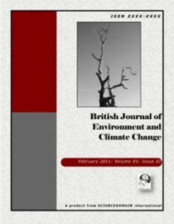

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Desertification Inherent Status Using Factors Representing Ecological Resilience

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Authors' contributions

This work was carried out in collaboration between all authors. Author AS designed the study, performed the statistical analysis, provided the maps, wrote the protocol and wrote the first draft of the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

In this research, desertification hazard has been analyzed by resilience range over eastern north of Iran. In this research was assumed that resilience of ecosystem refers to inherent properties of ecosystem. Soil erodibility, rainfall erosivity, topography and land cover- a reflection of land-use management- are assumed as representative factors of resilience range in this study. In order to calculate resilience range an integrated map was developed based on the combination of erodibility, erosivity and slope factors. Ultimately desertification vulnerability was estimated by multiplying resilience range and land cover into resultant maps. Results indicated that about 44% of study area is fragile ecosystems with high desertification vulnerability. Also the results showed that vegetation cover has main role to increase resilience potential of ecosystem to response perturbations.

Keywords: Resilience; desertification vulnerability; erodibility; Khorasan Razavi.

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1. INTRODUCTION

Desertification can be seen as a catastrophic change of the ecosystem, which gradually turns the green land to dry, barren and desert land. Desertification is the consequence of natural and anthropogenic impacts triggering catastrophic ecosystem [1]. In desertification studies distinguishing between vulnerable and resistant regions is important to manage desertification process and to run risk-crisis management. The assessment of desertification vulnerability requires the evaluation of different parameters and factors such as the type of element at risk, resistance, and implemented protective measures. Several research articles reviewed the concepts related to desertification assessment [2,3,4], and a number of assessment methods have been developed (e.g.: [5,6,7,8,9,10]). Also we can find many studies applied in recent decades to develop desertification indicator system such as EFEDA, MEDALUS, MODMED, MODULUS, MEDACTION, DESERTLINKS, the more recent DeSurvey, and several others [11].

The ability of an ecosystem to resist desertification and environmental perturbations can be defined as "*resilience*" potential of the ecosystem. Currently, resilience is defined as the capacity of a system to absorb disturbance and re-organize while undergoing change so as to retain essentially the same function, structure, identity and feedbacks [12]. Resilience is a critical concept in contemporary ecology and has been applied at the local, regional, and global scale, providing a useful framework for conceptualizing emergent behavior and in understanding complex responses to environmental change [12,13].

Since the seminal work by Holling (1973, 1986), resilience has become an issue of intense conceptual debate amongst ecologists. The literature provides many perspectives and interpretations of ecological resilience Alternative definitions have been provided, focusing on different system properties. For example, Pimm (1984) defines resilience as the speed with which a system returns to its original state following a perturbation. Irrespective of its definition, many ecologists argue that resilience is the key to sustainable ecosystem management and that diversity enhances resilience, stability, and ecosystem functioning (e.g.: [5,10,14]).

In (Fig. 1), an ecosystem has been presented as a ball in the valley. The depth of the valley reflects the degree of the ecosystem resistance to perturbations. This is consequence of ecosystem resilience range. In state 1, the valley is deep and the ecosystem has high resilience. With the start of the perturbations, the equilibrium level changes, with a loss of ecosystem resilience, and the resistance declines (states 2, 3). Ultimately the ecosystem, to escape this situation, finds a new equilibrium point (state 4). The new point has similar equilibrium conditions to the previous ones, but corresponds to the emergence of a new landscape in the ecosystem. This new landscape could be an undesirable state for human, such as a desert state.

Semi arid and arid ecosystems are fragile environments and have low resilience range to respond perturbations and maintain equilibrium. Various authors have argued that conceptions of equilibrium ecological dynamics are not relevant for semi arid systems (e.g.: [12,15,16,17]). Such authors argue that these systems display "non-equilibrium" behaviour [16,18,19,20]. For example, frequent droughts prevent livestock populations from growing large enough to reach or exceed equilibrium with their fodder resources due to drought-induced mortality in cattle herds [21].

