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Investigating the succession process of native desert plants over hydrocarbon-contaminated soils using remote sensing techniques

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ABSTRACT

Hydrocarbon-contaminated soils are considered as one of the major environmental issues that harm human well-being, particularly in arid regions of the world. Phytoremediation is a possible mitigation measure for this issue and has been suggested as it is cost-effective compared with other remediation technologies for soil clean-up, such as soil thermal treatment and soil washing. However, there are still gaps in the literature regarding the behavior of annual and perennial desert plants and their ability to survive in hydrocarbon-contaminated soils in arid ecosystems. Therefore, this study aims to develop an integrated approach using remote sensing techniques to understand the behavior of annual and perennial desert plants over different types of oil-contaminated soils (oil tarcrete, wet-oil lake, bare soil, and vegetation cover) in the Kuwait Desert and to explore the impact of climate and physical soil properties on the regrowth of native desert plants. The Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and ferrous iron ($Fe2+$) index (FI) were used to determine the changes in oil contamination and vegetation cover from 1992 to 2002, and 2013–2020. Subsequently, statistical tests were performed to determine the influence of climatic and soil physical characteristics on changes in hydrocarbon contamination and desert plant behavior. The results showed that hydrocarbon contamination was high at the study sites in the first six years (1992–1997) after contamination, and then decreased in the following years. However, vegetation cover was low in the first six years but significantly increased after 1998, reaching >65%. It was also found that annual plants had the highest distribution rate compared to perennial plants, which mainly depended on the soil type. We concluded that certain annual and perennial plants could successfully grow over tarcrete-contaminated sites, making these sites more suitable for the restoration of native desert plants than hydrocarbon-contaminated sites. We also observed that the succession process of vegetation growth over hydrocarbon-contaminated soils could be associated with vegetation growth on a clean sediment layer covering the oil layer. Additionally, we observed that the remobilization of aeolian sediment over many contaminated sites in Kuwait resulted in the accumulation of organic matter, plant seeds, and dust particles that create layers of nutrient-rich soil for the initial growth of plants.

1. Introduction

Hydrocarbons are a common cause of soil contamination and are harmful to vegetation communities. Different technologies, such as soil thermal treatment and washing, have been used to reduce petroleum hydrocarbon soil contamination (Ossai et al., 2020; Al-Ateeqi et al., 2021). However, these methods often tend to be costly and energy-intensive. In contrast, cultivating selected native plant species has been found to improve local ecosystem functions and soil quality (Blanco-Velázquez et al., 2020).

Some studies have found that native desert plants, such as *Sporobolus ioclados* (Trin.) Nees displayed a strong tolerance to petroleum

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hydrocarbon-contaminated soils (Al-Thani and Yasseen, 2020). Therefore, understanding the processes and responses of native plant species to soil hydrocarbon contamination can help develop proper phytoremediation management to mitigate and reduce contamination. Different vegetation species have different tolerances and respond differently to oil contamination. However, oil-contaminated soil could also shift plant communities at the site, with petroleum hydrocarbon-tolerant species making them the dominant vegetation species. Some of these species are *Cyperus conglomeratus* (Cyperaceae), *Rhanterium epapposum* (Asteraceae), and *Haloxylon salicornicum* (Amaranthaceae), which could be considered potential phytoremediators of petroleum hydrocarbons (Malallah et al., 1998; Abdullah et al., 2017b).

Kuwait witnessed one of the most intense environmental disasters during the Second Gulf War (1990–1991). Kuwait's offshore waters and deserts experienced the most extensive hydrocarbon disturbance, affecting the native desert vegetation during the war and beyond. The war resulted in the world's largest total petroleum hydrocarbon (TPH) spills in the history of the state of Kuwait. Around 6–8 million barrels of crude oil were spilled into terrestrial and marine environments, and an estimated 2–3 million barrels were burned and released into the atmosphere. Furthermore, the soil in Kuwait was contaminated by spillage from 729 oil wells and the deliberate destruction of oilfield installations (Omar et al., 2009; Al-Ateeqi et al., 2021), resulting in three types of hydrocarbon soil pollution: tarcrete, dry-oil lake (DOL), and wet-oil lake (WOL) (Al-Ateeqi, 2014; Kalander et al., 2021).

DOL and WOL result from damaged pipelines or well-heads that contain crude oil, leading to the accumulation of spilled oil in topographically low-lying sites within the oil fields (Kwarteng, 1998; Kalander et al., 2021). In contrast, tarcrete -polluted sites are formed by oil rain (oil mist) and oil soot. This type of pollution was found in the form of an unconsolidated soil layer on the upper layers of the soil, with a thickness of 2–8 mm. Consequently, the soil encountered more than 30 cm of petroleum penetration, destroying many species and significantly affecting wildlife and freshwater aquifers (Balba et al., 1998). The effects of oil contamination are still present in many areas across Kuwait and are predicted to persist for decades. This type of contamination covers approximately 6% of Kuwait's total area (Kwarteng, 1998). Consequently, many areas in the country are contaminated by oil lakes and tarcrete (Jones et al., 2008). Crude oil spills and military activities affect different ecosystems in the country. Such environmental disasters have affected and altered plant growth parameters (Malallah et al., 1998).

After the end of the war, the Kuwaiti government imposed stringent access restrictions on border areas, with Saudi Arabia and Iraq as precautionary measures. This has an impact on ecosystem recovery. Nevertheless, some types of native vegetation in Kuwait have been found to have the capability to grow in hydrocarbon-contaminated soil areas (Abdullah et al., 2020; Al-Ateeqi et al., 2021). However, the regrowth of native vegetation in areas with contaminated soil depends on the soil type, TPH contamination, and geomorphological features. The types of plant and oil contamination affected the recovery speed of phytoremediation over TPH-contaminated lands. Some studies have concluded that improving the phytoremediation efficiency requires a better understanding of the mechanisms underlying the accumulation of heavy metals in plants. Phytoremediation involves the mobilization of heavy metals, xylem loading, carbon sequestration, root uptake, and root-to-shoot transport (Yan et al., 2020).

Several studies have investigated the impact of oil contamination and military activities on the ecosystem in Kuwait. Some of these studies were conducted in areas that were used for military activities only and encountered the movement of heavy vehicles without considering hydrocarbon contamination [see, for example (Abdullah et al. 2015, 2017a)]. Abdullah et al. (2020) investigated the recovery mechanism of native desert vegetation from hydrocarbon contamination to assess ecosystem resiliency to hydrocarbon contamination in the Kuwait Desert after the Second Gulf War. Their study used remote sensing tools to trace and detect changes that occurred in the extent and coverage of the TPH contamination across the landscape and the vegetation coverage between 1992 and 1998. This study also explored the ecosystem factors that contributed to vegetation recovery during the removal of hydrocarbon contamination.

