam and the western border of Khuzestan are active due to a high percentage of times with wind speeds above the transport threshold (26–41%). From there it decreases rather sharply towards the central area near Ahvaz, which only showed a low percentage (5–7%) of threshold excess. In the southeastern part of the Khuzestan sand sea, the dune activity increases again because the wind speed percentage above the threshold reaches up to 18–20%. Rouhipour (2006) measured the migration rate of dunes in the central Khuzestan sand sea, between Ahvaz and Andimeshk cities, to be an average of 1 m/yr, with more movement towards the crest.

Regions with partly active dunes (100 < LMI〈2 0 0) were registered mainly in the Khartoran, central, southeastern and eastern parts of Rig Boland sand seas, as well as in the Nog, Tabas, Sabzevar, and Hasanabad dune fields. The Khartoran sand sea had almost constantly active dunes except for the interdunes with 20–22% of all winds above the transport threshold and a P/PET ratio of 0.14–0.18.

The Sarakhs sand sea, Kerman, Minab, and Chabahar dune fields showed active dune crests (50 < LMI〈1 0 0) because of the low percentage of winds above the transport threshold. In these regions, the ratio of P/PET ranged from 0.07 to 0.18 and the annual frequency of sand-transporting winds from 5 to 16%.

Inactive dunes (LMI < 50) are widespread in the northern part of Rig Boland (around Kashan and Aran Bidgol) and in the Booshroyeh sand sea. In these regions, the ratio of P/PET ranged from 0.10 to 0.12 and W% ranged from 2 to 4%.

3.3. Tsoar mobility index

The analysis of the Tsoar mobility index (TMI) (Tsoar, 2005) indicated that most of Iran's deserts fall into the "inactive and vegetated (M < 1)" and partially into the "unvegetated and active (M > 1)" categories (Fig. 6).

Regarding to the TMI, active dune fields were detected in Sistan, most parts of the Lut desert, the western part of Jazmorian, the northern regions of the Dasht-e Kavir desert, Zirkuh Qaien, and small part of Yazd desert (Fig. 7). In these regions, the sand drift potential (DP) ranged from 410 to 2516 (vu) and the RDP/DP ratio was between 0.17 and 0.97.

As the TMI works only where the annual average rainfall is above 50 mm, the sand dunes in the western parts of the Lut desert (Dehsief, Ravar) and in some parts of the Yazd province (Yazd and Bafg) were assumed primarily "unvegetated and mobile".

The TMI reveals that the Sistan and Zirkuh Qaien sand dunes are active due to the presence of the strong unimodal wind of Sadobist Roozeh, exactly as mentioned above (see chapter 3.1). The DP value in this region ranged from 2516 to 1717 vu and the RDP/DP ratio from 0.97 to 0.95.

In addition, most parts of the Lut desert were classified as "active and unvegetated" as the eastern part of Lut desert (Nosratabad) was characterized by a high wind energy environment with high DP (1199 vu). But the RDP/DP ratio of 0.17 revealed multidirectional winds. Dunes in the western part of the Lut desert were also classified as