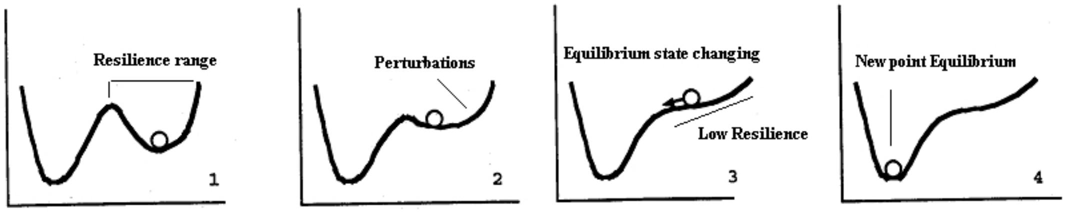

Fig. 1. The shift of ecosystem is consequence of resilience changes and emergence of new equilibrium point (After 22 with changes)

In this article, we assume that the formation of a "*desertified*" state is in relation to the resilience of the ecosystem and considered soil erodibility and climate erosivity to distinguish vulnerable areas towards desertification.

2. MATERIALS AND METHODS

2.1 Study Area

According to the global desertification vulnerability map presented at the 1: 5'000'000 scale (USDA-NRCS, 1995), the high vulnerability regions of the world are mainly located in the arid zone belts of Middle East countries. Iran, with more than 85% arid and semi-arid areas, includes wide range of ecosystems types, characterized by high vulnerability to desertification and soil degradation processes. The study has been conducted in the Khorasan Razavi province, including the second metropolitan city of Iran, Mashhad. This province is one of the regions at high erosion risk in Iran. The studied area covers about 128'430 square kilometres and is approximately located between East longitude 55º 17' to 61º 15' and between North latitude 30º 24' to 38º 17' (Fig. 2). More than 60% of the province includes desert and semi-desert areas. Thirteen cities are completely located in desert area, or a part of them is desert, and are characterized by difficult living conditions. It has low rainfall (about 210 mm/year) and extremely low vegetation cover. Typical vegetation formations are various species of Artemisia, Astragalus, Stipa, Luctuca, Festuca and Amygdalus. Clay plains (Dagh in Persian), playas, salty land and moving sand dunes are widespread morphologies. The most widespread soil types are aridisols, entisols, lithosols and rigosols. These conditions are high vulnerable to wind and water erosion, and prone to desertification.

2.2 Methodology

The objective of this study is defining and testing a method of desertification vulnerability mapping based on the ecosystem resilience range concept by means of erodibility and erosivity assessment. The methodology consisted in evaluating four diagnosis indices: *erodibility, erosivity, topographic and soil protection*. For choosing criteria and indicators of desertification vulnerability considering resilience changes, reference was made to two well known international methodologies for soil erosion prediction: COo Rdination of Information on the Environment (*CORINE*) and Universal Soil Loss Equation (*USLE*). Both methods operate in a raster GIS environment. The approach applied was developed as an equation of the main factors affecting ecosystem resilience, namely climate, soil characteristics, topography and land cover management.

More specifically, the model is expressed by the following formula 1 and 2:

The Resilience Potential (Sustainability range) = Soil Erodibility * Erosivity * Slope (1)

Vulnerability Degree = Resilience potential * land Cover (represent Land-use) (2)

