

Research Article

# An Integrated Geospatial Assessment of Desertification Hotspots in Iran: Multi-Scale Mapping and Sustainable Management Strategies

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## Abstract

Desertification represents a critical environmental and socio-economic challenge for Iran, severely affecting food security, rural livelihoods, biodiversity, and ecological stability. As a predominantly dryland country, Iran faces escalating land degradation driven by both climatic variability and unsustainable human activities. This study develops an integrated geospatial framework to assess desertification hotspots in Iran, leveraging remote sensing datasets including MODIS, Landsat-8, and Sentinel-2, alongside GIS-based spatial analysis. Key environmental indicators, including vegetation cover (NDVI trends), land use classifications, soil texture, and climatic variables, were incorporated into the Environmentally Sensitive Areas Index (ESAI) modeling framework, complemented by a Bayesian network to better capture the probabilistic relationships among drivers. The results showed that 85.57% of Iran's land area falls into fragile to critical desertification categories - a figure notably higher than in many other arid nations- with 60.42% classified as Medium Critical and 13.34% as High Critical. Provinces such as Sistan and Baluchestan, Kerman, and Yazd are identified as the most vulnerable due to a combination of severe aridity, shallow soils, and intense anthropogenic pressure. Correlation analyses reveal that the Management Quality Index (MQI) ( $r = 0.81$ ,  $P \leq 0.01$ ) and Vegetation Quality Index (VQI) ( $r = 0.50$ ,  $P \leq 0.05$ ) had high and moderate correlations with desertification risk, respectively, indicating the critical role of land use management and vegetation stability. Mitigation strategies proposed include the implementation of drip irrigation systems, agroforestry designs, biochar amendments for soil rehabilitation, watershed management projects, and participatory land-use planning. While some pilot programs on water conservation and reforestation exist, broad national-scale application remains limited due to policy barriers and funding constraints. This study underscores the urgent need for scientifically informed, region-specific interventions to enhance Iran's resilience to desertification. By integrating high-resolution remote sensing techniques and probabilistic modeling, the research provides a robust, actionable framework for sustainable land management and environmental policy reform in dryland regions. Consequently, this approach offers a practical solution to combat desertification and promote sustainable development in vulnerable areas.

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**Keywords:** Desertification, Remote Sensing, GIS-Based Analysis, Sustainable Land Management, ESAI, Land Degradation, Climate Resilience, Iran

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## 1. Introduction

Desertification is a critical global environmental challenge, especially in arid and semi-arid regions where land degradation threatens ecological and socio-economic stability (Abdullahi et al., 2023). In Iran, desertification has intensified dust storms and biodiversity loss, with recent studies reporting a 30% increase in dust events over two decades, largely due to expanding degraded lands (Silakhori et al., 2018; Zucca et al., 2022). Among various anthropogenic drivers, over extraction of groundwater has the most critical impact on desertification in Iran, with over 60% of aquifers facing severe depletion—exceeding the effects of deforestation or overgrazing, particularly in arid and semi-arid zones (D’Odorico et al., 2013).

These challenges necessitate comprehensive and systematic assessments to identify high-risk desertification zones and inform sustainable land management strategies (Salvati, 2016).

Over the past decades, numerous methodologies have been developed to assess and monitor desertification processes, including field-based observations, empirical techniques, and process-based models (Wang et al., 2023). Among these, traditional frameworks such as MEDALUS, LADA, and GLASOD have been used to evaluate desertification by integrating environmental indicators like soil quality, climate, vegetation, and land use (Team, 2006; Santini et al., 2010; Salvati, 2016). While these models have played a critical role in identifying environmentally sensitive areas and understanding the spatial distribution of desertification risk (Uzuner and Dengiz, 2020), their effectiveness is often constrained by reliance on static datasets and deterministic assumptions, which limit their capacity to reflect inter-annual variability, seasonal dynamics, and complex interactions between natural and anthropogenic drivers. Furthermore, many prior studies lack comprehensive spatial coverage and fail to leverage advancements in remote sensing technologies that could substantially improve the accuracy, scalability, and timeliness of desertification assessments.

Remote sensing and geographic information systems (GIS) have emerged as powerful tools for large-scale and high-resolution desertification monitoring, providing real-time and multi-temporal data to assess land degradation patterns over extensive Uzuner geographic areas (Wang et al., 2023). Integrating remote sensing-derived indicators, such as vegetation indices (e.g., NDVI, SAVI), soil moisture indices, and land surface temperature data, allows for a more comprehensive and dynamic evaluation of desertification risk (Binte Mostafiz et al., 2021). Moreover, GIS-based spatial analysis enables the synthesis of multiple environmental factors to systematically classify and map desertification-prone areas (Santini et al., 2010). Despite the growing application of these geospatial techniques, there remains a significant need to refine existing methodologies by incorporating advanced spatial modeling techniques that enhance predictive capabilities and improve decision-making for land management (Malczewski, 2004).

Several studies have assessed desertification in Iran using various methodologies; most have been limited by regional scope, methodological constraints, or a lack of integrated management strategies tailored to different levels of desertification risk (Sepehr et al., 2007; Silakhori et al., 2019). A key limitation in current research, as highlighted by (Vogt et al., 2011), is the insufficient linkage between desertification risk assessment and the development of sustainable management strategies. Identifying high-risk areas is only the first step; translating these assessments into actionable land management policies requires a structured approach considering ecological, socio-economic, and policy dimensions (Wang and Zhang, 2024). Effective desertification mitigation strategies should be region-specific and data-driven, incorporating a combination of land rehabilitation techniques, water resource conservation measures, sustainable agricultural practices, and community-based interventions (Jat et al., 2024). Furthermore, early warning systems and continuous monitoring frameworks are essential for adaptive management, allowing policymakers to implement proactive measures before land degradation reaches irreversible thresholds (Van den Elsen, 2020).