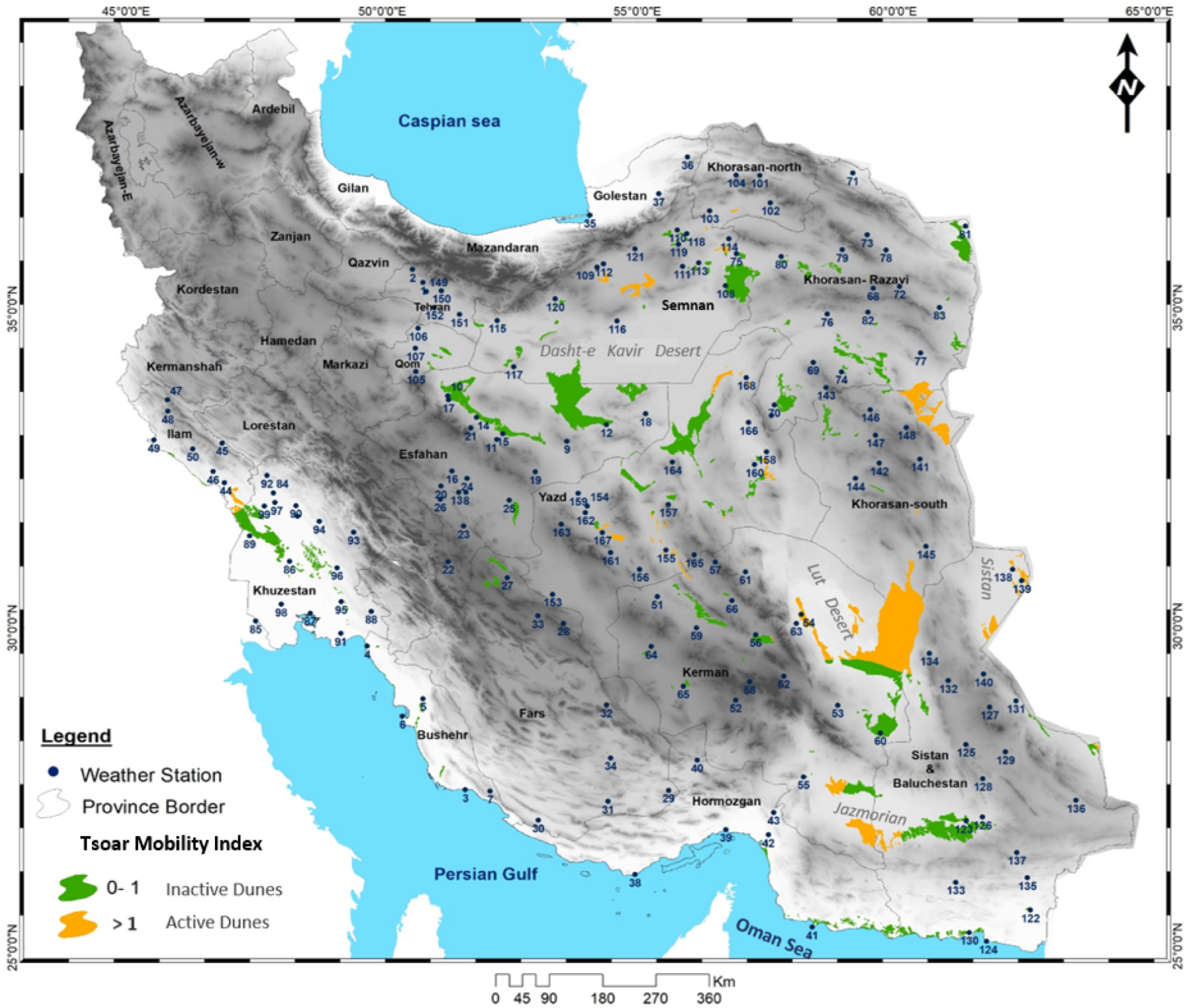

Fig. 7. Sand dune activity in Iran's deserts based on Tsoar's (2005) index.

"unvegetated" because of the low precipitation (< 50 mm rainfall at Shahdad and Dehsief), while the southern parts (Bam, Rahmatabad Rigan and Mohammadabad Koorin) were categorized as inactive dunes due to a moderate DP and a low to moderate RDP/DP ratio. These TMI results contradict the field observations, which showed that the dunes are active throughout the whole Lut desert because of low precipitation (53–57 mm) and extremely arid conditions.

Furthermore, the northern part of the Dasht-e Kavir desert, consisting of the Hasanabad (Damgan), Jajarm, Foromad, Yazdo, and Dastgerd Shahroud dune fields, contains active dunes because of the high wind energy, as discussed in chapter 3.1. The other dune fields around this desert were classified as "inactive", due to their low DP and RDP/DP ratio. Eshgabad Dastgardan, in the north of the Shotoran sand sea, also showed active dunes in the TMI classification, with a high drift potential and intermediate directional variability.

Based on the TMI analysis, the western part of the Khuzestan sand sea, near the border to Iraq (Mousian) was active due to a high DP. Towards the central and southeastern parts of this region the DP, and with it the activity of the dunes, decreased.

Another region with active dunes, based on the TMI, was the western part of the Jazmorian sand sea (Kahnouj). The activity of dunes there decreased gradually from west to east as the wind energy and the RDP/DP ratio decreased in the same direction over the sand sea.

The rest of the country's sand dunes were classified as inactive because the average annual wind power (DP) and the RDP/DP ratio were too low to sustain active dunes.

3.4. *Yizhaq mobility index (YMI)*

The main elements of Yizhaq model (Equation 8 in Table 1) are wind power, precipitation rate, and anthropogenic effects, such as grazing and wood gathering (Yizhaq et al., 2009). According to this model, dunes are classified into active, active and stabilized (semi-active), and stabilized. In this model there are three activity graphs due to different values of the ground vegetation cover ($v_c = 0.2, 0.25 and 0.3$), which is a function of precipitation. For this study $v_c = 0.3$ was used because most sand dunes in Iran are bare or have only a low vegetation cover due to the low precipitation and overgrazing.

The analysis of the YMI illustrates a significant spatial variation in the activity grades of sand dunes in Iran (Fig. 8). The active dunes covered the whole of Lut desert, Sistan plain, most parts of the sand dunes in Yazd province, and the northern and central areas of the Dasht-e Kavir desert (Fig. 9). The spatial distribution of the annual precipitation over active dunes ranged from 31 to 170 mm and the DP varied between 49 and 2,516 vu.

The sand dunes in the Lut desert are active because of the high wind energy in the eastern and southern parts (Nosratabad, Rahmatabad Rigan), a low precipitation and moderate wind energy in the western and southwestern parts (Shahdad, Dehsief, Bam and Azizabad Bam) and low precipitation in the northwest (Ravar). Sand dunes in the Sistan plain (Zabol and Zahak), Zirkuh Qaien (Khaf, Zohan), Hasanabad (Damgan), and in the Jajarm dunefields in the northern part of Dasht-e Kavir were also active because of the high wind energy.

