



Impacts of environmental and human factors on desertification-induced land degradation in arid areas

Ahmad Entezari Zarch¹ · Hassan Ahmadi² · Abolfazl Moeini¹ · Ebrahim Pazira³

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Abstract

Land degradation is often negatively exacerbated by anthropogenic processes. This phenomenon threatens food security and economic welfare. The purpose of this study is to evaluate the extent of land degradation in Yazd-Ardakan Plain, central Iran, to identify the most prominent criteria contributing to the degradation. The Iranian model of desertification potential assessment (IMDPA) with 9 criteria and 36 sub-criteria was employed for this purpose. Accuracy of the results was confirmed by the results of Spearman's and Mann–Kendall's non-parametric tests in terms of significance levels and a Kappa coefficient of 0.61, ending up with an overall validity of 81.7% for the desertification map. The results showed that 67% (mainly rangelands) and 33% (mainly residential lands and surrounding areas) of the study area were potentially exposed to moderate and severe desertification, respectively. The vegetation coverage, groundwater, and climate were found to be the main factors controlling the desertification severity across the region. The human factor was seen to impose, directly and indirectly, the greatest impact on the environmental conditions and land degradation. Focusing on the study area, several management strategies were found to be necessary for avoiding the risk of desertification and rather controlling the factors contributing to desertification phenomenon in an attempt to maintain the current status rather than letting it get even worse in areas exposed to low, moderate, severe, and very severe risks of desertification.

Keywords Criteria · Sub-criterion · Desertification · Management strategy · Yazd-Ardakan Plain

Introduction

Land degradation is a gradual process that is known to be intensified by human activities. Due to its gradual nature, it takes time for obvious symptoms of the land degradation to appear and hence gain attention from practitioners. In the meantime, one may not overlook the role of climate change in land degradation and desertification. Changes in

precipitation, land surface temperature, and soil moisture play significant roles in decreasing the vegetation growth and hence soil conservation while increasing barren vegetation and runoffs (Constantinidou et al. 2020; Tolba et al. 2020).

Pressure on land is associated with increasing population, changing lifestyles, escalated demand for water and energy, wars, improper land use strategies, poor technology, etc. (Abahussain et al. 2002). Regardless of its cause, land degradation imposes negative impacts on the food security, economic welfare, and environmental conditions (Biancalani et al. 2013). Changes in soil structure are primarily attributed to changes in vegetation structure. This causes a chain of reactions, with smaller input of organic matter (OM) to soil, decreased microbial biomass and activity, lesser macro-aggregation processes, etc. Erosion reduces soil fertility and water content, consequently lowering the yield. Upon changes in soil structure due to soil degradation, chemical and physical properties of soil suffer. These include water infiltration intensity, soil water content, soil OM, soil organisms, soil depth, soil production capacity, and soil quality.

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✉ Hassan Ahmadi
ahmadi@ut.ac.ir

¹ Department of Forest, Range and Watershed Management, Faculty of Natural Resources and Environment, Science and Research Branch, Islamic Azad University, Tehran, Iran

² Department of Reclamation of Arid and Mountainous Regions, Faculty of Natural Resources, University of Tehran, Karaj, Iran

³ Department of Soil Science, Science and Research Branch, Islamic Azad University, Tehran, Iran

Increased runoff on degraded soil tends to limit water infiltration and decrease plant growth and hence crop yield due to deficiency of key nutrients such as nitrogen, phosphorus, potassium, and calcium (Alexander 1978). OM is an essential component to soil and improves particular soil properties such as granulation, porosity, water permeability, structure, and soil production capacity. OM-induced increased water permeability facilitates cation exchange. As a result, root growth is improved and proliferation of soil organisms is accelerated. Much of the OM on the soil surface is sourced from leaf and stem decomposition, while topsoil erosion reduces the OM rapidly (Mojarad Ashena Abad and Rohani 2010). The lower the OM content of soil, the lower the count of organisms in the soil and hence the crop yield. In an arable land, drilling water wells to supply agriculture irrigation water regardless of relevant hydrological principles leads to significant drawdown of the water table and increased salinity of the groundwater and soil, greatly contributing to desertification and land degradation (Masoud 2020).

Desertification is a serious yet pervasive problem in many parts of the world, ignoring which might end up with harmful consequences in near future. It leads to the degradation and reduced fertility of land through expanding desert into non-desert areas and sand sheet movement. The problem of desertification is even worse in arid and semi-arid regions (Li et al. 2016). Researches indicate that over 125 million hectares of Iranian lands is affected by the desertification phenomenon. Moreover, about 90, 30, and 5 million hectares are affected by water erosion, wind erosion, and other desertification factors, respectively (Akbari et al. 2020a). Therefore, it seems necessary to evaluate the main causes of desertification in the country before proper management strategies for dealing with this phenomenon can be formulated. Measuring land resources and monitoring changes introduce the most direct approach to evaluating the degradation. In the early 1990s, attempts were made by the World Bank to monitor the land quality. The results, however, were highly controversial since the measurements were purely biophysical, largely ignoring economic and social sub-criteria, and the overall measurement errors exceeded actual changes in the resources (Batjes et al. 2014). Nowadays, many models, sub-criteria, and criteria are being developed and widely used around the world in order to investigate the factors affecting desertification and land degradation and formulate strategies to control or even reverse these phenomena. Each of these models has advantages and disadvantages over the others and account for a different set of factors and parameters depending on the area for which the model has been originally developed—this has made them region-specific models (Silakhori et al. 2019). Example of such models include UNEP-FAO (Pahlavanravi et al. 2013), ASSOD, GLASSOD (Kawy and Darwish, 2019), LADA (Garcia et al. 2019), MEDALUS (Pravalie et al. 2020), ICD, MICD (Kaviani et al. 2014), DMT (Turkes et al. 2020), and Iranian model

of desertification potential assessment (IMDPA) (Akbari et al. 2020b). Evaluating the land degradation in the Nile Delta, eastern Egypt, using the GLASSOD model, Mohamed et al. (2013) showed that the soil compaction, salinity and alkalinity, and exposure of water cycle to salinity are among the main contributors to land degradation across the region. Diving further into details, the land degradation is known to root mainly in anthropologic activities such as excessive irrigation, human involvement in the natural drainage, improper use of heavy machinery, and lack of soil conservation methods (Mohamed et al. 2013). Employing the MEDALUS model, Symeonakis et al. (2016) assessed the sensitivity to erosion and land desertification of rangelands in Iceland's islands, Europe, during 1990–2010. Information from the processes governing the study area showed that the vast majority of rangelands in this area have been susceptible to the desertification. The critical status of this region is mostly affected by human-induced factors in terms of population growth and groundwater quality (Symeonakis et al. 2016). Evaluating effectiveness of rangeland protection for reducing desertification using desertification sub-criteria of the IMDPA model, Rezaipoorbaghedar et al. (2015) figured out that this factor can positively contribute to combating desertification process through influencing some other sub-criteria (Rezaipoorbaghedar et al. 2015).