Given these research gaps, this study proposes an innovative geospatial platform that integrates multi-source remote sensing datasets—specifically Landsat, MODIS, and Sentinel-2 imagery—alongside GIS-based techniques to identify desertification hotspots across Iran. The primary objectives of this research are to (1) assess and classify desertification risk zones across Iran by integrating multi-source remote sensing datasets and GIS-based spatial analysis, (2) identify and quantify the key environmental and anthropogenic drivers contributing to desertification, and (3) develop evidence-based, region-specific land management strategies through geospatial analysis and policy assessment, aimed at fostering sustainable land use practices in vulnerable areas. By achieving these objectives, this study seeks to enhance the precision and applicability of desertification risk assessments in Iran while providing actionable insights for decision-makers.

## 2. Materials and methods

### 2.1. Study area

Iran covers ~1.65 million km<sup>2</sup> between 25°–39° N and 44°–63° E, encompassing diverse climates from humid Caspian lowlands to hyper-arid deserts in the central and southeastern regions (FAO, 2025). With an average annual rainfall of 250 mm—and over 70% of land receiving less—persistent moisture deficits prevail (Karimi et al., 2018). Vegetation ranges from dense forests in the north to sparse scrub in arid zones. These climatic gradients, combined with pressures like overgrazing and groundwater overuse, have made Iran highly prone to desertification, soil erosion, and land degradation, necessitating spatially informed land management (Fig 1).

**Table 1.** List of Variables and Data Sources Used in Desertification Modeling

Category	Variable	Reference database	Resolution	Time
Soil	Soil texture	OpenLandMap Soil Texture Class (USDA System) (Hengl, 2018)	250 m	2023
	Soil Depth	Harmonized World Soil Database HWSD (Jarvis et al., 2008)	30 arc-s	2023
	Gravel %	Harmonized World Soil Database HWSD (Jarvis et al., 2008)	30 arc-s	2023
Climate	Precipitation	TerraClimate: Monthly Climate (Abatzoglou et al., 2018)	4638.3 m	2000-2023
	Aridity	TerraClimate: Monthly Climate (Abatzoglou et al., 2018)	4638.3 m	2000-2023
Vegetation	Fire hazard	MCD12Q1.061 MODIS Land Cover (Friedl and Sulla-Menashe, 2022)	500 m	2023
	Vegetation%	MCD12Q1.061 MODIS Land Cover (Friedl and Sulla-Menashe, 2022)	500 m	2023
	Soil conservation	MCD12Q1.061 MODIS Land Cover (Friedl and Sulla-Menashe, 2022)	500 m	2023
Management	Land use	MCD12Q1.061 MODIS Land Cover (Friedl and Sulla-Menashe, 2022)	500 m	2023
	Population density	GPWv411: Population Count (Gridded Population of the World Version 4.11) (Warszawski, 2017)	927 m	2020

## 2.2. Data sources

Desertification modeling was based on multi-source datasets available via Google Earth Engine. Land cover, vegetation, and land use data were derived from MODIS (MCD12Q1), Sentinel-2 MSI, and Landsat-8 OLI imagery. Climate variables, including precipitation and aridity, were obtained from TerraClimate (Abatzoglou et al., 2018), while soil texture, gravel content, and depth were extracted from HWSD and Open Land Map (Jarvis et al., 2008). Population density data came from GPWv4 (Warszawski, 2017). The modeling framework employed the Environmentally Sensitive Areas (ESA) Index within the ESAS model, enhanced by a Bayesian network to incorporate uncertainty and probabilistic interactions among environmental factors, outperforming deterministic approaches in handling non-linear dependencies. All variables were harmonized to a common spatial grid using bilinear resampling to ensure consistency across layers. The collected indicators were categorized into four domains: soil (e.g., texture, gravel), climate (e.g., precipitation, aridity), vegetation (e.g., cover density, fire risk), and management (e.g., land use, population). This integration supported a comprehensive, spatially explicit analysis of desertification risk in Iran, as outlined in Table 1.

## 2.3. Desertification assessment

The Environmentally Sensitive Areas Index (ESAI), refined by (Kosmas et al., 1999), is a widely used framework for evaluating land degradation susceptibility

at regional scales. It integrates eleven indicators grouped into four quality domains: vegetation, climate, soil, and land management (Table 1). The final ESAI score is calculated as the geometric mean of these four domains, with higher values indicating greater desertification risk (Bakr et al., 2012; Silakhori et al., 2018). Each domain is derived from several variables assigned sensitivity scores ranging from 1 (low) to 2 (high), reflecting their contribution to land vulnerability and degradation potential. This indicator-based structure captures the spatial variability and severity of desertification across different ecological and management conditions (Kosmas et al., 1999).