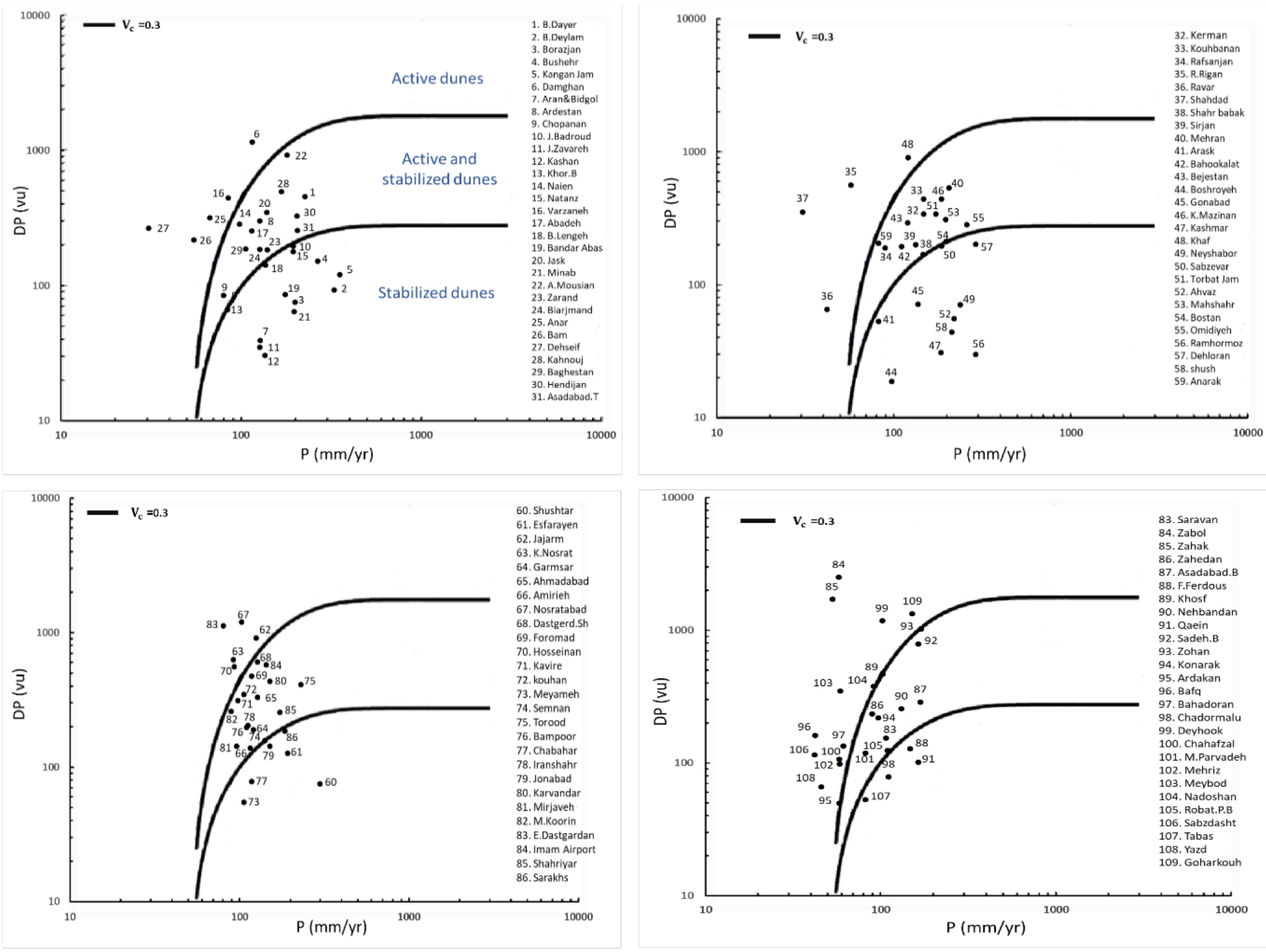

Fig. 8. Dune field mobility index values in Iran's deserts based on Yizhaq et al. (2009) model.

The northern part of the Shotoran sand sea (Eshgabad Dastgardan) and the Deyhook dunefields in the Yazd province were classified as active due to a high wind energy. In addition, the Yazd, Bahabad and Bafg dunefields were classified as active because of the low precipitation rates.

The Khartoran, Jazmorian, Rig-e Jinn, Khuzestan, and in southern part of the Shotoran sand seas, as well as the Kaleh, Kerman, Nog dune fields, and Omman Sea costal dunes between Konarak and Jask were categorized as semi-active with an annual average rainfall variability between 80 and 259 mm and a DP between 85 and 924 (vu).

Stabilized dunes were detected in the Sarakhs, Booshroyeh, and Rig Boland sand seas as well as in the Sagand, Esfrayen, Gonabad, Kashmar, Sabzevar, and Minab dune fields. In addition, the YMI analysis of the stabilized dunes revealed that the DP ranged from 19 to 202 (vu) and annual average rainfall from 82 to 329 mm.

3.5. Comparison of the three models and development of a new model

For comparing the three sand dune mobility models (LMI, TMI, YMI), 27 meteorological stations, which are located at the edges of dune fields, were selected. Table 3 shows the dune mobility classifications based on the three models as well as the relevant meteorological parameters. As mentioned above, LMI classifies dunes into four groups; fully active (A), active dunes with inter-dune stability (A.I.S), dunes where only the crest is active (C.A), and inactive or stabilized dunes (S). The TMI uses only two classes; stabilized (S) and active (A) dunes. Yizhaq's model categorizes dunes as active (A), stabilized and active (or semi-active) (S.A), and stabilized (S). Due to the unequal number of classes in the three models, a direct comparison of semi-active dunes is difficult. For this comparison study it was assumed that the C.A. and A.I.S. classes (LMI model) are equivalent to the S.A. class in Yizhaq's model (Table. 3).

When the wind energy environment is high all three models provide highly comparable results; e.g. all models show fully active sand dunes in Sistan (Zabol), the eastern part of the Lut desert (Nosratabad), Deyhook, and Jajarm. These results are also consistent with other studies, which revealed that the Sistan Hamouns lakes are one of the main dust and sand sources in western Asia (e.g. Cao, et al., 2015; Ekhtesasi and Gohari, 2013; Kaskaoutis et al., 2014; Miri et al., 2010; Rashki et al., 2013; 2012). Rezazadeh et al.,(2013) observed that the highest number of days with dust events in the Middle East occurred in Sistan as a result of the strong wind of Sadobist Roozeh. And field measurements place the average movement of big barchans in Sistan at 20 to 40 m/yr (Abbasi et al. 2019), which is one of the highest movement rates in comparison with other deserts e.g. 17 m/yr at the Northeastern Brazilian coast (Maia et al., 2005), 20 m/yr in the northern part of Mauritania in the Sahara Desert (Ould Ahmedou et al., 2007), 18 m/yr in the Salton Sea in California (Haff and Presti, 1995) or 8 m/yr in south of Dasht-e Kavir Iran (Maghsoudi et al., (2017). The sediment deflation rate from the Sistan ephemeral lakes, the source of material for the formation of sand dunes, has been measured directly in the field at about 2 cm in the wind of Sadobist Roozeh duration in 2013 (Abbasi et al., 2018).