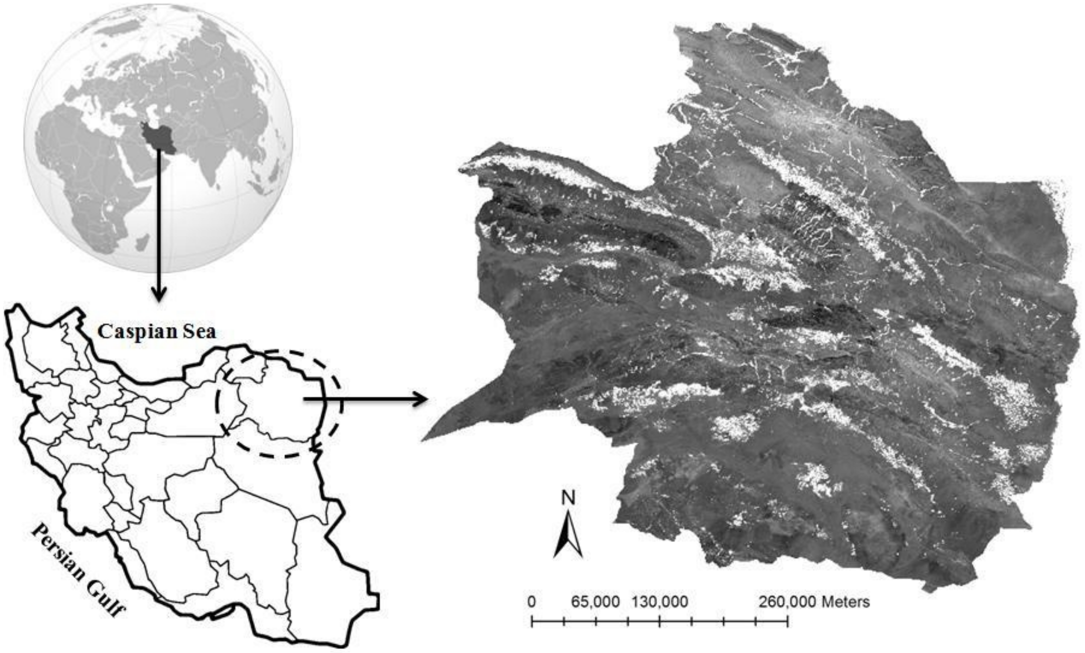

Fig. 2. The location of Khorasan Razavi province in the north east of Iran with more than 60% semi-arid land. The map obtained from MODIS satellite data

Resilience Potential is defined as the inherent susceptibility of the soil to water erosion, irrespective of vegetation cover or land-use. The vulnerability index relates to the resilience potential under present vegetation and land-use conditions. It is derived by modifying the estimated resilience potential index according to the vegetation cover. To estimate ecosystem resilience and ultimately desertification vulnerability, the required database parameters are soil erodibility, erosivity, topography (slope), and land cover (vegetation cover). In this study as land-use management leads to land cover viability, the land cover state was considered as a representation of land-use. The parameters are represented as separate indices, which are then combined (Fig. 3).

2.3 Data Analysis

The primary data set of climate included monthly rainfall and temperature values recorded from 1975 to 2013 from 10 climate synoptic stations in the region by the National Centre of Meteorology in Khorasan Razavi province. Two indices related to climate are considered to influence the overall climatic “erosivity”: the *Fournier index* (FI) defining erosivity *sensu stricto*, and the *Bagnouls–Gaussen index* (BGI), as a measure of drought conditions. FI [6] is calculated by the formula given below (3):

$$\sum_{i=1}^{12} \frac{Pi^2}{P} \tag{3}$$

where Pi is the total precipitation in (i) month (mm) and P is the annual average total precipitation (mm). BGI [6] is calculated by the formula given below (4):

$$\sum_{i=1}^{12} (2ti - Pi)Ki \tag{4}$$

where t_i is the monthly average temperature value in the (i) month (ºC), Pi the total precipitation in (i) month (mm), and ki the number of months when (2ti – Pi>0).