## 2.4. Soil quality index (SQI)

The Soil Quality Index (SQI) was assessed as a soil's capacity to support vegetation based on texture, depth, and rock fragment content, following the ESAI methodology (Kosmas et al., 1999). Soil data were obtained from the HWSD at 30 arc-second resolutions, allowing high-resolution evaluation (Salvati and Bajocco, 2011). Given the relative stability of soil properties across Iran, these indicators were treated as static variables and classified using standardized scoring criteria (Table 2). The final SQI was computed via a weighted average (Equation 1), integrating the three parameters. Weights were assigned through expert judgment and correlation analysis to reflect ecological relevance.

$$QI_i = \sqrt[n_i]{\prod_{j=1}^{m_i} X_{ij}} \quad (1)$$

Where:

$j=1$  to  $m_i$  and  $m_i$  represents the number of indicators considered for each quality index

$QI_1 = SQI$  (Soil Quality Index),

$QI_2 = CQI$  (Climate Quality Index),

$QI_3 = VQI$  (Vegetation Quality Index) and

$QI_4 = MQI$  (Management Quality Index).

## 2.5. Climate quality index (CQI)

Climate quality was assessed using annual precipitation and the Bagnouls-Gaussens Aridity Index (BGI), both derived from the Terra Climate dataset with ~4.6 km resolution (Darbandsari et al., 2024). Precipitation values were categorized into three classes based on a 280 mm threshold critical for plant growth. The BGI, selected for

its sensitivity to seasonal moisture deficits and widespread use in arid-zone studies, was calculated using monthly precipitation and temperature, then classified into five levels of aridity (Equation 2, Table 2). These indicators reflect spatial variability in climatic constraints that influence vegetation dynamics and land degradation. Compared to other indices (e.g., De Martonne), BGI better captures seasonal water stress relevant to desertification. Sensitivity scores were assigned based on defined thresholds, enabling standardized evaluation across the study area. The final CQI was computed as the geometric mean of the standardized precipitation and aridity layers, quantifying the climate's role in desertification susceptibility.

**Table 2.** Classification and Index Values for Soil Quality Assessment

Parameters	class	Definition-Vegetation Type	Assessment	score	
Soil Quality	Texture	1	CL; L; SCL; SL; LS	Good	1.0
		2	SiCL; SiL; SC	Medium	1.2
		3	C(h); SiC; C(l); Si	Poor	1.6
		4	S*	Very poor	2.0
	Depth	1	> 75 cm	Deep	1.0
		2	75-30 cm	Moderate	1.33
		3	15-30 cm	Shallow	1.66
		4	<15 cm	Very shallow	2.0
	Coarse Material (Rock fragments)	1	Coarse material > 60%	Very stony	1.0
		2	Coarse material 20–60%	Stony	1.3
		3	Coarse material < 20%	Bare and stony	2.0
	Climate Quality	Precipitation	1	>650 mm	High
2			650-280 mm	Medium	1.5
3			<280 mm	Low	2.0
Drought-Aridity (BGI)		1	50-100	Low	1.2
		2	100-125	Medium	1.4
		3	125-150	High	1.8
		4	>150	Very high	2.0
Vegetation Quality		Fire hazard	1	Bare land, perennial crops, annual Crops (e. g. maize, tobacco, sunflower)	Low
	2		Annual crops (e.g. cereals, grasslands), deciduous oak, mixed Mediterranean, macchia/evergreen forests	Moderate	1.3
	3		Mediterranean macchia	High	1.6
	4		Coniferous forests (pines)	Very high	2.0
	Plant cover	1	>40%	High	1.0
		2	10-40%	Low	1.8
		3	<10%	Very low	2.0
	Erosion Protection	1	Mixed Mediterranean macchia/evergreen forests	High	1
		2	Deciduous forests	Moderate	1.6
		3	Deciduous perennial crops (orchards and plantations)	low	1.8
		4	Annual crops (cereals), annual grasslands, vineyards	Very low	2.0
	Management Quality	Intensity of crop land	1	Low-level land use intensity	Low
2			Medium-level land use intensity	Moderate	1.5
3			High-level land use intensity	High	2.0
Population density		1	<170	low	1.0
		2	170-500	Moderate	1.5
		3	500-1400	High	1.8
		4	>1400	Very high	2.0

\* The soil texture classifications used in this study, including CL, L, SCL, SL, LS, SiCL, SiL, SC, C(h), SiC, C l, and S, represent various soil types based on their relative proportions of clay, silt, and sand

$$BGI = \sum_{i=1}^n (2t_i - p_i)k_i \quad (2)$$

Where:

$t_i$  is the mean temperature for the  $i$  time period (e.g., month or year).

$p_i$  is the total precipitation for the  $i$  time period.

$k_i$  is a coefficient that accounts for the relative contribution of each time period.

$n$  is the total number of time periods considered (e.g., number of months or years in the calculation).

## 2.6. Vegetation quality index (VQI)

VQI was calculated using three indicators: plant cover, fire hazard, and erosion protection capacity. Fire risk levels were classified based on dominant vegetation types in Mediterranean ecosystems, with weights assigned according to their flammability and ecological function (Table 2). Historical fire data from the GFED database were also used to refine classification accuracy. Vegetation characteristics were extracted from the MODIS Land Cover dataset (MCD12Q1.061) at 500-meter resolution. This dataset enabled standardized classification of vegetation density, type, and spatial distribution across the study area. Each vegetation parameter was scored from 1 (low sensitivity) to 2 (high sensitivity) based on its role in resisting degradation. The final VQI was computed using a weighted geometric mean of the three components, implemented on Google Earth Engine (GEE) for efficient spatial processing. This index provided a high-resolution assessment of vegetation quality and its contribution to mitigating land degradation in arid and semi-arid environments (Silakhori, 2015).