The detection of typical aeolian landscapes in the Lut desert shows that wind erosion is an active phenomenon in this area as well. The largest continuous Yardangs on Earth are > 100 km long and are

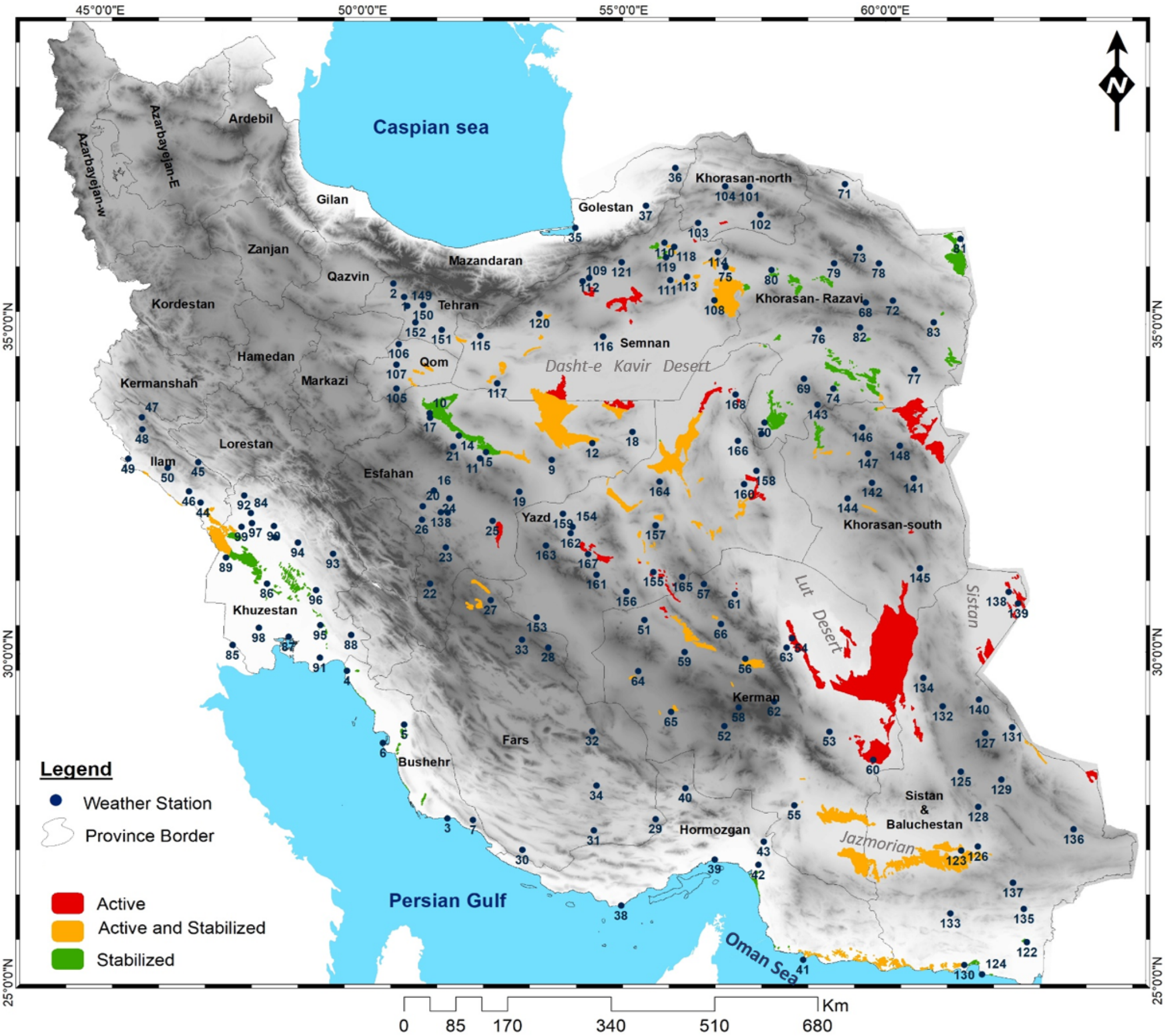

Fig. 9. Sand dune activity in Iran based on the Yizhaq et al. (2009) model.

located in the western part of the Lut desert (Ehsani and Quiel, 2008; Goudie, 2007; Radebaugh et al., 2017), while the tallest star dunes can be found in the southeast of the Yalan sand sea (Lorenz et al., 2015).

More differentiated results were obtained when the LMI classified dunes as active due to a high potential evapotranspiration, e.g. in the southern Lut desert (Rahmatabad Rigan) and the eastern part of Jazmorian (Bampoor and Iranshahr). Regarding to LMI and Yizhaq model, the Rigan dune field is active, while the TMI classified it as stabilized in spite of a high wind energy (DP = 562 vu) and a low ratio of RDP/DP. KNRWMO (2016) reported that dust storms and shifting sand are among the serious problems in the Rigan, Fahraj and Narmashir Bam regions. They cause damages to 250 rural communities and annually disrupt transport on 160 km of the Kerman-Zahedan railway. This shows that the TMI classification, in this case, did not match the conditions on site.

In the eastern part of the Jazmorian sand sea (Bampoor), characterized by a low wind energy and a high potential evapotranspiration, the three models delivered different results (Table 3). The LMI classified these dunes as active, the TMI as stabilized and the Yizhaq model as semi-active. As mentioned in chapter 3.1 and according to own field observation, these dunes are stabilized because of summer rainfall. Therefore, it seems that the temporal distribution of the precipitation, especially summer rainfall, which controls the vegetation growth, has a major effect on the dune activity. These summer rains do not reach the western part of the sand sea (Kahnouj) and the dunes there are, according to LMI and TMI, fully active, while the Yizhaq model categorized them as semi-active.