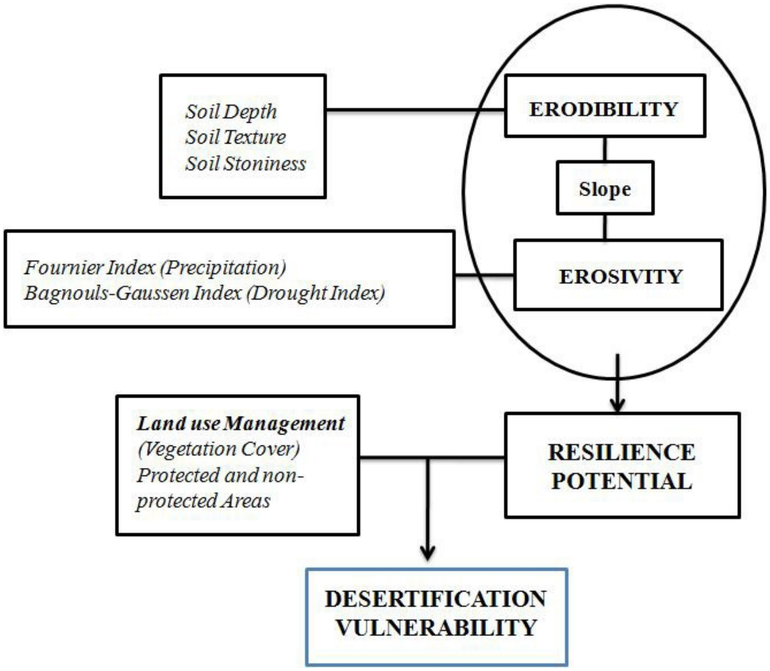

Fig. 3. The methodology used to assess desertification vulnerability. Lower case: single indices; upper case: combined indices

The FI and BGI maps were obtained by interpolating the FI and BGI indices calculated at multiplying stations by means of ARCGIS software and its extensions (3d analyst and spatial analyst), which have been used to make the required data processing during this study. The erosivity map was made by integrating the FI and BGI indices. The FI and BGI maps were classified into respectively 3 and 4 classes as shown in (Table 1). The maps of the obtained qualitative scores were then multiplied based on the multiplying algorithm in GIS environment to obtain the erosivity map. The latter was classified into four classes as shown in (Table 2). The erodibility map was made by integrating the texture, depth, and stoniness indices by means of a similar approach. The output was classified in three classes.

To extract data of soil parameters, the soil map of study area at the 1: 250,000 scale provided by research center of soil conservation (RCSC) was used. After generating soil parameters maps (texture, depth and stoniness), the data were refined by comparing with soil samples collected from 70 plots of known locations using GPS in the study area. The soil properties were analyzed in the soil laboratory of the college. The obtained texture, depth, and stoniness maps were classified into 3 classes as shown in (Table 3), and the scores were then multiplied to obtain the erodibility map. The latter was classified into three classes as shown in (Table 4). The sampling points' distribution in the study site is established according to the cross-sections of 10 km * 10 km grids. Bulk soil samples were dried at 105ºC for 24 h for finding oven dry weight, given as g/l. The texture of the soil was determined by Bouyoucous hydrometer method. Soil textural classification was determined according to international particle size taxonomy and the final database provided to prepare the maps in GIS. As a result of this analysis, an average soil erodibility parameter has been determined for each soil polygon.

Table 1. Classes of FI and BGI for the study area

Class	Fournier index (FI)	Bagnouls-gaussen index (BGI)
1	<40	<10
2	40-80	10-50
3	80-120	50-90
4	>120	>90

Table 2. Erosivity classes using integrating FI and BGI by multiplying algorithm

Erosivity class	Weight range	Severity class
I	<4	Low
II	4-8	Moderate
III	9-12	High
IV	>12	Very High

Table 3. Erodibility classes based on the multiplied layers

Soil Class	Texture	Soil depth	Stoniness
1	C, Sc, Sic	>70	>25
2	SCL, CL, SiCL, LS, S	30-70	10-25
3	L, SiL, Si, SL	<30	<10

Table 4. Erodibility classes based on the multiplied soil properties data

Erodibility class	Weight range	Severity class
I	<4	Low
II	4-12	Moderate
III	>12	High

One of the key factors in soil loss is topography, especially, when the ground slope exceeds a critical angle [23]. Topographic maps at the 1:25000 and 1:50000 scales have been used as main data sources to create the digital elevation model (DEM) of the studied area. The slope layer has been generated from DEM data and classified into 4 classes as shown in (Table 5).

The layers of soil erodibility, erosivity and slope were combined to produce the ecosystem resilience map, by multiplying their scores. This map was classified into 3 classes (Table 6).

The land cover in this research was developed based on the land-use map prepared by Natural Resources Organization (NRO) of the Khorasan Razavi province at the 1: 250,000 scale, based on the ETM+ imagery data. The land cover map reflects land-use management and vegetation cover. The classification of land cover was made by emphasizing protected and non-protected areas according to the land cover types (Table 7).

