Manara
Qatar Research Repository
by Qatar National Library

Characterizing the dynamics of climate and native desert plants in Qatar

Meshal Abdullah, Ammar Abulibdeh, Sophia Ghanimeh, Helmi Hamdi, Hezam Al- Awah, Talal Al-Awadhi, Midhun Mohan, Zahraa Al-Ali, Abdullah Sukkar, Ahmed M. El Kenawy

Item type
Journal Contribution

Terms of use
This work is licensed under a CC BY 4.0 license

This version is available at
https://manara.qnl.qa/articles/journal_contribution/Characterizing_the_dynamics_of_climate_and_native_desert_plants_in_Qatar/
Access the item on Manara for more information about usage details and recommended citation.

Posted on Manara – Qatar Research Repository on
2024-12-01

Journal of Arid Environments 225 (2024) 105274

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Characterizing the dynamics of climate and native desert plants in Qatar

Meshal Abdullah [a,b], Ammar Abulibdeh [c,*], Sophia Ghanimeh [d], Helmi Hamdi [e], Hezam Al- Awah [f], Talal Al-Awadhi [a], Midhun Mohan [g,h], Zahraa Al-Ali [i], Abdullah Sukkar [j], Ahmed M. El Kenawy [k,l]

[a] Geography Department, College of Arts and Social Sciences, Sultan Qaboos University, Muscat, P.O. Box 50, Oman
[b] Department of Ecology and Conservation Biology, Texas A&M University, College Station, TX 77843, USA
[c] Applied Geography and GIS Program Department of Humanities College of Arts and Sciences Qatar University, Qatar
[d] Environmental Science Center, Qatar University, Doha, P.O. Box 2713, Qatar
[e] Center for Sustainable Development, College of Arts and Sciences, Qatar University, Doha, Qatar
[f] Department of Chemistry and Earth Science, Collage of Arts and Science, Qatar University, Qatar
[g] Department of Geography, University of California—Berkeley, Berkeley, CA, 94709, USA
[h] Ecoresolve, San Francisco, CA 94105, USA
[i] Natural Environmental Systems and Technologies (NEST) Research Group, Ecolife Sciences Research and Consultation, Kuwait
[j] Graduate School, Geomatics Engineering Program, Istanbul Technical University, Istanbul, Turkey
[k] Instiuto Pirenaico de Ecologia, Consejo Superior de Investigaciones Cientificas (CSIC), Campus de Aula Dei, 1005, 50059, Zaragoza, Spain
[l] Department of Geography, Mansoura University, Mansoura, 35516, Egypt

A R T I C L E I N F O

Keywords:
Climate dynamics
Vegetation patterns
Native desert plants
Supplemental irrigation
Ecosystem restoration

A B S T R A C T

This study aims to measure changes in climatic factors and their relationship to vegetation growth in Qatar to develop a plant-climate characterization for native desert plants. By analyzing Landsat satellite images from 1985 to 2022 and their relation to rainfall patterns, we found significant impacts of climatic variables on vegetation coverage, particularly after 1990. Increased drought seasons correlated with changes in annual temperature, dew point, and soil temperature. Vegetation growth depended not only on rainfall amount but also on the number of rainfall events and accumulation. Optimal rainfall events per year ranged from 10 to 15, with 70 mm being the threshold for healthy vegetation growth. However, the probability of rainfall events over 80 mm was less than 5%, while low rainfall seasons (1–17 mm) were more likely (90–99% chance). Additionally, vegetation cover varied between protected sites, indicating the complexity of arid lands influenced by factors like topography and soil type. These findings suggest a continued decrease in vegetation coverage, leading to more drought seasons and impacting water and food security. We recommend further research on supplementary irrigation to support native species, understand their seasonal growth stages, and better comprehend soil-plant-water connections and water requirements. This study's findings will also inform strategies for managing water resources in protected areas and help in designing policies aimed at mitigating the impacts of climate change on Qatar's fragile desert ecosystems.

1. Introduction

Arid ecosystems are uniquely sensitive to the impacts of climate change and environmental degradation (Chen et al., 2020; Lee et al., 2021; Ochoa-Hueso et al., 2017). The inherent challenges of these regions—such as limited water availability, infertile soils, and sparse vegetation—are exacerbated by changing climate patterns. Studies have highlighted the increasing incidence of land degradation and desertification, affecting a quarter of the world's land surface (D'Odorico et al., 2013; Eswaran et al., 2019; Prăvălie, 2021). This degradation is particularly acute in arid regions, where even minor shifts in climate can lead to pronounced changes in the ecosystem. Furthermore, the frequency of unusually dry seasons has been on the rise in several arid areas, further stressing these fragile environments (Hadri et al., 2021; Huang et al., 2017). The vulnerability of arid ecosystems to these changes poses a significant risk not only to the biodiversity they support but also to the substantial portion of the global population that depends on them.

* Corresponding author.
E-mail address: aabulibdeh@qu.edu.qa (A. Abulibdeh).

https://doi.org/10.1016/j.jaridenv.2024.105274
Received 5 June 2024; Received in revised form 23 October 2024; Accepted 23 October 2024
Available online 28 October 2024
0140-1963/© 2024 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Given these challenges, the restoration and revegetation of arid ecosystems have become a global priority (Abdullah et al., 2017; Nirola et al., 2016; Stapleton et al., 2024). These efforts are crucial for maintaining the ecological balance and supporting the livelihoods of the communities that rely on these landscapes. However, the task is fraught with uncertainties, primarily due to the limited understanding of how desert vegetation responds to environmental stressors (Huebner et al., 2022; Svejcar and Kildisheva, 2017). The variability in response across different arid regions complicates the development of effective management strategies. As the world's population continues to grow, the importance of restoring and sustainably managing these ecosystems becomes even more critical (Miller et al., 2017; Monaco, 2024). Addressing these challenges requires a concerted effort from the global community, including research to better understand the dynamics of arid ecosystems, the implementation of innovative restoration techniques, and policies that support sustainable management practices.

When addressing the challenges of revegetation and ecosystem restoration in arid environments, it is crucial to factor in the overarching influence of climatic conditions, particularly in the context of ongoing climate change. Arid regions are characterized by their extreme temperatures and minimal precipitation, conditions that naturally limit the growth and diversity of vegetation cover (Abulibdeh, 2021; Jiao et al., 2021; Olmos-Trujillo et al., 2020). However, the escalating levels of greenhouse gasses in the atmosphere are intensifying these climatic extremes, further stressing these fragile ecosystems. The rise in air temperature, a direct consequence of increased greenhouse gasses, exacerbates the aridity, leading to longer drought periods and more intense heat waves (Aghakouchak et al., 2020; Overpeck and Udall, 2020). These changes can significantly alter the growth patterns and survival rates of native plant species, which are adapted to specific climatic conditions. Additionally, the variability in precipitation, both in terms of quantity and distribution, adds another layer of complexity, affecting seed germination, plant growth, and the overall health of the vegetation cover (Roy et al., 2023).

In light of these changing climatic conditions, restoration and revegetation efforts must be adaptive and forward-looking. This involves selecting plant species not only based on their current suitability but also on their potential resilience to future climatic scenarios (Brown et al., 2022; Prober et al., 2019). It also necessitates a deeper understanding of how changes in temperature and precipitation patterns will interact with local ecosystems. In arid landscapes, where water scarcity is a defining characteristic, precipitation stands as the most critical factor influencing vegetation growth, diversity, and the overall functioning of ecosystem processes (Naorem et al., 2023; Yu et al., 2023). The sparse and unpredictable nature of rainfall in these regions sets the stage for a challenging environment for plant life (El Kenawy, 2024). When rainfall does occur, it often triggers a rapid and significant response in the ecosystem, leading to bursts of plant growth and a temporary increase in biological diversity (Khan and Mehmood, 2023). These episodic and brief periods of rainfall are vital for the survival and reproduction of native plant species, which have adapted over time to capitalize on these short windows of water availability (Marcotti et al., 2021; Song et al., 2020). The moisture provided by rainfall supports germination, growth, and the completion of life cycles in many desert plants (Chen et al., 2019). Moreover, precipitation plays a pivotal role in soil nutrient cycling, influencing the availability of essential nutrients for plant growth and thus indirectly impacting the diversity and health of the vegetation (Lai et al., 2019; Tariq et al., 2024).

The importance of precipitation in arid ecosystems extends beyond direct impacts on plant life. It also plays a crucial role in maintaining broader ecosystem processes and services (Berdugo et al., 2022; Grünzweig et al., 2022). For instance, rainfall patterns affect the distribution and abundance of wildlife, as many animal species in arid regions rely on the vegetation for food and shelter (Creech et al., 2023). The presence of water can also influence patterns of animal movement and breeding. Furthermore, precipitation is integral to soil formation and erosion control (Ashraf, 2020). In arid landscapes, even minor changes in precipitation patterns can lead to significant shifts in ecosystem dynamics (Zeng et al., 2021). These changes can have cascading effects, altering the balance between different plant and animal species, and potentially leading to shifts in the overall structure and functioning of the ecosystem. Thus, in the context of arid landscapes, understanding and monitoring precipitation patterns is crucial for conserving biodiversity, managing natural resources, and ensuring the sustainability of these unique ecosystems.

Over the past few decades, the concept of irrigating native desert plants has gained traction among researchers as a strategy to bolster revegetation efforts in arid environments (Abdullah et al., 2022; Al-Yamani et al., 2019; Dinarvand et al., 2022; Madouh, 2022). This approach is particularly relevant in the context of the increasing variability and unpredictability of rainfall events, often linked to rising global temperatures due to climate change. In desert ecosystems, where water is the most limiting factor for vegetation growth, the supplementary irrigation of native plants can provide a much-needed boost to establish and sustain vegetation cover (Byambadorj et al., 2021; Huebner et al., 2022). Therefore, this study aims to model the relationship between climate factors (rainfall, temperature, soil moisture) and vegetation patterns in Qatar's protected areas to predict future changes in vegetation cover under ongoing climatic shifts. Specific objectives are to (1) assess the changes in climatic factors and understand their relationship to vegetation growth in Qatar, and (2) develop a plant-climate characterization for native desert plants.

Given Qatar's increasing vulnerability to extreme weather events such as prolonged droughts, this study provides crucial insights for policymakers aiming to implement sustainable land and water management strategies. This study is important since changes in climate are negatively impacting vegetation cover and soil quality, leading to a significant decrease in vegetation cover, biodiversity, carbon sequestration, etc. Also, loss in vegetation cover is also decreasing natural rangelands for livestock production, leading to more pressure on fodder cultivation and food security. The study will also provide a deeper understanding of the impact of climate change on vegetation cover and the main factors influencing the growth of vegetation in arid desert ecosystems. This is important for the restoration and management of desert ecosystems as they are more vulnerable to climate change and require specific strategies. Thus, coming up with optimum solutions and strategies requires a deep understanding of the climate-vegetation interconnections. Such understanding will also support decision-makers with a better understanding of the interconnection and help them develop more effective restoration and revegetation planning for future programs. This study's findings will inform strategies for managing water resources in protected areas and help in designing policies aimed at mitigating the impacts of climate change on Qatar's fragile desert ecosystems.

2. Study area

Qatar, located in the eastern Arabian Peninsula, is a rapidly developing nation with a land area of about 11,437 square kilometers (Abulibdeh, 2024). The country is renowned for its remarkable transformation from a quiet pearl-fishing community to a global hub of commerce and culture. It is characterized by a hot, arid climate with minimal rainfall (Balakrishnan et al., 2023; Abulibdeh et al., 2024a). The discovery of hydrocarbon resources has fueled its economic and population growth, with a significant number of expatriates contributing to its current population of 2.8 million (Mansour et al., 2022; Mohammed et al., 2023). This growth has placed immense pressure on its limited natural resources, particularly water (Jawarneh and Abulibdeh, 2024). Qatar has responded to these challenges by investing in desalination to produce freshwater and subsidizing water and energy for its residents (Abulibdeh et al., 2024b). The country's economic strategies and infrastructure developments are aligned with Qatar Vision

2030, aimed at diversifying the economy and enhancing living standards through massive investments in various sectors, including transport and tourism (Abulibdeh, 2023; Al-Awadhi et al., 2022).