Previous studies also demonstrated that 42 Kuwaiti native plants survived and grew in hydrocarbon-contaminated soils (such as the perennial sedges *Cyperus conglomeratus*, *Haloxylon salicornicum*, and *Rhanterium eppaposum*) (Al-Ateeqi, 2014). For instance, in another study Al-Ateeqi et al. (2021), conducted a field survey of 200 quadrat sampling plots to investigate the recovery of desert vegetation from hydrocarbon contamination after 20 years of the war in seven hydrocarbon-contaminated areas in Kuwait. The dominant species were *R. epapposum*, *Haloxylon salicornicum*, *Cyperus conglomeratus*, and *Haloxylon salicornicum*. In this study, the tissues of *Cyperus conglomeratus*, *Haloxylon salicornicum*, and *Rhanterium eppaposum* were analyzed. The results indicate the accumulation of numerous polycyclic aromatic hydrocarbons (PAHs), with a value of 200 μg in the most contaminated sites. Therefore, they concluded that some desert plant species could recover from severe oil-contaminated soil. Furthermore, they found that *Haloxylon salicornicum* can be used as a phytoremediator in oil-polluted desert soils. These results affirm the possibility that several native plant species are able to grow in desert soils contaminated with petroleum hydrocarbons and that these plants can function as phytoremediators in these soils.

Soil chemical properties and existing levels of TPH concentration could also impact the succession process of native plant survival and growth in the Kuwait Desert. Kalander et al. (2021) assessed the concentration of soil parameters and levels of vegetation cover as indicators of resilience levels in TPH-contaminated sites on three types of hydrocarbon contamination: tarcrete, WOLs, and dry-oil lakes. They found that TPH concentration was significantly higher in WOL and DOL than in tarcrete, which indicates the presence of increased soil minerals and heavy metals in these areas and that this higher amount affects the resilience of native plants. However, these studies predominantly focused on understanding the response of native desert perennial plants to oil-contaminated soils without considering the succession process of both annual and perennial plants over different oil-contaminated soils. We believe that considering annual plants is critical in restoration and revegetation planning because they play a significant role in supporting the growth of perennial plants as they have the ability to store a large amount of water and have a higher content of organic matter and prosphoras for plant uptake, providing higher biomass for perennial plants (Abdullah et al., 2021a; Abdullah et al., 2021b). They also did not consider using special analysis to develop a clear understanding of the succession process of native plants growing over hydrocarbon-contaminated sites by developing methods using remote sensing technologies. The development of such models is crucial as they can integrate a large amount of data, can be implemented on larger scales and are time efficient. Therefore, our study aims to develop an integrated approach using remote sensing techniques to understand the behavior of annual and perennial desert plants over different types of oil-contaminated soils (i.e., oil tarcrete, wet-oil lake, bare soil, and vegetation cover) in the Kuwait Desert and to explore the impact of climate and physical soil properties on the regrowth of native desert plants. Understanding the factors that influence native desert plants will enable decision-makers to evaluate locations that are more suitable for the revegetation of native plants on a large scale using the method developed in this study.

2. Materials and methods

2.1. Study area

The study was conducted on three oil fields in the state of Kuwait: the Umm Gudair (252 km^2), Sabriyah-Bahrah (428 km^2), and Burgan (568 km^2) oil fields (Fig. 1). The soils at these locations were significantly impacted as a result of the Second Gulf War, containing three types of crude oil soil contamination: oil tarcrete, DOL, and WOL (see Fig. 1) (Al-Ateeqi, 2014; Kalander et al., 2021). Kuwait is located in the northeastern Arabian Peninsula (29.3117° N, 47.4818° E). The country is considered a flat arid landscape, which is characterized by hot weather in the summer, with an average temperature of 46 °C, and cold winter, with an average annual rainfall of 118 mm. Native desert plants vary between years, mainly relying on wet seasons and the amount of precipitation received between October and March (Alsharhan et al., 2001). Native plants can be divided into two groups: perennials and annuals. There are eight major perennial plants are presented in Kuwait, including *Haloxylon*, *Rhanterietum*, *Cyperetum*, *Stipagrostietum*, *Zygophyllum*, *Centropodietum*, *Halophyletum*, and *Panicetum* (Halwagy and Halwagy, 1974; Omar and Zaman, 2000). According to the vegetation map of Kuwait, four perennial plants were found in the study area: *Cyperus*, *Stipagrostis*, *Haloxylon*, and *Rhanterium*.

3. Methodology

In this study, spatio-temporal analysis was conducted to understand the changes in oil tarcrete, oil lakes, and vegetation coverage in the three considered areas from 1992 to 2002 and from 2013 to 2020, years 2003–2012 were excluded since the scan line corrector (SLC) in the ETM + instrument of Landsat 7 failed. Different techniques using remote sensing, GIS, and statistical analysis were utilized to achieve the main objectives of this study, the following three major stages (Fig. 2):1) utilizing remote sensing techniques to determine the temporal changes in oil tarcrete, oil lakes, and vegetation cover; 2) implementing GIS techniques to identify the native plant communities that can grow over hydrocarbon contamination; and 3) understanding the hydrocarbon and vegetation response to environmental factors, including the soil physical properties and climatic factors (such as rainfall, average temperature, maximum temperature, and minimum temperature). The third task was executed using analysis of variance (ANOVA) and regression analysis, which helped us explore the relationships between climatic factors, vegetation, and soil hydrocarbon contamination and examined environmental factors.

3.1. Satellite Imagery Data Collection

Multispectral georeferenced images were obtained from the United States Geological Survey (USGS). These images were acquired from different Landsat sensors (TM, ETM+, and OLI) from 1992 to 2002 and