Overall the three models delivered comparable results in some instances and diverging results in others. The reasons for this are the use of different parameters and their impact on the model construction. The main contradictions of the three models results are revealed when the wind blows for only short times but with a high energy, like in the north of the Dasht-e Kavir desert (Damagan, Foromad) and at some stations in the wind of Sadobist Roozeh domain (Sedeh Birjand). Field observation demonstrated that dunes in these areas are completely active, but the LMI classified them as inactive or semi-active because of a low to moderate percentage of wind events above the transport threshold (10–23%). At the same time the DP in this region showed high values (475–1159) and thus the TMI classified the dunes as active, while the Yizhaq model classified them as active or semi-active. In fact, in spite of

Table 3
Comparison of the three sand dune activity models and relevant meteorological parameters in Iran for selected meteorological stations in and around Iranian deserts.

Sand dunes (meteorological stations)	Rain (mm)	PET (mm/yr)	W %	DP (vu)	Lancaster MI	Tsoar MI	Yizhaq Model	MLI	Field Observation
Sistan (Zabol)	58	1556	46	2516	A	A	A	A	A
Yalan (Nosratabad)	103	1234	49	1200	A	A	A	A	A
Yalan (Dehsief)	31	3805	16	267	A	A	A	A	A
Yalan (Shahdad)	31	3805	11	353	A	A	A	A	A
Yalan (R.Rigan)	58	1574	27	562	A	S	A	A	A
Bafg	42	1357	15	161	A	A	A	A	A
Deyhook	102	1543	50	1182	A	A	A	A	A
Jajarm	125	983	26	912	A	A	A	A	A
Jazmorian (Bampoor)	110	2806	17	196	A	S	S.A	A	C.A
Jazmorian (Kahnouj)	168	2836	26	496	A	A	S.A	A	A
Booshroyeh	97	1204	3	19	S	S	S	S	S
Rig Boland (Aran Bidgol)	128	1212	4	39	S	S	S	S	S
Rig Boland (J.Badroud)	195	1491	27	196	A	S	S.A	C.A	C.A
Rig Boland (Naien)	98	921	0.22	285	A	S	S.A	A.I.S	A.I.S
Khartoran (K.Mazinan)	187	1012	22	439	A.I.S	S	S.A	A.I.S	A.I.S
Khartoran (Ahmadabad)	128	926	20	330	A.I.S	S	S.A	A.I.S	A.I.S
Khartoran (Foromad)	118	789	22	475	A.I.S	A	S.A	A	A
Hasanabad (Damgan)	116	970	23	1159	A.I.S	A	A	A	A
Khuzestan (A.Mousian)	180	2807	19	924	A	A	S.A	A	A
Khuzestan (Bostan)	198	1908	17	212	A.I.S	S	S.A	A.I.S	A.I.S
Khuzestan (Ahvaz)	220	2965	7	55	C.A	S	S	S	S
Ilam (Mehran)	205	2171	25	543	A	S	S.A	A	A
Rig-e Jinn (Chopanan)	80	1685	10	85	A	S	S.A	A.I.S	C.A
Jask	139	2002	31	348	A	S	S.A	A	A
Rafsanjan	90	1016	13	189	A.I.S	S	S.A	A.I.S	A.I.S
Gonabad	137	981	7	71	C.A	S	S	S	S
Sabzevar	187	1012	19	196	A.I.S	S	S	C.A	C.A
Kerman	148	841	16	340	C.A	S	S.A	A.I.S	A.I.S
Seh Galeh Sarayan	164	784	10	786	S	A	S.A	A	A
Yazd	45.6	1284	7	66	A.I.S	A	A	A.I.S	A.I.S
Fully Active%					66	31	42	64	
Semi-active%					34	–	43	33	
Stabilized%					1	69	15	3	

A: Active dunes; S.A: Stabilized and Active (semi-active); C.A: Crest Active; A.I.S; Active dunes, interdunes Stabilizes; S: Inactive and Stabilized dunes:

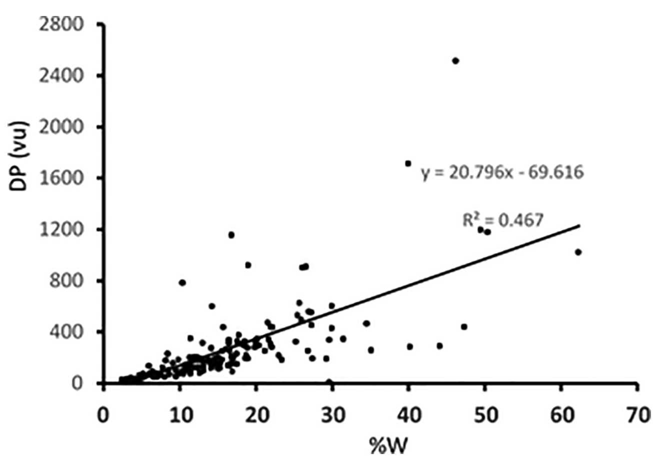

Fig. 10. Relation between sand drift potential (DP) and the percent time wind above transport threshold (W) in selected meteorological stations in Iran.

high wind energy, the percentage of winds above threshold was rather low, as high speed winds only occur during the warm season, while the rest of the year is characterized by calm weather (Maghsoudi et al., 2013).

The nature of the wind power parameter varies from the LMI (W%) to the TMI and YMI (DP). DP reflects the quantity (frequency) and quality (intensity) of the wind power, but W% only shows its quantity (frequency of winds above the transport threshold). It seems that if DP was used in the LMI instead of W%, it would provide more favorable results. In addition, the statistical analysis (correlation coefficient) between DP values and the percentage of wind events above the transport threshold (%W) at the meteorological stations in the study area (Fig. 10) shows a moderate correlation ($r^2 = 0.47$).