## 2.7. Management quality index (MQI)

The Management Quality Index (MQI) quantifies anthropogenic impacts on desertification, integrating land use intensity and population density into the ESAI framework. These factors capture pressures from agriculture, urbanization, and resource exploitation, which are key drivers of land degradation. Population data were sourced from the GPWv4.11 dataset (~927 m resolution) (Taghipour-Javi et al., 2016), while land use indicators were derived from MODIS-based products and national census reports. Land use intensity was assessed based on cropland density, urban expansion, and agricultural conversion. Each variable was classified using standardized criteria and scored based on its contribution to environmental stress (Table 2). The final MQI was calculated using a weighted geometric mean, where higher values denote stronger human-induced degradation risk. By incorporating MQI into the overall ESAI model, this study enables spatially explicit identification of areas with unsustainable land

management practices, supporting targeted policy interventions.

## 2.8. Final ESAI calculation

The final Environmentally Sensitive Areas Index (ESAI) was computed by integrating four quality indices—Soil (SQI), Climate (CQI), Vegetation (VQI), and Management (MQI)—using a weighted geometric mean (Equation 3). All indices were standardized to a common scale (0 to 1) to ensure comparability, with higher ESAI values indicating greater susceptibility to desertification (Salvati et al., 2016; Zambon et al., 2017). To maintain balance among components and avoid index dominance, a fourth root transformation was applied. This mitigates skewness and ensures that no individual factor disproportionately influences the composite ESAI score. The approach enables consistent and spatially explicit classification of degradation risk across land use types, supporting targeted interventions (Cudlín et al., 2021). Although direct field validation was not conducted, the methodology builds on established, peer-reviewed frameworks with demonstrated reliability (Zambon et al., 2017), reinforcing its utility as a robust decision-support tool for desertification management, as shown in Table 3.

$$ESAI = \sqrt[4]{SQI \times CQI \times VQI \times MQI} \quad (3)$$

Where SQI is the Soil Quality Index, CQI is the Climate Quality Index, VQI is the Vegetation Quality Index and MQI is the Management Quality Index.

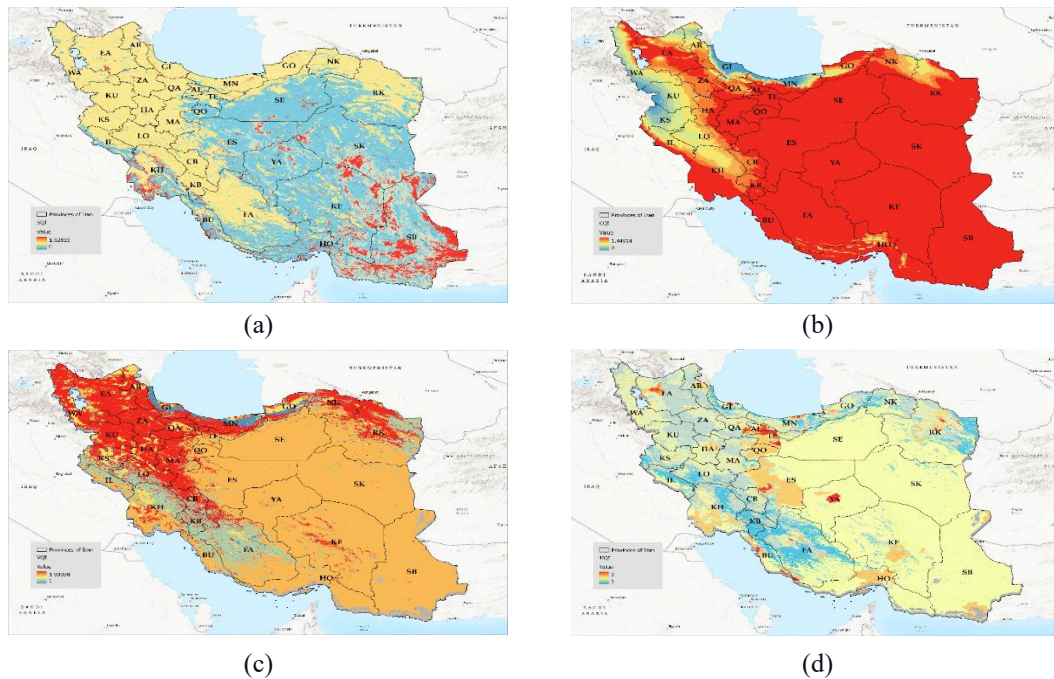
## 3. Result

### 3.1. Soil criterion

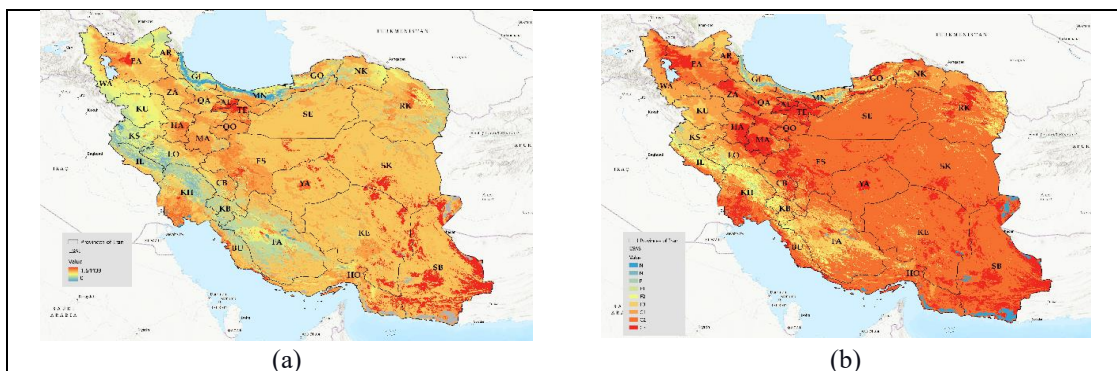
The Soil Quality Index (SQI) was calculated from three sub-indicators: soil texture, gravel percentage, and soil depth. Texture values ranged from 0.98 to 1.27, with provinces like Sistan and Baluchestan exhibiting high values (~1.27), indicating poor physical structure, while Golestan and Gilan showed lower values (~0.98–1.00), reflecting more favorable soil composition. Gravel content varied from 1.30 to nearly 2.00, with East Azerbaijan, Zanjan, and Razavi Khorasan reaching the upper limit, suggesting limited moisture retention. Soil depth values were lowest in northern provinces (~1.00) and highest in arid central and southeastern regions (~1.20–1.38), indicating shallow profiles and erosion risk. The aggregated SQI ranged mostly from 1.20 to 1.40, but values above 1.60 appeared in Esfahan, Khuzestan, and parts of Sistan and Baluchestan. Even in relatively stable regions like Gilan, mountainous zones exhibited elevated SQI values (>1.40), pointing to local erosion potential (Fig 1a).