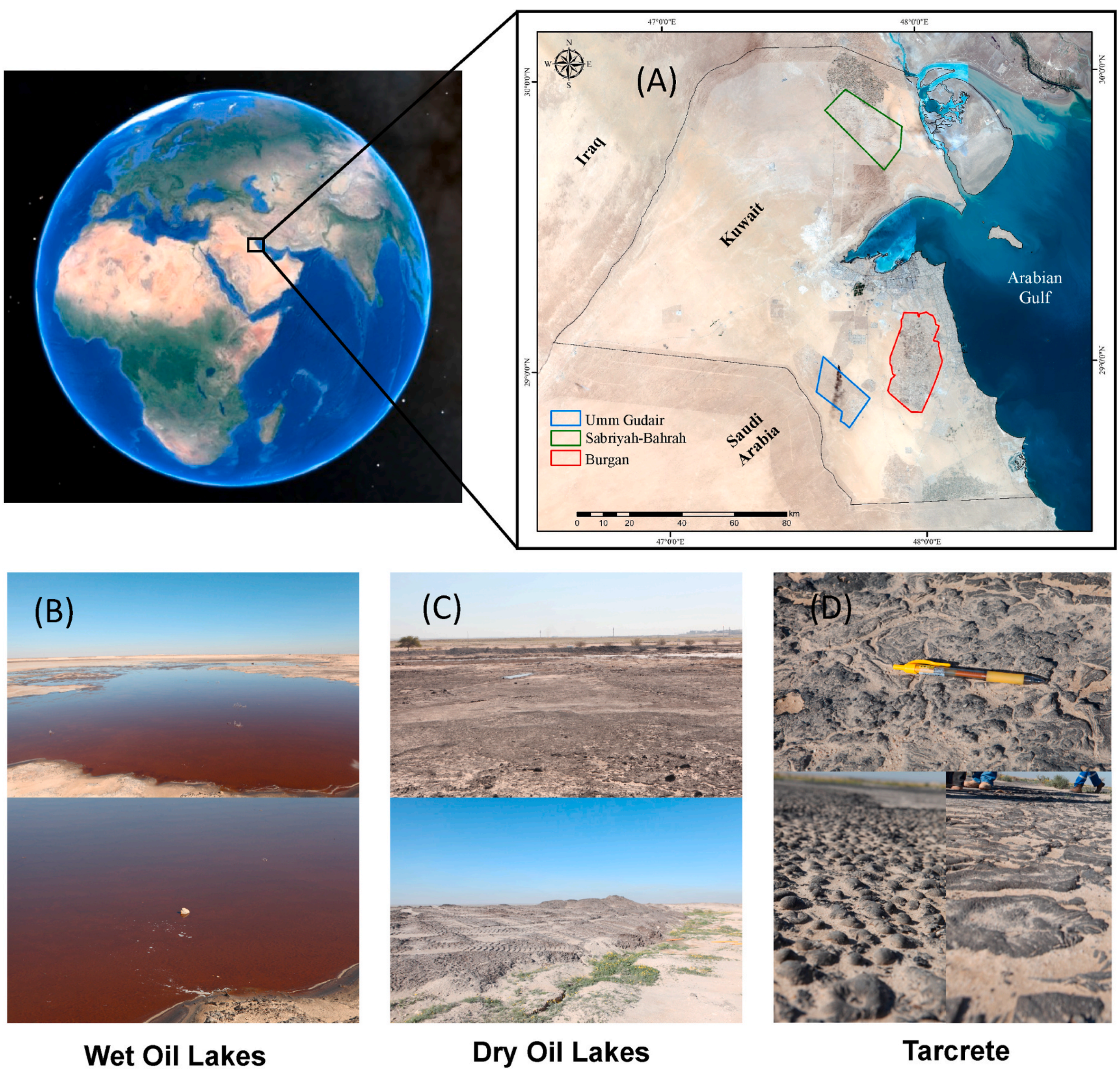

Fig. 1. Study area – (A) three oil fields in the State of Kuwait with three types of hydrocarbon-contaminated soils, (B) wet-oil lakes, (C) dry-oil lakes, and (D) tarcrete).

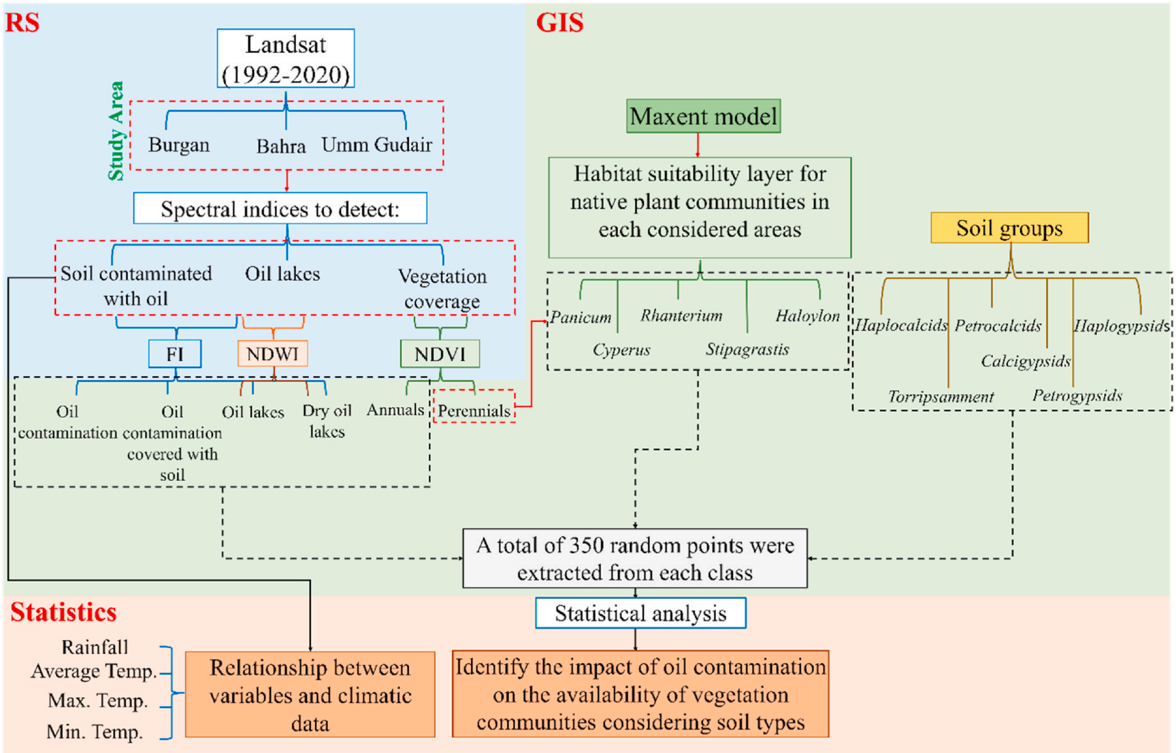

Fig. 2. Study methodology consists of three main stages: remote sensing (RS) analysis using spectral indices (Ferrous iron index (FI), Normalized Difference Water Index (NDWI), and Normalized Difference Vegetation Index (NDVI)); GIS: Geographic Information System analysis; and statistical analysis.

from 2013 to 2020 (Table 1). A total of 76 images were acquired to cover the three considered locations (Burgan, Bahra, and Umm Gudair) during the spring (March) and summer (June). The spring season was selected to assess the response of vegetation to oil contamination because the highest vegetation cover is observed in this season as rainfall events occur and temperature decreases during this time (Abdullah et al., 2017a; Asadalla et al., 2021). However, we also used summer season images as supplementary data to help better detect oil lakes by avoiding any mixed pixels between oil contamination and vegetation cover.

3.2. Vegetation and oil contamination indices

Three spectral indices were implemented and derived from the Landsat data. In general, satellite images are captured over several wavelength ranges (visible to near-infrared range). Land surface is generally described using vegetation indices that provide arithmetic combinations of these spectral bands. The satellite-derived Normalized Difference Vegetation Index (NDVI) is considered to be the most effective tool for monitoring vegetation and land changes across a large scale in different environments. Therefore, our study used the NDVI to estimate vegetation cover changes among a wide range of vegetation communities in different soil types and classes, as it is considered an effective and most common index in arid ecosystems (Al-Ali et al., 2020). The NDVI threshold value was adjusted to be greater than 0.09, which is the optimum value to detect vegetation in hot desert arid regions (Ma et al., 2020).

Table 1
Basic information about utilized Landsat images.

Year	Month	Landsat	Sensor	Spatial resolution	Utilized spectral bands
1992–1999	March June	L5	TM	30 m	G R
2002	March June	L7	ETM+		NIR SWIR1
2013–2020	March June	L8	OLI		

L: Landsat, TM: Thematic Mapper, ETM+: Enhanced Thematic Mapper Plus, OLI: Operational Land Imager, G: Green, R: Red, NIR: Near-Infrared, and SWIR1: Short-wave infrared.

$$NDVI = \frac{NIR - R}{NIR + R} \quad (1)$$

where, NIR is the Near-Infrared band, and R is the Red band.