The main aim of the present study is to evaluate the state of desertification in Yazd-Ardakan Plain, central Iran. We further attempt to identify the most prominent criteria controlling the desertification in this area using the IMDPA model. This study is based on the hypothesis that empirical models (e.g., IMDPA model) can efficiently identify and discriminate the most important factors contributing to desertification and land degradation in arid areas. This will be valuable in compiling effective management strategies for land protection and controlling desertification in the region. Most of the relevant studies have considered multiple criteria independently and rather failed to consider them simultaneously to evaluate their combined effects. In this respect, simultaneous examination of all criteria and sub-criteria in the IMDPA model is a novelty of the present study. This was done to evaluate the capability of the model to accurately demonstrate the impact of human and environmental factors on intensification/alleviation of desertification. This study was carried out in Yazd-Ardakan Plain, Iran, in 2019.

Materials and methods

Study area

Yazd-Ardakan Plain is one of the largest and most important plains of Yazd Province, Iran. It is the most densely populated plain across the province. Due to the dominant climatic and geographical conditions of this plain, it suffers from

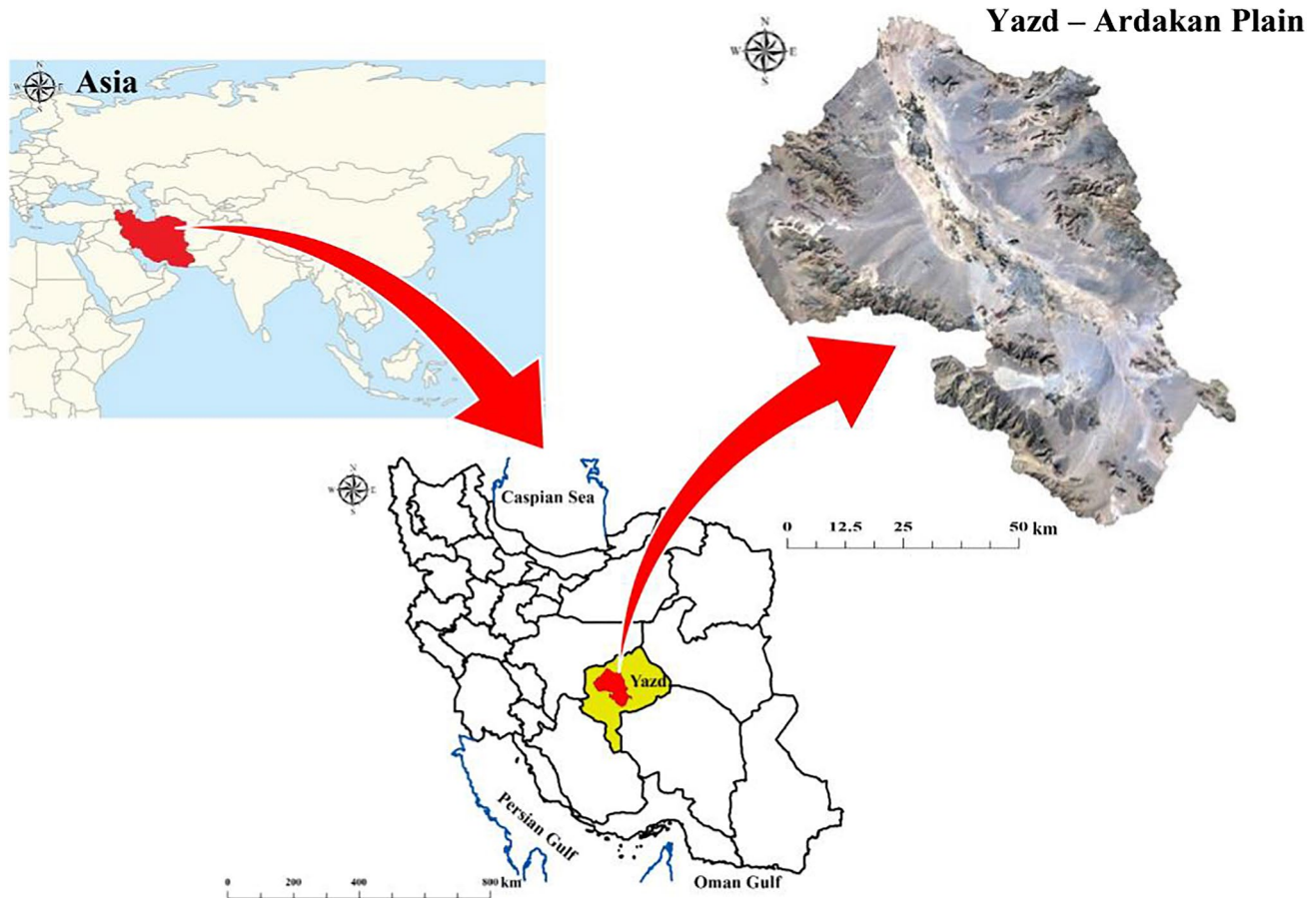


Fig. 1 Location map of Yazd-Ardakan Plain in Yazd Province, Iran

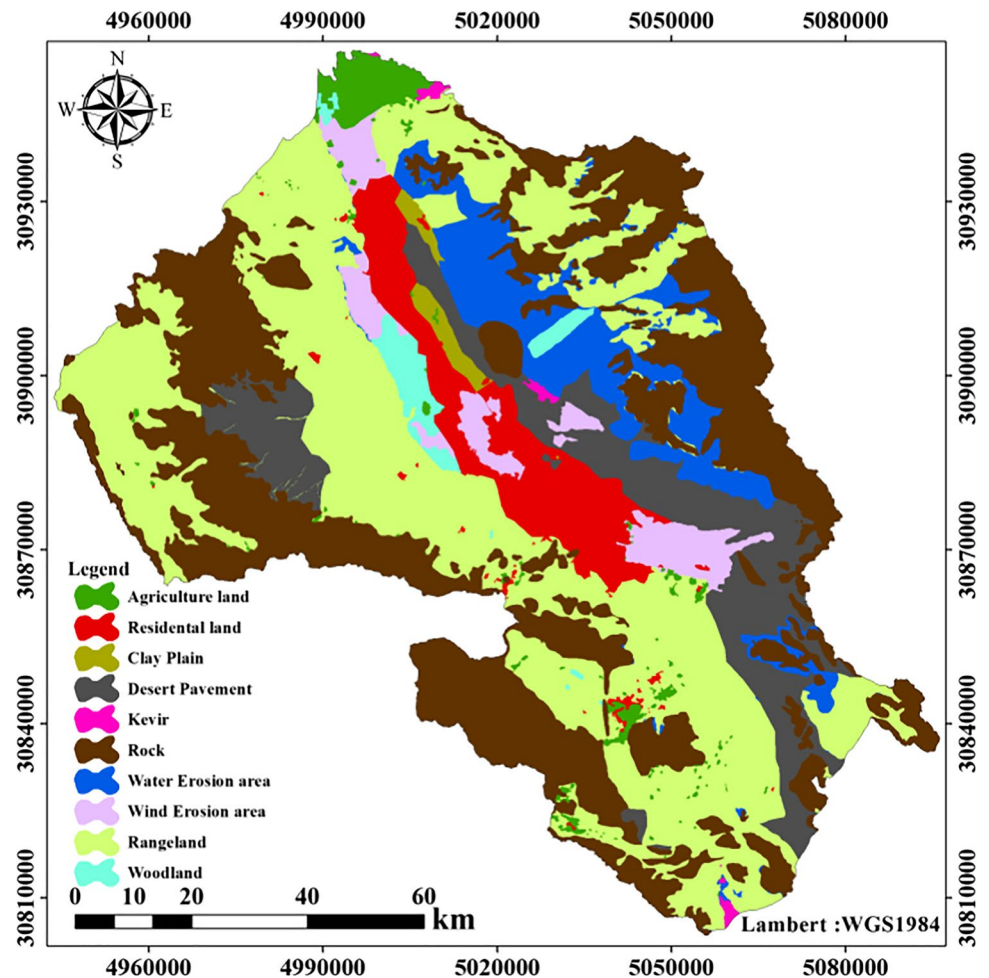
a handful of environmental problems, including erosion, land degradation, water scarcity, and soil- and plant-related problems (Fattahi 2013; Ghordfaramarzi et al. 2019). This plain is located in the central plateau of Iran ($31^{\circ} 13.5' E$ to $32^{\circ} 36.1' E$ and $53^{\circ} 24.7' N$ to $54^{\circ} 56.7' N$) and covers an approximate area of $11,545 \text{ km}^2$ (Fig. 1). The importance of this plain lies in its natural resources, population density, and economic prospects, with it suffering from high-temperature fluctuations as it is located under the high-pressure subtropical center. Reportedly, mean daily temperatures in the coldest and warmest months are -2 and 40.1°C in January and June, respectively. The precipitations in this area are low and irregular, averaging at 69 mm over the last 20 years. Regional evaporation ranges between 2200 and 3200 mm . According to geological maps, the study area hosts outcrops of some of the oldest and youngest geological formations. Due to the arid and hyper-arid climatic conditions prevailing in the region as well as the diversity of lithological units from Precambrian to Quaternary, various geomorphological facies types and wind erosion forms such as sand dunes, barchans, nebkas, and yardangs can be seen in this plain. The vegetation density in this area varies from 0 to 20% .