Based on this argumentation, W% has been replaced by the sand drift potential (DP vu) as the wind energy parameter in Lancaster mobility index (1988), as seen in Equation (12).

$$M = \frac{\mathrm{DP}}{P/PET} \tag{12}$$

where M is the mobility index, DP is the annual sand drift potential in vector units based on Fryberger and Dean (1979) (Eq. (10)), P is the annual precipitation in mm, and PET is the annual potential evapotranspiration estimated from Thornthwaite's (1948) method in mm/yr.

The result is a Modified Lancaster Index (MLI). In order to group the index results into four distinct mobility classes, extensive field observations and expert interviews were used to identify the class thresholds which is outlined in the rightmost column in Table 4. Based on this Iranian ground data, dunes are fully active when M exceeds 3,000; active dunes with stabilized interdunes areas are found when M lies between 1,500 and 3,000; stabilized dunes with activity only at the crests can be related to an M between 750 and 1,500; and completely stabilized dunes occur when M is < 750. Lancaster and Hesse (2016) further developed the MLI for their mapping of the global digital dune activity and categorized dunes into the four classes active, partly active, inactive and degraded.

Table 3 compares the results of the MLI with the other three indices and shows that dunes in the Sistan plain, Zirkuh Qaien, the whole of the Lut desert, and some parts of the Yazd, Khuzestan and Dasht-e Kavir deserts are fully active (Fig. 11). These results are confirmed by the LMI and YMI and in parts by the TMI. But there are also some differences in the northern part of the Dasht-e Kavir desert (Damgan and Foromad), the central part of the Rig Boland (Jangle Badroud and Naien), Seh

Table 4
A summary of present conditions of dune activity in Iran.

Deserts or Sand dunes names (weather station)	Present conditions of dune activity	MLI*	Reference
Sistan (Zabol)	Fully active crescentic and sand sheets	A	Abbasi et al. (2019)
Lut, Yalan (Nosratabad)	Fully active barchans and liners	A	Field observations
Lut, Yalan (Dehsief)	Fully active sand sheets and Nebkhas	A	Yazdi et al. (2014), Field observation
Lut, Yalan (Shahdad)	Fully active dunes into and margin of Yardangs	A	Ehsani and Quiel (2008), Field observation
Lut (Rigan)	Fully active barchans	A	KNRWMO (2016),(Heidari et al. 2017)
Bafg	Fully active barchanoid and transverses dunes	A	Ahmadi, et al. (2001)
Deyhook	Fully active crescentic and topographic dunes	A	Field observation and expert interviews
Jazmorian (Bampoor)	Inactive and stabilize liner dunes	A	Field observation and Abbasi (2012)
Jazmorian (Kahnouj)	Fully active barchans and liner dunes	A	Field observation and Abbasi (2012)
Booshroyeh	Inactive transverse dunes	S	Expert interviews
Rig Boland (Aran Bidgol)	Inactive barchans	S	Ahmady Birgani et al. (2017) and Field observation
Dasht-e Kavir (K.Mazinan)	Active sand sheets, interdunes stabilizes	A.I.S	Expert interviews
Khartoran (Ahmadabad)	Active barchans and transverse dunes, interdunes stabilizes	A.I.S	Mashhadi et al.(2007) and Field observation
Dasht-e Kavir (Foromad)	Fully active topographic dunes	A	Field observation and expert interviews
Hasanabad (Damgan)	Fully active barchan dunes	A	Field observation and expert interviews
Khuzestan (A.Mousian)	Fully active sand sheets	A	Field observation and Abbasi (2012)
Khuzestan (Bostan)	Active sand sheets and transverse , interdunes stabilizes	A.I.S	Field observation and Rouhipour (2006)
Khuzestan (Ahvaz)	Crest active liner dunes	S	Rouhipour (2006)
Ilam (Mehran)	Active sand sheets	A	Field observation and Abbasi (2012)
Rig-e Jinn (Chopanan)	Active liner dunes, interdunes stabilizes	A.I.S	Field observation
Coastal dunes (Jask)	Fully active sand sheets	A	Ekhtesasi and Dadfar (2014)
Rafsanjan	Active barchans, interdunes stabilizes	A.I.S	Field observation and expert interviews
Gonabad	Inactive and stabilizes by vegetation	S	Field observation and expert interviews
Sabzevar	Crest Active, plinths Inactive	C.A	Field observation and expert interviews
Kerman	Artificial stabilized by vegetation	A.I.S	Field observation
Seh Galeh Sarayan	Active topographic dunes	A	Expert interviews
Yazd	Active dunes. interdunes stabilizes	A.I.S	Ekhtesasi and Sepehr (2009)
Sarakhs	Sand sheet vegetated	C.A	Field observation
Dasht-e Kavir Deseret, north of Rig-e Jinn (Hosseinan)	Fully active dunes	A	Expert interviews
Zirkuh Qaien (Khaf)	Fully active barchans, artificial stabilized	A	Field observation and Tavakoli (2002)
Shotoran (E. Dastgardan)	Active liners, stars and barchans	A	Field observation and expert interviews

* MLI: Modified Lancaster Index, A: Active dunes; C.A: Crest Active, plinths stablize ; A.I.S; Active dunes, interdunes Stabilizes; S: Inactive and Stabilized dunes

Galeh Sarayan, Kerman, Bejestan and Gonabad dune fields, and the southeastern part of Rig-e Jinn (Chopanan) as seen in Fig. 12.