**Table 3.** Land Classification Based on ESAI Values

Class	Sub-class	Sub-class symbol	ESAI
Critical	High	C3	>1.53
	Medium	C2	1.53-1.42
	Low	C1	1.41-1.38
Fragile	High	F3	1.37-1.33
	Medium	F2	1.32-1.27
	Low	F1	1.26-1.23
Potential		P	1.22-1.17
Non affected		N	<1.17



**Figure 1.** Spatial distribution of quality indices used in the ESAS model across Iran: a) Soil Quality Index (SQI); b) Climate Quality Index (CQI); c) Vegetation Quality Index (VQI); d) Management Quality Index (MQI)



**Figure 2.** a) Spatial variation of ESAI score in Iran, and b) Desertification risk classification in the study area

**Table 4.** Classification of Desertification Hazard Based on ESAI in Iran: Area Distribution by Class

Class	Sub-class symbol	area (Km <sup>2</sup> )	Area (%)
Non affected	N	7671.2	0.47
Potential	P	9960.7	0.60
Fragile	F1	6250.6	0.38
	F2	62163.2	3.77
	F3	151791.4	9.21
Critical	C1	194568.4	11.81
	C2	995708.4	60.42
	C3	219886.1	13.34
Sum		1648000	100

### 3.2. Climate criterion

The Climate Quality Index (CQI) was derived from aridity and precipitation sub-indicators. Aridity scores across Iran generally hover around 1.00, indicating widespread arid to semi-arid conditions, particularly in provinces like Sistan and Baluchestan, Kerman, and the Khorasan region. Even relatively wetter provinces near the Caspian Sea (e.g., Gilan and Golestan) show only slightly lower aridity values (~0.95–1.00), suggesting moderate dryness. Precipitation scores were notably high (~2.00) in central, eastern, and southern provinces such as Yazd, Tehran, and Kerman, reflecting limited and irregular rainfall. Northern provinces, including Mazandaran and Golestan, exhibited lower values (~1.20–1.80) but still indicated suboptimal precipitation. Overall, provinces with homogeneous arid climates—like Semnan and South Khorasan—had CQI averages above 1.20. In contrast, climatically diverse regions such as East Azerbaijan or Khuzestan showed wider internal variation (up to 1.40), due to contrasting conditions between mountainous and lowland zones (Fig 1b).

### 3.3. Vegetation criterion

The Vegetation Quality Index (VQI) was calculated from vegetation percentage, soil conservation, and fire hazard sub-indicators. Vegetation percentage ranged from 1.45 to 1.99, with higher values—seen in Sistan and Baluchestan or Yazd—indicating vegetation under ecological stress rather than denser cover. In contrast, provinces like Gilan and Kohgiluyeh displayed lower values (~1.45–1.63), suggesting more stable vegetation. Soil conservation values peaked (~1.99) in Zanjan, Hamedan, and West Azerbaijan, highlighting fragile ecosystems. Fire hazard was highest in Kohgiluyeh and Boyer-Ahmad (~1.52), but minimal (~1.00) in arid provinces due to limited biomass.

Combined, these sub-indicators pushed VQI above 1.90 in some northwestern and mountainous provinces, whereas more arid zones like Kerman or Fars showed values around 1.60–1.75. Certain provinces also exhibited wide internal VQI ranges (e.g., 0.50 to 1.93), reflecting a mix of degraded and resilient vegetation zones within the same region (Fig 1c).

### 3.4. Management criterion

The Management Quality Index (MQI), based on land use and population density, generally ranges from 1.20 to 1.50. However, in provinces with high urbanization or demographic pressure—such as Tehran, Alborz, Razavi Khorasan, and Sistan and Baluchestan—land-use scores may reach 1.80–2.00, with population density values in Tehran and Alborz exceeding 1.40. Mountainous regions like Kohgiluyeh and Boyer-Ahmad or Chaharmahal and

Bakhtiari tend to have moderate MQI scores (~1.25–1.35), though certain industrial or urban zones exceed 1.70. This results in wide intra-provincial MQI variation. In highly urbanized provinces, MQI drops to approximately 1.00 in rural areas but rises above 2.00 in fast-growing outskirts, underscoring the stark contrast between sustainable rural management and escalating degradation in peri-urban zones (Fig 1d).