As of current, the vegetation is predominantly composed of *Artemisia sieberi*, *Salsola yazdiana*, *Seidlitzia Rosmarinus*, and *Hammada salicornica*. The predominant soil type in the study area is categorized as Aridisols in Soil Taxonomy system.

IMDPA model

After the conclusion of international convention to combat desertification in June 1994, the Islamic Republic of Iran was one of the first countries to join this convention in January 1995. Paragraph 1 of Article 9 of this convention emphasizes the provision of a national action plan to combat desertification within the framework of national development plans. As a necessary measure for implementing the national action plan and combat desertification, one should determine the sub-criteria and criteria of this phenomenon in Iran. This was accomplished in 2004 within the framework of a national plan to determine the desertification sub-criteria and criteria by the Bureau of Sand Stabilization and Desertification of the Forests, Range and Watershed Management Organization of Iran. The plan was aimed at transitioning

Fig. 2 Map of land units across Yazd-Ardakan Plain



from qualitative to quantitative recognition stage, especially in order to assess the desertification potential and provide for managing this phenomenon considering specific ecological, social, economic, and cultural conditions of Iran. Accordingly, the IMDPA model, as a method of evaluating the desertification potential, was formulated in 2005 with the cooperation of the Faculty of Natural Resources at University of Tehran, Yazd University, and the Deputy for Rangeland and Soil Affairs of the Forests, Range and Watershed Management Organization of Iran. Later on, this model was evaluated in three areas of Iran dominated by arid, semi-arid, and dry sub-humid climates. In this model, 9 criteria and 36 sub-criteria are considered for the desertification assessment (Bakhshandehmehr et al. 2013).

Materials

A requirement for any map preparation task is the availability of reliable data at appropriate scales. Despite the inherently limited availability of such information, we herein used data repositories of various governmental department and semi-public organizations to gather the required data. In

some cases, field surveys were further performed and necessary analyses were performed in laboratory to update the required data (e.g., soil characteristics).