We also implemented the ferrous iron (Fe^{2+}) index (FI), which has been used as an indicator of hydrocarbon-contaminated soils in previous studies (Garain et al., 2019b; Al Farid, 2020; Enoh et al., 2021). This index was developed by Rockwell (2012) using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) bands, which provide efficient correlation with Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data. This index also showed satisfactory results in detecting hydrocarbon micro-seepage in the Assam-Arakan Fold Belt in India (Garain et al., 2019a). FI index is a ratio index developed based on four spectral bands, as shown in Equation (2).

$$FI = \frac{G + SWIR1}{R + NIR} \quad (2)$$

where FI is ferrous iron (Fe^{2+}), G is the Green band, SWIR1 is the Short-Wave Infrared 1 band, R is the Red band, and NIR is the Near-Infrared Band.

The Normalized Difference Water Index (NDWI) was used for the detection of oil lakes, as shown in Equation (3). This index was developed to delineate open surface water and to detect water turbidity (McFeeters, 1996). However, we applied this index to extract WOLs at the study sites, as these lakes are in a liquid state (Tcibulnikova, 2021).

$$NDWI = \frac{G - NIR}{G + NIR} \quad (3)$$

where G is the Green band, and NIR: Near-Infrared Band.

3.2.1. Assessing the Spatio-temporal Dynamics of Hydrocarbons and Vegetation Within the Examined Years (1992–2002 and 2013–2020)

The indices calculated in the previous section were implemented to classify different types of soil contamination and vegetation cover using the Support Vector Machine (SVM) classification method. The different classes include vegetation cover, DOLs, wet-oil lakes, tarcrete, and bare soil. Accuracy assessment was conducted to the classified imageries using the Confusion Matrix method in ENVI software. The overall accuracy of all classified images was >86% (Table 2), which exceeded the satisfactory standards (Al-Ahmadi and Hames, 2009). Then, the number of pixels for each class was transferred to an Excel spreadsheet to calculate the percentage coverage in the study areas to understand the changes over the years. We also used the one-way ANOVA test and post-hoc Tukey HSD tests using the JMP[11]™ software to determine the existence of a significant difference the three study areas in terms of wet-oil lakes, oil tarcrete (including dry lakes and tarcrete), and vegetation cover. A one-way ANOVA test was used to determine whether the statistical evidence showed that the oil contamination and vegetation means between the three study sites were significantly different.

Table 2
Accuracy assessment results for the classified imageries.

Years	Classes	Overall Accuracy (%)	Kappa Coefficient	Producer Accuracy (%)	User Accuracy (%)
1992	OL	93.5	0.90	100	100
	OC			100	80.7
	BG			85.2	100
1993	OL	93.5	0.90	100	87.5
	OC			100	95.2
	BG			80.9	100
1994	OL	90.4	0.82	100	82.6
	OC			95	100
	BG			90	100
1995	OL	95	0.92	100	86.9
	OC			100	100
	BG			85	100
1996	OL	90.3	0.85	95.4	91.3
	OC			100	83.3
	BG			75	100
1997	OL	95.3	0.92	100	95.2
	OC			100	91.3
	BG			86.9	100
1998	OL	91.9	0.87	95.4	100
	OC			80	94.12
	BG			100	83.33
1999	OL	96.7	0.95	100	100
	OC			90	100
	BG			100	91
2000	OL	96.72	0.95	100	100
	OC			95	95
	BG			95.2	95.2
2001	OL	96.8	0.95	100	91.3
	OC			100	100
	BG			90.4	100
2002	OL	93.5	0.90	85	94.4
	OC			100	88
	BG			95	100
2013	OL	95.1	0.92	90	100
	OC			95	95
	BG			100	90.9
2014	OL	95.3	0.929	85.7	100
	OC			100	88.4
	BG			100	100
2015	OL	85.4	078	95.4	100
	OC			60	92.31
	BG			100	71.43
2016	OL	98.41	0.97	100	100
	OC			100	95.4
	BG			95.2	100
2017	OL	96.8	0.95	95	100
	OC			100	91.30
	BG			95.4	100
2018	OL	85.4	0.78	75	100
	OC			93.3	70
	BG			88.2	93.7
2019	OL	92.68	0.85	85.7	100
	OC			100	86.9
	BG			100	98
2020	OL	86.1	0.79	100	100
	OC			71.4	83.3
	BG			87.5	77.7

3.3. Response of native desert plants to hydrocarbon-contaminated soils

Understand the response of native desert plants to contaminated soils, we calculated the percentage change in vegetation coverage over the different types of soil contamination, including oil tarcrete and oil lakes, at the three study sites. We used the classified images to determine the area (km^2) for each class using ArcMap (ESRI, Redlands, CA, USA, 10.7.1). We also observed changes in the vegetation cover percentage for both annual and perennial plants over contaminated (oil tarcrete and oil lakes) and uncontaminated soils.

In this study, it was important to distinguish between annual and perennial plants by using satellite imagery. This was done by considering that perennial plants always appear at the exact location; however, the distribution of annual plants varies depending on rainfall fluctuations. Therefore, we overlaid the NDVI layer using Raster Calculator in ArcGIS for the examined years. Each classified layer was assigned values of 1 and 0, where 1 represented vegetation and 0 implied no vegetation. According to the results of the Raster Calculator, areas where vegetation always appeared were considered perennial plants, and areas where the distribution of vegetation varied over the years were deemed to be annual, which is more likely related to rainfall fluctuations. We then used the vegetation community layer, which was established in our previous work using MaxEnt modeling (Asadalla et al., 2021) to extract the vegetation community for the perennial plant layer to determine the communities within the study sites. Similarly, we determined the percentage of perennial communities and annual plants in each soil-contaminated group (oil tarcrete, oil tarcrete covered with soil, and dry-oil lakes). Finally, we extracted a total of 350 random points within the classes and ran stepwise regression analysis using JMP[11]™ software to study the relationship between perennial and annual plants and different types of oil contamination. Stepwise regression analysis was used to develop a model that integrates all independent variables by adding potential descriptive variables in succession and testing the statistical significance after each iteration.

3.4. Response of native desert plants to climatic factors

In this work, we focused on analyzing the impacts of climatic factors on soil contamination for the three oil contamination types and the distribution of vegetation coverage. Monthly climatic data, including precipitation, average temperature, maximum temperature, and minimum temperature, were used in this study. Meteorological data were obtained from the Kuwait Airport Meteorological Station from 1992 to 2020. Our study considered the rainy season extending from September to October. This is important because the germination season of native desert vegetation in the study areas (occurring between January and March) mainly depends on the rainfall received between September and October (Abdullah et al., 2022). Then, a stepwise regression analysis using the JMP software was performed to study the relationship between the climatic variables and the changes in oil contamination and vegetation cover over the years.

4. Results

4.1. Spatio-temporal dynamics of Hydrocarbon and vegetation cover (1992–2002 and 2013–2020)

According to the results of ferrous iron (Fe^{2+}) and NDVI indices, the study sites were classified into four main categories: oil contamination (dry-oil lakes and tarcrete), wet-oil lakes, bare soil, and vegetation cover. It was observed that the spatio-temporal distribution of these classes differed significantly during the examined years (1992–2020) (Fig. 3). As expected, the Burgan site was covered with oil contamination (tarcrete and dry-oil lakes), followed by the Bahra site. The highest amount of oil contamination was observed in the first six years (1992–1997), with coverages of ≤39% and ≤48.5% for Burgan and Bahra sites, respectively (Fig. 3a and b). In the following six years, a notable reduction was observed in the Bahra site, while in the Burgan site, the oil contamination still exceeded the variation in oil contamination coverage. However, a slight oil contamination coverage (3%) was observed at Umm Gudair site in the year 1992, which disappeared in the following years (Fig. 3c). Subsequently, the wet-oil lake occupied the lowest coverage among the considered sites, with the highest coverage occurring at Burgan site (≤2%), and it was almost absent (≤0.2) in both Bahra and Umm Gudair sites. A slight increase in oil contamination was detected at the Burgan and Bahra oilfields in some years, which is more likely related to the changes in wet-oil lakes as some lakes dried after several years. However, both types of oil contamination disappeared after the first year at Umm Gudair.

