



Mangrove health along the hyper-arid southern Red Sea coast of Saudi Arabia

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Abstract Changes in land use and land cover have severely influenced the sustainability of mangrove vegetation, especially in the hyper-arid, hyper-saline Red Sea coastal waters of Saudi Arabia. The present study investigates the effect of effluents released from an adjoining shrimp farm on the sustainability of a nearby mangrove woodland during operation and after closure of the farm. In addition, the consequences of dredging activities to fill coastal waters for land reclamation to develop a mega seaport at Jazan Economic City are explored. A band image-difference algorithm was applied to Landsat 5 Thematic Mapper and Landsat 08 Operational Land Imager satellite images obtained on different dates, which revealed a prominent vigour boom in the mangrove forest while the shrimp farm operated but a gradual decrease in vigour after its closure. During the investigation time frame of 2016 and 2017, spectral vegetation analysis of Sentinel-2A

satellite images highlighted a strong negative correlation between dredging operations for seaport construction and the adjacent fragile mangrove forest. Dredging operations were responsible for a reduction of 19.30% in the Normalized Difference Vegetation Index, 27.5% in the Leaf Area Index, and 19.0% in the Optimized Soil Adjusted Vegetation Index. The results clearly show the potential application of spectral vegetation indices in the monitoring and analysis of anthropogenic impacts on coastal vegetation. We suggest strong management efforts for monitoring, assessing, and regulating measures to offset the negative trends in the sustainability of mangroves in Red Sea coastal regions.

Keywords Remote sensing · Multispectral · Ecosystems · Coastal wetlands · Mangrove forests · Dredging · Water pollution

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Introduction

Human exploitation of ecological systems has severely compromised their future sustainability. Coastal wetlands provide important ecosystem services for human welfare, including carbon sequestration and flooding resistance (Yang and Guo 2019; Adam et al. 2010; Fisher et al. 2009; Eid et al. 2017). According to the Ramsar Convention, coastal wetlands encompass mangroves, seagrass, swamps, coral reefs, estuaries, shorelines, and coastal water bodies within a depth of 6 m (Romañach et al. 2018). Mangrove wetlands dominate approximately 75% of the world's tropical and subtropical coastlines between

25 °N and 25 °S latitude (Ramsey and Jensen 1996). Numerous studies have used remote sensing techniques to examine mangrove wetlands (Almahasheer 2018; Valderrama-Landeros et al. 2018; Pham et al. 2019; Pastor-Guzman et al. 2018). Notable anthropogenic drivers in coastal swamps include pollution, channelization, dam development, dredging, and the construction of dikes and roads that influence the hydrologic and edaphic states of mangroves (Wemple et al. 2018; Jaramillo et al. 2018; Kamali and Hashim 2011). The Millennium Ecosystem Assessment (MEA) was an international work program intended to address the needs of stakeholders for scientific information related to the consequences of ecosystem changes for human welfare and different alternatives for reacting to these changes (Board 2005). It was a monumental effort produced by more than 1300 researchers. One of the key findings of the MEA was that of 24 ecosystem services, nearly 15 have been seriously destroyed, which will eventually result in extensive and negative effects on human welfare (Board 2005; Fisher et al. 2009).

According to Alatorre et al. (2016), mangrove forests, a key component of coastal vegetation, are among the most undermined habitats. At the turn of the last century, 50% of the world's mangroves had been destroyed for timber harvesting and land reclamation. Rising ocean levels are less troubling for the survival of mangrove forests than their transformation into aquafarms, contamination, and drainage activities (Alatorre et al. 2016; Gilman et al. 2008; Duke et al. 2007). Coastal and riverine dredging practices are playing a major role in the economic and industrial development of numerous countries. Dredging is carried out to construct new and maintaining existing seaside infrastructures, including navigable waterways, harbours, and stream channels (Caballero et al. 2018). Feola et al. (2016) noted that coastal land recovery has raised various types of ecological issues, such as soil erosion and instant pollution of shallow seaside waters, home to the richest marine habitats. Dredging operations also result in the transportation of suspended solids and deposition of sediments as a dredging plume, a well-known environmental issue causing irreversible damage to the benthic layer (Feola et al. 2016). Dredging of coastal land reclamation for the formation of harbours, ports, moorings, and loading and unloading facilities and deep channels for navigation and industry ruins mangrove forests in wetland environments (Anonymous 1983). As indicated by Paling et al.

(2003), hydrocarbon spills, hyper-salinity, and erosion are also important factors contributing to mangrove mortality. Ecosystem deterioration is an important environmental concern at the global, regional, and local scales and is mainly influenced by ill-planned land use and land cover (LULC) changes by decision-makers. LULC change analysis is mainly used to assess the anthropogenic degeneration of the environment and to mitigate its unplanned development. Regular monitoring of LULC changes is among the essential responsibilities of local stakeholders to protect and maintain sustainable ecosystems.

In the hyper-arid environment of Saudi Arabia, green vegetation is a precious resource and demands full attention. All available resources should be in place to protect, monitor, and restore the sustainability of mangrove forests along the Red Sea coastal regions, which are facing severe pressure from anthropogenic encroachment. Steps to conserve mangrove wetlands in the hyper-arid environment of the Red Sea coastal regions of Saudi Arabia are therefore urgently needed.

The objectives of this study were to (1) evaluate, using Landsat 5 TM and Landsat 08 OLI high-resolution satellite images, the impact of organic effluents released from a shrimp farm on the sustainability of mangrove forest located in the southwest direction during operation and after closure of the farm and (2) evaluate the use of vegetation indices (VIs) to assess the impact of dredging and filling of coastal waters to reclaim land for developing a mega seaport at Jazan Economic City (JEC) on the mangroves located on its northeast side using Sentinel-2A high-resolution satellite data. The time frame for studying the impact of the shrimp farm on the mangroves was between 1985 and 2010 and 2010–2015, whereas the time period for studying the influence of dredging operations on mangroves was between 15 March 2016 and 21 October 2017. During the study period of 1985–2010, a substantial positive trend in the mangrove's land cover was observed due to the release of organic effluents from the shrimp farm. This study is the first in Saudi Arabia to explore the application of image band-difference change detection to evaluate the effect of organic waste released from shrimp farms and spectral vegetation indices to assess the consequences of dredging practices for the surrounding mangrove forest. The results of this study have worldwide applications because they can be extrapolated to similarly high-value ecosystems to mitigate their degradation in other parts of the planet.