Table 5. The slope classes generated by DEM layer of the study area

Slope class	Slope %	Degree
I	<5	very gentle to flat
II	5-15	gentle
III	15-30	steep
IV	>30	very steep

Table 6. The ecosystem resilience classes of the study area

Resilience class	Weight range	Resilience potential
I	< 6	high resilient
II	6-16	moderate resilient
III	> 16	low resilient

Table 7. land cover classification based on the vegetation type status as an evidence for resilience

Land cover type	Protection role	Quantitative class
Forest and good pastures	Fully protected	I
Cultivated areas and scattered cover	Semi-protected	II
Desert, Playas, Sebkha, Bare lands	Non-protected	III

Ultimately the vulnerability of desertification was mapped by multiplying the inherent resilience potential map the land cover map. This final map was classified into 3 classes (Table 8).

Table 8. The desertification vulnerability classes by multiplying resilience and land cover layers

Desertification class	Weight range	Desertification vulnerability
I	<3	Low
II	3-6	Moderate
III	>6	High

3. RESULTS AND DISCUSSION

The obtained maps (erosivity, erodibility, slope, resilience potential, land cover, and desertification vulnerability are shown in (Fig. 4). The results indicated that about 55% areas of studied region have high erosivity and that 85% are highly erodible (Table 9). In the study area, the soils are very shallow. These conditions, together with the low stoniness percentage determined the high erodibility of the soils.