The country has established several protected areas to safeguard its unique biodiversity and natural landscapes (Fig. 1), each offering a distinctive ecosystem and contributing to the preservation of the region's natural heritage (Burt et al., 2017; Grichting, 2020). In this study, we focused on the three main protected sites in Qatar, including Al-Reem, Al-Thakhirah, and Khor Al-Adaid Protected sites. These protected areas include both terrestrial and marine regions, each offering a haven for a diverse range of flora and fauna (Weber, 2024). The selected protected areas represent critical habitats for native desert vegetation and serve as benchmarks for assessing the impacts of climate dynamics on arid ecosystems.

Qatar established Al-Reem Biosphere Reserve in 2006, which is recognized by UNESCO (Sillitoe et al., 2010). Al-Reem Protected Area, located in the western region of Qatar, stands as a testament to the country's commitment to preserving its unique desert ecosystem (Grichting et al., 2019). This vast reserve covers an area of approximately 1230 square kilometers, making it one of the largest protected zones in Qatar. The area is characterized by its stunning desert landscapes, which include a mix of sandy plains, rocky outcrops, and intermittent saltpans. This diverse topography shapes the region's natural beauty and provides a habitat for a wide range of wildlife species. The biodiversity of Al-Reem Protected Area is one of its most remarkable features (Grichting et al., 2019). The reserve is home to a variety of flora and fauna that have adapted to the harsh desert conditions. Among its inhabitants are several endangered species, such as the Arabian Oryx and the Reem Gazelle, both of which are iconic symbols of the Arabian wildlife heritage. The area also supports a range of bird species, reptiles, and small mammals. Additionally, the reserve's plant life includes unique desert shrubs and grasses, which play a crucial role in stabilizing the sandy terrain and supporting the food chain.

Al-Thakhira protected area, another protected site located in the northeast of Qatar near the town of Al-Khor, is one of the country's most significant natural reserves (Grichting et al., 2019). This area is particularly known for its large expanse of mangrove forests, which are among the few in the Arabian Gulf region (Rondon et al., 2023). The major mangrove types in Qatar include *Avicennia marina* (Grey mangrove), *Rhizophora mucronata* (Red mangrove), and *Avicennia officinalis* (Indian mangrove) (Pitumpe Arachchige et al., 2024). These mangrove forests, predominantly made up of the *Avicennia marina* species, commonly known as the grey mangrove, play a vital role in the coastal ecosystem (Jameson et al., 2009; Mohan et al., 2024; Moussa et al., 2024). The area covers several square kilometers and includes a diverse mix of coastal and marine environments, from mudflats and sandy beaches to salt marshes, providing a rich habitat for a wide variety of wildlife (Grichting, 2020). The biodiversity in Al-Thakhira includes mangroves, which serve as a nursery for many species of fish and crustaceans, crucial for maintaining the health of the local marine life.

Khor Al-Adaid, also known as the Inland Sea, is an extraordinary natural reserve located in the southeastern part of Qatar, near the border with Saudi Arabia. This remarkable area is one of the few places in the world where the sea encroaches deep into the heart of the desert, creating a unique landscape of dunes and tidal embayment (Jameson et al., 2009). The Inland Sea is a large, shallow, saltwater inlet surrounded by vast, rolling sand dunes, offering a stunning contrast between the arid desert environment and the aquatic ecosystem. The ecological importance of Khor Al-Adaid is immense (Rivers et al., 2020). It serves as a critical habitat for a variety of wildlife species, both terrestrial and marine. The area is particularly renowned for its rich marine life, including various species of fish and crustaceans. It is also an important nesting site for hawksbill and green turtles, which are considered endangered (Grichting, 2020). Additionally, the surrounding desert environment is home to a range of mammal species such as the Arabian gazelle and small mammals, as well as various reptiles and bird species. The area's unique ecosystem supports a delicate balance of life, adapted to the extreme conditions of the desert and the marine environment.

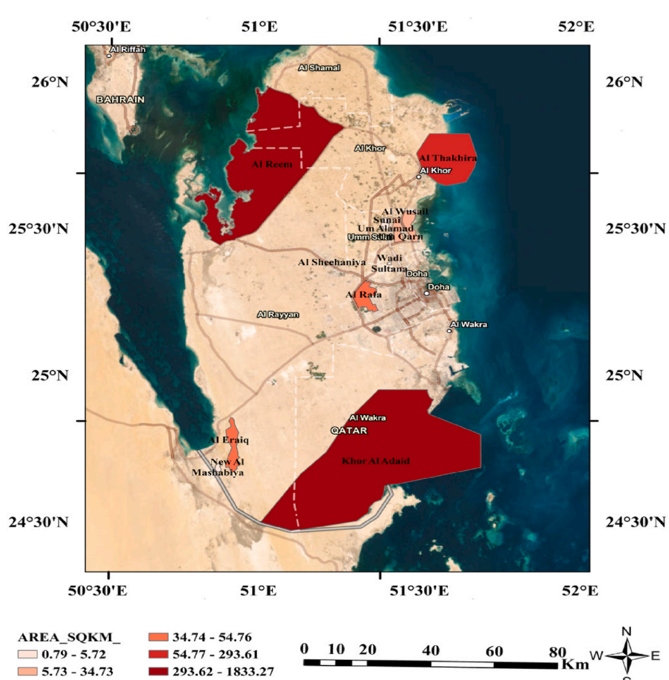

Figure (1). the study region comprising of the protected areas.

3. Methods

To accomplish the objectives of this work, we followed several steps: (1) climatic data were collected from ERA5-Land which is an upgraded version of ERA5, (2) vegetation data was collected from Google Earth Engine (GEE) by downloading the NDVI images of the Landsat 5, 7 and 8 satellites from 1985 to 2022 with a spatial resolution of 30m, (3) develop a regression model to understand the relationship and interconnection between vegetation and climate variables, and (4) calculate the return period of optimum rainfall events to support vegetation growth. In this work, we compared three protected sites in Qatar. The time period from 1985 to 2022 was selected to capture the major climatic shifts observed in the region, particularly in response to global warming trends, and to analyze vegetation changes in the context of evolving land management policies. More details on the methods are explained in the following sections.

3.1. Data collection, preparation, and pre-processing

3.1.1. Climatic data collection

ERA5-Land is an upgraded version of ERA5, the fifth generation of the European Center for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis data of the world's climate (Dai et al., 2023). ERA5-Land improves the spatial resolution to $0.1^\circ \times 0.1^\circ$ compared to the $0.25^\circ \times 0.25^\circ$ of the ERA5, which results in more accurate reflectance of the spatial attributes of the surface properties (Munoz-Sabater et al., 2021). The ERA5-Land dataset has been linearly interpolated from the ERA5 dataset using a triangular mesh approach (Wu et al., 2023). In this study, several ERA5-Land daily parameters have been used, including temperature 2m, dew point temperature 2m, soil temperature level 1, total precipitation, total evaporation, u component of wind 10m and v component of wind 10m. These parameters have been used to drive other daily parameters like relative humidity, wind speed, wind direction, rainfall intensity, and the standardized precipitation index

(SPI). Then, the daily parameters were averaged monthly, and new monthly parameters were generated, including the number of rainfall events, accumulated rainfall, and maximum and minimum metrics measurements of temperature 2m, dew point temperature 2m, and soil temperature level 1 (Table 1). The ERA5-Land dataset was accessed, and the meteorological parameters were downloaded through the Google Earth Engine (GEE) platform. Meanwhile, the pre-processing procedures were conducted locally using Python programming language through different libraries such as pandas, numpy, openpyxl, and scipy.

The u and v components of Wind 10m were used to calculate the wind speed and direction (Baranov et al., 2018). The wind speed (the magnitude of the wind vector) was calculated by using the Pythagorean equation (Eq. (1)). While the arctangent 2 function was used to determine the wind direction (Eq. (2))

$$Wind\ Speed = \sqrt{u^2 - v^2} \quad \text{(Eq. 1)}$$

$$Wind\ Direction = atan\ 2(u, v) \quad \text{(Eq. 2)}$$

The study area receives little rainfall due to its aridity, so a threshold was applied to the daily precipitation data to classify, find, and count precipitation events. If the precipitation in a day is $\geq$ 0.05 mm, it is considered a precipitation event (Meslier and DiRuggiero, 2019; WAD, 2019). Then, these events were accumulated for each month to find the monthly precipitation accumulation. The daily precipitation intensity was also calculated and added to the precipitation parameters. The maximum and minimum monthly metrics observations of the Dewpoint Temperature 2m, Temperature 2m, and Soil Temperature Level 1 parameters were selected by the highest and lowest daily observations, respectively.

Relative Humidity (RH) is a significant climatic factor that is defined as the ratio of air vapor pressure (e_a) to saturated vapor pressure (e_s), typically multiplied by 100 and presented as a percentage (Wu et al., 2021). RH (Eq. (3)) indicates the proximity of air to saturation rather than the actual amount of water vapor present in the air (Nugent et al., 2019).

$$RH = \frac{e_a}{e_s} \times 100 \quad \text{(Eq. 3)}$$

The saturation vapor pressure (e_s) and actual vapor pressure (e_a) are given by Eq. (4) and Eq. (5), respectively (Allen et al., 1998; Upreti and Ojha, 2017):

$$e_s = 0.6108\ exp\left[\frac{(17.27 \times T_{dew})}{T_{dew} + 237.3}\right] \quad \text{(Eq. 4)}$$

$$e_a = 0.6108\ exp\left[\frac{(17.27 \times T)}{T + 237.3}\right] \quad \text{(Eq. 5)}$$

Where T_{dew}, and T are the dewpoint temperature and temperature 2m, respectively.

For the purpose of evaluating and monitoring droughts, the SPI was developed by McKee et al. (1993). It is a widely utilized drought index that depends only on the precipitation as a variable to monitor all types of drought in any region with a precipitation record (Spinoni et al., 2015; Espinosa et al., 2019; Lorenzo et al., 2023). The World Meteorological Organization considers the SPI index to be a global standard measure for assessing the severity of drought (WMO, 2012). The SPI is determined by standardizing the precipitation values and representing them as the number of standard deviations away from the average over a lengthy period of time (Tirivarombo et al., 2018). It is assumed that the precipitation follows a normal distribution, as stated in (Eq. (6)).

$$SPI = \frac{x_i - \overline{x}}{\sigma} \quad \text{(Eq. 6)}$$

Where x_i is the precipitation measurement of the selected period, $\overline{x}$ the mean precipitation of the long-term period, and σ is the standard

Table 1
The parameters description.