### 3.5. ESAI framework

Based on the ESAI classification, less than 2% of Iran falls into the Non-Affected (0.47%) and Potential (0.60%) categories. Fragile areas (F1–F3) cover approximately 10%, while the vast majority of the country lies within Critical classes, particularly C2, which alone comprises 60.42% of the territory. This distribution reflects widespread land degradation driven by persistent climatic stress, vegetation decline, and unsustainable land use. C1 and C3 together account for nearly 25% (11.81% and 13.34%, respectively), highlighting areas of either escalating or extreme degradation linked to groundwater depletion, salinization, and industrial expansion. Despite harmonization of datasets with varying resolutions (250–4638 m), some spatial variability may persist due to residual scale effects. Nevertheless, the ESAI provides a robust spatial representation of desertification severity across Iran (Fig 2, Table 4). Iran's mean ESAI values (1.30–1.45) are notably higher than those reported in comparable dryland regions like North Africa and Central Asia (1.20–1.35), underscoring the need for urgent, region-specific land management strategies aligned with global best practices.

Average ESAI values across Iran's 31 provinces typically range between 1.30 and 1.45, placing most regions in the "Fragile" or "Moderate Critical" categories. While no province's mean exceeds the "High Critical" threshold of 1.53, localized zones within Alborz, Sistan and Baluchestan, and Khuzestan do reach such levels. Provinces like Tehran and Alborz report averages of 1.42–1.50, indicating considerable environmental and anthropogenic pressure, whereas Esfahan and Markazi fall near the "Low Critical" boundary (1.38–1.41). Gilan and Mazandaran, with averages around 1.26–1.31, remain in the "Fragile" category but may include critical pockets. No province's mean drops below 1.17, confirming that desertification affects nearly all of Iran. High intra-provincial variation—evidenced by wide ESAI ranges in Khuzestan and East/West Azerbaijan—contrasts with more homogeneous provinces like Semnan. Compared to other dry regions (e.g., North Africa, Central Asia), Iran's ESAI averages are generally higher, suggesting greater vulnerability. Overall, these findings highlight the

widespread, though uneven, nature of desertification risk across the country.

Box plot analysis highlights substantial variability in VQI and MQI, reflecting spatial heterogeneity in vegetation conditions and land management across Iran. VQI displays the widest in-terquartile range and numerous outliers, while MQI also shows a broad distribution—underscoring uneven anthropogenic pressures. In contrast, CQI exhibits a relatively stable distribution with a few outliers, while SQI displays minimal variability, indicating stable soil properties nationwide. ESAI values cluster near the median, indicating a moderate aggregated risk of desertification (Fig 3a). The correlation heat map reveals strong positive correlations between ESAI and both MQI ( $r=0.81$ ,  $P\leq 0.01$ ) and CQI ( $r=0.73$ ,  $P\leq 0.05$ ), affirming the dominant role of management and climatic factors in desertification. VQI shows a moderate correlation ( $r=0.50$ ,  $P\leq 0.05$ ), while SQI exhibits a weak negative correlation ( $r=-0.20$ ), suggesting that in some areas, better soils do not mitigate degradation if human or climatic stresses are high. Additionally, negative correlations of SQI with MQI and CQI ( $-0.44$  and  $-0.46$ , respectively) imply that improved soil conditions may co-occur with more favorable management or climate settings (Fig 3b).

### 3.6. Financial support and stakeholder engagement

Effective desertification control, especially in high-risk (C3) zones, depends on continuous financial investment and active involvement from both government and non-government stakeholders. However, high implementation costs, limited engagement in rural areas, and fragmented institutional policies present major challenges. For example, in central and eastern Iran—where freshwater shortages are severe—solutions like desalination or interbasin transfer are costly. Without focused financial support and coordinated stakeholder efforts, such measures are not feasible. Tackling these issues requires clear governance, cross-sector collaboration, and long-term funding aligned with national and global environmental goals.

### 3.7. Adaptive management phases Linked to ESAI classes

Desertification management is structured around a phased yet adaptive framework: Sustainable Monitoring is recommended for Non-Affected (N) and Potential (P) areas; Prevention and Hardening strategies are suited to Fragile zones (F1–F3); while Integrated Management and Emergency Response are essential for Critical classes (C1–C3).

To align management strategies with observed land degradation levels, a multi-tiered intervention framework

was developed, linking ESAI classes to appropriate response measures.