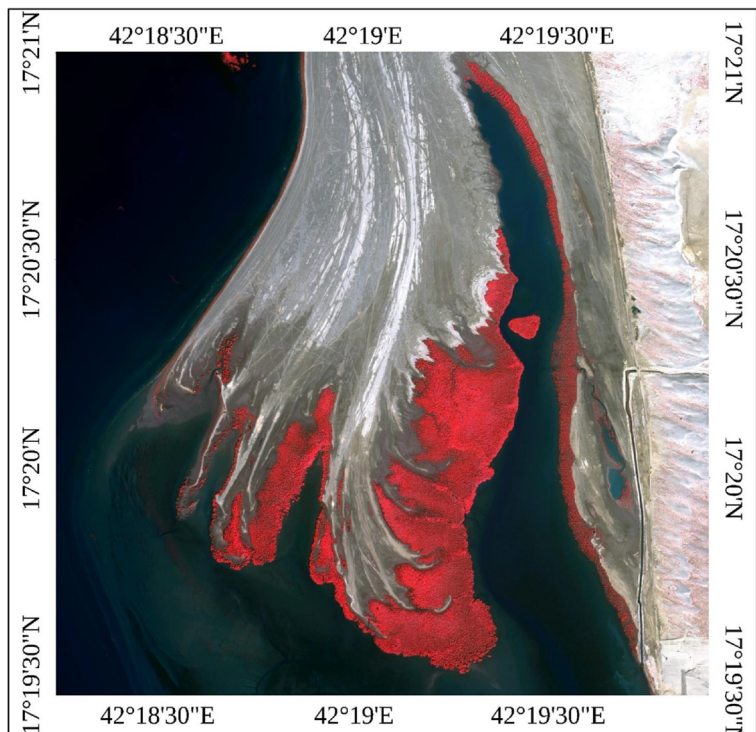
Study area

JEC is situated in the province of Jazan, Saudi Arabia, along the Red Sea coast at Baish, 60 km from the capital city of Jazan in Jazan Province (lat: 17.309, long: 42.376; Fig. 1). In 2006, Saudi Arabia’s government announced the development of JEC as a multi-billion mega industrial city (Arshad et al. 2018). Since its inception, the region has experienced rapid industrial development and the construction of an enormous seaport to accommodate the overwhelming traffic of ships. JEC’s main components include seaport, power and desalination facilities, oil refining, pharmaceuticals, and food processing along with the production of aluminium, steel, copper and agri-tech products (Peterson 2009). The scattered mangrove forests in the study area are mainly *Avicennia marina* (El Juhany 2009) and are situated on the left and right flanks of the seaport (Figs. 1 and 2). These forests are growing in a hyper-arid climate with high salinity (> 40 g L⁻¹) and no river discharges (Almahasheer et al. 2017). The yearly mean precipitation in the area varies between 2.8 and 22.3 mm year⁻¹ with temperatures surpassing 45 °C.

Materials and methods

Remote sensing applications have been widely utilized for the estimation of manmade changes in mangrove forests (Conchedda et al. 2008; McCarthy et al. 2018; Otero et al. 2018; Kirwan and Megonigal 2013). The main advantage of remote sensing over conventional procedures is that it is quick and cost effective for observing the spatial extent and temporal distribution of mangrove ecosystems by utilizing historical and recent satellite images (Alatorre et al. 2016; Lee and Yeh 2009; Jensen et al. 1991; Pasqualini et al. 1999). Recent advances in spectral resolution and multispectral satellite sensors have enabled the calculation of numerous important spectral vegetation indices (e.g. French SPOT 6 and 7, Korean KOMPSAT 3 and 3A, European Space Agency Sentinel-2 and -3, and Landsat 8 of the USA). Scientists were previously restricted to the use of broadband spectral indices that grouped wavelengths in the regions of blue, green, red, and near-infrared to study the overall abundance of vegetation, burned areas, water, and other features of interest (e.g. Thenkabail and Lyon 2016; Delegido et al. 2015; Eitel et al. 2011; Plourde et al. 2007; Fernández-Manso et al. 2016; Hawbaker et al. 2017).

Fig. 1 False colour GeoEye-1 image of healthy mangrove forests at JEC, Baish, Saudi Arabia