Regarding MLI results, the dunes in the northern part of the Dasht-e Kavir deserts (Damagan and Foromad) are fully active, with 1159 and 475 v.u DP, as observed in the field as well as in expert's interviews, while LMI and TMI classified these dunes as semi-active. In addition, the dunes in the central Rig Boland sand sea (Jangle Badroud and Naien) are semi-active, with 195 and 285 v.u DP, while the LMI see them as fully active. This result matches with own field observations and with Ahmady Birgani et al. (2017) studies that showed only > 200 ha/yr were added to the eastern part of Rig Boland sand sea and that there is no encroachment in the north and western parts. The northern part of Rig-e Jinn, near the Hosseinan weather station in the central Dasht-e Kavir desert, has been classified as fully active by the MLI, but it decreases to semi-active in the southern part (Chopanan) due to a low wind energy, while the LMI categorized it as fully active. The results of activity classification in Seh Galeh Sarayan dunefields based on MLI and LMI are also completely different as the MLI classified it as fully active while the LMI categorized it as stable (Table 3) because the percentage of wind events above the transport threshold is low (10%) in spite of high DP (786 v.u).

Totally, the results show a good relationship between the dune activity and these climatic parameters for the Iranian deserts, especially in the north of the Dasht-e Kavir desert and in the Kerman and Seh Galeh Sarayan dune fields, where the model agreement was better than for the other three mobility indices.

4. Conclusions

The stabilization of dunes has been a major objective of anti-desertification programs over the past half-century in Iran (Amiraslani and Dragovich, 2011). Accordingly, the identification of areas with active dunes is of paramount importance in prioritizing the monitoring and stabilization efforts. Such an approach, however, requires suitable models on a national scale. With regards to this objective, the wind energy environment based on DP and three more commonly used dune activity models were evaluated in and around Iran's deserts. The comparison of the models showed that the Lancaster and Yizhaq models yield very similar results except for those cases in which percentage of times of winds above the transport threshold (W%) isn't following the DP, e.g. in the north of Dasht-e Kavir and in the Seh Galeh Sarayan dune fields. By combining both approaches, a modified Lancaster mobility index, based on DP, precipitation and potential evapotranspiration was used with good results. The spatial variation of the wind energy, based on the sand drift potential, has changed from high to low in the Iranian sand dunes. According to this variation of DP, precipitation and potential evapotranspiration, the dune activity in Iran shows large spatial variations on a national scale.

From common points of results, four models classified dunes in Sistan plain, whole of Lut desert, Zirkuh Qaien and Deyhook as fully active and in the northern and western part of Rig Boland, Booshroyeh and Neyshabor dunefields as stabilized dunes. For other dunes, there are obvious differences in activity classification, at least between the TMI and two other models. The highest similarities were found between the LMI and MLI, followed by the Yizhaq model.

As the meteorological stations are not homogeneously distributed across Iran's deserts, and are far away from the dune fields e.g. in the central part of the Lut and Dasht-e Kavir, the assessment of the dune activity requires complementary field observations, as was already pointed out by Bullard et al., (1997).

It seems that further studies are needed to consider different climate change scenarios to prediction sand dunes activity in Iran.