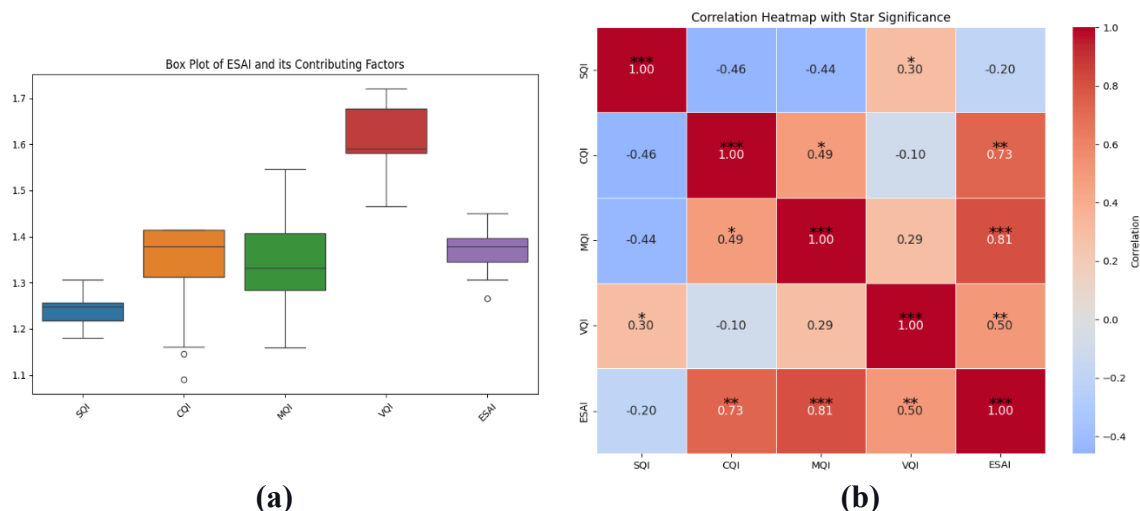
- Non-Affected (N) & Potential (P): Found mainly in humid northern zones or southwestern plains, these areas require preventive action through continuous monitoring of land-use dynamics and water extraction, alongside the development of early warning systems to preempt degradation.
- Fragile Classes (F1–F3): Common in the Caspian coastal belt, mid-Zagros, and western rangelands, these areas face threats from deforestation, overgrazing, and agricultural expansion. Targeted interventions include optimizing cropping systems, regulating grazing, advancing watershed management, and curbing unplanned construction in sensitive landscapes.
- Critical Classes (C1 & C2): Widespread in central, eastern, and southern regions, these zones are affected by aquifer overexploitation, urban sprawl, and industrial encroachment. Mitigation requires an integrated approach, including limiting groundwater extraction, enforcing land-use regulations, rehabilitating degraded lands (e.g., through the use of vegetative barriers), and promoting demographic balance.
- High Critical (C3): Although rare at the provincial scale, C3 zones occur in densely populated fringes and arid southeastern areas, where extreme groundwater depletion and salinity coincide with weak governance. These areas demand urgent action, including grazing bans, halting water withdrawal, and stabilizing dunes using mechanical and ecological techniques.

Each province may simultaneously apply different strategies across its sub-regions based on localized ESAI values. For example, while one area may require only preventive monitoring, adjacent zones may demand urgent restoration. This dynamic, multi-tiered approach ensures context-sensitive intervention planning.

Successful implementation requires overcoming institutional fragmentation and ensuring coordinated action across governmental agencies, NGOs, and local communities. Tailoring strategies to region-specific environmental and socio-economic contexts—from deforestation threats in the humid north to overexploitation in the arid south—can enhance both effectiveness and resilience (Table 5).

## 4. Discussion

Desertification in Iran is closely linked to soil fragility, especially in hyper-arid provinces such as Yazd, Kerman, and Sistan and Baluchestan. Factors such as poor texture, shallow depth, and high gravel content contribute significantly to topsoil erosion and fertility decline.



**Figure 3.** Comparison of desertification indicators based on the ESAS model in Iran: a) Boxplot of ESAI and its associated criteria; b) Correlation heatmap of desertification indices across the country. Stars represent correlation significance: \*, \*\*, \*\*\* are significant at 0.10, 0.05, and 0.01 probability levels, respectively

**Table 5.** Final Integrated Table for Integrated Desertification Management Based on Class and Intervention Phase

Class	ESAI	Management Phase	Strategic Approaches
Non-Affected (N)	< 1.17	Sustainable Monitoring	Periodic monitoring and maintaining the current condition; preventive planning to enhance resilience against climate variations.
Potential (P)	1.17 – 1.22	Prevention & Hardening	Actively avert entry into the Fragile classes; strengthen managerial and infrastructural capacities, along with preparedness for drought or climatic shifts.
Fragile Low (F1)	1.23 – 1.26	Prevention & Hardening	Emphasize soil and vegetation stabilization; rigorously manage water use and control land-use change.
Fragile Medium (F2)	1.27 – 1.32	Prevention &Hardening	Increase ecosystem resilience; regulate livestock density and water consumption; closely monitor vegetation in sensitive zones.
Fragile High (F3)	1.33 – 1.37	Integrated Management	Carry out broad interventions for vegetation restoration and soil conservation; closely oversee steep slopes, saline areas, and wetland edges; prevent the conversion of forests and rangelands into unsuitable uses.
Critical Low (C1)	1.38 – 1.41	Integrated Management	Immediately control groundwater overuse; restrict water-intensive urban or industrial expansions; firmly address improper land-use conversions; and systematically track soil and vegetation conditions.
Critical Medium(C2)	1.42 – 1.53	Integrated Management	Utilize integrated measures and resource mobilization to curb desertification; restore degraded lands; intensify controls on urban/industrial land-use changes; and organize population in high-risk districts.
Critical High (C3)	> 1.53	Emergency Intervention	Urgent actions to combat severe erosion and water scarcity; prohibit any unsustainable industrial or urban activities; mobilize funding and manpower to mitigate ecosystem destruction.

ESAI = Environmentally Sensitive Areas Index

These findings are consistent with prior studies emphasizing erosion control and soil restoration via organic matter enrichment (AbdelRahman et al., 2016; Abuzaid et al., 2021). GIS-based soil conservation strategies are recommended to identify and stabilize high-risk zones (AbdelRahman et al., 2019; AbdelRahman and Tahoun, 2019a).

Climatic stress, particularly aridity and uneven rainfall distribution, intensifies water scarcity and vegetation stress across Iran's drylands. The high Climate Quality Index (CQI) scores in provinces like Semnan and Kerman reflect the dominance of these stressors. Recent studies suggest that integrating watershed management and climate-adaptive irrigation policies is essential to mitigate desertification (AbdelRahman and Arafat, 2020; Abuzaid et al., 2021).