Methods

IMDPA model implementation

The IMDPA model was used to assess and prepare the map of desertification intensity and land degradation in Yazd-Ardakan Plain. This model is based on four main groups of criteria, namely water and climate, landform, vegetation coverage, and human, each of which having certain criteria and sub-criteria (Fig. 2). The water and climate-related criteria refer to groundwater and climatic conditions and are measured by several sub-criteria, including groundwater drawdown, negative water balance, sodium absorption ratio, salinity, drought persistence, aridity sub-criterion, and annual precipitation in the region. The land criteria refer to geologic and geomorphologic conditions and soil and erosion criteria, which are evaluated through the following sub-criteria: physiographic conditions, stone

Table 1 Classification of desertification criteria in IMDPA model (adapted from Khosravi et al. 2019)

Sub-criterion value	Range of criteria value	Desertification potential	Intensity of desertification class
1	1–1.5	Low to negligible	I
2	1.6–2.5	Moderate	II
3	2.6–3.5	Severe	III
4	> 3.5	Very severe	IV

sensitivity, type of land use, soil deep gravel percentage, electrical conductivity, number of days with dust storm sub-criterion (DSI), vegetation coverage, abiotic covering density, emergence of erosive facies, type and intensity of water erosion, type of land use, and vegetation density. The vegetation coverage criteria focuses on the vegetation and agriculture, which are measured by evaluating the vegetation utilization, vegetation coverage and vegetation regeneration sub-criteria, utilization of inputs and machinery, cultivation pattern, and crop yield. Finally, the human-induced factors deal with socioeconomic, urban, and industrial development criteria and are measured by a number of sub-criteria, namely socioeconomic factors, organizational and awareness participation, experience, indigenous knowledge, institutional-legal factors, poverty and economy, conversion of the horticultural and agricultural lands to urban/industrial arenas, transformation of forests and rangelands to urban/industrial areas, inappropriate farming, per-capita green space, and density of roads and mines.

Here, we measure each sub-criterion initially using the corresponding guidelines before assigning a score to its effect on desertification from a scale of 0–4 according to regional conditions, field studies, and expert judgments. Finally, geometric mean of the scores for different sub-criteria is calculated according to Eq. 1 to obtain an overall score for the corresponding criterion. Then, score of each criterion is qualitatively evaluated as shown in Table 1.

$$\text{IndexX} = [(\text{Layer1}) \cdot (\text{Layer2}) \dots (\text{Layern})]^{1/n}, \tag{1}$$

where *dexX*, *Layer*, and *n* denote the corresponding criterion, sub-criteria of each criterion, and the number of sub-criteria, respectively (Khosravi et al. 2019).

It should be noted that some sub-criteria and criteria refer to specific land uses. For example, socioeconomic criteria refer to residential areas only. In such cases, non-assessed areas are considered score-free regions and the desertification potential evaluation calculations are not performed for them.

Preparation of land unit map

Altitudes, slopes, and geographic orientations are main components for determining different units of landform; this can then be combined with other basic maps such as geological, land use, or vegetation coverage maps. In Iran with its particular climatic conditions, major land units (i.e., geobiofacies) include rocks, urban and rural lands, pastures, woodlands, farm lands, forests, water erosion, wind erosion, lakes, wetlands and swamps, gravelly and clay plains, and deserts (Ekhtesasi and Sepehr 2011). Given this, land unit maps were prepared by combining land use maps, geomorphology facies, and slope and lithology information across the region, ending up with 10 land units (Fig. 2).

Preparation of desertification intensity map based on the IMDPA model

GIS is a powerful system for collecting, storing, retrieving, converting, and displaying spatial data from real world for specific purposes. In this study, a GIS was implemented in ArcGIS 10.3 software environment to prepare different maps of the sub-criteria and criteria involved in the IMDPA model with the final aim of developing a desertification intensity map of Yazd-Ardakan Plain. For this purpose, each sub-criterion was modeled as an information layer and different layers (sub-criteria) were weighted and compiled to evaluate the effect of corresponding criterion on the desertification phenomenon. Next, based on Table 1, the map of each criterion was classified into four classes of desertification risk referring to low, moderate, severe, and very severe risk levels. Finally, a final map of desertification potential of Yazd-Ardakan Plain was provided from Eq. 2 based on the four groups of criteria considered in the IMDPA model by geometrically averaging the scores of different criteria and then proceeding to classification according to Table 1.

$$\text{DM} = (\text{QC} \times \text{QV} \times \text{QS} \times \text{QG} \times \text{QA} \times \text{QE} \times \text{QW} \times \text{QSE} \times \text{QT})^{1/9}, \tag{2}$$

where DM denotes the desertification map and QC, QV, QS, QG, QA, QE, QW, Q (S-E), and QT stand for the climate quality, vegetation quality, soil quality, geology and geomorphology quality, agricultural quality, erosion quality, water quality, socioeconomic quality, and technogenic quality (referring to urban and industrial factors), respectively.

Accuracy assessment of desertification potential map

Accuracy of the results and desertification potential maps was visually assessed by field surveys and expert judgments. For this purpose, after preparing the desertification map, 171 points were randomly selected across the map and states of

desertification and land degradation were examined at each point on the basis of field surveys expert judgments by five local specialists. After that, the desertification map obtained via the IMDPA model in the ERDAS Imagine 2014 software was compared with the findings of the field surveys and expert judgments. The overall accuracy and corresponding Kappa coefficient were determined according to Eq. 3 and Eq. 4, respectively.

Overall Accuracy

$$O^c = \frac{\sum_{i=1}^k n_{ii}}{|T|} \quad (3)$$

$$k = \frac{N \sum_{i=1}^r x_{ii} - \sum_{i=1}^r (x_{i+} \times x_{+i})}{N^2 - \sum_{i=1}^r (x_{i+} \times x_{+i})} \quad (4)$$

where O^c is the overall accuracy, $|T|$ is the total number of points, n_{ii} is the number of correct points, k is the kappa coefficient, r is the number of rows and columns in the error matrix, N is the total number of observations (pixels), x_{ij} is the observation in row i and column j , x_{i+} is the total number of observations in row i (right margin), and x_{+i} is the total number of observations in column i (bottom margin).