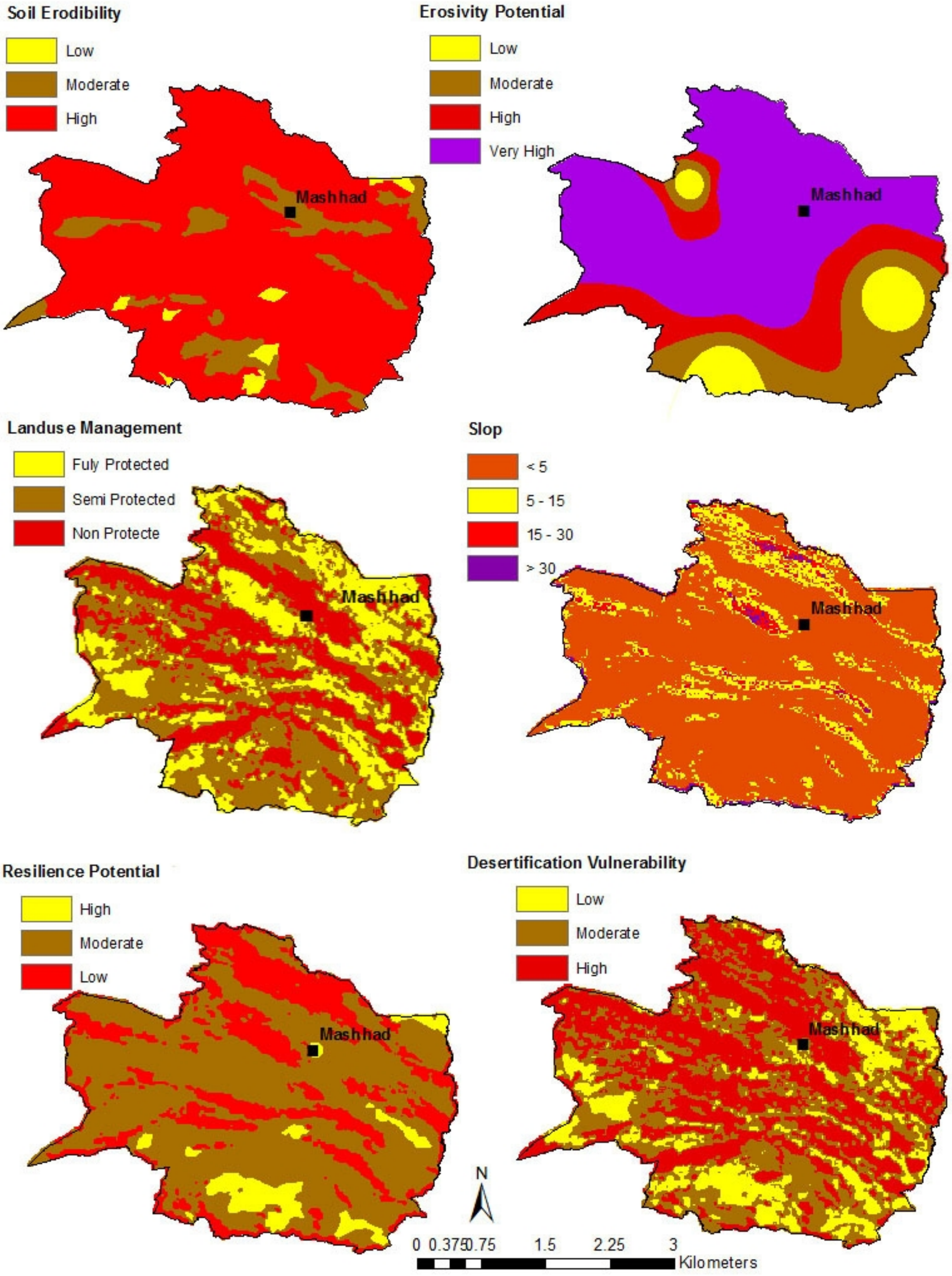

Fig. 4. The desertification vulnerability map by integrating layers of erodibility, erosivity, slope, land management and resilience potential in the study area

Table 9. Quantitative and qualitative classes of erodibility, erosivity and slope for the studied area ecosystem

Erodibility		Erosivity		Slope	
Class	**Area (%)**	**Class**	**Area (%)**	**Class**	**Area (%)**
Low	1.93	Low	7.83	< 5	81.46
Moderate	12.68	Moderate	18.22	5 – 15	16.28
High	85.38	High	18.87	15 – 30	2.04
		Very High	55.07	> 30	0.22
Total	100		100		100

On the other hand, if the slope factor is considered, about 98% of the study area has flat to gentle slope (less than 15%), which may significantly increase the potential soil and ecosystem resilience in relation to perturbations. The resilience potential of the study area is low (25% of the area) to moderate (69%), as shown in (Table 10). Vegetation cover is the most crucial element to increase the inherent resilience of ecosystem, since it is the only factor that can readily be altered by land-use, and directly influences soil vulnerability. In the study area, 34% of the land is not protected (bare lands, desert and playa), and about 40% is poorly protected (agricultural lands and open areas). Only less than 26% of the study area is protected by forest and conservation policies (Table 10). Ultimately the desertification vulnerability map indicated the overall high vulnerability in the studied area. More than 40% of the ecosystem has been categorized in high vulnerability class. About 36% is moderately vulnerable to desertification and only 19% has low vulnerability.

Table 10. Desertification vulnerability of the studied area based on inherent resilience of ecosystem and vegetation cover

Land cover		Resilience potential		Desertification vulnerability	
Class	**Area (%)**	**Class**	**Area (%)**	**Class**	**Area (%)**
Fully protected	25.8	High	5.96	Low	19.32
Poorly protected	40.27	Moderate	69.46	Moderate	36.86
Non Protected	33.92	Low	24.58	High	43.82
Total	100		100		100

In the study area the precipitation gradient (Fig. 5) determines a natural diversity, and different ranges of ecosystem resilience and susceptibility to desertification. Based on the rainfall oscillation, a wide range covers the study area from desert landscapes to forest ecosystems. Resilience increases with elevation over gradients of available resources and net productivity (vegetation density), along with more rapid recovery potential after disturbance, increased capacity to compete with invaders, and less degradation. From homogeneous ecosystems (desert) towards heterogeneous ecosystems (green landscapes), we are seeing an ascending trend in the resilience potential.

Also in relationship between the variety of the ecosystems and desertification vulnerability map, it is perceptible that there is a positive correlation between high resilience ecosystems and desertification vulnerability level. Surely desert landscape and low resilience ecosystem show high desertification vulnerability, in other hand green states indicate low vulnerability in the province.