Parameter	Unit	Resolution	Type	Description
Dew point Temperature 2m	K	0.1°	Raw	Represents the temperature where the air at 2 m above the Earth's surface would have to be cooled in order for saturation to happen. It is a measurement of air humidity.
Maximum Dewpoint Temperature 2m	K	0.1°	Derived	The maximum observation of the d ew point Temperature 2m in a month.
Minimum Dewpoint Temperature 2m	K	0.1°	Derived	The minimum observation of the Dewpoint Temperature 2m in a month.
Temperature 2m	K	0.1°	Raw	Represents the measurement of air temperature at a height of 2 m above the land or sea surface.
Maximum Temperature 2m	K	0.1°	Derived	The maximum observation of the Temperature 2m in a month.
Minimum Temperature 2m	K	0.1°	Derived	The minimum observation of the Temperature 2m in a month.
Soil Temperature Level 1	K	0.1°	Raw	Represents the temperature of the soil from 0 to 7 cm, where the surface is at 0.
Maximum Soil Temperature Level 1	K	0.1°	Derived	The maximum observation of the Soil Temperature Level 1 in a month.
Minimum Soil Temperature Level 1	K	0.1°	Derived	The minimum observation of the Soil Temperature Level 1 in a month.
Potential Evaporation	m	0.1°	Raw	Represents how conducive near-surface air conditions are to the evaporation process.
U Component of Wind 10m	$m.s^{-1}$	0.1°	Raw	The eastward element of the 10-m wind.
V Component of Wind 10m	$m.s^{-1}$	0.1°	Raw	The northward element of the 10-m wind.
Wind Speed	$m.s^{-1}$	0.1°	Derived	The magnitude of the wind vector obtained from the U and V components of the wind.
Wind Direction	°	0.1°	Derived	The direction of the wind vector obtained from the U and V components of the wind.
Total Precipitation	m	0.1°	Raw	Represents the amount of liquid and frozen water, including both rain and snow, that precipitates onto the Earth's surface.
Number of Events		0.1°	Derived	Represents the count of precipitation instances in a month.
Precipitation Accumulation	m	0.1°	Derived	Represents the total amount of precipitation in a month.
Precipitation Intensity	$m.h^{-1}$	0.1°	Derived	Represents the rate of precipitation per hour.
Standardized Precipitation Index		0.1°	Derived	It is a statistical drought index based on the precipitation parameter only.
Relative Humidity		0.1°	Derived	Represents t the amount of atmospheric moisture, it was calculated based on the Dewpoint Temperature 2m and Temperature 2m parameters.

deviation for the given period.

3.1.2. Vegetation data collection and pre-processing

In order to track the ever-changing desert vegetation cover, the Normalized Difference Vegetation Index (NDVI) was used in the present study since we are assessing changes in vegetation cover for a long period, which is only available with Landsat data. NDVI is used to quantify vegetation greenness and helps determine vegetation density and changes in plant health. NDVI focuses on the ratio between the red (R) and near-infrared (NIR) values in traditional fashion: (NIR - R)/(NIR + R). Over the years, NDVI has shown to be a valuable tool for researchers in several studies involving drought monitoring, classification, and vegetation dynamics (Jawarneh et al., 2024; Dutta et al., 2015; Abdullah et al., 2017a,b). The GEE was utilized to access and download the NDVI images of the Landsat 5 and 8 satellites from 1985 to 2022 with a spatial resolution of 30m. However, between 2003 and 2013, the acquisition of images was impeded by the presence of a scan line mistake in Landsat 7. A threshold was applied to classify the NDVI images into two classes: vegetation and non-vegetation. Due to the aridity nature of the study area, the threshold value was >0.1 to consider the pixel of the NDVI image as vegetation (Elagib et al., 2020; Ma et al., 2020).

The vegetation cover was calculated by aggregating information from the NDVI layer. The monthly vegetation cover was determined for each image by counting the pixels that were already classified as vegetation. If there were more than NDVI images within the same month, the average vegetation cover of those images was calculated. For each month from 1985 to 2022, the layer was classified into vegetation and non-vegetation. Then, the percentage of areas covered with vegetation was calculated to determine the vegetation cover. This is important since NDVI represents vegetation density, and vegetation cover refers to the physical presence and extent of vegetation in a given area. Both vegetation types could be impacted by different climatic factors.

3.2. Data statistical analysis

3.2.1. Understanding seasonal native desert vegetation growth to rainfall fluctuation

In this section of the work, we hypothesize that increased evaporation rates and decreased rainfall events, exacerbated by rising temperatures, are the main drivers of the reduction in vegetation cover in Qatar's protected areas. All data collected from the previous steps were exported from the raster data in Arc GIS to a point shapefile and transferred to an Excel sheet to perform the statistical analysis utilizing JMP™ statistical software, Version 11. The points were extracted from each pixel within the three examined protected sites, covering the dependent variables (vegetation cover and NDVI) and climatic variables In this stage of the work, we mainly focused on developing a regression model to develop a deeper understanding of the interconnection between vegetation and climatic variables. First, we performed a simple linear regression analysis to determine the relationship between each climatic variable and vegetation distribution. A 95% confidence interval was selected for the regression models. Then, we performed the multivariate regression model analysis (using forward stepwise regression) to understand the relationship between changes in vegetation and climatic factors as a model, putting all variables together to determine the most influential climatic variable. Before implementing the multi-regression model, multicollinearity was tested since some independent variables were correlated together. The multicollinearity was tested based on the variance Inflation Factor (VIF), as variables with high VIF values were excluded from the final analysis. The vegetation variables, including vegetation cover and NDVI values, were considered dependent variables in the model, and the climatic variables were considered independent variables. We examined six climatic factors including monthly precipitation, number of rainfall events, accumulated rainfall, humidity, SPI, and temperature. The regression model was implemented twice, for the vegetation cover and NDVI values. For the regression analysis, we assumed that vegetation cover in the examined areas could be highly influenced by most of the climatic variables, but at the same time, they may differ in terms of the variables affecting each site even though we are dealing with the same desert country. We also assumed that changes in vegetation cover and NDVI may also be influenced by different climatic factors, which is possible due to the sensitivity of arid lands as the type of plants and soil characteristics may play a major role.

3.2.2. The probability and return period of favorable rainfall events

The probability of rainfall events for vegetation growth was determined using the Markov Chain Monte Carlo method (MCMC) with @RISK software. This method, which is widely used to simulate precipitation occurrence and distribution, takes into account different parameters such as mean (μ), standard deviation (σ), maximum, and minimum. To determine the rainfall probability, 5000 iterations were simulated for each month of the year. Finally, the return period (T) was estimated by calculating the inverse of the probability of precipitation occurrence. The equation used for this estimation is as follows:

$$T = \frac{1}{P} * 100 \quad (2)$$

where, T is the return period, and P is the probability of occurrence of precipitation.

4. Results

4.1. Changes in vegetation cover and NDVI values

The results illustrate that vegetation cover in the protected areas differed within the examined years (Fig. 2). A significant decrease in vegetation cover was found in Al-Reem and Khor Al Adaid protected areas. Vegetation increased from 42% in 1986 to 80% in the mid-90s, but then it decreased significantly to reach <20% in most years starting from 2000 to 2022. Khor Al-Adaid also showed a similar trend compared with the Al-Reem site with a low percentage of vegetation cover where the maximum amount of vegetation cover was also found in the mid-90s, which reached >35% and decreased to <30% in most examined years. However, the Al-Thakhira site did show significant changes in vegetation cover, as the highest coverage was 35% in the mid-90s, and the lowest coverage was less than 20%. It was also illustrated from the results that the maximum vegetation cover differs from one location to another. It was found that the highest maximum vegetation was presented at the Al-Reem protected site (88%), Khor Al-Adaid (70%), and Al-Thakhira (32%). Reaching the maximum vegetation coverage at each site depends mainly on the variation in the climatic variables. On the other hand, NDVI values within the three examined protected sites showed an increasing trend, which illustrates an increase in the greenness of the plants. This is an interesting controversy as the coverage of the plants decreased while unexpectedly the NDVI values increased.

4.2. Changes in climatic variables

Such changes in vegetation cover in the examined protected areas are more likely related to the changes in climatic trends. The trend analysis showed that all precipitation variables significantly decreased over the past 45 years (Fig. 3). However, the Mann-Kendall (MK) analysis did not show any significant decrease in the precipitation variables at the protected areas except the Al-Thakhira protected site, which showed significant changes in the total annual precipitation and in the rainfall intensity (p-value <0.05). Such a significant decrease could clearly explain the low vegetation coverage at the Al-Thakhira protected site compared with the Al-Reem and Khor Al-Adaid protected sites – where the vegetation cover is higher.

On the other side, the results showed significant changes in the

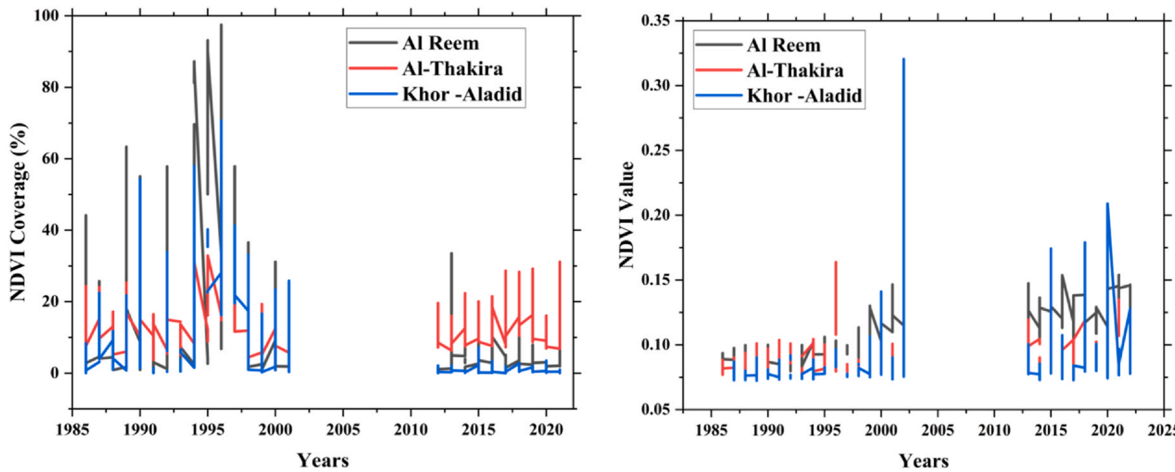

Fig. 2. Changes in vegetation coverage and NDVI values from 1958 to 2022.

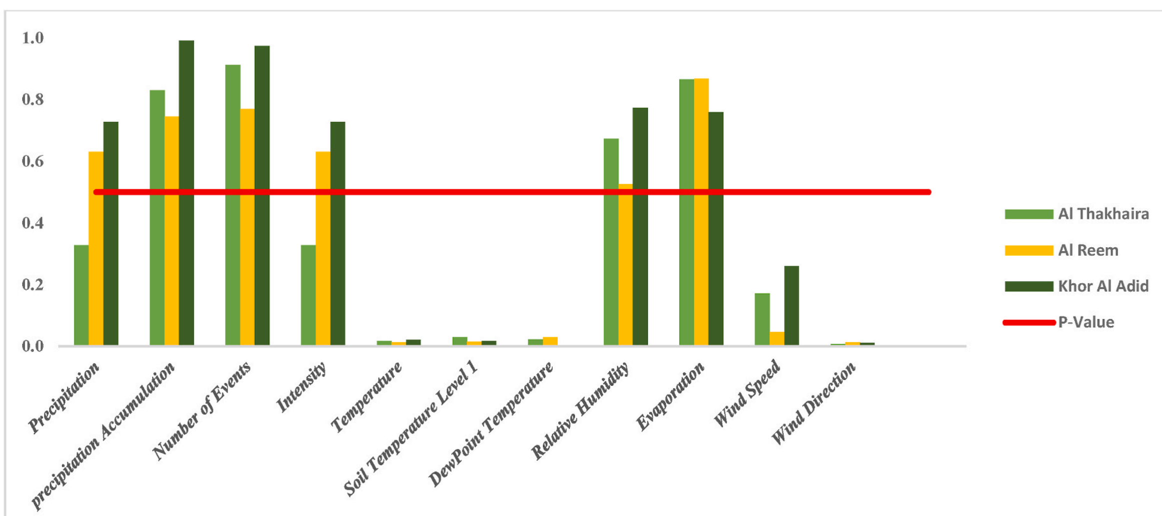

Fig. 3. Mann-kendall analysis.

annual temperature, soil temperature, and Dewpoint Temperature (p-value <0.01) at the three examined protected sites as it significantly increased in the past 45 years by 2 °C, which increased evaporation levels approximately from −0.53 to −0.508. This is a large increase in temperature that could significantly impact vegetation growth. Such changes in the climatic variables increased the drought seasons in the study areas as the results of the MK trend analysis showed that the SPI decreased significantly (p-value <0.01), which is more likely related to the significant decrease in vegetation cover.