In order to select the best model, in addition to the Kappa coefficient, which assessed the general validity of the obtained maps, statistical comparisons were performed using Spearman's and Kendall's non-parametric tests. The Spearman's rank correlation coefficient (r_s) is used for analyzing ranked data or those converted to ranked ones. Spearman's and Kendall's correlation tests return statistics in the range of -1 (indicating maximum inverse correlation) to $+1$ (indicating maximum direct correlation).

Results and discussion

Desertification intensity assessment based on the IMDPA model

Evaluating the desertification potential of Yazd-Ardakan Plain using the IMDPA model based on the 9 studied criteria reflected differences in the contribution of each of the criteria (Fig. 3) and criterion groups (Fig. 4) into the desertification potential.

Analyzing weighted mean of each sub-criterion, criterion, and criterion group involved in the desertification, it was found land use and climate-related criteria (Fig. 4); in general, and vegetation coverage and groundwater criteria, in particular, impose significant impacts on the current climatic circumstances and tend to impose the study area to severe risk of desertification and land degradation (Table 2). Besides, one cannot ignore anthropogenic

activities and their negative impacts on the aggravation of the current situation.

Desertification leads to land degradation. In the assessment of a degradation process, one must consider different aspects of four major factors, namely soil, vegetation, climate, and humans. Previous studies have shown that soil quality is crucially linked to land degradation and is controlled by physical, chemical, and biological characteristics of the soil and different soil processes (Turan et al. 2019). In the present research, we investigated 9 prominent criteria in four groups to assess the desertification severity (Fig. 4). As far as climate quality sub-criterion (classified under climate group including climate and groundwater criteria) was concerned, the risk of desertification was evaluated as severe. Irrigation system, aridity sub-criterion, and average annual rainfall were found to impose the largest contributions into this sub-criterion. The group of landform-related criteria was found to play a moderate role in desertification across the study area, as measured by the soil quality sub-criterion. Among other sub-criteria of this group, however, type and depth of soil and canopy density imposed the largest impacts on the desertification. The group of vegetation coverage-related criteria was found to play the most significant role in severe desertification in the study area. In this respect, vegetation coverage, vegetation regeneration, and vegetation utilization were the strongest drivers of desertification process. This group provides a measure of vegetation quality in the study area. Scarcity of vegetation coverage had accelerated desertification in erosion-sensitive areas. Results of human-related criteria indicated that anthropogenic factors including socioeconomic factors and urban/industrial development had moderately contributed to desertification potential in the study area. The participation and communities and per-capita green space played the most important role in increasing the desertification process. Furthermore, the results showed that humans have also indirect effects on desertification severity by imposing changes into other criteria.

Calculating total score of desertification potential by geometrically averaging over the 9 studied criteria (Eq. 2), the result showed that the Yazd-Ardakan Plain is exposed to desertification at two levels of risks, namely moderate and severe. Accordingly, 67% of the study area (mainly rangelands) was found to be exposed to moderate risk of desertification while the remaining 33% were severely exposed to the risk (Table 3). Overall, the study area was found to suffer from desertification at moderate intensity, as indicated by a weighted mean of 2.4, clearly indicating the high risk of approaching severe desertification. Moreover, parts of the study area in the northeast and human settlements were found to be exposed to severe desertification potential (Fig. 5).

The results indicated that, for most part, Yazd-Ardakan Plain is exposed to moderate risk of desertification, a finding