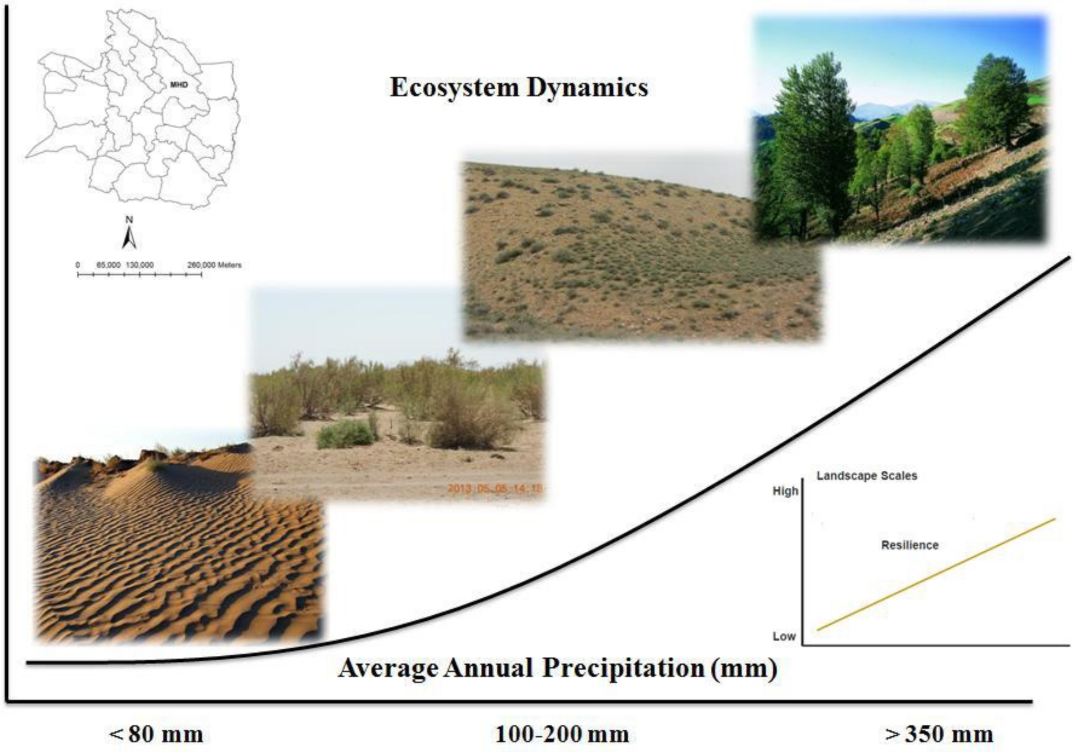

Fig. 5. Ecosystem dynamics in the study area; a consequence of the precipitation fluctuations

According to the soil erodibility map, the ecosystem of the studied area is very fragile. In other words, the high sensitivity of soil to be degraded by erosion implies the low resilience of the area. The most appropriate means to increase the soil resistance against erosion refer to methods for increasing vegetation. By far the most cost-effective way of doing this is land-use management. Restoration also has both significant advantages; however, it is expensive and brings solutions in the long term.

As vegetation cover increases the resilience range of the ecosystem, if, as an example, land-use is changed towards a forest, it provides greater ground cover and increase the ecosystem ability to resist desertification. In this condition, an ecosystem could more easily return to the original state after an environment perturbation, and the recovery time for this ecosystem is shorter. Substantial changes in land-use are occurring in the study area, particularly in the fragile ecosystem, involving grazing pressure and land degradation. Rangeland ecosystems of the study area are being exploited by grazing. This intensity and pressure is having a significant impact on desertification vulnerability. For example, many northern pastures of the province with non-protected conditions show a low resilience state with high susceptibility to desertification process. This topic is highlight in parts with high grazing pressure.

(Fig. 6) shows a fragile ecosystem of the studied area, where a road cut generated a sharp change of the slope angle, locally increasing erosion and changing the vegetation pattern. This pattern change reveals a low resilience with minimum resistance to desertification.