The results of the one-way ANOVA and post-hoc Tukey HSD tests (Fig. 4) showed significant differences ($p < 0.0001$) between the various oil categories at the three examined sites. The results indicated that the oil-contaminated and oil lakes varied significantly between the Burgan and Umm Gudair sites ($p < 0.0001$) and between Bahra and Umm Gudair sites ($p = 0.0026$) (Fig. 4). It was found that the oil contamination was significantly higher at Burgan and Bahra compared with Umm Gudair, with a deficient contamination level. However, the largest oil lakes were found at Burgan, which was considerably higher than Bahra and Umm Gudair oilfields ($p < 0.05$). Unlike oil contamination and wet-oil lakes, vegetation cover was very low during the first 3 years at all the considered sites. The results showed a higher level of land degradation at the Burgan site (almost zero percentage) compared to the other two

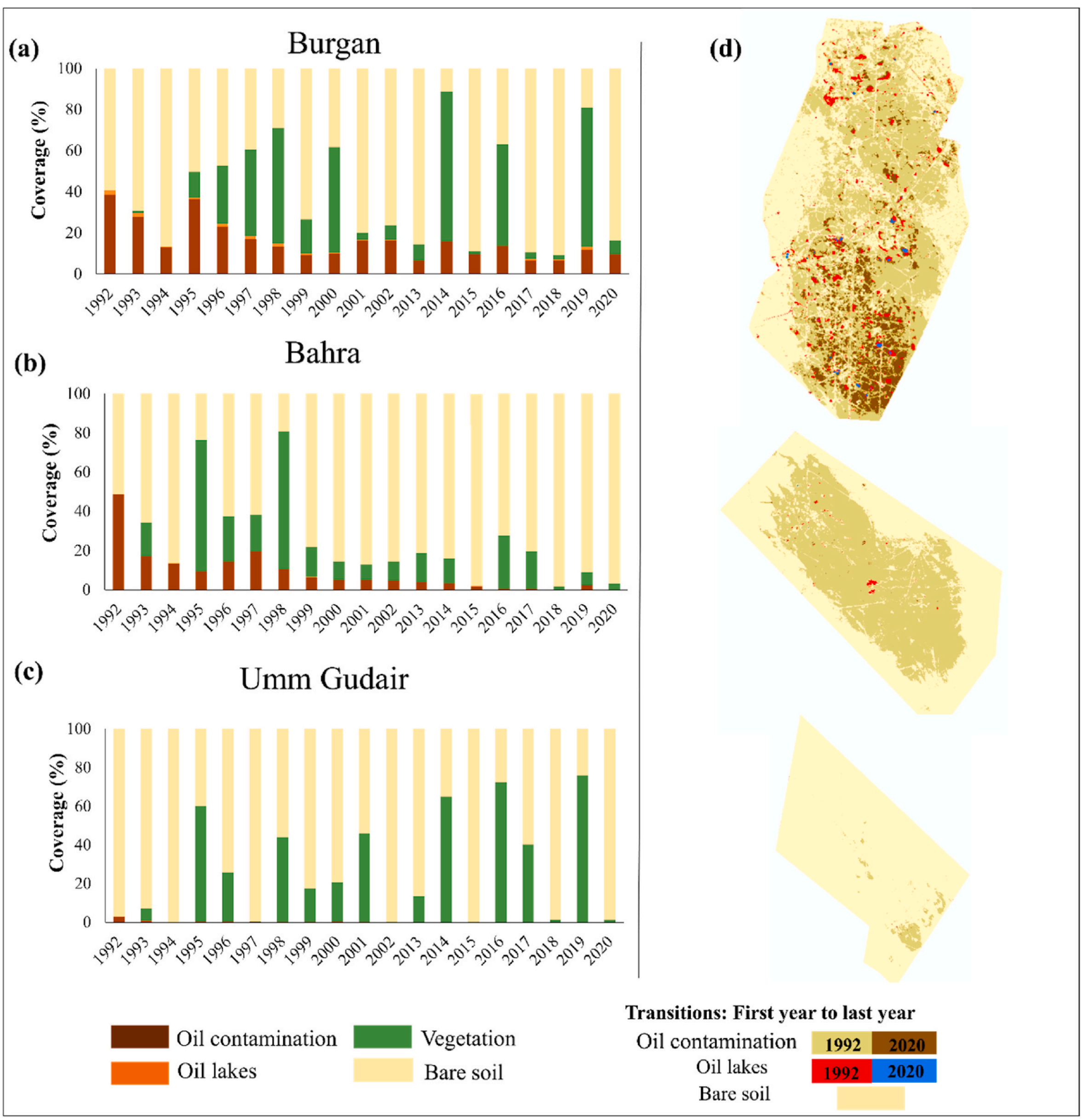

Fig. 3. Spatio-temporal dynamics of oil contamination classes (oil contamination, wet-oil lakes, vegetation cover, and bare soil) from 1992 to 2020 in Kuwait. a) Burgan oil field, b) Bahra oil field, c) Umm Gudair oil field, d) soil contamination transitions layers for the investigated sites, covering the first year (1992) and last year (2020).

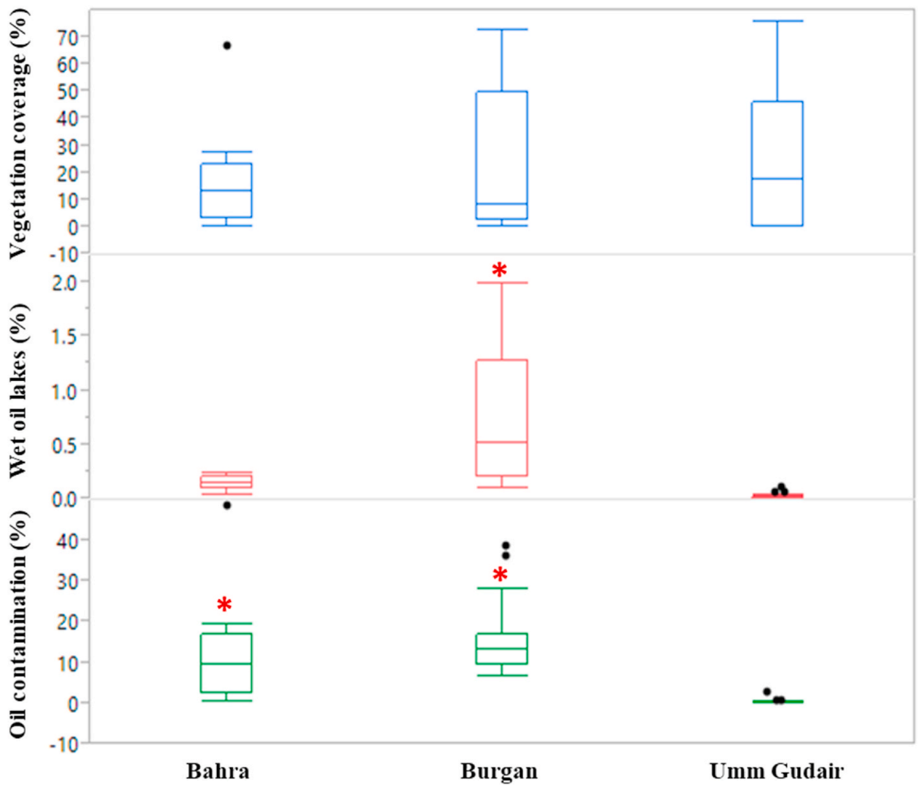

Fig. 4. Box and whisker plots displaying the relationship between hydrocarbon contamination using the extracted random points for the examined years (oil contamination, wet-oil lakes, and vegetation cover) at different sites.