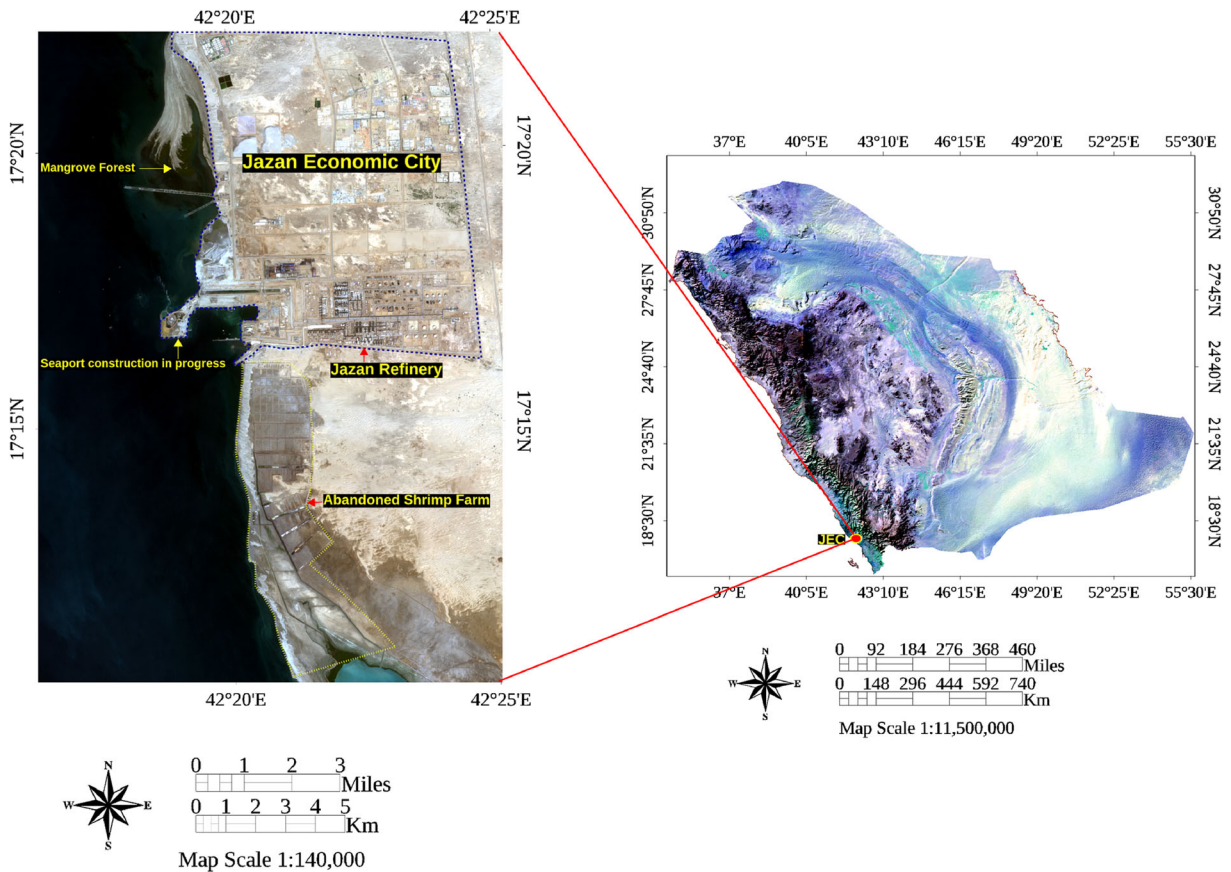


Fig. 2 Jazan Economic City at Baish on the southern coast of Saudi Arabia

Recent advances in spectral resolution have allowed scientists to use narrowband spectral indices that combine explicit mixtures of wavelengths to examine the quantity of photosynthetic material in vegetation, for example, nitrogen concentration and canopy water content in vegetation (e.g. Berni et al. 2009; Haboudane et al. 2002; Mutanga and Skidmore 2004). One widely utilized VI is the normalized difference vegetation index (NDVI), which is a measure of healthy vegetation. NDVI values range between -1 and 1 , and the common range of NDVI for green vegetation is 0.2 to 0.8 . The soil adjusted vegetation index (SAVI) is similar to NDVI but suppresses the effects of soil pixels. The optimized soil adjusted vegetation index (OSAVI) is best used in areas with relatively sparse vegetation, where soil is visible through the canopy. The leaf water content index (LWCI) is used to monitor the state of vegetation growth. The leaf area index (LAI) is mainly used to estimate foliage cover. The burn area index (BAI) is mainly used to highlight areas damaged by fires. The red edge normalized difference vegetation index

(RENDVI) is a modification of NDVI that uses bands along the red edge instead of the main near-infrared and red bands. The plant senescence reflectance index (PSRI) is used to monitor canopy stress. The normalized difference water index (NDWI) reflects water stress in plants. The chlorophyll absorption in reflectance index (CARI) indicates the abundance of chlorophyll in vegetation, and the transformed chlorophyll absorption in reflectance index (TCARI) indicates the relative abundance of vegetation chlorophyll.

In this research, we used NDVI, LAI, and OSAVI to evaluate and confirm our hypothesis that dredging activities have seriously impacted the health of the fragile mangrove's ecosystem. We downloaded and used data from Landsat 5 TM and Landsat 08 OLI available at the USGS website (<http://earthexplorer@usgs.gov>) and Sentinel-2A, which is freely accessible for download at the European Space Agency (ESA) website (<http://scihub.copernicus.eu>). The Landsat 5 satellite carries Thematic Mapper™ and Multispectral Scanner

(MSS) sensors and offers the longest operating Earth remote sensing mission in the history of satellites (Zhang and Roy 2016). On 23 June 2015, ESA launched its first Sentinel-2 polar-orbiting satellite as part of the Copernicus Earth observation program for studying Earth’s surface. The satellite circles around Earth at a distance of 786 km and has a swath width of 290 km (ESA 2015; Du et al. 2016). As indicated by the program, a couple of satellites are intended to procure reflected sunlight in the optical wavelengths. These wavelengths are particularly sensitive to variations in vegetation status and are incredibly valuable for studying crops and forests. The downloaded Sentinel-2 images are an orthorectified, top-of-atmosphere (level 1C), 100 km × 100 km in UTM/WGS84 projection with 13 spectral bands in the visible (VIS), near-infrared (NIR), and short-wave infrared (SWIR) regions (Table 1). Sentinel-2 images have 4 bands at 10 m, 6 bands at 20 m, and 3 bands at 60-m spatial resolutions (Table 2). As reported by ESA (2015) and Drusch et al. (2012), the level-1C product has been handled for radiometric and geometric corrections, including orthorectification and spatial registration on a worldwide reference system with subpixel accuracy. However, frequent cloud cover in the study area greatly reduced the number of images for exploitation.

Table 1 Wavelengths and bandwidths of MSI instrument spatial resolutions on the Sentinel-2 satellite system (retrieved from the earth.esa.int website)

Spatial resolution (m)	Band number	Central wavelength (nm)	Bandwidth (nm)
10	2	496.6	98
	3	560.0	46
	4	664.5	39
	8	835.1	133
20	5	703.9	20
	6	740.2	18
	7	782.5	28
	8a	864.8	32
	11	1613.7	141
60	12	2202.4	238
	1	443.9	45
	9	945.0	27
	10	1373.5	76

In order to accomplish the study objectives, two specific tasks were carried out:

- Pre-processing of data: After download, the Landsat 5 TM, Landsat 08 OLI, and Sentinel-2A satellite images were processed for geometric and radiometric corrections. Atmospheric correction, spectral subsetting, layer stacking, resampling, and masking of the region of interest (ROI) were also carried out. Geometric correction is necessary to increase the similarity of the satellite imagery to Earth’s surface by removing distortions caused by the sensor optics, the speed of the scanning system and the platform, the platform’s elevation, attitude, and terrain relief besides Earth’s curvature and rotation. Radiometric correction enhances the interpretability and quality of satellite data (images) and is helpful when comparisons between temporal datasets are needed. Atmospheric correction is an important pre-processing step of satellite images that must be performed to remove erroneous effects of the atmosphere from the satellite images where temporal comparisons are to be made.
- Data analysis: An image differencing technique based on spectral differences was carried out to classify pixels between the two dates of satellite images. To assess the mangrove’s dynamics in response to the shrimp farm and dredging activities for seaport construction at JEC, we used spectral vegetation indices (SVIs) such as NDVI, LAI, and OSAVI for the delineated regions of interest.

For the time frame between 1985 and 2010, only Landsat 5 TM images were used to judge the impact of the shrimp farm on the nearby mangroves. For the time period between 2010 and 2015, Landsat 05 TM and Landsat 08 OLI satellite images were also used. However, to evaluate the impact of dredging for seaport construction on mangroves, we used the high-resolution Sentinel-2A satellite images.