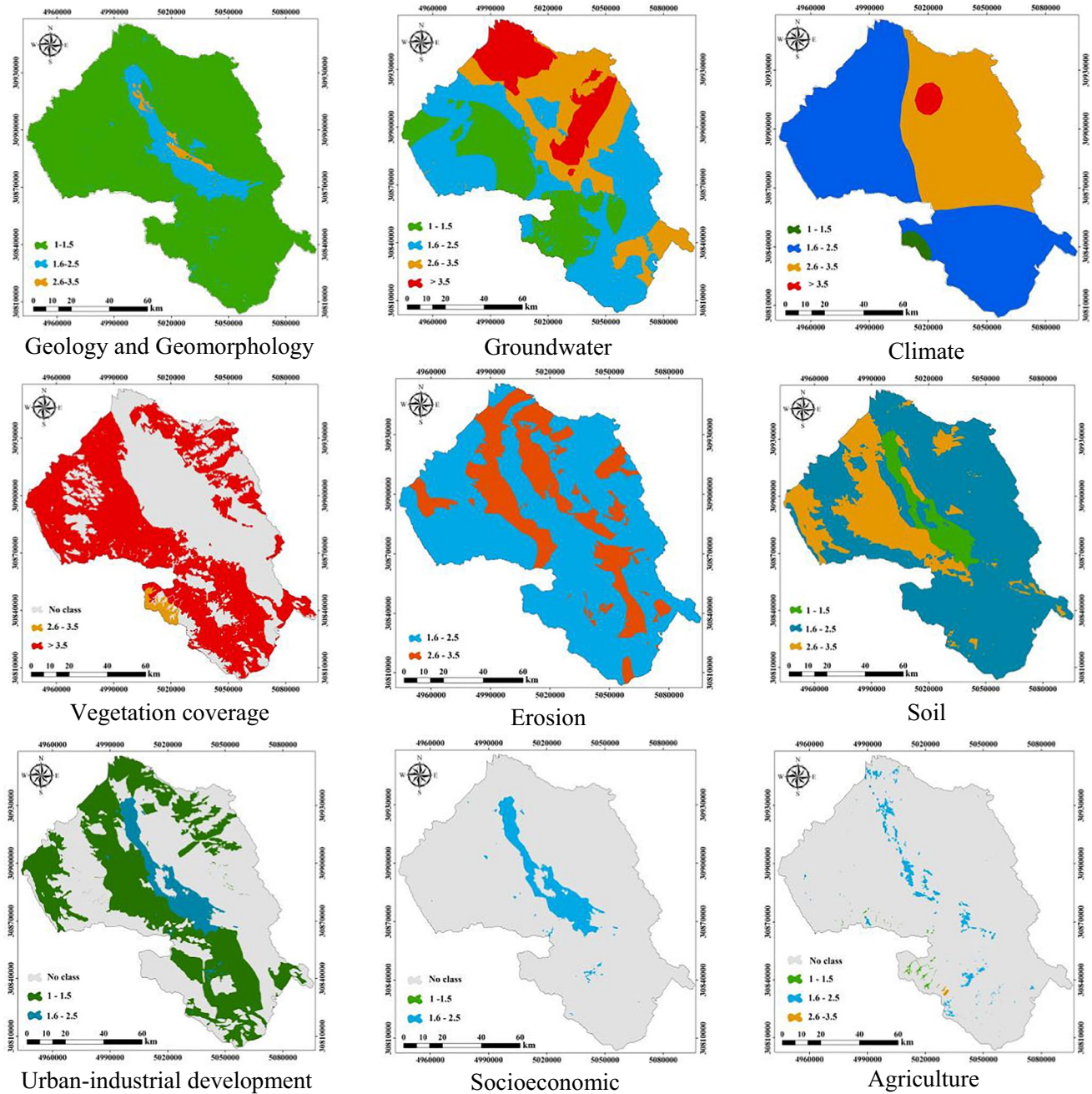


Fig. 3 Desertification potential maps according to the 9 criteria of the IMDPA model for Yazd-Ardakan Plain

that is consistent with the results reported by Silakhori et al. (2014) and Nikoo et al. (2015) and opposes the ones published by Akbari et al. (2020b). In the present study, the vegetation criterion was introduced as the most prominent factor in increasing the desertification intensity. Arami et al. (2014), Silakhori et al. (2019), and Ownegh et al. (2020) reported similar findings. Among the sub-criteria considered in this work, the drought sub-criterion, as a sub-criterion of climate criterion, the irrigation system type sub-criterion, as a sub-criterion of the water and irrigation criterion, the soil

texture and vegetation coverage, utilization and regeneration sub-criteria ended up with scores above 3.5 (Table 2). Hence, the severe desertification status and land degradation in the region is affected by these sub-criteria. Evaluation of desertification in Yazd-Ardakan Plain using remote sensing data shows that the highest rate of land degradation is happening in human settlements and rangelands (Fathizad et al. 2018). In terms of location, the findings of Fathizad et al. are in agreement with the map developed by the IMDPA model in this study. Soleimani Sardoo et al. (2015) used

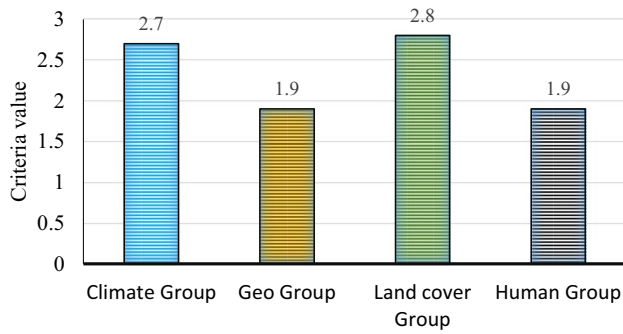


Fig. 4 Contribution of each group of criteria to desertification status of Yazd-Ardakan Plain

the MEDALUS model to introduce two classes of areas in central part of Yazd-Ardakan Plain in terms of sensitivity to desertification, namely moderate and severe sensitivity areas (Soleimani Sardoo et al. 2015). The result shows that the residential areas and the surrounding environment are severely sensitive to desertification, which confirms the results of the IMDPA model in the present study. In general, poor soil surface coverage is the main factor in increasing the desertification intensity across the study area. This is a combined effect of natural- and human-induced destructive factors in the region. Indeed, over-exploitation of groundwater supplies, unprofessional land use conversions, and improper industrial and mining activities have damaged the soil coverage,

Table 2 Contribution of each criterion and sub-criterion to desertification status of Yazd-Ardakan Plain

Criteria	Sub-criterion	Sub-criterion value	Criteria value
Climate	Average of annual rainfall	3	2.6
	Aridity sub-criterion	4	
	Drought persistence	1.4	
Groundwater	EC	2.7	2.8
	SAR	2.3	
	Groundwater drawdown	2.6	
	Irrigation system	4	
Geology and geomorphology	Slope	1.3	1.1
	Land use utilization	1.3	
	Stone sensitivity	1.7	
Soil	EC	2.6	2.3
	Depth	3.1	
	Type	3.7	
	Soil deep gravel percentage	1.2	
Erosion	Emergence of facies	2.2	2.4
	Abiotic covering percentage	2.9	
	Vegetation coverage percentage	2.6	
	Dust storm sub-criterion	2.6	
	Canopy density	3.9	
	Land use	2.1	
	Type and density	2.3	
Vegetation coverage	Vegetation coverage	3.7	3.8
	Vegetation utilization	3.1	
	Vegetation regeneration	3.8	
Agriculture	Cultivation pattern	2	1.8
	Crop yield	1.3	
	Utilization of inputs	2.6	
Socioeconomic	Population	2.3	2.3
	Poverty and economy	2.5	
	Institutional factors	2.5	
	Participation and communities	3.5	
Urban-industrial development	Orchard land conversion	1.8	1.5
	Rangeland conversion	1	
	Road and mine density	2.1	
	Per-capita green space	3.3	

Table 3 Desertification potential of Yazd-Ardakan Plain based on the IMDPA model

Range	Desertification severity class	Class	Area (ha)	Area (%)
1.6–2.5	Moderate	2	77,074.4	66.8
2.6–3.5	Severe	3	383,786.8	33.2

thereby contributing to land degradation. Water-and-irrigation criterion represents the second predominant factor contributing to severe desertification potential in the study area. The arid nature of the study area and precipitation scarcity, long drought periods, high temperature and evaporation intensity, high salinity of groundwater and aquifers, and improper exploitation of land resources are the main reasons why the mentioned criterion acts as dominant contributor to desertification intensity in Yazd-Ardakan Plain. Widespread application of water pumps to exploit groundwater the damage induced by qanats¹ in this region has contributed to significant drawdowns of water table and reduced quality and increased salinity of water. Reflecting these problems, sub-criteria of groundwater drawdown and salinity represent severe desertification (2.6 and 2.7, respectively). In general, climatic conditions and ecosystem of Yazd-Ardakan Plain were found to impose tremendous impacts on intensifying the desertification process, although improper human interventions and over-exploitation of resources have even accelerated this process.