examined sites (<2% in Burgan and <13 in Bahraa and Umm Gudair). However, we observed autogenic recovery in vegetation cover in the following years. A significant increase in vegetation cover was observed at the three examined sites (>65% vegetation cover), associated with a decrease in the oil contamination. Burgan and Bahra had the highest vegetation cover, which was significantly different from that of Umm Gudair.

4.2. Impact of climate variables on oil contamination, oil lakes, and vegetation cover

Hydrocarbon contamination and changes in vegetation coverage are generally associated with several climatic and soil factors (Table 3). In our case, among the studied variables, only the maximum temperature (~40 °C) played a vital role in oil-contaminated sites ($p < 0.05$). No significant relationship was observed between the climatic variables and oil lakes. It should be noted that the annual temperature widely varied during the years; the maximum temperature ranged between ~37 °C and ~41 °C (mean ~39 °C), the average temperature ranged between ~25 °C and ~28 °C (mean ~ 26.5 °C), and minimum temperature ranged between ~12 °C and ~15 °C (mean ~14 °C). In contrast, it was found that vegetation cover was significantly associated with annual rainfall fluctuation, average temperature (~25 °C), and minimum temperature (~12 °C) ($p < 0.05$).

Table 3
One-way ANOVA for climatic variables and soil classes using post-hoc Tukey HSD test.

Variables	Classes		
	Oil contamination	Wet-oil lakes	Vegetation cover
Rainfall (mm)	–	–	0.0143[a]
Maximum temperature (°C)	0.0114[a]	–	–
Minimum temperature (°C)	–	–	0.0447[a]
Average temperature (°C)	–	–	0.0048[a]
Vegetation cover (%)	–	–	–

[a] Significant difference at p-value <0.05.

4.3. Influence of soil physical properties on vegetation cover

The native vegetation cover in Kuwait comprises annuals and perennials. The results demonstrated that the vegetation types in the six soil groups were Haplocalcids, petrocalcids, torripsamments, calcigypsids, petrogypsids, and haplogypsids. The obtained coverage of annual vegetation in different soil groups was in the range of 38–70% (with an average value of 55.26%). It was observed that the distribution of annual vegetation cover (%) was dominant in petrogypsides (70.74%), petrocalcids (61.56%), haplogypsids (57.6%), Calcigypsids (53.72%), Haplocalcids (49.75%), and Torripsamment (38.23%). In contrast, the distribution of perennial plant communities was characterized by a negligible percentage across all tested soil groups (0–20%).

4.4. Impact of soil physical properties on the response of annual and perennial plants

We analyzed the soil physical properties to understand the changes in the distribution of the vegetation community according to the soil groups at the contaminated study sites, exposing different petroleum-contaminated soil classes (oil-contaminated, wet-oil, and dry-oil lakes). The results showed that annual plants were able to grow on most of the soil groups at the study sites (Fig. 5). The most significant number of annual plants were found to be growing on oil-contaminated soils covered with a layer of clean soil (23%). However, a lower percentage of annual plants were able to develop roots directly from the oil contamination, as the results showed that 4.2% of annual plants grow

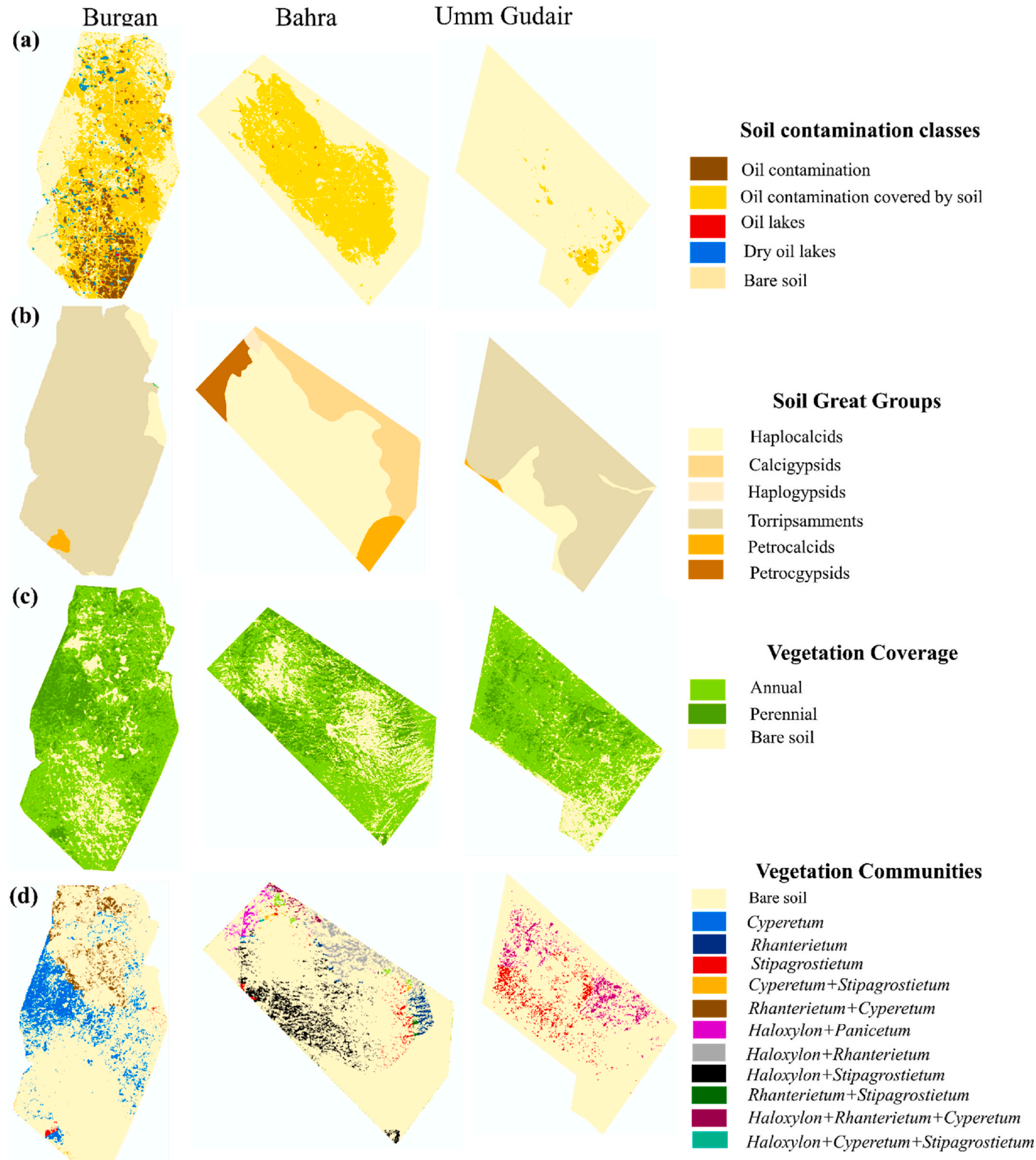

Fig. 5. Layers for the investigated areas, a) Soil contamination classes, b) Soil great groups, c) vegetation coverage including annual and perennials, and d) Vegetation communities.

directly over oil contamination (4.2%), and 4.5% of annual plants over contaminated Petrocalcids soils.