These conditions caused a non-equilibrium state in the ecosystem. We can express based on the used methodology that the high erodibility and high erosivity conditions determine non-equilibrium state in the ecosystem. When an ecosystem is sensitive and near to the tipping point (critical threshold), a small brunt (such a slope change, or grazing density) could changes equilibrium condition in the ecosystem and its vegetation pattern dynamics. When such thresholds are crossed, an ecosystem does not return to the original state via natural processes following disturbance, and requires active management to recover. So the shift from green state to desert landscape can be described in these terms.

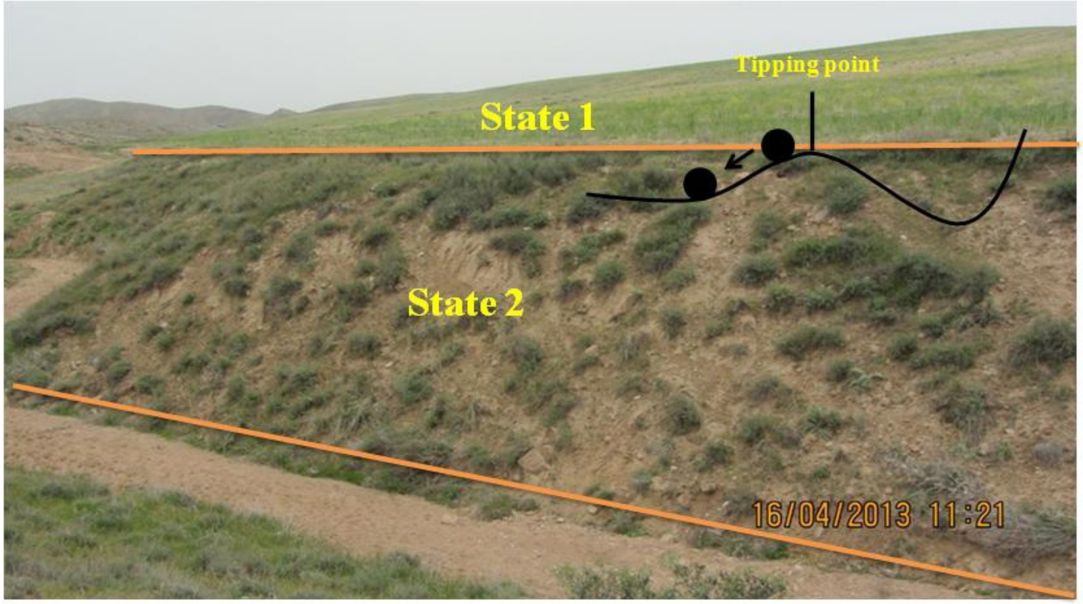

Fig. 6. The high vulnerability generated by a local sharp change in slope angle and the lack of protection of vegetation cover

The comparison of our results with previous studies (e.g.: [24]) indicates that main reason of the high desertification vulnerability in the studied area is overexploitation of the rangelands capacity and vegetation degradation by grazing pressure and land-use changes. According to the report of Natural Resources and Watershed Management Organization of Khorasan Razavi (2009), about 70% of animal unit of province is over pastures capacity. This force has been lead to desertified landscape appearance, soil degradation and decreasing biological production in recent years. Also, field investigations confirm the role of grazing pressure on degradation and accelerated desertification in province. In typical study area conditions, the ecological changes that have been brought about by grazing can be linked with more fundamental changes in ecosystem function.

4. CONCLUSION

In this research has been investigated the vulnerability degree of ecosystem to desertification based on resilience range which was referred to erodibility and erosivity potential according to the topographic conditions. By integrating soil erodibility, climate erosivity, and slope layers, the potential resilience map was generated and due to this map there is a low resilience in the ecosystem of the study area. The high leveled desertification vulnerability area decreases when it is protected by vegetation cover which also indicates the effect of vegetation cover. Results indicated that about 44% of the ecosystem area is susceptible to desertification where recovery potential has long period in consequences of low resilience. A basic approach for managing and restoring these ecosystems using the concepts of resistance and resilience is recommended. Results indicated low resilience influenced by high grazing and overexploitation of the ecosystem. Development of an understanding of ecological resistance and resilience and relationship to thresholds for the prone ecosystems to desertification is suggested.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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