Accuracy assessment of desertification intensity map obtained via the IMDPA model

There is no specific method for directly and comprehensively validating a desertification potential map generated by a model against actual field data (Parvari et al. 2011). Thus, a common practice is to compare various models and select the superior one based on a general view rather than employing a specific method. Some researchers evaluated the accuracy of their results by using non-parametric statistical relationships based on the so-called Cohen's Kappa coefficient (Akbari et al. 2020b; Silakhori et al. 2014). Estimation of the

¹ A qanat is an underground aqueduct that carries water from an aquifer or groundwater aquifer to lower lands. It consists of several wells that are drilled vertically on a sloping surface, and these wells are connected to each other underground with a corridor at a gentle slope with respect to the ground surface. The depth of the first well (spring), which is usually immersed in an alluvial cone, is greater than the groundwater level. The vertical wells are drilled at a spacing in the range of 20 to 200 m and act to connect the wet and dry areas of the aqueduct. From above, the aqueduct system resembles a path from an ant nest that starts at the foot of a mountain and extends to a point where water is extracted in the desert.

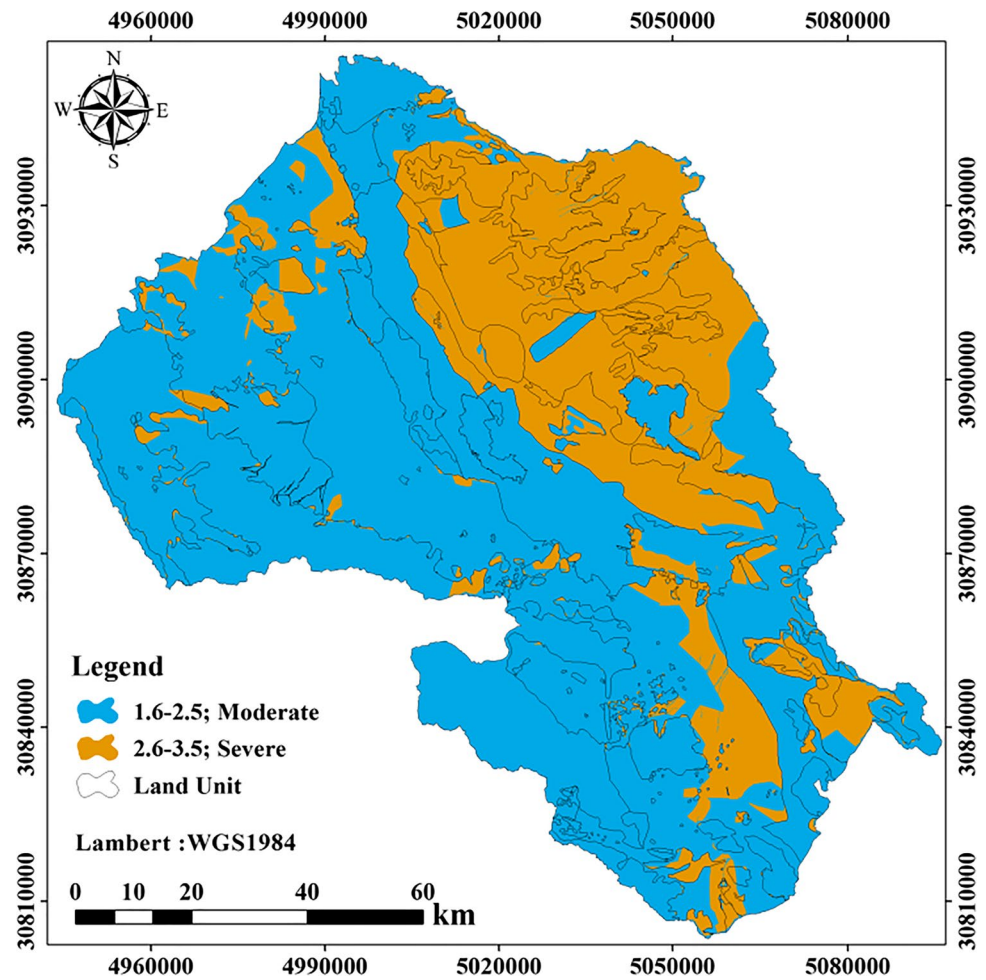
overall accuracy and Kappa coefficient of the desertification potential maps prepared via the IMDPA model in this work demonstrated their relatively moderate accuracy in relation to actual realities on the ground. Examining non-parametric correlation of the mentioned model further confirmed the map accuracy (Table 4).

The relatively moderate accuracy of the desertification map of Yazd-Ardakan Plain indicated that, despite the incorporation of many different sub-criteria into the mentioned model in accordance with the conditions of Iran, some of them impose merely insignificant effects on the desertification severity in particular areas. This affects the final estimation of the desertification intensity in the region and lowers the overall accuracy. Therefore, it seems necessary to revisit the list of sub-criteria considered in this model and eliminate the insignificant ones when it comes to desertification potential, so as to provide more accurate results about regional status.