The distribution of perennial plants differed according to soil type (Fig. 5). It was found that some perennial species grew at oil-contaminated sites. *Haloxylon* and *Stipagrostis* communities were only able to grow on oil-contaminated sites covered with Haplocalcids soil (covering 6% of the contaminated areas). Subsequently, the *Cyperus* community covered 2% of *Torripsamment* soils exposed to oil contamination, and 4.5 of the community coverage grew on oil-contaminated Petrocalcids soils. It was indicated that *Stipagrostietum* could only grow on Petrocalcids soil with oil contamination covered with clean soils (2.12%). However, *Rhanterium* communities were found to be present in contaminated Calcigypsid soils, covering 2% of these soils.

5. Discussion

Our results provide evidence that native desert plants can grow more effectively in certain types of hydrocarbon-contaminated soils. It was found that tarcrete-contaminated soils have high potential to support the growth of native desert plants. This type of hydrocarbon-contaminated soil is considered a thin-layer mixture of desert sand and gravel combined with oil and soot to form a layer of hardened soil. This type of oil contamination covers a large area of Kuwait. According to Kalander et al. (2021), the surface and sub-surface soils below the tarcrete layer are not polluted, which could support the growth of native desert plants as they grow within the cracks of these layers. The growth of vegetation over the tarcrete could more likely be related to the high soil moisture beneath the tarcrete layers, as they play a significant role in decreasing evaporation and evapotranspiration rates, providing a higher moisture content for plant uptake. However, the results indicate that it is difficult for native desert plants to grow over oil lakes. The results showed a deficiency in the survival levels, as the depth of the oil lakes could range from 2 to 6 m, making it difficult for many perennial plants to grow over these areas. However, the results showed that annual plants might grow around these lakes, which is more likely related to the mixture of moist soils and oil around the lakes, the tiny root systems of annual plants, and the high soil moisture content. Annual plants could also be more suitable to grow over soil layers covering oil contamination due to the tiny root systems, unlike perennial plants that could grow over oil contamination due to longer and deeper root systems, reaching $>$3 m (Kirschner et al., 2021) (see Fig. 6).

Even though native desert plants are able to grow over tarcretes because they are less contaminated than oil lakes, it is important to keep in mind that the level of disturbance is not the only factor that reflects the recovery speed of native desert plants. Our results show that autogenic recovery of native plants occurred at the study sites. However, plant growth varied across these sites; vegetation coverage was higher at the Burgan and Umm Gudair sites than at the Bahra site, which showed a lower growth rate. These results are interesting because the contamination rate was higher at the Burgan field, including oil contamination and wet-oil lakes, providing a clear indication that the degree and level of contamination are not the only factors influencing the growth of native desert plants.

Our results also show that climatic variables and soil physical properties of the site play a major role in the reduction of hydrocarbon contaminants and support the recovery of native plants. Climatic variables significantly influenced the reduction of oil contamination in the soil and supported vegetation growth. The high temperatures in Kuwait, especially during the summer season, could significantly decrease oil contamination in the soil. The results showed that maximum temperature was significantly correlated with the reduction in hydrocarbon contamination, which is more likely related to the high temperature of the country during the summer season ($>$40 °C). These results agree with previous studies, which found that temperature plays a vital role in reducing hydrocarbon contamination, as it affects the solubility of hydrocarbons (Das and Chandran, 2011). Biodegradation of hydrocarbon contamination in the soil ranges from 30 to 40 °C. Stetter (1998) also found that high temperatures could increase the biodegradation, as the optimum growth temperature of thermophilic microorganisms is $>$ 40 °C. In contrast, our results indicated that minimum temperature and precipitation play an important role in supporting the growth of native plants over hydrocarbon contamination, as evaporation and evapotranspiration rates significantly decrease with decreasing temperature. A significant relationship was observed between plant growth, minimum temperature, and precipitation.

In addition, the physical characteristics of soils play an essential role in the autogenic recovery of vegetation and this need to be included as a factor when assessing the recovery of native desert plants in contaminated soils. It was also observed that specific soil types at the contaminated sites accelerated the growth of native desert plants. It was found that the highest vegetation cover occurred in Burgan and Umm Gudair, which is more likely related to the presence of *Petrocalcids* soils, which

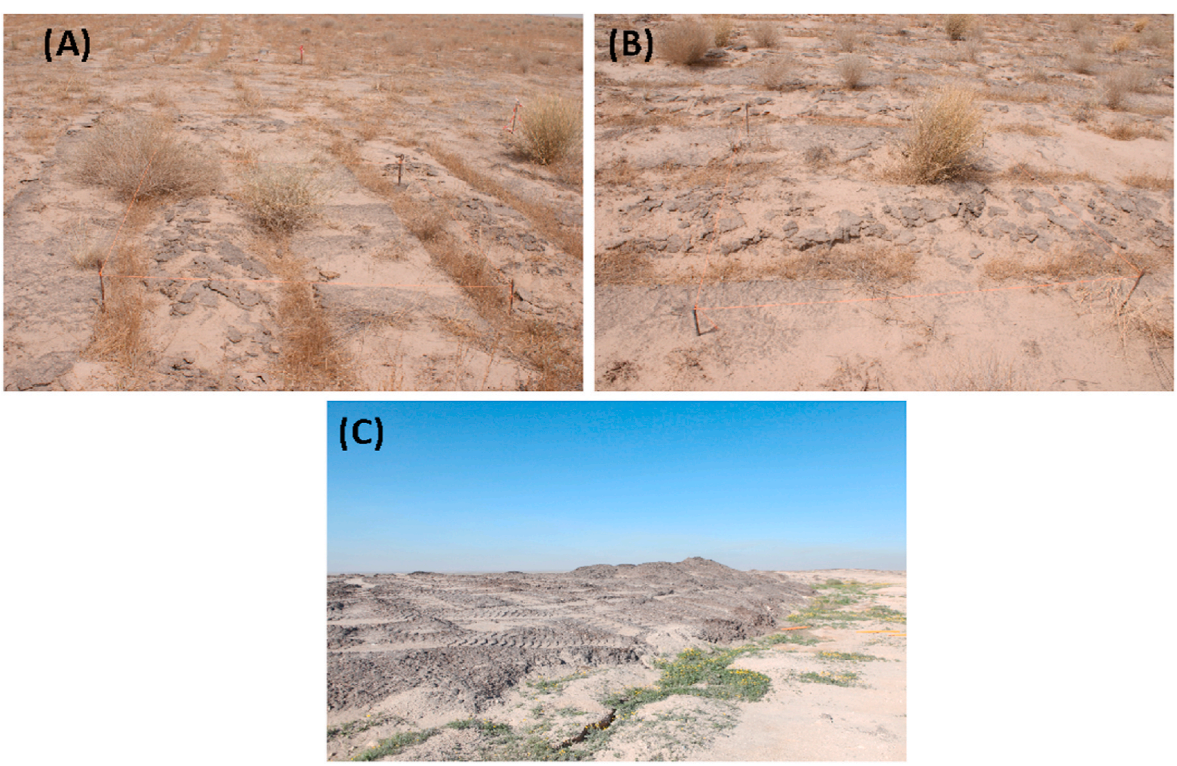

Fig. 6. Growth of native desert plants over hydrocarbon-contaminated soils. (A) and (B) represents the growth of annual and perennial plants over tarcrete contaminants, and (C) represents the growth of annual plants around a dry-oil lake.