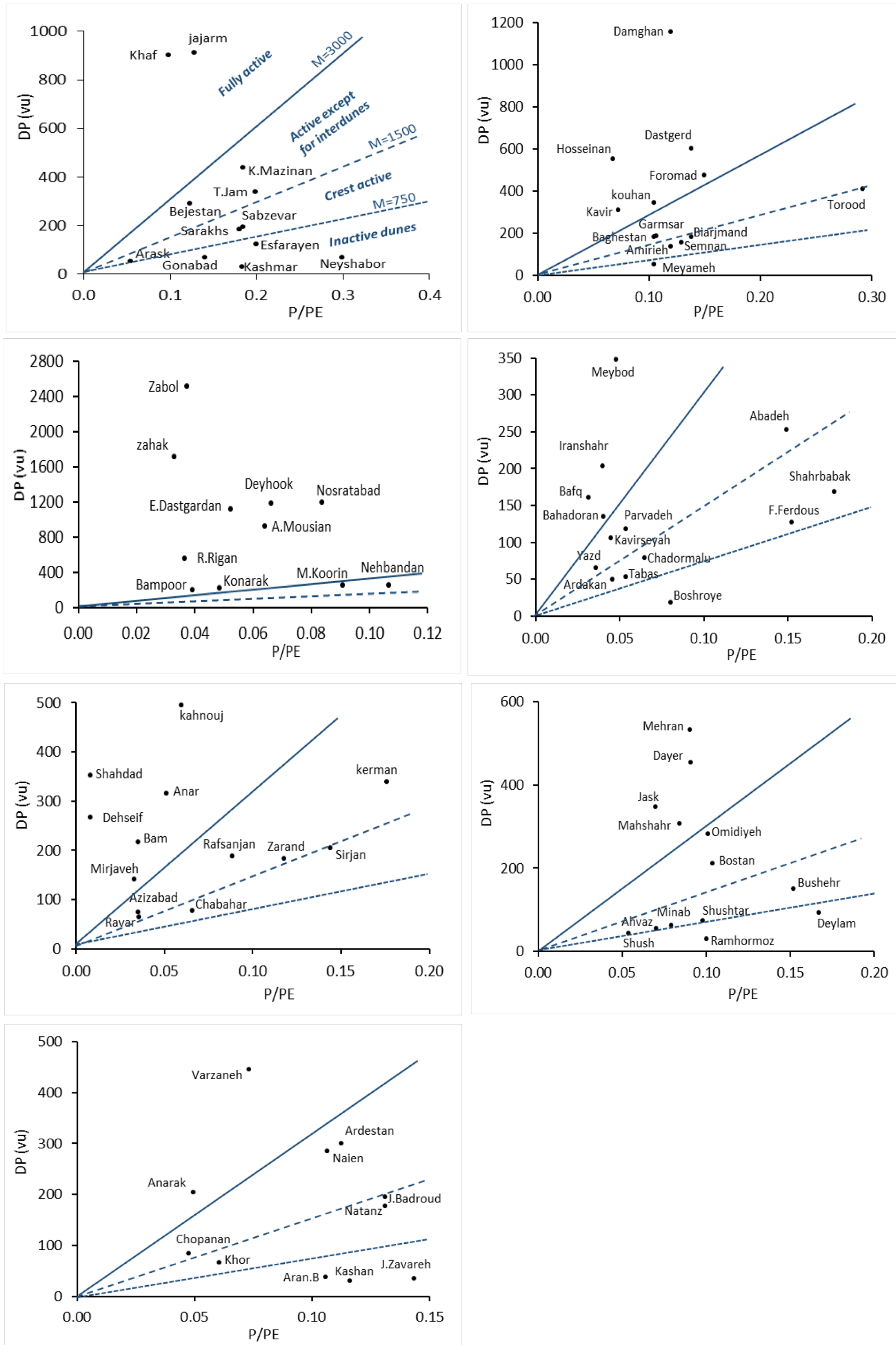

Fig. 11. Dune field mobility index values based on the Modified Lancaster Index (MLI) in Iran's deserts.

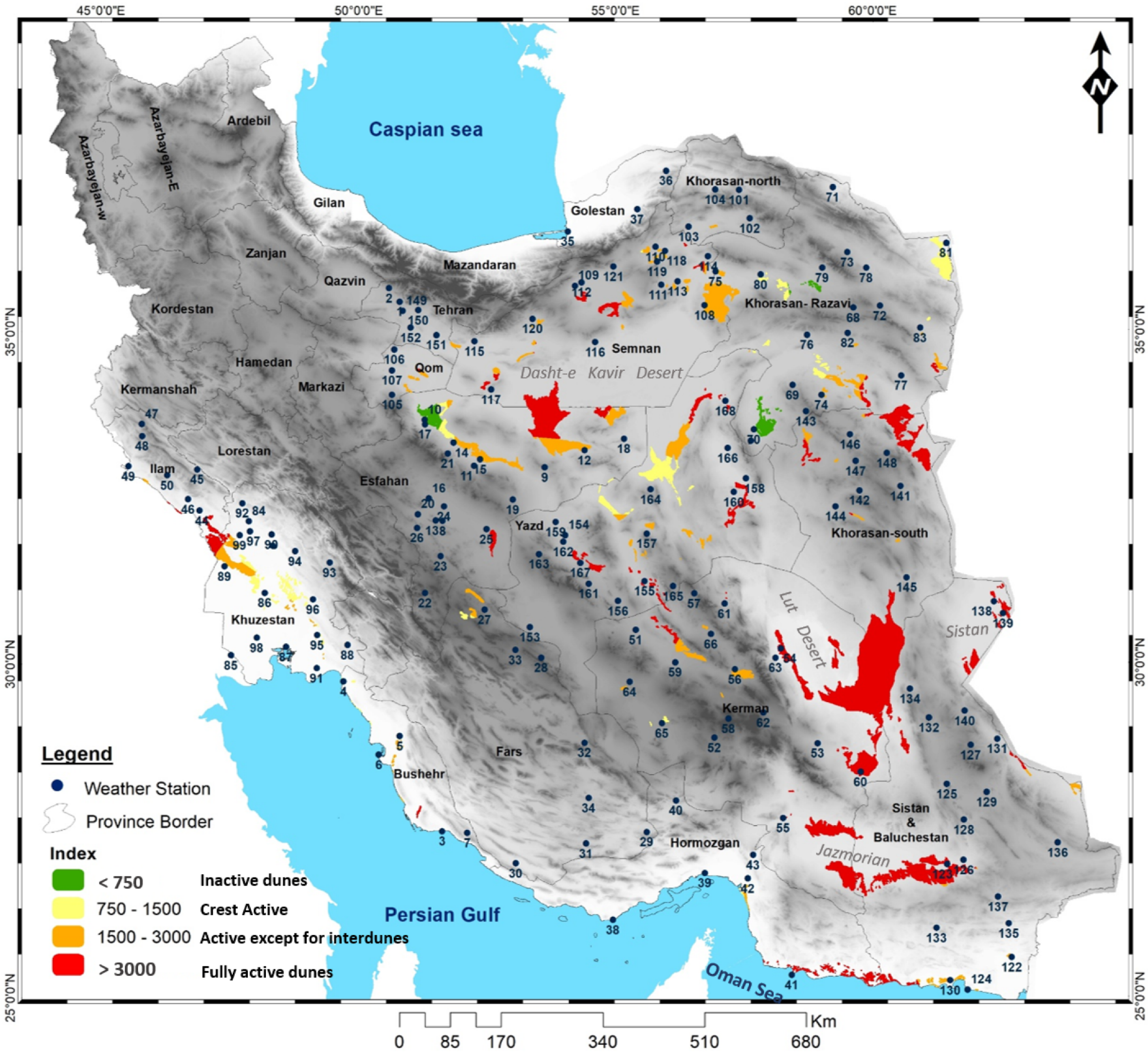

Fig.12. Sand dune activity in Iran based on the Modified Lancaster Index (MLI).

Acknowledgments

This work has benefited from access to the Iran Meteorological Organization database. The authors gratefully acknowledge Dr. Victor Miguel Ponce in San Diego State University, who provided an online calculator for the potential evapotranspiration using the Thornthwaite method on his website:

http://ponce.sdsu.edu/onlinethornthwaite.php.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aeolia.2019.07.005.

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