It was also illustrated that wind speed and direction decreased significantly (p-value <0.05) in the three protected areas. Such changes in wind speed and direction could also impact the ecological processes by impacting the seed distribution leading to less vegetation coverage at the protected sites.

4.3. Factors influencing changes in vegetation coverage

It was demonstrated from the regression analysis results that the relationship between the climatic variables and vegetation is similar in some variables and differed in others among the three examined protected sites. The variables influencing the vegetation cover and the NDVI values of vegetation were also found to differ. The results of the simple linear regression (Table 2) showed that vegetation cover at Al-Reem protected site was significantly influenced by all examined variables except rainfall intensity and evaporation. Al-Thakhira protection site was also significantly influenced by all variables except accumulated rainfall, number of rainfall events, temperature, and humidity. However, vegetation at the Khor Al-Adaid protected site did not show any significant relationship with all variables except the number of rainfall events, temperature, soil temperature, and humidity. It was illustrated that four variables had a significant influence on vegetation cover at the three sites including precipitation, SPI, and dew point.

The stepwise regression analysis showed that the best-fit model for Al-Thakhira protected site depends on evaporation and dew point, compared to evaporation and soil temperature for the Al-Reem site. In contrast, the vegetation at Khor Al-Adaid showed that the best-fit model depends on the combination of number of rainfall events, SPI, evaporation, and dew point. The result of the stepwise regression showed that evaporation rates are the major variable influencing vegetation cover at the three sites.

The NDVI values were affected differently by the examined climatic variables (Table 3). The results of the single linear regression analysis showed that all variables influenced the NDVI value in Al-Thakhira and Al-Reem sites except annual precipitation, number of rainfall events, temperature, and humidity for Al-Thakhira, and rainfall intensity and evaporation for Al-Reem site. However, the temperature was the only significant variable influencing the NDVI value at Khor Al-Adaid site. This illustrates that changes in temperature are the main factor

Table 2
Regression analysis results for the relationship between vegetation coverage and climatic variables.

Independent Variable	r^2	coefficient	p-value	r^2 added	coefficient	p-value
Al Thakhira						
Variables	*Simple linear regression*			*Multivariate, step-wise*		
Accumulated precipitation	0.006	0.051	0.105			
precipitation	0.01	3.569	**0.02***			
Number of Rainfall events	0.008	0.19	0.07			
SPI	0.01	3.22	**0.04***			
Rainfall Intensity	0.03	49.8	**0.02***			
Temperature	0.007	−0.11	0.08			
Evaporation	0.05	−6.69	**0.001****	0.01	−6.726	**0.001** ***
Humidity	0.003	0.136	0.84			
Soil Temperature	0.01	−0.128	**0.04***			
Dew point	0.01	−0.17	**0.038***	0.06	−0.179	**0.02***
Al Reem						
Variables	*Simple linear regression*			*Multivariate, step-wise*		
Accumulated precipitation	0.01	0.249	**0.03***			
precipitation	0.03	11.01	**0.002****			
Number of Rainfall events	0.11	0.823	**0.03***			
SPI	0.02	13.08	**0.03***			
Rainfall Intensity	0.03	263.84	**0.002****			
Temperature	0.06	−0.091	**0.001****			
Evaporation	0.01	−11.82	0.058	0.02	−6.726	**0.02***
Humidity	0.02	0.532	**0.0007*****			
Soil Temperature	0.06	−0.84	**0.0001*****	0.07	−0.883	**0.0001*****
Dew point	0.05	−0.032	**0.0003*****			
Khor Al adid						
Variables	*Simple linear regression*			*Multivariate, step-wise*		
Accumulated precipitation	0.005	0.073	**0.04***			
precipitation	0.006	0.085	**0.04***			
Number of Rainfall events	0.0009	0.0895	0.4	0.13	−0.084	**0.009****
SPI	0.01	4.54	**0.002****	0.03	7.892	**0.0001*****
Rainfall Intensity	0.006	55.905	**0.04***			
Temperature	0.003	−0.097	0.1			
Evaporation	0.09	−6.473	**0.01***	0.01	−11.243	**0.001****
Humidity	0.009	−0.577	0.9			
Soil Temperature	0.003	−0.088	0.09			
Dew point	0.01	−0.263	**0.005****	0.14	−0.443	**0.008****

influencing the health of vegetation at all examined sites. However, the variation in other variables affecting vegetation health is more likely related to the variation in the types of plants at each site, as well as the variation in soil characteristics and landscaping. The stepwise regression analysis showed that the best-fit model for Al-Thakhira combines the following variables: evaporation, dew point, soil temperature, number of monthly rainfall events, SPI, and rainfall intensity. The stepwise regression for the Al-Reem site showed that the best-fit model combines the precipitation and the number of monthly rainfall events. However, Khor Al-Adaid showed that the best-fit model was only temperature. This illustrates that rainfall fluctuations significantly influence the vegetation health at Al-Thakhira and Al-Reem. However, temperature plays a major role in Khor Al-Adaid, which is also more likely related to the variation in plant types, soil, and landscaping.

To conclude, temperature and precipitation seem to be the main factors influencing native vegetation growth in arid landscapes. In fact, the stepwise regression analysis showed that the best-fit model for vegetation coverage for the study sites combines the following variables: temperature, evaporation, accumulated rainfall, and the number of monthly rainfall events ($R^2 = 0.58$, p-value <0.05). The results showed that temperature negatively affects vegetation growth during summer, reaching up to 4 °C, rendering the plants dormant from June to September (dry months). However, during the remaining months of the year, from October to May, when the temperature decreases, precipitation fluctuation is considered the influential primary variable to vegetation growth through several sub-variables, including (1) rainfall intensity and frequency (accumulated rainfall and number of events) and (2) the timing and months when rainfall was received.

4.4. *Changes in drought seasons*

It was illustrated from the regression analysis that vegetation cover was highly influenced by the SPI, showing that the significant changes in the temperature and rainfall trends significantly increase the drought seasons in Qatar. The results of the drought analysis showed that the drought seasons mainly increased at the beginning of the 90s (See Fig. 4). According to the SPI index analysis, it was illustrated that most of the drought events before 1991 were less than −0.5, with very rare high events that reached −1, especially in 1981 and 1982. However, in the remaining years, from 1983 to 1990, the drought events were ≤ 0.5. After 1990, drought seasons and months have increased, reaching −1. Also, increases in the wet seasons (November to January) were observed from the 90s until 2022, which is more likely related to the increase in rainfall intensity.

4.5. *Optimum rainfall events for vegetation growth and the return period*

Such significant changes in rainfall patterns and the increase in drought seasons (SPI) led to a significant decrease in vegetation in the past 20 years, especially the number of rainfall events and the accumulated rainfalls – which decreased during the past years. With respect to the number of rainfall events, the optimum number of events ranged between 10 and 15 events per year. For instance, the seasons showing high vegetation coverage were those with a number of rainfall events equal or higher than 15; and when the number dropped below 10–15, during the past 20 years, the vegetation significantly declined. On the other hand, as to accumulated rainfall, the 70 mm yearly value appears

Table 3
Regression analysis results for the relationship between NDVI values and climatic variables.

Independent Variable	r^2	coefficient	p-value	r^2 added	coefficient	p-value
Al Thakhira						
Variables	*Simple linear regression*			*Multivariate, step-wise*		
Accumulated precipitation	0.006	0.051	0.105			
precipitation	0.01	3.569	**0.02***			
Number of Rainfall events	0.008	0.19	0.07	0.122	0.0038	**0.0001*****
SPI	0.01	3.22	**0.04***	0.017	−0.0147	**0.013***
Rainfall Intensity	0.03	49.8	**0.02***	0.08	−0.2644	**0.0001*****
Temperature	0.007	−0.11	0.08			
Evaporation	0.05	−6.69	**0.001****	0.032	0.01568	**0.0008*****
Humidity	0.003	0.136	0.84			
Soil Temperature	0.01	−0.128	**0.04***	0.009	0.00039	**0.05***
Dew point	0.01	−0.17	**0.038***			
Al Reem						
Variables	*Simple linear regression*			*Multivariate, step-wise*		
Accumulated precipitation	0.01	0.249	**0.03***			
precipitation	0.03	11.01	**0.002****	0.38	−0.013	**0.0001*****
Number of Rainfall events	0.11	0.823	**0.03***	0.08	0.0023	**0.0001*****
SPI	0.02	13.08	**0.03***			
Rainfall Intensity	0.03	263.84	0.002			
Temperature	0.06	−0.091	**0.001****			
Evaporation	0.01	−11.82	0.058			
Humidity	0.02	0.532	**0.0007*****			
Soil Temperature	0.06	−0.84	**0.0001*****			
Dew point	0.05		**0.0003*****			
Khor Al adid						
Variables	*Simple linear regression*			*Multivariate, step-wise*		
Accumulated precipitation	0.003	0.0004	0.6			
precipitation	0.003	0.00302	0.6			
Number of Rainfall events	0.01	0.00302	0.4			
SPI	0.0004	0.0044	0.34			
Rainfall Intensity	0.0006	0.0726	0.6			
Temperature	0.02	0.0975	**0.001****	0.01	−0.0004	**0.001****
Evaporation	0.003	0.0057	0.4			
Humidity	0.004	0.0002	0.5			
Soil Temperature	0.007	−0.0003	0.09			
Dew point	0.005	0.0003	0.2			

to be the threshold for healthy vegetation growth. It was illustrated from the results that during the period of high vegetation growth, in the 1990s, the accumulated rainfall exceeded 80 mm a year at Al-Thakhirah and Al-Reem sites, and higher 70 mm in the Khor Al-Adaid site; whereas during the past 20 years, when vegetation growth clearly declined, the accumulated rainfall showed a decrease by 10 mm and more in the 3 protected sites (Fig. 4).

The probability analysis of the rainfall data showed that the chances of receiving the optimum rainfall events that are higher than 80 mm are less than 5%. However, it is more likely (90–99%) to receive low rainfall seasons with an amount of rainfall ranging from 1 to 17 mm. This indicates that vegetation coverage is more likely to continue decreasing, leading to more drought seasons in the future. Thus, supplemental irrigation could be a significant option to support the restoration and revegetation of the native desert plants to overcome the deficit in water resources due to the significant increase in temperature and evaporation rates, as the regression analysis results showed the evaporation rates were the most influential variables affecting the three sites.

5. Discussion

5.1. Climatic impacts on vegetation cover

The work's results showed the importance of considering new approaches that are particularly relevant in the context of the increasing variability and unpredictability of rainfall events, often linked to rising global temperatures due to climate change. The results showed a significant decline in vegetation cover at the protected sites examined after the mid-90s. This illustrates that desert areas in the GCC, such as Qatar, are more vulnerable than other ecosystems worldwide, which requires more in-depth analysis and strategies to restore and protect these areas. This reduction in vegetation is mainly due to changes in climatic variables, such as a considerable rise in temperature. The results of the trend analysis showed that there was a significant increase in temperature, soil temperature, dew point, and drought seasons, as well as changes in rainfall intensity and frequency. These changes had a significant impact on vegetation growth in the protected areas, starting in the 90s. The results of this study are consistent with an earlier study that assessed climate changes and their impact on vegetation cover in Kuwait (a GCC country with similar climate conditions as Qatar). The previous study revealed that after 1995, the temperature increased, and rainfall decreased in Kuwait, leading to significant changes in rainfall patterns and ultimately resulting in a considerable reduction in vegetation cover (M. Abdullah et al., 2024).