are considered the dominant soil type at these sites. Similarly, Abdullah et al. (2020) found that the autogenic recovery of native desert plants occurred in contaminated areas in Kuwait, and native desert vegetation is capable of recovering from this type of contamination. They also found that areas covered by *Petrocalcids* and *Petrogypsids* soils witnessed higher regrowth of native plant cover because these soils can store high quantities of water, which is necessary for plant uptake during dry periods. Petrocalcids are formed through the accumulation of Carbonate $CaCO3$, which can plug the soil pores producing a laminar cap that controls downward soil-water movement (Gile et al., 1966). Duniway et al. (2007) indicated that Petrocalcids have the potential to hold a considerable amount of water in arid regions, especially during drought seasons. However, lands covered with Petrogypsids, which have a layer of gypsum crystals, are mainly used for rangeland grazing as they support the growth of annual plants and hold water (Stetter, 1998; KISR, 1999). Moreover, the presence of annual plants is mainly related to *petrocalcids* soil, as loamy and sandy loam soils on the sub-surface play a significant role in supporting the growth of annual plants. It is important to consider that the high density of annual plants could significantly decrease evaporation and evapotranspiration rates, providing more water storage for plant uptake. Annual plants could also play a key role in supporting the growth of perennial plants, as the biomass of perennial plants was found to be considerably higher in areas surrounded by annual plants, since the soil moisture content was 50% higher at locations surrounded by annual plants, as well as the concentration of organic matter and phosphorus was 40% higher (Abdullah et al., 2021a).

According to the results of this study, we expect the succession process of vegetation survival and growth in contaminated soils could be associated with three main scenarios. First, certain native desert plants can grow directly in contaminated soil. Previous studies have demonstrated that perennial plants in Kuwait can grow directly from hydrocarbon contamination. Al-Ateeqi et al. (2021) found that several desert plant communities, such as *H. salicornicum, C. conglomeratus*, and *R. epapposum*, thrived in oil-contaminated soils in Kuwait. They displayed the ability to take up PAHs that can potentially serve as effective phytoremediators to clean-up PAH residues from desert soils in Kuwait. Another study found that soil-contaminated sites contain several heavy metals, including chromium III, copper, nickel, lead, zinc, and vanadium. However, the concentration of TPH and heavy metals varied within the types of hydrocarbon contamination, showing a lower concentration at the tarcrete sites, which is associated with the growth of plants at these sites. This indicates that native desert plants can survive over a certain concentration of TPH and heavy metals, which also varies according to the type of plant. For example, a previous study indicated that tissues of native desert plants in Kuwait accumulated some PAHs, which mainly depend on the type of species and specific PAH compounds. For instance, *H. salicornicum* species have been found to grow in areas with PAHs >200 μg kg $^{-1}$. Another scenario of the succession process of vegetation survival and growth could be interlinked with vegetation growth on a clean sediment layer covering the oil layers (Abdullah et al., 2020). Finally, massive remobilization of sand sheets occurred in many contaminated sites in Kuwait, could be playing a major role in supporting the growth of native desert plants over these soil layers (Koch and El-Baz, 1998). For instance, vegetation can grow over Nabkhas (phytogenic hillock), which is considered an aeolian sediment, accumulating organic matter, plant seeds, and dust particles that create layers of nutrient-rich soil for the initial growth of plants (Al-Dousari et al., 2008; El-Sheikh et al., 2010).

5.1. Research limitations and future research plans

Our work provides an observational analysis of the recovery of native desert plants from different types of hydrocarbon-contaminated soils using remote sensing techniques. This study showed that remote sensing techniques using satellite imagery provided critical ecological information on the succession process of native desert plants over hydrocarbon-contaminated soils. The method and indices utilized in this study could also help to investigate the vegetation response to hydrocarbon contamination in similar regions. However, our study did not provide detailed quantitative explanations of the interactions between vegetation, oil, soil, water, and the atmosphere. Providing a detailed quantitative description is difficult in this work because of the medium resolution of satellite imagery and because the oil spills occurred in 1990, making it impossible to consider field data collection. Thus, we believe that future studies should focus on building a quantitative relationship between the processes of natural systems by integrating field-based experiments and spatial analysis using modern remote sensing technologies. We believe that integrating Unmanned Arial Vehicles (UAVs) and field-based experiments in future studies could provide more detailed information on the ecological process because of the very high resolution of these images. Additional studies are needed to consider plant physiology and enhance rhizosphere remediation to shed further light on the effectiveness of native desert plants in remediating contaminated soils in arid and semi-arid ecosystems.

6. Conclusion

Our work demonstrated the power of the integrated method using remote sensing techniques to improve our understanding of vegetation recovery over hydrocarbon-contaminated soils for a relatively large area when there are limited historical data available for reference. Our results indicate that certain native desert plants can grow under soil hydrocarbon contamination. However, to implement proper restoration and revegetation programs, the selection of revegetated plants needs to be based on the type of hydrocarbon contamination and the combination of physical soil characteristics and climatic factors. Exploring the relationships among these factors will improve our understanding of the succession process of native desert plants. Such knowledge will also help us determine favorable ecological conditions for different native plants, which will accelerate the succession process and reduce the chances of failure of revegetation. It is also essential to consider tarcrete-contaminated areas in restoration and revegetation planning because they showed a higher plant recovery, which is more likely related to the uncontaminated sub-surface soils and higher quantity of water moisture content. Nevertheless, further studies should be conducted to quantify the mechanisms of vegetation succession by developing a quantitative characterization of the interactions between native desert plants and environmental factors. Future studies should focus on explaining the role of annual plants and how they interact with perennial plants. We also believe that utilizing UAVs in future research could provide more detailed information regarding the recovery of native desert plants owing to their very high spatial resolution.

Credit author statement

Meshal Abdullah: Conceptualization, Visualization, Methodology, Data Collection, Data Analysis, Writing - Original Draft. Zahraa Al Ali: Conceptualization, Methodology, Data Analysis. Ammar Abulibdeh: Visualization, Writing and Reviewing. Midhun Mohan: Visualization, Writing- Reviewing and Editing. Shruthi Srinivasan: Writing- Reviewing and Editing. Talal Al-Awadhi: Writing- Reviewing and Editing.

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.

Data availability

Data will be made available on request.

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