Of the 13 Sentinel-2 spectral bands, only eight bands (B2, B3, B4, B5, B6, B7, B8, and B8a) were layer stacked, and bands B5, B6, B7, and B8a were resampled to a pixel size of 10 m. The images were atmospherically corrected using the Quick Atmospheric Correction (QUAC) algorithm in ENVI software to obtain ground-level reflectance images (level 2A) and, shown in Fig. 6, subsetting to (a) delineate mangrove forest alongside JEC, (b) delineate

Table 2 List of Sentinel images used in this study

Mission	Product	Observation date	Spatial resolution resampled (m)	Swath width (km)
Sentinel-2A	Multispectral image Level-1C	15 March 2016	10	100
		21 October 2016		
		29 January 2017		
		21 October 2017		

land recovered for development of the industrial seaport, and (c) show the seabed dredged to permit heavy ships for transportation activities of crude petroleum and various raw materials to and completed products from Jazan refinery and other heavy and medium industries. The outcomes of this study can be extended to the examination and restoration of mangrove wetlands at other regional and global locations.

Results

In the study area, the dominant species of mangroves is *A. marina*, with a total coverage of not more than

600 ha in the immediate vicinity of JEC. In some areas, the height of the mangroves reaches 2 m. Figure 1 shows a false-colour image of healthy mangroves surrounded by the pristine Red Sea coastal waters before the ground-breaking of JEC in 2006. A newly manmade seaport at JEC (Fig. 2) was dredged to allow transportation of various goods and raw materials for processing in different industries, including crude petroleum for the Jazan refinery, and back into national and international markets after treatment into finished products. Application of the image differencing change detection technique (see Figs. 3c and 4c) clearly revealed the differences due to the opening and closure of the shrimp farm. Mangroves were lean in the LandsatTM-05 image

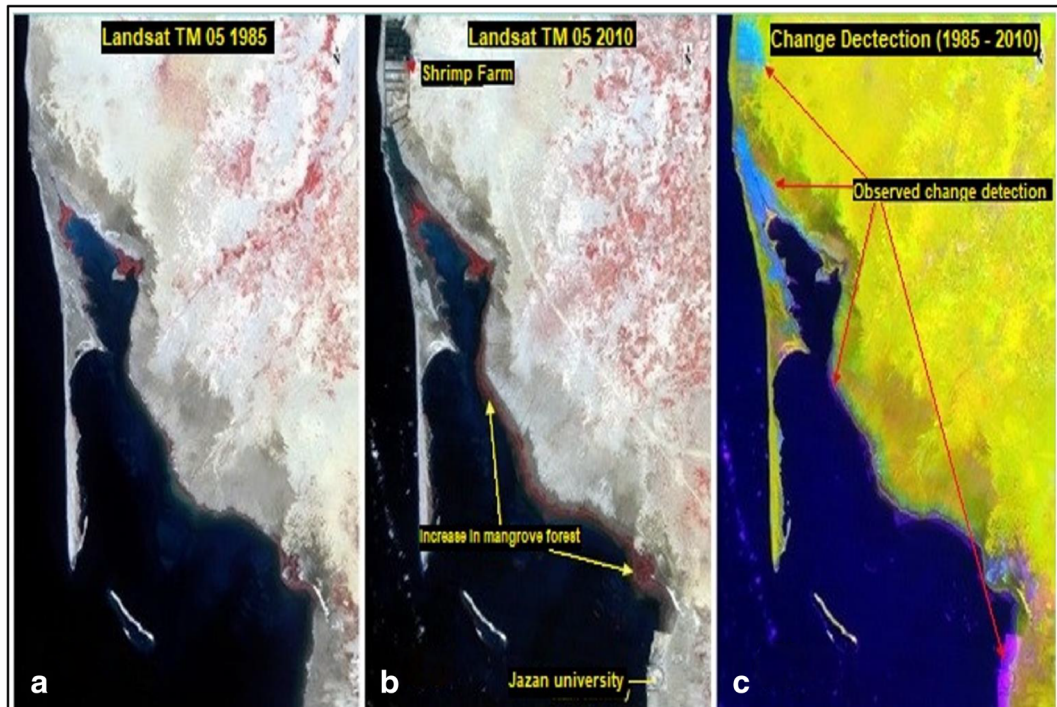


Fig. 3 Landsat TM 5 change detection image showing an increment in vegetation biomass due to the release of organic materials from the recently built shrimp farmland

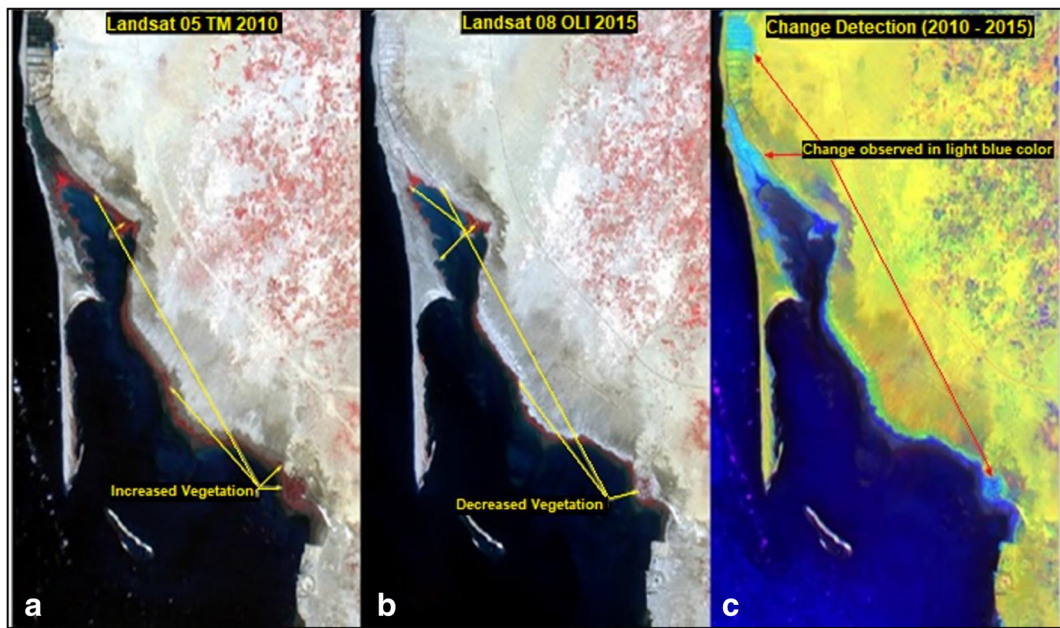


Fig. 4 Landsat 5 TM change detection image showing a decrease in vegetation biomass due to stoppage of the release of organic materials from the abandoned shrimp farmland

captured in 1985 (see Fig. 3a). However, the LandsatTM-05 image captured in 2010 (see Fig. 3b), after the shrimp farm began disposing of its organic waste into the Red Sea coastal waters, shows that the mangroves reacted vigorously to the organic release, with improved photosynthetic activity of neighbouring mangroves over a vast length and the development of eutrophic conditions.