The significant impact of climatic changes, namely temperature and precipitation patterns on vegetation growth and health is well documented. Yet, surprisingly, this work shows that climatic variables affecting vegetation cover differed within the sites. It was also found that evaporation rates are the most significant variable affecting vegetation cover. This is interesting as the study site is small and showed such variation in vegetation response to climatic variables. We believe that such variation likely represents the complexity of arid ecosystems, as simple variations in vegetation types, soil characteristics, and landscaping could significantly impact vegetation growth, coverage, and health. Thus, the restoration of arid systems requires a detailed assessment before developing the plans. It is also important to include climate

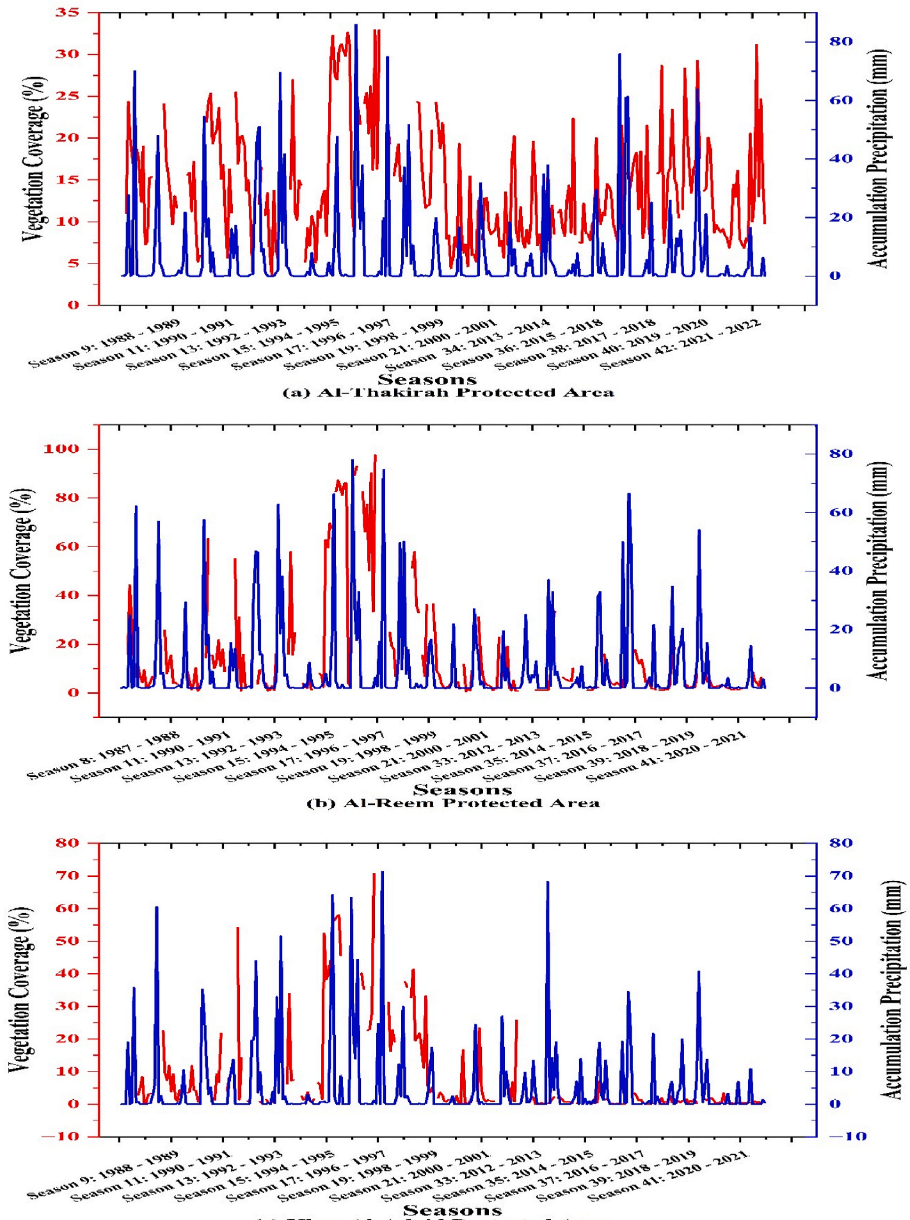

Fig. 4. Vegetation response to climatic variables. (A) Al-Thakirah Protected Site, (B) Al-Reem Protected Site, and (C) Khor-Al-Adaid Protected Site.

change in the restoration assessment as our results showed significant changes in the trends of most climatic variables, which led to a significant increase in desertification as the results showed the drought seasons increased significantly, especially in the 90s, and continued to increase.

It was also demonstrated from the results that the healthiness of the plants (NDVI values) significantly differed from vegetation cover, as vegetation healthiness was influenced by different climatic factors. Temperature and precipitation play a major role in the healthiness of vegetation. The results showed that the increase in temperature, especially in the 90s, impacted the healthiness of vegetation negatively since extreme temperatures can stress plants and reduce NDVI values if they exceed optimal ranges for photosynthesis. Also, the increase in temperature led to an increase in evaporation rates, leading to more water deficit for plant growth. Thus, distinguishing between vegetation cover and healthiness is an important aspect that needs to be considered in the restoration planning and assessment since both cover different aspects of the native desert plants and are mainly influenced by different climatic variables.

It was also observed that vegetation coverage significantly decreased, and the NDVI values increased within all three examined protected sites in Qatar. This does not necessarily mean that the available vegetation became healthier, but it could be attributed to changes in vegetation communities in response to the significant changes in climate. In fact, shifts in vegetation communities under climate change have been reported, including (1) changes in vegetation type such as phenological, physiological, and distributional; and (2) level changes such as species, community, and ecosystem levels. Also, abiotic and biotic constraints, including fragmentation of the landscape, land use, grazing, seed availability, resource availability, dispersal capabilities of individual species, available space, geographical barriers, topography, soil types, and biotic interactions, can lead to changes and shifting of native desert plants (Al Blooshi et al., 2020; Hufnagel and Garamvölgyi, 2013; McNichol and Russo, 2023; Munson et al., 2012). Another reason for higher NDVI could be the increase of native annual plants during the spring season since the spring weather conditions and summer and previous-autumn temperatures are linked to the peak growing season.

NDVI values of annual plants are commonly higher due to the greener leaves compared with perennial plants (i.e. less woody parts) (Crichton et al., 2022; Ghebrezgabher et al., 2020). This is further justified by the observation in Kuwait that the majority of vegetation cover is commonly annual plants in open areas and perennial plants in protected sites (M. M. Abdullah et al., 2024).

5.2. Spatial variation in vegetation cover

The results showed that maximum vegetation coverage significantly differed between locations. While climatic variables were reportedly (directly or indirectly) correlated to the growth of native plants, given the relatively small size of the studied area, it is unlikely that climatic factors are the main drivers for the differences in the growth and coverage of the vegetation. Thus, the topography and soil's physical and chemical properties may be the main determinants of the observed variation between the three sites. In fact, the results showed that Al-Thakhirah has the lowest vegetation growth, which is more likely related to the majority of the gypsum soils in the site (Peng et al., 2016). Al-Reem showed a higher vegetation cover than Al-Thakhirah since the site was dominated by gypsum and calcide soils. In comparison, Khor Al-Adaid, which was mainly dominated by calcide soils, presents the highest vegetation coverage compared to the other protected sites. This can be attributed to the fact that calcides soils have a better ability to store water for longer periods to support plant uptakes. Petrocalcid soils, for example, store a relatively high quantity of water, potentially making it available for plant uptake during dry times (Abdullah et al., 2020; Duniway et al., 2007).

The observation above is further justified by the results of the multi-regression model. Those showed that temperature-related parameters (evaporation, dewpoint, soil temperature) are the most influential variables affecting vegetation growth at Al-Thakhirah and Al-Reem area. In contrast, rainfall-related parameters (number of rainfall events and rainfall intensity) mostly influenced Khor Al-Adaid site – which benefits the most from rainfall due to its long water retention characteristic.

5.3. Optimum strategies to support the restoration of native desert plants

The results of this work show a correlation between droughts and the percentage of vegetation coverage. One option to support vegetation growth is using supplemental irrigation techniques, as they were recommended and used in vegetation restoration in Kuwait deserts (UNCC, 2002; Omar, 2014). However, even though this option is an effective option, it is still important to consider the water scarcity in arid regions since intensive watering may not be sustainable for long-term planning. The main disadvantages of supplementary irrigation for desert vegetation include high cost, intensive maintenance requirements (Ahmed et al., 2023; Bainbridge, 2002), and potential soil salinization (Abdullah et al., 2017; Misak et al., 2002). Thus, it is important to consider that this option should be evaluated carefully to avoid future complications. This is mostly true because increasing water storage in the soil through irrigation may provide a temporary success that is quickly followed by poor plant adaptation and an eventual failure (Naorem et al., 2023; Padgett et al., 2000). However, supplemental irrigation may be effective only during the months before seed germination and at low temperatures to avoid high evaporation rates. This observation aligns with a previous work implemented in Kuwait, which shows that the supplemental irrigation is effective two months before the growth season, especially in October and November (Abdullah et al., 2022). These months are considered the most influential months for plant growth, and the probability of receiving the optimum rainfall events is low. Therefore, supplemental irrigation could be an optimum strategy for these months.

Another important point is to focus on alternative options for supplemental irrigation, such as the use of treated wastewater. The use of treated wastewater for supplemental irrigation represents a promising strategy for revegetation efforts in arid environments. Treated wastewater (TWW) in Qatar and other GCC countries is underutilized, with only 39% being reused, mainly for landscaping and industrial purposes, while the remainder is discharged into the sea (Ahmed et al., 2023; Qureshi, 2020). The potential for using TWW in agriculture is substantial but limited due to various social, health, and environmental concerns (Darwish and Mohtar, 2013; Lahlou et al., 2023). It is noted that treated wastewater can safely be used to grow food and forage crops if managed with appropriate practices, suggesting a significant opportunity to relieve the pressure on freshwater resources (Hussain et al., 2019). Furthermore, this approach aligns with the broader goals of sustainable resource management and environmental conservation (Cai et al., 2018). It enables the restoration of native ecosystems while mitigating the risks associated with freshwater scarcity. Therefore, there is a need for robust plans and an integrated approach in Qatar to increase the agricultural use of TWW. This involves overcoming the hesitations of farmers and the public, who are concerned about health impacts and the quality of food products grown with treated wastewater. Education and awareness campaigns are suggested to address these concerns and enhance the acceptance of TWW for irrigation. Implementing supplemental irrigation with treated wastewater can help establish and maintain native plant species that are resilient to the harsh climatic conditions of Qatar. This method can provide a steady water supply, essential for the survival and growth of vegetation during prolonged dry periods. Additionally, it can foster biodiversity, stabilize soils, and contribute to the ecological balance of arid regions.

5.4. Limitations and research gaps for future studies

The results of this work demonstrated the interconnection between changes in climatic factors and vegetation response of the coverage and the healthiness. However, there were still some limitations with the satellite imagery analysis as we mainly depended on medium-resolution satellite information, which helped us understand the effect of climatic changes on the coverage and healthiness of desert native plants. Also, the paper examined 40 years with different climatic variables. However, the years 2003–2012 were not covered, as in May 2003, the scan line corrector (SLC) in the ETM + instrument failed with Landsat 7. So, we believe that future work should focus on small scale studies that can present more detailed information on the vegetation-climate interconnection. Thus, future research needs to consider UAVs (very high resolution) sensors to provide more details on the dynamics of different plant communities and their relation to rainfall patterns.

This study proved that, in arid ecosystems, the impact of climatic parameters on vegetation may differ in various aspects (pattern, intensity, influential factors, etc.), even within a small-scale area. Also, the regression model showed low R^2, which is more likely related to the complex relationship between the climatic variables and vegetation cover, as well as the high multicollinearity between the independent climatic variables. This clearly highlights the complexity of arid ecosystems and illustrates the need for a deeper understanding of the complexity of arid lands. In this respect, a quantitative assessment of the soil-plant-water interconnection remains needed to provide a strong basis for desert management planning, resulting in desertification control and enhanced vegetation growth and biodiversity.