Land degradation management

Focusing on natural resources and environment management, four approaches can be adopted for attenuating the land degradation intensity in the study area. In areas with low land degradation intensity, no special and costly projects are required. In such areas, efforts should be made to preserve the current status. In some areas where the degradation impact is moderate, it is necessary to consider methods of ecosystem sustainability maintenance and land coverage improvement to avoid the desertification risk. For areas suffering from severe and very severe land degradation, one must take special measures to control and even reduce the degradation intensity while dealing with negative impacts of this phenomenon. Combined effects of natural and anthropogenic factors in Yazd-Ardakan Plain have established two classes of areas, namely those suffering from moderate and severe land degradation intensity. Therefore, in order to optimize the managerial response to the problem of desertification, one may formulate different management measures for different criteria depending on the most prominent sub-criterion(s) for that criterion. According to the climate-based map of desertification potential (Fig. 3), one-third of the study area is at severe risk of desertification while the level of risk is moderate for the rest of region. Focusing on the climate criterion, aridity and precipitation are the most prominent factors contributing to increased desertification potential in the study area. Emphasizing on the water criterion, 40% of the study area exhibit potentials for desertification at severe and very severe levels (Table 5), while 39.5% are exposed to moderate risk of desertification. In order to better manage the groundwater, it is necessary to take measures to at least preserve the current condition in areas with low desertification potential, alleviate the risk of

Fig. 5 Final map of desertification potential across Yazd-Ardakan Plain according to the IMDPA model



desertification in areas exposed to moderate risk of desertification, and control and even combat the desertification in regions exposed to severe and very severe risk of desertification. Implementation of newly designed water supply plans and provision of training material to farmers and consumers of water resources must be seen as top priority in any management program. Accordingly, the greatest focus should be on improving the status of groundwater drawdown sub-criteria and type of irrigation system in the region (Table 2).

The geological and geomorphological settings of the area do affect natural factors, but the impacts of human-induced factors are more significant in disrupting the soil coverage. A large part of the study area is exposed to low or negligible risk of

desertification in terms of geological setting. Therefore, it is necessary to preserve the current condition in these areas. In the residential land unit, the desertification risk was evaluated as moderate, calling for implementation of risk avoidance programs. The severe desertification potential due to the geological criteria requires taking control measures. In parts of the study area, the desert pavement land unit is disturbed by destructive human activities. So, it is recommended to prevent soil disruption and aggravation of land degradation through proper management measures. About 30% of the study area was found to be exposed to severe risk of desertification in terms of the soil criterion (Table 5), which requires control measures. In other areas, it is necessary to carry out risk avoidance programs.

Table 4 Kappa coefficient, overall accuracy, and correlation tests for accuracy assessment of desertification potential map obtained via the IMDPA model for the Yazd-Ardakan Plain

Variable	Overall accuracy	Kappa coefficient	Conditional kappa		Non-parametric correlation test	
			Class 2	Class 3	Spearman's	Kendall's
IMDPA map versus actual data on the ground	81.7%	0.61	0.51	0.73	0.698**	0.679**

Table 5 Area (ha) of each of the desertification intensity classes of Yazd-Ardakan Plain based on different IMDPA model criteria

Qualitative classes	Low to negligible	Moderate	Severe	Very severe	No data
Range of class	1–1.5	1.6–2.5	2.6–3.5	3.5 <	NAN
Criteria					
Climate	13,509.5	685,496.7	435,627.3	19,900.7	-
Groundwater	247,783.3	476,373.8	307,453.4	175,784.5	-
Geology	1,029,281.2	103,804.6	17,808	3640.4	-
Soil	74,230	826,340	252,749.7	1214.5	-
Erosion	-	933,470.9	221,063.3	-	-
Vegetation coverage	-	-	14,046.9	617,884.2	522,603.1
Agriculture	4521.4	29,909.2	807.8	-	1,119,295.8
Socioeconomic	-	75,483.7	-	-	1,079,050.5
Urban-industrial development	447,877.4	75,271.3	-	-	631,385.5

Investigating the impact of erosion on the land degradation intensity considering water and wind erosion criteria, 19% of the region was found to suffer from severe desertification. In these areas, it is recommended to use abiotic windbreaks² and practice biological stabilization by cultivating prominent and low-water plant species. It was found that vegetation coverage is the most important criterion affecting the desertification and land degradation intensity in Yazd-Ardakan Plain (Table 2). According to Table 5, the desertification potential is severe and very severe in terms of this criterion. Therefore, in order to manage land degradation in terms of vegetation coverage, it is necessary to take special measures to deal with the severity of this criterion. Benefiting from biomechanical operations in rangelands by constructing multi-purpose structures and dams represents an effective managerial strategy for controlling the desertification phenomenon and reducing its destructive effects. Controlling land use conversions and over-cultivation, as human factors contributing to land degradation, is of paramount importance for combating desertification. Particular changes in the soil lead to land abandonment and desertification. Therefore, it is necessary to preserve currently proper land uses and keep them against possible changes to avoid desertification and manage land degradation.

Conclusion

Desertification is advancing at a sharp pace in the Yazd-Ardakan Plain. In this work, we assessed desertification potential of different areas in the plain and classified them under either of four classes of desertification risk, namely low, moderate, severe, and very severe risk levels. The values obtained for

the moderate-risk areas were very close to those of the severe-risk areas, as per the results of the IMDPA model. Residential land unit and surrounding area were found to exhibit severe desertification potentials and hence high land degradation intensities. This points to the very prominent and negative role of the human factor in increasing the desertification and degradation intensity of the lands in the study area. Application of geometric mean, flexibility in using prominent sub-criteria in assessing desertification, and use of GIS to combine layers and produce reliable maps of desertification and land degradation are among the advantages of using the IMDPA model. In this work, a total of 9 criteria and more than 30 sub-criteria were used to assess desertification based on the IMDPA model. However, it was found that consideration of too many factors may not necessarily represent the best way. This can significantly affect final assessment of desertification. In the study area, some urban/industrial development-related criteria were found to impose insignificant impacts in the desertification; these include orchard land conversion and rangeland conversion. In the meantime, their consideration reduced the reliability of the final desertification assessments. We surveyed human sub-criteria only in residential and industrial regions, so that the corresponding results cannot be generalized to other parts of the study area. This is while we know that the effects of human activities on the land degradation are well beyond a specific area.

Author contribution All authors whose names appear on the submission made substantial contributions to the acquisition, analysis, and interpretation of data.

Declarations

Ethics approval Since this study did not involve human subjects, it did not require ethical approval statement.

Consent to participate This study did not involve human participants.

Conflict of interest The authors declare no competing interests.

² Windbreak is an obstacle placed in front of the wind to attenuate the wind speed below an allowable threshold. There are two types of windbreaks, namely biotic (e.g., planting trees, shrubs, and shrubs) and abiotic windbreaks (e.g., canopies, mats, straws, etc.).

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