However, during 2010–2015, after closure of the shrimp farm, a significant negative trend in mangrove land cover can be observed based on the application of the image differencing change detection algorithm (see Fig. 4c). In 2015, as shown in the Landsat 08 OLI image in Fig. 4b, when the loadings of organic waste ceased due to closure of the shrimp farm, the photosynthetic activity of the mangroves also decreased. The soil sediment plume due to dredging operations for seaport development is also evident in Figs. 5 and 6. In the images from March 2016 and October 2017, severe soil erosion is apparent due to the dredging operations for seaport construction (Figs. 5 and 6). Table 3 presents the decreases in the values of NDVI, LAI, and OSAVI.

Discussion

Failure to implement prompt and proper mitigation measures to protect mangrove forests may lead to irreversible damage to the mangrove forests in the study area and its surrounding areas along the Red Sea coast. As indicated in Rogers et al. (2016), the most significant anthropogenic processes contributing to the loss of saline coastal wetlands are land reclamation and drainage. Numerous analysts (e.g. Proisy et al. 2018; Ahmed and Thompson 2019; Islam and Tabeta 2019; Jayanthi et al. 2018) have observed that the tremendous development of shrimp farms business is another anthropogenic menace to mangrove forests. SVIs, particularly those in the visible and near-infrared areas of the electromagnetic spectrum, are employed to assess vegetation health (Viña et al. 2011). Overall decreases in NDVI, LAI, and OSAVI are shown in Fig. 7. The Sentinel-2 images for the time frame from March 2016 to October 2017 revealed a noticeable decline in the values of NDVI, LAI, and OSAVI, highlighting the poor health of the mangrove forest due dredging operations for seaport development (Figs. 7, 8, 9, and 10).

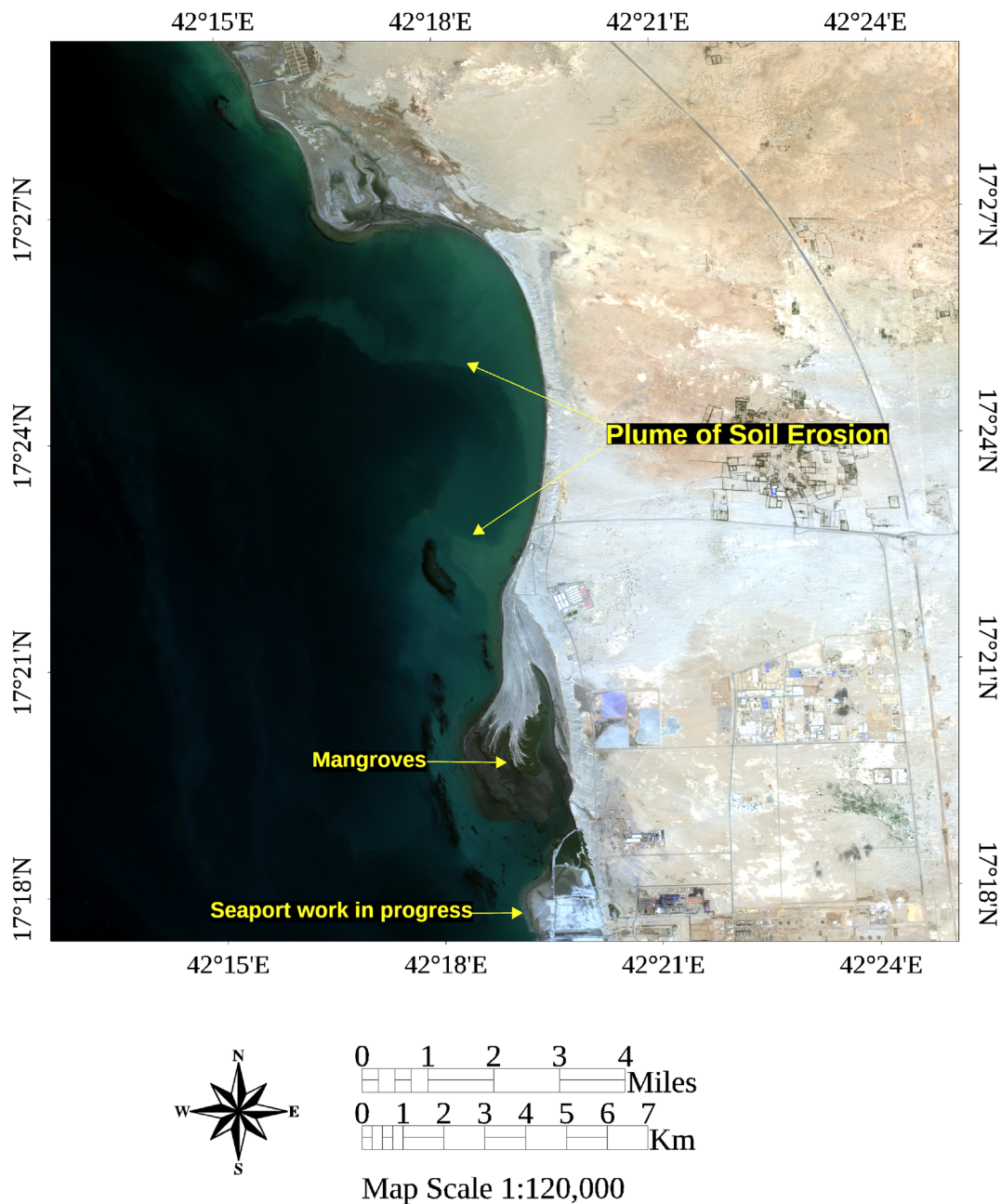


Fig. 5 Sentinel-2A image captured in March 2016 (10 m pixel size). A soil sediment plume is seen due to dredging activity at the seaport building site

NDVI is commonly used to provide estimates of aboveground biomass, primary productivity, and wetland species distribution and to assess the impacts of anthropogenic activities and episodic events (Suir and Sasser 2019a, b). Comparison of Fig. 8 a and d reveals a decrease in NDVI from 0.83 to 0.67,

corresponding to a total loss of greenness of 19.28%. The most likely reason for this decrease in NDVI is the colossal influx of soil sediments from dredging operations for land recovery and seaport development. NDVI is a vigorous remote sensing indicator of vegetation health, and a reduction in