Specifically, this work spotted future research needs for a better ecohydrological understanding of desert plants, allowing accurate analysis of water-saving opportunities. Supplemental irrigation could be considered one of the optimum solutions to enhance vegetation cover and perennial plant growth. However, implementing such strategies requires a better understanding of the future. Thus, future studies should consider the biological and physiological attributes of desert native species, which are critical aspects for the resident plant species, such as rooting system, acclimatizing potential, and other adaptations (e.g., stem and leaf water storage capabilities) that define desert-plant responses (growth and distribution) to dry conditions, with occasional rain pulses. Future research should also address the role of groundwater and its seasonal dynamics, or lack thereof, in the control of vegetation dynamics, which may be essential for the survival of deep-rooted desert species. Shallow-rooted species may also be differentially affected if present in the landscape. Moreover, plant and species-level information is needed to evaluate their degree of survival under future climate conditions.

6. Conclusion

This study revealed that the vegetation cover in Qatar significantly declined after alterations in climatic variables and demonstrated a strong correlation between yearly rainfall and vegetation cover. It was found that the total amount of rainfall and its daily intensity alone cannot accurately predict high vegetation cover. Instead, the frequency, distribution, and timing of rainfall play a crucial role in the growth of vegetation cover during the growing season. The study also highlighted that the probability of rainfall occurring at the right time is low, which leads to a high likelihood of low vegetation cover. It is crucial to note that irrigation is generally not a viable option due to the limited water resources in the arid region, which may have negative long-term consequences. However, supplementary irrigation should be further researched to support native species and understand the stages of their seasonal growth, as well as better comprehend the water requirements and soil-plant-water connections. Therefore, it is imperative to have a deeper quantitative understanding of the climatic vegetation-soil nexus in future studies, especially given the current climate trends. We also believe that decision-makers need to also consider the types of plants that are more resistant to climatic changes to develop more sustainable restoration programs and planning for the future.

Even though the results presented promising results on the plant climate interconnections and tradeoffs there were still some limitations that need to be considered in future research, including the resolution of the satellite imagery, providing a deeper quantitative assessment of the soil-plant-water interconnection, which remains needed in future research as soils play a major role in vegetation growth and distribution, especially that the results showed that vegetation cover differed with the study sites, and more studies on the efficiency of supplemented irrigation as a sustainable approach for enhancing the growth and productivity of native desert plants.

CRediT authorship contribution statement

Meshal Abdullah: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Ammar Abulibdeh:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sophia Ghanimeh:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Formal analysis, Conceptualization. **Helmi Hamdi:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Formal analysis. **Hezam Al- Awah:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Funding acquisition. **Talal Al-Awadhi:** Writing – review & editing, Writing – original draft, Resources, Methodology, Funding acquisition. **Midhun Mohan:** Writing – original draft, Visualization, Validation, Investigation. **Zahraa Al-Ali:** Writing – review & editing, Writing – original draft, Validation, Software, Formal analysis. **Abdullah Sukkar:** Writing – original draft, Validation, Software, Data curation. **Ahmed M. El Kenawy:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This publication is made possible by a High Impact Grant (HIG) award [211] from Qatar University, Qatar. The open access publication of this article was funded by the Qatar National Library (QNL).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jaridenv.2024.105274.

Data availability

Data will be made available on request.

References

Abdullah, M.M., Addae-Wireko, L., Tena-Gonzalez, G.A., 2017a. Assessing native desert vegetation recovery in a war-affected area using multispectral and hyperspectral imagery: a case study of the Sabah Al-Ahmad Nature Reserve, Kuwait. Restor. Ecol. 25 (6), 982–993. https://doi.org/10.1111/REC.12527.

Abdullah, M.M., Feagin, R.A., Abdullah, M.T., Al-Musawi, L., 2017b. Will autogenic succession be sufficient to recover from vegetation cover loss or will soil condition need to be addressed in the arid lands of Kuwait? Arabian J. Geosci. 10 (5), 1–14. https://doi.org/10.1007/S12517-017-2911-6/FIGURES/8.

Abdullah, M.M., Assi, A.T., Abdullah, M.T., Feagin, R.A., 2020. Arid ecosystem resilience to total petroleum hydrocarbons disturbance: a case-study from the State of Kuwait associated with the Second Gulf War. Land Degrad. Dev. 31 (2), 155–167. https://doi.org/10.1002/LDR.3435.

Abdullah, M.M., Assi, A., Zubari, W.K., Mohtar, R., Eidan, H., Al Ali, Z., Al Anzi, B., Sharma, V.K., Ma, X., 2022. Revegetation of native desert plants enhances food security and water sustainability in arid regions: integrated modeling assessment. Sci. Total Environ. 806, 151295. https://doi.org/10.1016/J.SCITOTENV.2021.151295.

Abdullah, M., Asadalla, N., Gharabi, Y., Mohan, M., Al Naabi, S., Al Ali, Z., Al Hashash, N., Srinivasan, S., Al Awadhi, T., Abulibdeh, A., 2024. Predictive modeling of green water availability: the role of annual plants as an ecological indicator in dryland ecosystems. J. Arid Environ. 223, 105179. https://doi.org/10.1016/J.JARIDENV.2024.105179.

Abdullah, M.M., Assi, A.T., Al-Ali, Z.M., Feagin, R.A., Al-Awadi, T., Al-Naabi, S., Abdullah, M.T., Mohan, M., Whisenant, S., 2024. Navigating water scarcity: rainfall considerations to optimize native vegetation growth in arid lands. Environ. Dev. Sustain. 1–21. https://doi.org/10.1007/S10668-024-04886-X/FIGURES/5.

Abdullah, M.M., Assi, A.T., Al-Ali, Z.M., et al., 2024. Navigating water scarcity: rainfall considerations to optimize native vegetation growth in arid lands. Environ. Dev. Sustain. https://doi.org/10.1007/s10668-024-04886-x.

Abulibdeh, A., 2021. Analysis of urban heat island characteristics and mitigation strategies for eight arid and semi-arid gulf region cities. Environ. Earth Sci. 80 (7). https://doi.org/10.1007/s12665-021-09540-7.

Abulibdeh, A., 2023. Analysis of mode choice affects from the introduction of Doha Metro using machine learning and statistical analysis. Transp. Res. Interdiscip. Perspect. 20, 100852. https://doi.org/10.1016/J.TRIP.2023.100852.

Abulibdeh, A., 2024. Geospatial assessment of the carbon footprint of water and electricity consumption in residential buildings in Doha, Qatar. J. Clean. Prod. 445, 141262. https://doi.org/10.1016/J.JCLEPRO.2024.141262.

Abulibdeh, A., Al-Ali, M., Al-Quraishi, D., Al-Suwaidi, W., Al-Yafei, B., Al-Mazawdah, S., 2024a. Assessing the spatial distribution and accessibility of public and private schools in Qatar: a GIS-based analysis for educational planning and policy. Geomatica 76. https://doi.org/10.1016/j.geomat.2024.100015.

Abulibdeh, A., Jawarneh, R.N., Al-Awadhi, T., Abdullah, M.M., Abulibdeh, R., El Kenawy, A.M., 2024b. Assessment of carbon footprint in Qatar's electricity sector: a comparative analysis across various building typologies. Renew. Sustain. Energy Rev. 189, 114022. https://doi.org/10.1016/J.RSER.2023.114022.

Aghakouchak, A., Chiang, F., Huning, L.S., Love, C.A., Mallakpour, I., Mazdiyasni, O., Moftakhari, H., Papalexiou, S.M., Ragno, E., Sadegh, M., 2020. Climate Extremes and Compound Hazards in a Warming World 48, 519–548. https://doi.org/10.1146/ANNUREV-EARTH-071719-055228.

Ahmed, Z., Gui, D., Murtaza, G., Yunfei, L., Ali, S., 2023. An overview of smart irrigation management for improving water productivity under climate change in drylands. Agronomy 13 (8), 2113. https://doi.org/10.3390/AGRONOMY13082113, 2023, Vol. 13, Page 2113.

Al Blooshi, L.S., Mohammad, S., Issa, G., Ksiksi, T., Al-Blooshi, L.S., Issa, S., 2020. Assessing the environmental impact of climate change on desert ecosystems: a