Vegetation Quality Index (VQI) variability reflects ecosystem instability, particularly in semi-arid zones where fire risk, biomass loss, and vegetation degradation are common. Provinces such as Kohgiluyeh and Boyer-Ahmad showed both moderate vegetation resistance and susceptibility to degradation. Strategies such as reforestation, fire prevention, and agroforestry can enhance vegetation resiliency (AbdelRahman et al., 2019).

High Management Quality Index (MQI) values in urbanized and industrialized provinces (Tehran, Alborz, and Razavi Khorasan) confirm the dominant role of human activity in accelerating land degradation. Management-induced pressures—urban expansion, intensive agriculture, and infrastructure growth—are major contributors to desertification. Spatial land-use modeling and decision-support systems based on GIS are essential for planning resilient land management interventions (AbdelRahman and Tahoun, 2019b; Abuzaid, et al. 2021).

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ESAI analysis showed that virtually no province is fully free from desertification. While no province means ESAI exceeds the “High Critical” threshold ( $>1.53$ ), localized hotspots (e.g., in Alborz, Sistan and Baluchestan) do cross this boundary. Urban growth, poor management, and climatic pressures converge to elevate risk in many

regions. For example, despite relatively lower ESAI means in Esfahan, Khuzestan, Gilan, or Mazandaran, certain subregions may still reach critical conditions. This highlights the need for localized, rather than provincial-average-based, interventions.

Compared to North Africa or Central Asia, Iran exhibits higher ESAI averages (1.30–1.45), indicating a more severe national vulnerability. The heterogeneity across provinces—arid plateaus in Yazd and Semnan, saline lowlands in Khuzestan, and forest-conversion zones in the north—demands region-specific mitigation plans. Soil conservation, groundwater regulation, and land-use restrictions are urgent in provinces nearing critical thresholds.

Correlation analysis confirms that MQI has the strongest relationship with ESAI ( $r=0.81$ ), followed by CQI ( $r = 0.73$ ). This reinforces the conclusion that human-induced stress and climatic imbalance are primary desertification drivers. VQI also contributes, especially where vegetation degradation is high. In contrast, the weak correlation of SQI ( $r = -0.20$ ) suggests that while soil quality matters, it acts more as a background condition rather than an active driver.

The findings highlight the centrality of adaptive land management, climate-resilient policy frameworks, and stakeholder engagement. While long-term climate change remains a key factor, short-term mitigation should focus on controlling vegetation loss and improving land-use practices. Implementation faces barriers such as limited financial resources, fragmented governance, and low community participation. Overcoming these requires integrated, multi-scale planning and external support mechanisms (AbdelRahman and Arafat, 2020).

Ultimately, the study underscores the importance of multi-criteria geospatial approaches and localized risk mapping in shaping evidence-based, regionally tailored desertification control strategies. GIS and remote sensing tools must remain central to early warning systems and long-term sustainability planning (Abuzaid et al., 2021).

## 5. Conclusion

The four criteria—Soil, Climate, Vegetation, and Management—indicate that desertification in Iran stems from the combined influence of natural factors and human activities. The integration of the Environmentally Sensitive Areas Index (ESAI) into this study provides a robust framework for identifying and quantifying Iran's high vulnerability, reinforcing the critical need for immediate action. For instance, provinces scoring high on the Soil Index (including Sistan and Baluchestan, Kerman, and Yazd) generally perform poorly in climate metrics as well (precipitation sub-indicator ranging from 1.80 to 2.00), an interplay that can accelerate

desertification. Although climate conditions are slightly more favorable along the Caspian coast, certain forested zones exhibit high soil-conservation scores (around 1.90–2.00) and notable fire hazards. Meanwhile, in highly urbanized regions like Tehran and Alborz, land use and demographic pressures have become decisive factors for land degradation. Without these issues, desertification will likely spread to suburban fringes and beyond. The results highlight that the southeastern provinces, including Sistan and Baluchestan, are the most vulnerable due to compounded soil and climate stresses, whereas urban pressure dominates in Northern provinces like Tehran and Alborz. These findings emphasize that a one-size-fits-all strategy would be ineffective; instead, region-specific interventions are essential. Consequently, mitigating desertification requires a unified plan that concurrently addresses all four criteria. In areas with acute soil constraints, interventions aimed at improving soil texture and structure, along with limiting overgrazing and regulating tillage, are key. Provinces suffering from severe dryness demand water-conscious strategies and integrated water-resource management. Fragile ecosystems rely on strict vegetation protection and efficient fire-prevention measures. Finally, resolving management problems—ranging from high population density to unsustainable land-use practices—calls for well-conceived legislation, rigorous oversight, and strengthened local community capacities. Successful mitigation will require coordinated efforts from national government bodies, regional authorities, non-governmental organizations (NGOs), and local communities to ensure effective policy enforcement and long-term sustainability. Moreover, integrating advanced technologies such as smart irrigation systems, remote sensing for land monitoring, and data-driven decision-making platforms can significantly enhance the resilience of vulnerable ecosystems and improve the efficiency of desertification control measures. Iran can effectively contain escalating desertification and safeguard its vulnerable ecosystems over the long term by coordinating efforts across these four dimensions.

#### Authors Contribution

All the authors have participated sufficiently in the intellectual content, conception and design of this work or the analysis and interpretation of the data (when applicable), as well as the writing of the manuscript.

#### Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

#### Conflict of interests

The author states that there is no conflict of interest.

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