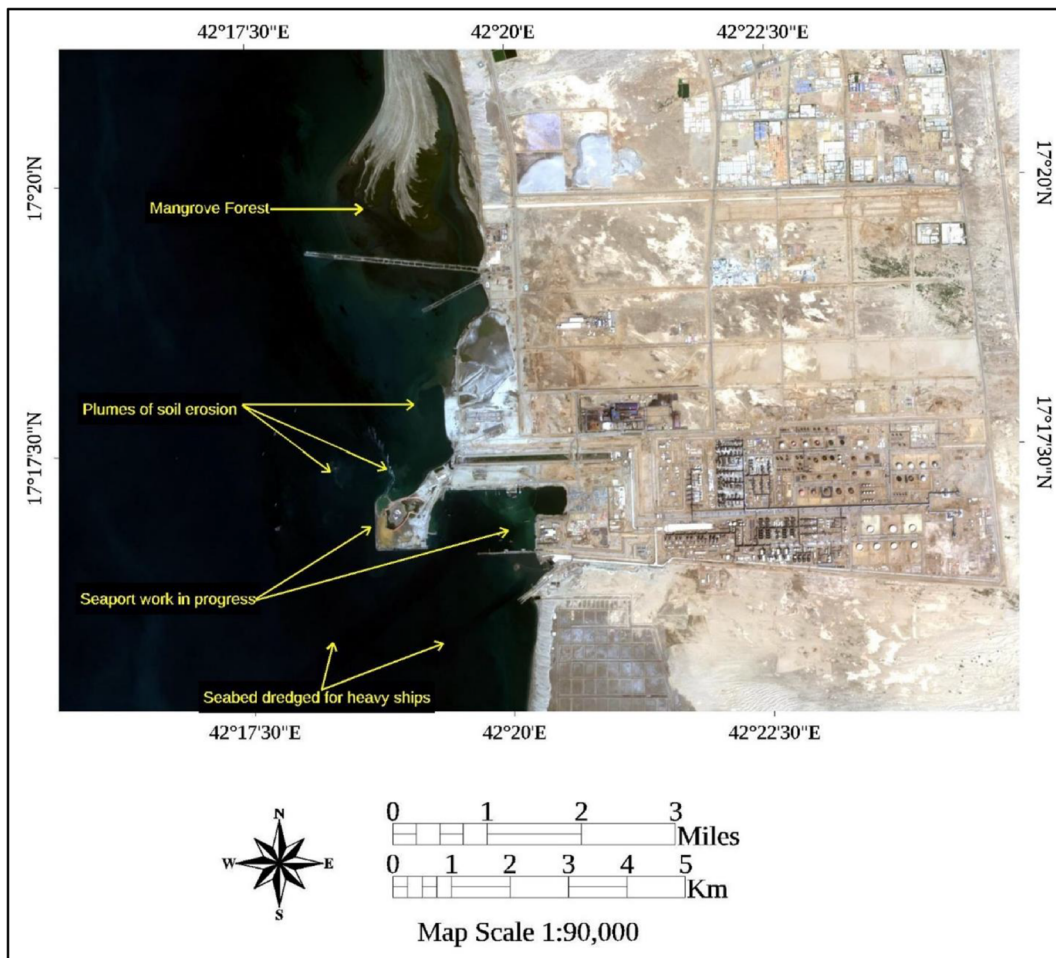


Fig. 6 Sentinel-2A image captured in October 2017 (10 m pixel size) showing a severe rise in turbidity and siltation caused by dredging activities for land reclaimed for seaport construction near the mangrove forest

the NDVI strongly indicates a decrease in vegetation greenness in ecological examinations of mangroves (Alatorre et al. 2016). Our assessment confirms this relationship. Since the relationship between remote

sensing indices and environmental factors takes into consideration a productive assessment of the basic environmental response, it can be utilized for coastal planning and management (Alatorre et al. 2016).

Table 3 Results of normalized difference vegetation index (NDVI), leaf area index (LAI) and optimized soil-adjusted vegetation index (OSAVI)

	Month/years				
Vegetation indices	15 Mar 2016	21 Oct 2016	29 Jan 2017	21 Oct 2017	Percent decrease
NDVI	0.83	0.74	0.73	0.67	19.28
LAI	2.0	1.76	1.63	1.45	27.5
OSAVI	0.58	0.52	0.53	0.47	19.0