review. Researchgate.NetLS Al-Blooshi, S Issa, T KsiksiAdvances in Ecological and Environmental Research, 2020•researchgate.Net. https://www.researchgate.net/profile/Salem-Issa/publication/339498689_Assessing_the_Environmental_Impact_of_Climate_Change_on_Desert_Ecosystems_A_Review/links/5e57603392851cefa1c7f4e9/Assessing-the-Environmental-Impact-of-Climate-Change-on-Desert-Ecosystems-A-Review.pdf. (Accessed 7 May 2024).
Al-Awadhi, T., Abulibdeh, A., Al-Masri, A.N., Bin Touq, A., Al-Barawni, M., El Kenawy, A.M., 2022. Spatial and temporal changes in electricity demand regulatory during pandemic periods: the case of COVID-19 in Doha, Qatar. Energy Strategy Rev. 41, 100826. https://doi.org/10.1016/J.ESR.2022.100826.
Al-Yamani, W., Kennedy, L., Green, S., Kemp, P., Clothier, B., 2019. The historical basis and future options for native plant-species in the hyper-arid forests of Abu Dhabi. Land Use Pol. 88, 104186. https://doi.org/10.1016/J.LANDUSEPOL.2019.104186.
Ashraf, A., 2020. Risk modeling of soil erosion under different land use and rainfall conditions in Soan river basin, sub-Himalayan region and mitigation options. Modeling Earth Systems and Environment 6 (1), 417–428. https://doi.org/10.1007/S40808-019-00689-6/FIGURES/11.
Bainbridge, D.A., 2002. Alternative irrigation systems for arid land restoration. Ecol. Restor. 20 (1), 23–30.
Balakrishnan, P., Abulibdeh, A., Kabir, T., 2023. Assessment of the impact of anthropogenic evolution and natural processes on shoreline dynamics using multi-temporal satellite images and statistical analysis. Water 15 (8), 1440. https://doi.org/10.3390/W15081440, 2023, Vol. 15, Page 1440.
Baranov, Nikolay, Petrov, Gleb, Shiriaev, Ilia, 2018. Wind speed vector restoration algorithm. EPJ Web Conf. 176. https://doi.org/10.1051/epjconf/201817606012.
Berdugo, M., Vidiella, B., Solé, R.V., Maestre, F.T., 2022. Ecological mechanisms underlying aridity thresholds in global drylands. Funct. Ecol. 36 (1), 4–23. https://doi.org/10.1111/1365-2435.13962/SUPPINFO.
Brown, M.B., Morrison, J.C., Schulz, T.T., Cross, M.S., Püschel-Hoeneisen, N., Suresh, V., Eguren, A., 2022. Using the conservation standards framework to address the effects of climate change on biodiversity and ecosystem services. Climate 10 (2), 13. https://doi.org/10.3390/CLI10020013/S1.
Burt, J.A., Ben-Hamadou, R., Abdel-Moati, M.A.R., Fanning, L., Kaitibie, S., Al-Jamali, F., Range, P., Saeed, S., Warren, C.S., 2017. Improving management of future coastal development in Qatar through ecosystem-based management approaches. Ocean Coast Manag. 148, 171–181. https://doi.org/10.1016/J.OCECOAMAN.2017.08.006.
Byambadorj, S.O., Chiatante, D., Akhmadi, K., Lunten, J., Ochirbat, B., Park, B.B., Scippa, G.S., Montagnoli, A., Nyam-Osor, B., 2021. The effect of different watering regimes and fertilizer addition on the growth of tree species used to afforest the semi-arid steppe of Mongolia. Plant Biosystems - An International Journal Dealing with All Aspects of Plant Biology 155 (4), 747–758. https://doi.org/10.1080/11263504.2020.1779845.
Chen, Yanfeng, Zhang, L., Shi, X., Ban, Y., Liu, H., Zhang, D., 2019. Life history responses of spring-and autumn-germinated ephemeral plants to increased nitrogen and precipitation in the Gurbantunggut Desert. Sci. Total Environ. 659, 756–763. https://doi.org/10.1016/J.SCITOTENV.2018.12.368.
Chen, Yaning, Zhang, X., Fang, G., Li, Z., Wang, F., Qin, J., Sun, F., 2020. Potential risks and challenges of climate change in the arid region of northwestern China. Regional Sustainability 1 (1), 20–30. https://doi.org/10.1016/J.REGSUS.2020.06.003.
Creech, T.G., Williamson, M.A., Sesnie, S.E., Rubin, E.S., Cayan, D.R., Fleishman, E., 2023. Effects of changing climate extremes and vegetation phenology on wildlife associated with grasslands in the southwestern United States. Environ. Res. Lett. 18 (10), 104028. https://doi.org/10.1088/1748-9326/ACF8DB.
Crichton, K.A., Anderson, K., Charman, D.J., Gallego-Sala, A., 2022. Seasonal climate drivers of peak NDVI in a series of Arctic peatlands. Sci. Total Environ. 838, 156419. https://doi.org/10.1016/J.SCITOTENV.2022.156419.
Dai, W., Zeng, Y., Jing, T., Wang, Z., Zong, R., Ni, L., Fang, N., 2023. Estimation of rainfall erosivity on the Chinese Loess Plateau: a new combination of the ERA5 dataset and machine learning. J. Hydrol. 624, 129892. https://doi.org/10.1016/j.jhydrol.2023.129892.
Dinarvand, M., Arami, S.A., Sarab, S.A.M., 2022. Evaluation of changes in native vegetation cover of dust sources in the southwest of Iran under different irrigation systems and rainfall patterns in seedling cultivation areas. Arid Ecosystems 12 (1), 22–33. https://doi.org/10.1134/S207909612201005X/FIGURES/6.
Duniway, M.C., Herrick, J.E., Monger, H.C., 2007. The high water-holding capacity of petrocalcic horizons. Soil Sci. Soc. Am. J. 71 (3), 812–819. https://doi.org/10.2136/sssaj2006.0267.
Dutta, D., Kundu, A., Patel, N., Saha, S., Siddiqui, A., 2015. Assessment of agricultural drought in Rajasthan (India) using remote sensing derived vegetation condition index (VCI) and standardized precipitation index (SPI). The Egyptian Journal of Remote Sensing and Space Science 18 (1), 53–63. https://doi.org/10.1016/j.ejrs.2015.03.006.
D'Odorico, P., Bhattachan, A., Davis, K.F., Ravi, S., Runyan, C.W., 2013. Global desertification: drivers and feedbacks. Adv. Water Resour. 51, 326–344. https://doi.org/10.1016/J.ADVWATRES.2012.01.013.
El Kenawy, A.M., 2024. Hydroclimatic extremes in arid and semi-arid regions: status, challenges, and future outlook. In: Hydroclimatic Extremes in the Middle East and North Africa: Assessment, Attribution and Socioeconomic Impacts, pp. 1–22. https://doi.org/10.1016/B978-0-12-824130-1.00012-6.
Elagib, N.A., Khalifa, M., Babker, Z., Musa, A.A., Fink, A.H., 2020. Demarcating the rainfed unproductive zones in the african sahel and great green wall regions. Land Degrad. Dev. 32 (3), 1400–1411. https://doi.org/10.1002/ldr.3793.
Espinosa, L.A., Portela, M.M., Rodrigues, R., 2019. Spatio-temporal variability of droughts over past 80 years in Madeira Island. J. Hydrol. Reg. Stud. 25, 100623. https://doi.org/10.1016/j.ejrh.2019.100623.
Eswaran, H., Lal, R., Reich, P.F., 2019. Land degradation: an overview. Response to Land Degradation 20–35. https://doi.org/10.1201/9780429187957-4.
Ghebrezgabher, M.G., Yang, T., Yang, X., Eyassu Sereke, T., 2020. Assessment of NDVI variations in responses to climate change in the Horn of Africa. The Egyptian Journal of Remote Sensing and Space Science 23 (3), 249–261. https://doi.org/10.1016/J.EJRS.2020.08.003.
Grichting, A., 2020. Blue design for urban resilience in drylands: the case of Qatar. Contemporary Urban Design Thinking, Part F178, 175–208. https://doi.org/10.1007/978-3-030-26717-9_9/COVER.
Grichting, A., Alfaraidy, M., Ali, N., 2019. Blue bridges, blue peace: transboundry planning for peace and biodiversity conservation in the gulf. Asian Journal of Middle Eastern and Islamic Studies 13 (4), 621–641. https://doi.org/10.1080/25765949.2019.1682307.
Grünzweig, J.M., De Boeck, H.J., Rey, A., Santos, M.J., Adam, O., Bahn, M., Belnap, J., Deckmyn, G., Dekker, S.C., Flores, O., Gliksman, D., Helman, D., Hultine, K.R., Liu, L., Meron, E., Michael, Y., Sheffer, E., Throop, H.L., Tzuk, O., Yakir, D., 2022. Dryland mechanisms could widely control ecosystem functioning in a drier and warmer world. Nature Ecology & Evolution 2022 6 (8), 1064–1076. https://doi.org/10.1038/s41559-022-01779-y, 6(8).
Hadri, A., Saidi, M.E.M., Boudhar, A., 2021. Multiscale drought monitoring and comparison using remote sensing in a Mediterranean arid region: a case study from west-central Morocco. Arabian J. Geosci. 14 (2), 1–18. https://doi.org/10.1007/S12517-021-06493-W/FIGURES/3.
Huang, J., Li, Y., Fu, C., Chen, F., Fu, Q., Dai, A., Shinoda, M., Ma, Z., Guo, W., Li, Z., Zhang, L., Liu, Y., Yu, H., He, Y., Xie, Y., Guan, X., Ji, M., Lin, L., Wang, S., et al., 2017. Dryland climate change: recent progress and challenges. Rev. Geophys. 55 (3), 719–778. https://doi.org/10.1002/2016RG000550.
Huebner, L., Fadhil Al-Quraishi, A.M., Branch, O., Gaznayee, H.A.A., 2022. New approaches: use of assisted natural succession in revegetation of inhabited arid drylands as alternative to large-scale afforestation. SN Appl. Sci. 4 (3), 1–10. https://doi.org/10.1007/S42452-022-04951-Y/FIGURES/2.
Hufnagel, L., Garamvölgyi, Á., 2013. Impacts of climate change on vegetation distribution. No. 1: climate change induced vegetation shifts in the palearctic region. http://www.ecology.uni-corvinus.hu.
Jameson, J., Puls, D.D., Kozar, M.G., 2009. Holocene sabkha and coastal systems of Qatar: process models for the interpretation of ancient arabian plate carbonate-evaporite reservoirs. Society of Petroleum Engineers - International Petroleum Technology Conference 2009, IPTC 2009 3, 2106–2113. https://doi.org/10.2523/IPTC-13679-MS.
Jawarneh, R., Abulibdeh, A., 2024. Geospatial modelling of seasonal water and electricity consumption in Doha's residential buildings using multiscale geographically weighted regression (MGWR) and Bootstrap analysis. Sustain. Cities Soc. 113, 105654. https://doi.org/10.1016/J.SCS.2024.105654.
Jawarneh, R.N., Abulibdeh, A., Hashem, N., Awawdeh, M., Al-Awadhi, T., Abdullah, M. M., El Kenawy, A.M., 2024. Assessing and predicting land cover dynamics for environmental sustainability in Jordan's arid ecosystems using CA-Markov model. Remote Sens. Appl.: Society and Environment 35, 101262. https://doi.org/10.1016/J.RSASE.2024.101262.
Jiao, K., Gao, J., Liu, Z., 2021. Precipitation drives the NDVI distribution on the Tibetan plateau while high warming rates may intensify its ecological droughts. Rem. Sens. 13 (7), 1305. https://doi.org/10.3390/RS13071305, 2021, Vol. 13, Page 1305.
Khan, N., Mehmood, A., 2023. Revisiting climate change impacts on plant growth and its mitigation with plant growth promoting rhizobacteria. South Afr. J. Bot. 160, 586–601. https://doi.org/10.1016/J.SAJB.2023.07.051.
Lahlou, F.Z., AlNouss, A., Govindan, R., Hazrat, B., Mackey, H.R., Al-Ansari, T., 2023. Water and sludge resource planning for sustainable agriculture: an energy-water-food-waste nexus approach. Sustain. Prod. Consum. 38, 130–148. https://doi.org/10.1016/J.SPC.2023.03.027.
Lai, L., Chen, L., Zheng, M., Jiang, L., Zhou, J., Zheng, Y., Shimizu, H., 2019. Seed germination and seedling growth of five desert plants and their relevance to vegetation restoration. Ecol. Evol. 9 (4), 2160–2170. https://doi.org/10.1002/ECE3.4910.
Lee, R.H., Navarro-Navarro, L.A., Ley, A.L., Hartfield, K., Tolleson, D.R., Scott, C.A., 2021. Spatio-temporal dynamics of climate change, land degradation, and water insecurity in an arid rangeland: the Río San Miguel watershed, Sonora, Mexico. J. Arid Environ. 193, 104539. https://doi.org/10.1016/J.JARIDENV.2021.104539.
Lorenzo, M., Pereira, H., Alvarez, I., Dias, J., 2023. Standardized precipitation index (SPI) evolution over the iberian Peninsula during the 21st century. Atmos. Res. 107132. https://doi.org/10.1016/j.atmosres.2023.107132.
Ma, Y.J., Shi, F.Z., Hu, X., Li, X.Y., 2020. Threshold vegetation greenness under water balance in different desert areas over the silk road economic belt. Rem. Sens. 12 (15), 2452. https://doi.org/10.3390/rs12152452.
Madouh, T.A., 2022. Eco-physiological responses of native desert plant species to drought and nutritional levels: case of Kuwait. Front. Environ. Sci. 10, 785517. https://doi.org/10.3389/FENVS.2022.785517/BIBTEX.
Mansour, S., Alahmadi, M., Abulibdeh, A., 2022. Spatial assessment of audience accessibility to historical monuments and museums in Qatar during the 2022 FIFA World Cup. Transport Pol. 127 (August 2021), 116–129. https://doi.org/10.1016/j.tranpol.2022.08.022.
Marcotti, E., Amoroso, M.M., Rodríguez-Catón, M., Vega, L., Srur, A.M., Villalba, R., 2021. Growth resilience of Austrocedrus chilensis to drought along a precipitation gradient in Patagonia, Argentina. For. Ecol. Manag. 496, 119388. https://doi.org/10.1016/J.FORECO.2021.119388.
McKee, T., Doesken, N., Kleist, J., 1993. The relationship of drought frequency and duration times scales. 8th Conference on Applied Climatology. Amer. Meteor. Soc., Anaheim, California, pp. 179–184.