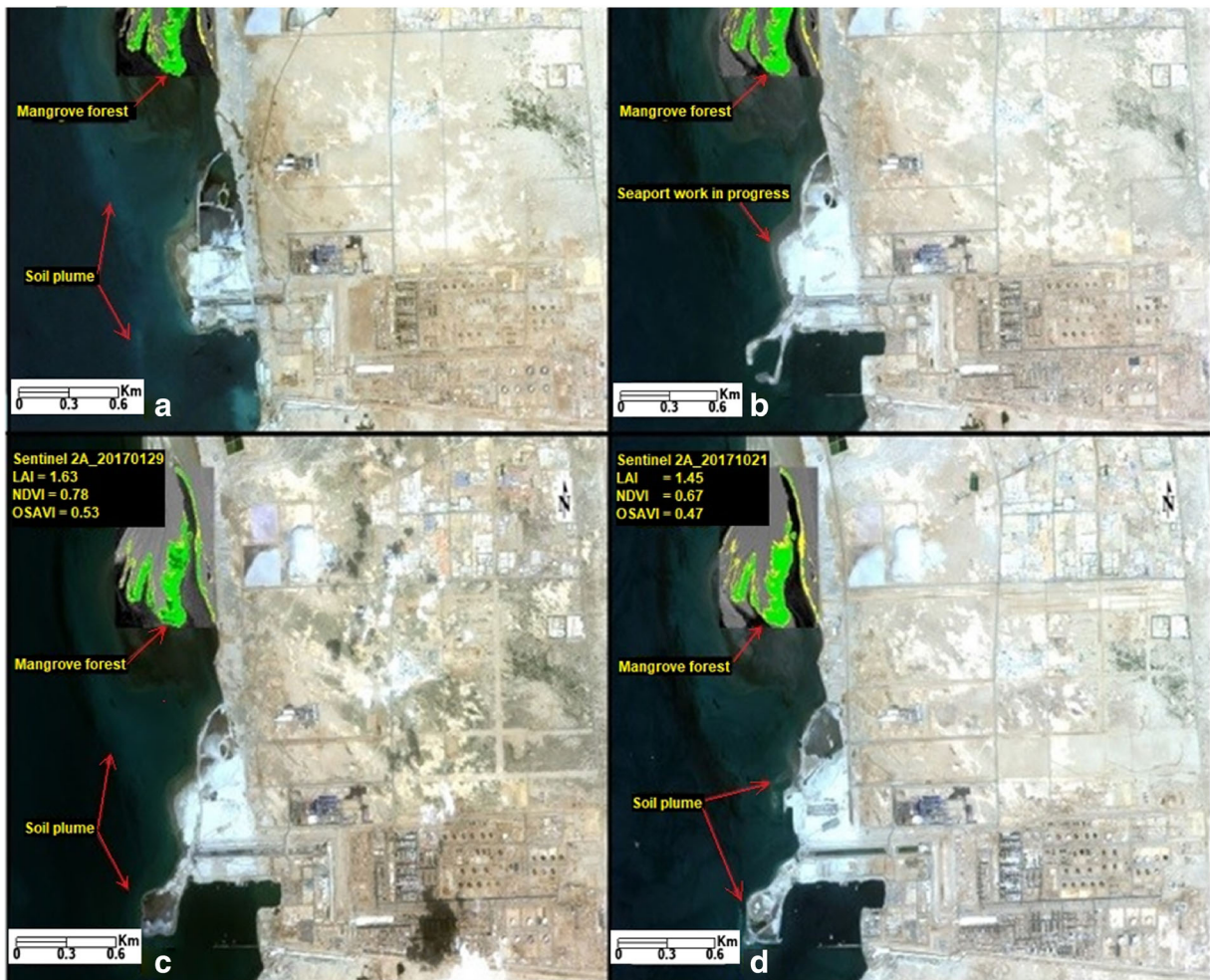


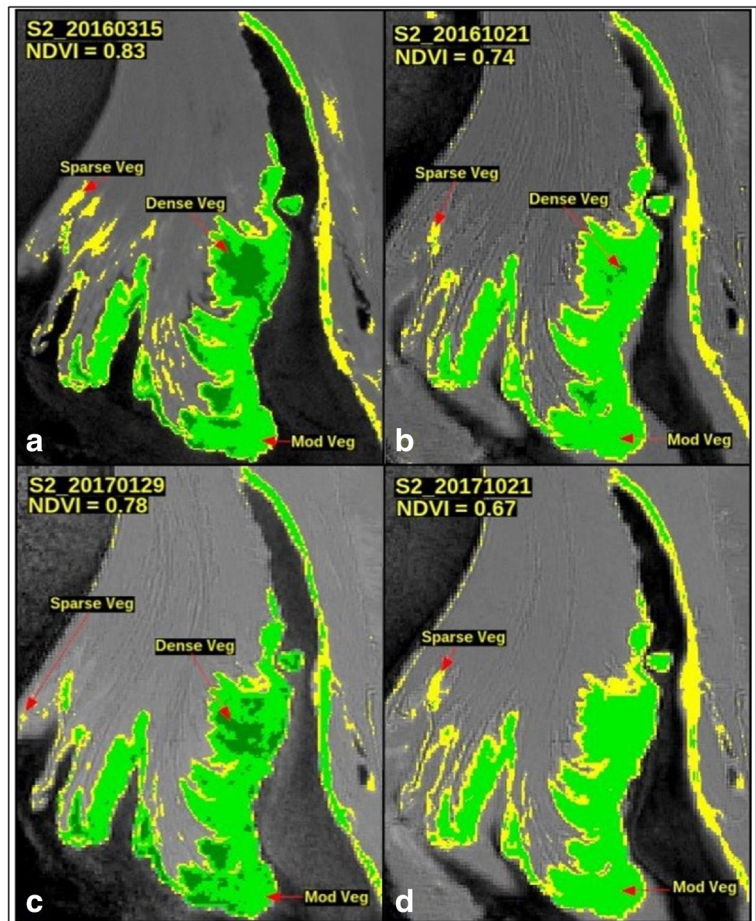
Fig. 7 Decreases in NDVI, LAI, and OSAVI on different dates of Sentinel-2 images due to the release of soil sediments by the dredging operation for seaport construction can be clearly observed

Similarly, comparing Fig. 9 a and d shows a decrease of 27.5% in LAI, and comparing Fig. 10 a and d highlights an overall loss of 19.0% in OSAVI. Major ecological problems originate because of soil erosion and sedimentation caused by landfill and dredging activities, resulting in loss and degeneration of productive coastal habitats (Khalil 2004). Excessive sedimentation caused by dredging operations is also detrimental to mangroves by blocking the exchange of water, nutrients, and gases within the base and overlying water. When exchange is completely blocked, mangroves die within a period of days (Anonymous 1983). Partial blockage of exchange imposes stress on mangroves, which

indisputably reduces productivity and survival (Anonymous 1983).

Another index of significance in vegetation studies is LAI. Figure 9 shows a clear reduction in the LAI of the mangroves due to dredging operations. The measure of foliage in the plant canopy is an essential ecological characteristic that is usually estimated by LAI (Breda 2008). LAI is also used to monitor changes in canopy structure due to contamination and environmental change (Green et al. 1997) and is frequently employed to survey forest health status, supplement supply, and aboveground biomass (Gitelson et al. 2003). Researchers have observed strong correlations of NDVI with LAI,

Fig. 8 Decreases in NDVI on different dates of Sentinel-2 images due to the release of soil sediments by seaport construction can be clearly observed



vegetation biomass, and green cover (Suir and Sasser 2019a, b9; Huemmrich et al. 1999; Myneni et al. 1996; Chaurasia et al. 2006; Chen et al. 2006; Davi et al. 2006; Heiskanen 2006; Lee and Yeh 2009; Jensen 2007). As indicated by Pettorelli et al. (2005), regardless of the established utility of NDVI in many ecological studies, in certain circumstances, other vegetation indices may be more appropriate. Asrar et al. (1984) showed that NDVI is primarily impacted by soil reflectance in areas where LAI is under 3 (sparsely vegetated). By contrast, the relationship between NDVI and the near-infrared (NIR) saturates when LAI is greater than 6 (densely vegetated). The diminishing pattern of LAI estimates shown in Fig. 9 implies that the higher quantity of sediments arising due to dredging operations is stressing the health of mangroves, as observed by Anonymous (1983), by preventing the exchange of water, nutrients, and gases inside the benthic locale.

According to Fang and Liang (2008), leaf surfaces are the essential borders of vitality and mass exchange, and important processes, for example, evapotranspiration, canopy interception, and gross photosynthesis, are directly proportional to LAI. However, because of the saturation of NDVI at high LAI, this relation may be disrupted (Wang et al. 2005). In semi-arid regions, NDVI produces biased estimates of green biomass and vegetative cover, as these areas are mostly sparsely vegetated and feature sandy soils (Bowers and Hanks 1965; Huete 1988; Gu et al. 2008). Baret et al. (1993) and Rondeaux et al. (1996) examined the sensitivity of some VIs to soil background by simulating the performance of VIs for various soil surfaces, moisture levels, and roughness utilizing the Scattering from Arbitrarily Inclined Leaves (SAIL) model. They built up OSAVI to minimize the variation of soil background. They recommended an ideal SAIL value of 0.16 to diminish the impact of soil background.

Fig. 9 Decreases in LAI values on different dates of Sentinel-2 images due to the release of soil sediments by seaport construction are shown

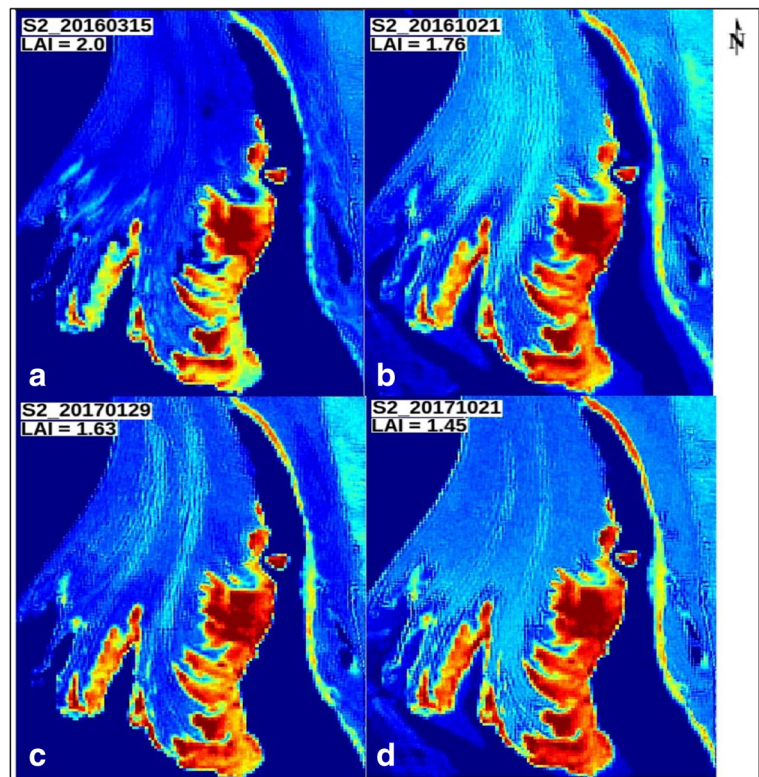
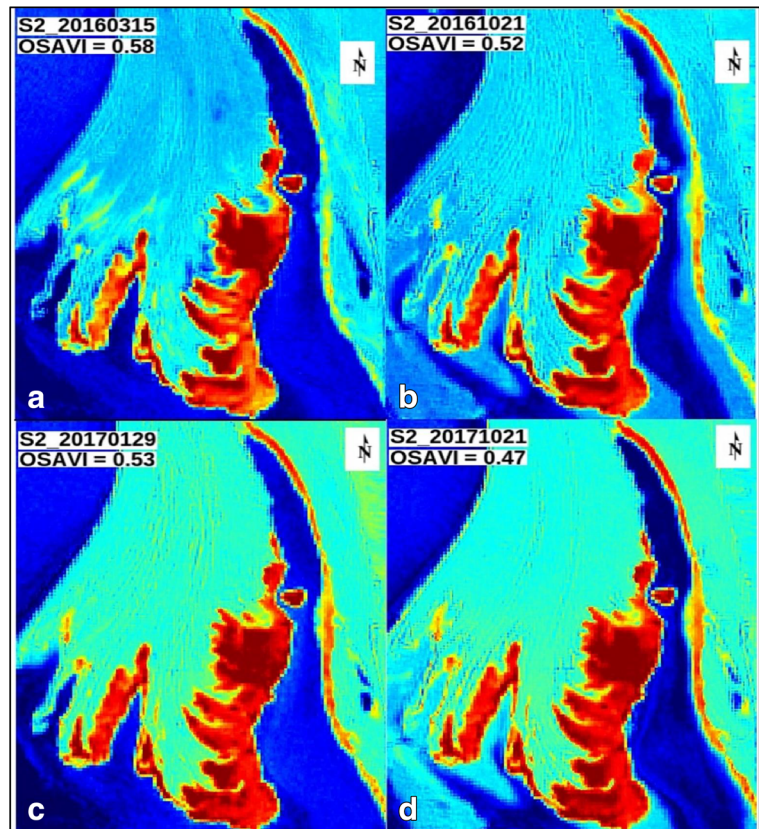


Fig. 10 Decreases in OSAVI values in different Sentinel-2 images due to the release of soil sediments by seaport construction can be clearly observed



As indicated by Haboudane et al. (2002), the application of OSAVI is very relevant in locations where earlier information about moisture status and true soil properties is not available. To decrease the effect of soil background, OSAVI was evaluated to assess the impact of dredging activities on the health of the mangrove woodland. Figure 10 indisputably shows a decrease in OSAVI from March 2016 through October 2017, indicating a negative effect of dredging operations on the vigour of the mangrove woodland. All of the above-expressed VIs have been effectively used in research on the negative effects of dredging operations on the soundness of mangrove forests. The key information that can be derived from the results of crucial VIs is that dredging operations for seaport construction are the main reason for the deterioration of forest health.

Conclusion

With advances in hyper-spectral and multispectral remote detecting procedures, numerous valuable VIs have been created and applied to extract meaningful results. This study presents an evaluation of the impact of the release of shrimp farm organic wastes and soil erosion in coastal waters resulting from dredging practices for seaport construction on the sustainability of mangrove forests in the hyper-arid coastal wetlands of Saudi Arabia. The optical VIs provide an important assessment of the negative impact of the dredging operations on the physiological status of mangrove forests in the vicinity of JEC. Based on the results, we strongly recommend that local stakeholders adopt geospatial procedures using relevant vegetation indices to assess, monitor, and preserve the ecological environment surrounding mangrove forests.

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