McNichol, B.H., Russo, S.E., 2023. Plant species' capacity for range shifts at the habitat and geographic scales: a trade-off-based framework. Plants 12 (6), 1248. https://doi.org/10.3390/PLANTS12061248, 2023, Vol. 12, Page 1248.
Meslier, V., DiRuggiero, J., 2019. Endolithic Microbial Communities as Model Systems for Ecology and Astrobiology. Elsevier eBooks, pp. 145–168. https://doi.org/10.1016/b978-0-12-812742-1.00007-6.
Miller, B.P., Sinclair, E.A., Menz, M.H.M., Elliott, C.P., Bunn, E., Commander, L.E., Dalziell, E., David, E., Davis, B., Erickson, T.E., Golos, P.J., Krauss, S.L., Lewandrowski, W., Mayence, C.E., Merino-Martín, L., Merritt, D.J., Nevill, P.G., Phillips, R.D., Ritchie, A.L., et al., 2017. A framework for the practical science necessary to restore sustainable, resilient, and biodiverse ecosystems. Restor. Ecol. 25 (4), 605–617. https://doi.org/10.1111/REC.12475.
Misak, R., Al-Awadhi, J., Omar, S., Shahid, S., 2002. Soil degradation in Kabd area, southwestern Kuwait City. Land Degrad. Dev. 13 (5), 403–415.
Mohammed, S., Alkhereibi, A.H., Abulibdeh, A., Jawarneh, R.N., Balakrishnan, P., 2023. GIS-based spatiotemporal analysis for road traffic crashes; in support of sustainable transportation Planning. Transp. Res. Interdiscip. Perspect. 20, 100836. https://doi.org/10.1016/J.TRIP.2023.100836.
Mohan, M., Dutta Roy, A., Montenegro, J.F., Watt, M.S., Burt, J.A., Shapiro, A., Ouerfelli, D., Daniel, R., de-Miguel, S., Ali, T., Ortega Pardo, M., Al Sayah, M., Aboobacker, V.M., El Beyrouthy, N., Reef, R., Adrah, E., AlMealla, R., Arachchige, P.S.P., Selvam, P., et al., 2024. Mangrove forest regeneration age map and drivers of restoration success in Gulf Cooperation Council countries from satellite imagery. Remote Sens. Appl.: Society and Environment 36, 101345. https://doi.org/10.1016/J.RSASE.2024.101345.
Monaco, S., 2024. SDG 15. Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss. In: Identity, Territories, and Sustainability: Challenges and Opportunities for Achieving the UN Sustainable Development Goals, pp. 145–155. https://doi.org/10.1108/978-1-83797-549-520241016.
Moussa, L.G., Mohan, M., Burmeister, N., King, S.A.L., Burt, J.A., Rog, S.M., Watt, M.S., Udagedara, S., Sujud, L., Montenegro, J.F., Heng, J.E., Carvalho, S.A., Ali, T., Kozhikkodan Veettil, B., Arachchige, P.S.P., Albanai, J.A., Sidik, F., Shaban, A., Lucia, M., et al., 2024. Mangrove ecotourism along the coasts of the gulf cooperation council countries: a systematic review. Land 13 (9), 1351. https://doi.org/10.3390/LAND13091351, 2024, Vol. 13, Page 1351.
Munoz-Sabater, J., Dutra, E., Agusti-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D.G., Piles, M., Rodriguez-Fernandez, N.J., Zsoter, E., Buontempo, C., Thepaut, J.N., 2021. ERA5-Land: a state-of-the-art global reanalysis dataset for land applications. Earth Syst. Sci. Data 13 (9), 4349–4383. https://doi.org/10.5194/essd-13-4349-2021.
Munson, S.M., Webb, R.H., Belnap, J., Andrew Hubbard, J., Swann, D.E., Rutman, S., 2012. Forecasting climate change impacts to plant community composition in the Sonoran Desert region. Global Change Biol. 18 (3), 1083–1095. https://doi.org/10.1111/J.1365-2486.2011.02598.X.
Naorem, A., Jayaraman, S., Dang, Y.P., Dalal, R.C., Sinha, N.K., Rao, C.S., Patra, A.K., 2023. Soil constraints in an arid environment—challenges, prospects, and implications. Agronomy 13 (1), 220. https://doi.org/10.3390/AGRONOMY13010220, 2023, Vol. 13, Page 220.
Nirola, R., Megharaj, M., Beecham, S., Aryal, R., Thavamani, P., Vankateswarlu, K., Saint, C., 2016. Remediation of metalliferous mines, revegetation challenges and emerging prospects in semi-arid and arid conditions. Environmental Science and Pollution Research 2016 23 (20), 20131–20150. https://doi.org/10.1007/S11356-016-7372-Z, 23(20).
Ochoa-Hueso, R., Munzi, S., Alonso, R., Arróniz-Crespo, M., Avila, A., Bermejo, V., Bobbink, R., Branquinho, C., Concostrina-Zubiri, L., Cruz, C., Cruz de Carvalho, R., De Marco, A., Dias, T., Elustondo, D., Elvira, S., Estébanez, B., Fusaro, L., Gerosa, G., Izquieta-Rojano, S., et al., 2017. Ecological impacts of atmospheric pollution and interactions with climate change in terrestrial ecosystems of the Mediterranean Basin: current research and future directions. Environ. Pollut. 227, 194–206. https://doi.org/10.1016/J.ENVPOL.2017.04.062.
Olmos-Trujillo, E., González-Trinidad, J., Júnez-Ferreira, H., Pacheco-Guerrero, A., Bautista-Capetillo, C., Avila-Sandoval, C., Galván-Tejada, E., 2020. Spatio-Temporal response of vegetation indices to rainfall and temperature in A semiarid region. Sustainability 12 (5), 1939. https://doi.org/10.3390/SU12051939, 2020, Vol. 12, Page 1939.
Overpeck, J.T., Udall, B., 2020. Climate change and the aridification of North America. Proc. Natl. Acad. Sci. U.S.A. 117 (22), 11856–11858. https://doi.org/10.1073/PNAS.2006323117/ASSET/639D4D28-97E0-4643-A157-7F4C7312BAE9/ASSETS/PNAS.2006323117.FP.PNG.
Padgett, P.E., Kee, S.N., Allen, E.B., 2000. The effects of irrigation on revegetation of semi-arid coastal sage scrub in southern California. Environ. Manag. 26 (4).
Pitumpe Arachchige, P.S., Rondon, M., Roy, A.D., Watt, M.S., Davies, M., Ouerfelli, D., Ewane, E.B., Abulibdeh, A., Abdullah, M., Al-Awadhi, T., Sharma, A., Prentice, R.M., Doaemo, W., Mohan, M., 2024. Current status of mangrove conservation efforts in Qatar: a review. Regional Studies in Marine Science, 103822. https://doi.org/10.1016/J.RSMA.2024.103822.
Prăvălie, R., 2021. Exploring the multiple land degradation pathways across the planet. Earth Sci. Rev. 220, 103689. https://doi.org/10.1016/J.EARSCIREV.2021.103689.
Prober, S.M., Doerr, V.A.J., Broadhurst, L.M., Williams, K.J., Dickson, F., 2019. Shifting the conservation paradigm: a synthesis of options for renovating nature under climate change. Ecol. Monogr. 89 (1), e01333. https://doi.org/10.1002/ECM.1333.
Rivers, J.M., Dalrymple, R.W., Yousif, R., Al-Shaikh, I., Butler, J.D., Warren, C., Skeat, S. L., Abdel Bari, E.M.M., 2020. Mixed siliciclastic-carbonate-evaporite sedimentation in an arid eolian landscape: the Khor Al Adaid tide-dominated coastal embayment, Qatar. Sediment. Geol. 408, 105730. https://doi.org/10.1016/j.sedgeo.2020.105730.
Rondon, M., Ewane, E.B., Abdullah, M.M., Watt, M.S., Blanton, A., Abulibdeh, A., Burt, J. A., Rogers, K., Ali, T., Reef, R., Mohtar, R., Sidik, F., Fahrenberg, M., de-Miguel, S., Galgamuwa, G.A.P., Charabi, Y.A.R., Arachchige, P.S.P., Velasquez-Camacho, L.F., Al-Awadhi, T., et al., 2023. Remote sensing-based assessment of mangrove ecosystems in the Gulf Cooperation Council countries: a systematic review. Front. Mar. Sci. 10, 1241928. https://doi.org/10.3389/FMARS.2023.1241928.
Roy, P., Pal, S.C., Chakrabortty, R., Saha, A., Chowdhuri, I., 2023. A systematic review on climate change and geo-environmental factors induced land degradation: processes, policy-practice gap and its management strategies. Geol. J. 58 (9), 3487–3514. https://doi.org/10.1002/GJ.4649.
Sillitoe, P., Alshawi, A.A., Al-Amir Hassan, A.K., 2010. Challenges to conservation: land use change and local participation in the Al Reem Biosphere reserve, west Qatar. J. Ethnobiol. Ethnomed. 6 (1), 1–31. https://doi.org/10.1186/1746-4269-6-28/TABLES/5.
Song, W., Chen, S., Zhou, Y., Lin, G., 2020. Rainfall amount and timing jointly regulate the responses of soil nitrogen transformation processes to rainfall increase in an arid desert ecosystem. Geoderma 364, 114197. https://doi.org/10.1016/J.GEODERMA.2020.114197.
Spinoni, J., Naumann, G., Vogt, J.V., Barbosa, P., 2015. The biggest drought events in Europe from 1950 to 2012. J. Hydrol. Reg. Stud. 3, 509–524. https://doi.org/10.1016/j.ejrh.2015.01.001.
Stapleton, J., Bates, S., Lewis, M., Turner, S.R., Warne, D., Florentine, S., 2024. A global review on arid zone restoration: approaches and challenges. Restor. Ecol. 32 (6), e14078. https://doi.org/10.1111/REC.14078.
Svejcar, L.N., Kildisheva, O.A., 2017. The age of restoration: challenges presented by dryland systems. Plant Ecol. 218 (1), 1–6. https://doi.org/10.1007/S11258-016-0694-6/FIGURES/2.
Tariq, A., Graciano, C., Sardans, J., Zeng, F., Hughes, A.C., Ahmed, Z., Ullah, A., Ali, S., Gao, Y., Peñuelas, J., 2024. Plant root mechanisms and their effects on carbon and nutrient accumulation in desert ecosystems under changes in land use and climate. New Phytol. 242 (3), 916–934. https://doi.org/10.1111/NPH.19676.
Tirivarombo, S., Osupile, D., Eliasson, P., 2018. Drought monitoring and analysis: standardised precipitation evapotranspiration index (SPEI) and standardised precipitation index (SPI). Phys. Chem. Earth, Parts A/B/C 106, 1–10. https://doi.org/10.1016/j.pce.2018.07.001.
UNCC, 2002. Report and Recommendations Made by the Panel of Commissioners Concerning the Third Instalment of "F4: Claims. United Nations Compensation Commission Governing Council Kuwait.
WAD, 2019. World atlas of desertification. https://wad.jrc.ec.europa.eu/patternsaridity.
Weber, A.S., 2024. The ecotourism landscape of Qatar. Lecture Notes in Networks and Systems 774, 303–309. https://doi.org/10.1007/978-3-031-43733-5_27.
Wu, X., Wang, P., Ma, Y., Gong, Y., Wu, D., Yang, J., Huo, Z., 2021. Standardized relative humidity index can be used to identify agricultural drought for summer maize in the Huang-Huai-Hai Plain, China. Ecol. Indicat. 131, 108222. https://doi.org/10.1016/j.ecolind.2021.108222.
Wu, X., Su, J., Ren, W., Lü, H., Yuan, F., 2023. Statistical comparison and hydrological utility evaluation of ERA5-Land and IMERG precipitation products on the Tibetan Plateau. J. Hydrol. 620, 129384. https://doi.org/10.1016/j.jhydrol.2023.129384.
Yu, Y., Hua, T., Chen, L., Zhang, Z., Pereira, P., 2023. Divergent changes in vegetation greenness, productivity, and rainfall use efficiency are characteristic of ecological restoration towards high-quality development in the yellow river basin, China. Engineering. https://doi.org/10.1016/J.ENG.2023.07.012.
Zeng, H., Wu, B., Zhang, M., Zhang, N., Elnashar, A., Zhu, L., Zhu, W., Wu, F., Yan, N., Liu, W., 2021. Dryland ecosystem dynamic change and its drivers in Mediterranean region. Curr. Opin. Environ. Sustain. 48, 59–67. https://doi.org/10.1016/J.COSUST.2020.10.013.